PRINCIPLES OF RADIO

FOURTH EDITION

By KEITH HENNEY

AVERAGE CHARACTERISTICS

AMPLIFIERS, DETECTORS,

Tube Type	Purpose	Cathode Type	Filament	
			Volts	Amp
1C5	Power amp. pentode	Filament	1.4	0.1
1S4	Power amp. pentode	Filament	1.4	0.1
2A3	Power amp. triode	Filament	2.5	2.5
6C5	General purpose	Heater	6.3	0.3
6F6	Power amp. pentode	Heater	6.3	0.7
6K7	Super-control amp.	Heater	6.3	0.3
6L6	Beam power tube	Heater	6.3	0.9
6SF5	High-mu triode	Heater	6.3	0.3
6S7	Super-control amp.	Heater	6.3	0.15
6T7	Diode-triode	Heater	6.3	0.15
35L6	Beam power tube	Heater	35	0.15

RECTIFYING TUBES

Tube Type	Purpose	Filament Volts	Amp	Typical Operating Conditions	
				A-c voltage per plate, rms	D-c output ma
1-V	Half-wave	6.3	0.3	325	45
5U4-G 5Z3 5X4-G	Full-wave	5.0	3	450	225
5V4-g	Full-wave	5.0	2	500	175
5Y3-G 80	Full-wave	5.0	2	500	125
12Z3	Half-wave	12.6	0.3	235	55
25Z5	Rectifier-doubler	25.0	0.3	235	75 per plate

—RECEIVING TUBES

OSCILLATORS, ETC.

Plate		Screen Volts	Grid Volts	Plate Resistance, Ohms	Transconductance	Mu	Power Output, Watts	Load Resistance, Ohms
Volts	Ma							
90	7.5	90	− 7.5	115,000	1550	.....	0.240	8000
45	3.8	45	− 4.5	0.25 meg.	1250	.....	0.065	8000
250	60	...	−45	800	5250	4.2	3.5	2500
250	8	...	− 8.0	10,000	2000	20	.....	....
250	35	250	−16.5	80,000	2500	.....	3.2	7000
250	7	100	− 3.0	0.8 meg.	1450	.....	.....	....
250	76	250	−14.0	22,500	6000	.....	6.5	2500
250	0.9	...	− 2.0	66,000	1500	100	.....	....
250	8.5	100	− 3.0	1 meg.	1750	.....	.....	....
250	1.2	...	− 3.0	62,000	1050	65	.....	....
110	40	110	− 7.5	13,800	5800	.....	1.5	2500

CONVERTER TUBES

Type	Filament		Plate		Screen		Control Grid, Volts	Plate Resistance, Megohms	Conversion Conductance, Micromhos
	Volts	Amp	Volts	Ma	Volts	Ma			
1A7–G	1.4	0.05	90	0.055	90	0.6	0	0.6	250
1C7–G	2.0	0.12	135	1.3	67.5	2.5	−3	0.6	300
1D7–G	2.0	0.06	135	1.2	67.5	2.5	−3	0.4	275
1R5	1.4	0.05	45	0.7	45	1.9	0	0.6	235
6A8	6.3	0.3	250	1.1	100	1.3	−3	0.36	550
6D8–G	6.3	0.15	250	3.5	100	2.6	−3	0.4	550
6K8	6.3	0.3	250 *	2.5	100	6.0	−3	0.6	350
			100 †	3.8					
6SA7	6.3	0.3	100	3.2	100	8.0	0	0.5	425

* Mixer plate.
† Oscillator plate.

PRINCIPLES OF RADIO

PRINCIPLES OF Radio

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Fourth Edition

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PREFACE

Just thirteen years ago, the first printing of this book appeared. It was originally written for the student who had little background in radio upon which to build and yet who wanted to know the basis upon which radio communication existed. The problem of the student who must do his learning without benefit of a teacher was not forgotten. Every attempt was made to make the text lucid and practical. This viewpoint has persisted through subsequent editions. This, the Fourth Edition, has been brought up to date, new problems have been added, new phases of radio science have taken the places of other phases which have disappeared.

The book has been used in trade schools, for which it was intended, and in colleges for which it was not aimed. The author has resisted the suggestions of college instructors that more mathematics be included, and he has also refused to make it mathematic-less. Only through working problems similar to those that the student will find in practice can the "feel" of radio be found. Little beyond arithmetic or the simplest algebra will be found within these pages—but this much "math" is still there!

In preparing this new edition, the author has not been unmindful of his responsibility. Many men now in uniform will get part of their training from this book; so will many civilians, soon to be in uniform, or soon to carry on the essential radio jobs being vacated by men who are leaving them for their country's sake. The author hopes that the same qualities in this text which have appealed to students using previous editions will help students, military and civilian, in the present situation, and thus in some measure acquit him of his feeling of deep responsibility.

KEITH HENNEY

June, 1942

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CHAPTER I

FUNDAMENTALS

No one can learn a great deal about the theory and practice of radio who does not also know a few fundamental facts about electricity, for radio is but one aspect of a much broader field, electrical engineering. And since electricity is but a movement of the smallest known bit of matter and energy, the electron, it is necessary that a study of electricity must be preceded by a slight knowledge of the electron.

1. The electron. The entire universe is made up of various combinations of about ninety substances known as **elements.** These elements are composed of negative electrical charges known as **electrons,** and positive charges known as **protons.** The electrons are all alike. The only difference between copper and aluminum lies in the difference in the number and position of their electrical charges.

2. Charged bodies. The term charge is used in various ways. A body on which there is an equal amount of negative and positive electricity is said to be in equilibrium; but if the body has an excess of either negative or positive electricity it is said to be **charged.** Sometimes the body itself is called a **charge** and of course may be referred to as a positive or a negative charge. If it has a great excess of either of the two kinds of electricity, it is said to be highly charged. In this condition it is in a state of very unstable equilibrium, and at the least chance some change will occur to bring the body into a state of greater equilibrium.

3. The laws of electrical charges. These electrical charges obey simple laws: like charges, whether positive or negative, repel each other; unlike charges, that is, a positive and a negative charge, attract each other. The more highly charged the bodies are the greater will be the repulsion or attraction. The closer together the charges are the greater will be the attraction or repulsion. Doubling the distance between two unlike charges divides their attraction by four. The greater the magnitude of the individual charges the greater is the attraction or repulsion; the greater the distance between the charges the less the attraction or repulsion.

4. The atom. The simplest form in which an element can exist by itself is called the atom. A combination of two or more atoms is called a molecule. Ordinarily the atom or molecule is in electrical equilibrium with its surroundings. If, however, through some severe mechanical shock, for example, it should lose an electron it would be charged and then would follow the laws cited above. It would then attract or get rid of an electron at the first opportunity and become neutral again.

It is the motion of electrons that we know as the **electric current.** When there is a sufficient number of electrons, a billion billion per second, for instance, there is current enough to light an incandescent lamp or heat an electric iron.

The atoms and molecules in matter are in constant motion, carrying with them in their movements the electrons that constitute them; in the bumping of one atom against another, electrons are lost, gained, and interchanged.

Atoms of matter are inconceivably small. Everyone has seen many-colored oil films on the street. It is possible to obtain oil films less than half a ten-millionth of an inch thick. The atoms composing these films cannot be thicker than this figure; the electrons are much smaller. We think the distances in the solar system of which the earth is part are beyond comprehension, the sun, for example, being about 90 million miles from the earth; but the dimensions of the electrons in their smallness are even more difficult to picture. The diameter of the electron is estimated to be about 1 ft divided by a hundred million million. Each of these electrons resembles its brother exactly, so that when an electron is knocked out of an atom by a collision it is free to combine with any other body near by which may have a deficit of negative electricity, regardless of what the body may be made. The electron is the unit out of which everything is made.

5. The ether. The fact that one charge can exert a force, either of attraction or repulsion, upon another implies that something connects the two. For instance, a rubber comb which has been rubbed on a coat sleeve will pick up bits of paper. Even though the comb does not actually touch it, the paper jumps to the comb while the two are still some distance apart. Evidently something exists in the space between the comb and the paper. That it is not air may be demonstrated by performing a similar experiment under a jar from which all the air has been pumped.

This leads us to a conception of what is commonly known as the **ether.** It is simply the place or the substance, or whatever one may choose to call it, wherein the attraction or repulsion of electrical charges exists. The ether is a concept made necessary by our difficulty in conceiving how one body can exert an effect upon another except through some intervening medium. Between two charged bodies are said to exist **lines of force** which tend to decrease the distance between the bodies if they are oppositely charged or to increase it if the bodies are charged alike. The sum of these lines of force is called an **electrical field** and every charged body is surrounded by such a field. Since a radio aerial is but a charged system of wires it too has a field about it. This field extends in all directions through what we call the ether.

6. The electric current. In an ordinary piece of copper wire the electrons are moving about in a haphazard fashion at the rate of about 35 miles per second. If this wire is in an electrical circuit, in addition to this to and fro motion there is a comparatively slow drift of electrons from one end of the wire to the other. It is this slow drift of electrons in a given direction that we ordinarily call the electric current. Because each electron can carry an extremely small quantity of electricity, it is only movements of large numbers of them in which we are interested. It has been estimated that it would take all the inhabitants of the earth, counting night and day at the highest rate of speed possible, 2 years to count the number of electrons which pass through an ordinary electric light in a second. This is about the same number that is necessary to light the tubes in a modern ac–dc receiver.

The flow of electrons from one end of the wire circuit to another can be explained by the two fundamental laws of electrical charges (Section 3). When a wire is attached to the positive terminal of a battery there is a momentary movement of the electrons nearest the end of the wire toward the battery. This movement soon ceases because the flow of electrons into the battery leaves a dearth of them at the other end of the wire which must be supplied. If both ends are attached to the battery a steady drift of electrons takes place out of the negative pole or terminal of the battery, through the wire, and to the battery again at the positive terminal.

Thus the actual motion of the electrons is from the negative toward the positive end of a circuit. This is in the opposite direction from the rule established many years before the electron had been discovered, namely, that current flows from positive to negative. In problems the student can assume either direction so long as he is consistent. We know that the electrons flow from negative to positive; electrical workers assume the current flows from positive to negative. In this book we shall follow the latter rule, but the student should remember that the actual carriers of electricity move in the opposite direction.

7. Insulators and conductors. It is a matter of common knowledge that the current does not flow through the non-metallic parts of a radio set, or through the insulating material around a broken conductor. How does it happen that some materials are such good conductors, copper and silver for example, whereas others, such as glass or Bakelite, appear not to conduct at all? Here again we are dealing with the building stones of all matter, the atom and the electron. Atoms of the so-called non-conductors maintain their hold on their individual electrons very tightly; few electrons escape. In the conductors, the electrons of the various atoms are freer to move about, and so to be interchanged among atoms. A **conductor** is made of material through which charges move easily. A **non-conductor** is made of material in which electric charges do not move easily.

A good conductor is a material whose electrons are freer to move about than those of a poor conductor. Strictly speaking, there are no non-conductors. All materials will carry current to some degree. Glass, for example, which is generally considered a very good insulator, conducts electricity fairly well when it is in a molten state.

The best insulators—that is, the poorest conductors—are amber, rubber, sulphur, shellac, porcelain, quartz, silk, air. Dry wood, paper, cotton and linen thread are semi-conductors. The best conductors are the metals, acids, moist earth, etc.

8. Conductivity. All materials have a certain characteristic called **conductivity,** which describes their ability to conduct an electric current. Among pure metals silver has a very high conductivity, copper is next, and near the bottom lies iron with about one-ninth the conductivity of copper. The **conductance** of a circuit is a term expressing its ability to pass an electric current. The greater the conductance, the greater the current. The unit of conductance is the **mho.**

9. Resistance. Those metals which have a high conductivity may be said to offer little **resistance** to the flow of electrons through them. Thus, copper has a low resistance, whereas some combinations of copper, nickel, and iron-manganese, for example, have resistances many times that of copper. A device added to a circuit to increase its resistance is called a **resistor.** Note that resistance is a property of a material or a circuit, whereas a resistor is a device used for supplying resistance to a circuit.

Resistors used in radio apparatus are of several types. A "fixed" resistor has a definite and fixed number of ohms. A "variable" resistor can be varied in value. Some resistors are made of wire wound on a form; others are made of extruded composition material.

The resistance of two wires of the same material and at the same temperature depends upon two things, the length of the wires and the area of their cross section. Naturally, the longer the wire the fewer electrons can pass through it in a given time; similarly, the smaller the diameter of a wire the greater the resistance, just as you can get more gallons of water per second from a 3-in. fire hose than from a 1-in. garden hose, although they may be attached to the same hydrant.

Similarly, a wire 2 ft long has twice the resistance of a wire 1 ft long but of the same diameter. Of two wires of the same

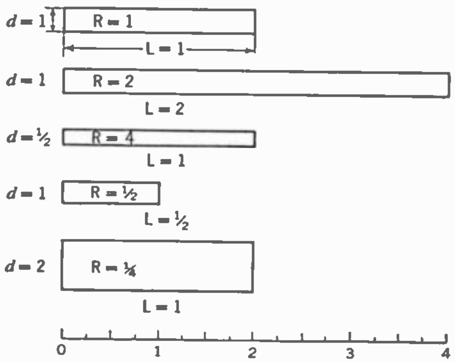


FIG. 1. **Resistance depends upon the length and size of a conductor.**

length the one having the smaller diameter will have the greater resistance. The resistance is inversely proportional to the area of the wire or to the square of the diameter. This is demonstrated in the copper wire table on page 8 by noting that a No. 10 wire has a diameter 102 wire mils and a resistance of approximately 1 ohm per 1000 ft, whereas No. 16 wire, with one-half the diameter, has four times the resistance.

There are several ways in which the absolute value of the resistivity of a substance may be indicated. The most useful to electrical engineers, since they use so much of their resistance material in the form of wires, is the **ohm per mil foot.** This is the resistance in ohms of a wire 1 mil in diameter and 1 ft long. A mil is a thousandth of an inch (0.001 in.). Tables showing the resistivity of many materials will be found in handbooks used by electrical and radio engineers. In general, however, wire tables showing the actual resistance in ohms of wires of various sizes are most practical to use.

The resistances of several metals compared to silver are as follows:

Silver	1.00	Platinum	6.15
Copper	1.06	German silver	20
Aluminum	1.74	Constantan	27
Nickel	4.25	Mercury	59
Soft iron	6.00	Carbon	215

Problem 1-1. How many times higher in resistance is mercury than silver? Than copper?

Problem 2-1. Two wires of the same length and diameter have resistances in the ratio of 5.65 to 1. If the lower-resistance wire is copper, could you identify the other wire material from the above table?

Problem 3-1. Two wires, one of soft iron and the other of platinum, are to have the same resistance. They have the same diameter. The platinum wire is 1 ft long. What is the length of the soft iron wire?

10. The ohm. The unit of resistance is the **ohm.** It is arbitrarily defined by international agreement as the resistance of a column of mercury weighing 14.4521 grams, having a uniform cross section and a height of 106.3 cm at 0° centigrade. A 9.35-ft length of No. 30 copper wire has a resistance of about 1 ohm. The table on page 8 gives sizes and resistance per thousand feet of copper wire. The resistance per foot may be obtained from such a table by dividing the resistance per thousand feet by one thousand. In this table will be found the size of wires according to the B & S gage, the diameter in thousandths of an inch, the resistance in ohms per thousand feet, the weight, and the numbers of turns of the wire that can be got into an inch of winding space when the wire is covered with various insulations. "S.c.c." refers to "single cotton covered," "d.c.c." refers to "double cotton covered," indicating that two layers of cotton thread are wound about the wire as insulation. Similarly "s.s.c." refers to silk thread insulation.

Note that decreasing the size of wire by three numbers, that is, from No. 20 to No. 23, doubles the resistance of the wire from 10.15 to 20.36 ohms; going from No. 30 to No. 27 lowers the resistance from 103.2 to 51.5 ohms per thousand feet.

Copper is used in electrical and radio circuits because of its high conductivity compared to other metals and its low cost com-

Copper Wire Table

Resistance at 68° F (20° C)

Mils, 0.001 in.

Size of Wire B. & S. Gage	Diameter of Wire Mils	Ohms per 1000 Ft	Pounds per 1000 Ft	Turns per Linear Inch			
				Scc	Dcc	Ssc	Dsc
0000	460	0.049	641	2.14	2.10		
000	410	0.0618	508	2.39			
00	365	0.0779	403	2.68	2.62		
0	325	0.0983	319	3.00			
1	289	0.1239	253	3.33	3.25		
2	258	0.1563	201	3.75			
3	229	0.1970	159	4.18	4.03		
4	204	0.2485	126	4.67			
5	182	0.3133	100	5.21	5.00		
6	162	0.3951	79.5	5.88			
7	144	0.4982	63	6.54	6.25		
8	128	0.6282	50.0	7.35			
9	114	0.7921	39.6	8.26	7.87		
10	102	0.9989	31.4	9.25			
11	91	1.260	24.9	10.3	9.80		
12	81	1.588	19.8	11.5			
13	72	2.003	15.7	12.8	12.2		
14	64	2.525	12.4	14.3			
15	57	3.184	9.86	15.9	14.9		
16	51	4.016	7.82	17.9	16.7	18.9	18.3
17	45	5.064	6.20	20.0			
18	40	6.385	4.92	22.2	20.4	23.6	22.7
19	36	8.051	3.90	24.4			
20	32	10.15	3.09	27.0	24.4	29.4	28.0
21	28.5	12.80	2.45	29.9			
22	25.9	16.14	1.94	33.9	30.0	36.6	34.4
23	22.6	20.36	1.54	37.6			
24	20.1	25.67	1.22	41.5	35.6	45.3	41.8
25	17.9	32.37	0.97	45.7			
26	15.9	40.81	0.769	50.2	41.8	55.9	50.8
27	14.2	51.47	0.610	55.0			
28	12.6	64.90	0.484	60.2	48.6	68.5	61.0
29	11.3	81.83	0.384	65.4			
30	10.0	103.2	0.304	71.4	55.6	83.3	72.5
31	8.9	130.1	0.241	77.5			
32	8.0	164.1	0.191	83.4	62.9	101	84.8
33	7.1	206.9	0.152	90.0			
34	6.3	260.9	0.120	97.1	70.0	121	99.0
35	5.6	329.0	0.0954	104			
36	5.0	414.8	0.0757	111	77.0	143	114
37	4.5	523.1	0.0600	118			
38	4.0	659.6	0.0476	125	83.3	167	128
39	3.5	831.8	0.0377	135			
40	3.1	1049	0.0299	141	90.9	196	145

pared to metals of higher conductivity. It is readily obtainable and easily worked.

The term **megohm** is frequently used in radio literature. It is equal to one million ohms.

Problem 4–1. What size of soft iron wire will have approximately the same resistance as No. 32 copper?

Problem 5–1. What is the resistance of 1 ft of No. 20 copper? Of No. 24 aluminum?

Problem 6–1. A two-wire telegraph line is to be run a distance of 2 miles. If the total resistance of the line must be kept below 20 ohms, what size of copper wire must be used? If iron wire must be used because of expense, what size will be required? If copper and iron wire have about the same relative weights (555 to 480) what will the iron line weigh?

11. The effect of molecular motion on resistance. Why do some substances have greater resistance than others? Let us again consider the electrons, atoms, and molecules which make up the wires carrying the currents. Not only are the electrons in motion, but the atoms and molecules themselves are also in a sluggish motion, the violence of this motion depending upon the temperature of the wire and the material of which the wire is made.

Although molecules cannot traverse the electric circuit as the electrons can, in their to and fro motion they impede the progress of the electricity bearers by countless collisions with them. The greater this molecular motion, the greater the resistance to a progressive flow of electrons, and the greater the wire's electrical resistance.

12. The effect of temperature on resistance. The resistance of all pure metals rises with increase in temperature. This is because of the greater molecular agitation at higher temperatures, making it more difficult for the electrons to drift in their progressive motion around the circuit.

At absolute zero, 273 degrees below zero centigrade, all molecular motion is supposed to stop, making the resistances of metals practically zero. At the lowest temperature reached it has been found that the resistance of a coil of wire is so low that current will flow for some time after the driving force is removed. Scientists have approached to within a fraction of a degree of absolute zero.

13. Temperature coefficient of resistance. Conductors in which radio engineers are interested increase or decrease in resistance at a regular rate with respect to temperature. The

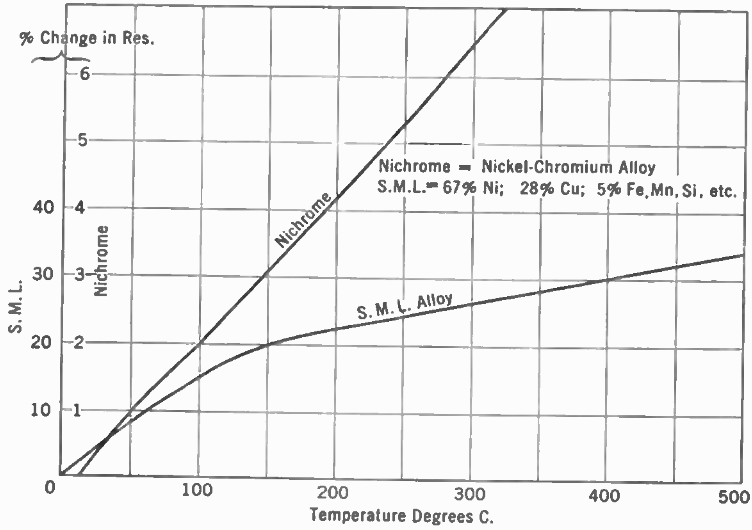


FIG. 2. Effect of temperature on resistance.

change in resistance of a given wire may be computed from the following facts. The **temperature coefficient** of resistance is a term which gives the amount the resistance increases for each degree rise in temperature for each ohm at the original temperature. For example, if a copper wire with a temperature coefficient of 0.0042 has a resistance of 80 ohms at 0° C, this resistance will be increased by 80 × 0.0042 for each degree rise in temperature. At 50° C the resistance increase would be 80 × 0.0042 × 50 or 16.8 ohms, and the resistance would now be 80 + 16.8 or 96.8 ohms. Manganin wire, composed of 84 per cent copper, 12 per cent manganese, 4 per cent nickel, has a very low temperature coefficient of resistance. It is 0.000006. The change in resistance of two alloys with temperature is shown in Fig. 2.

Typical temperature coefficients of resistance for several metals and alloys used in the radio profession are as follows:

Material	Coefficient
Constantan (an alloy)	0.000002
Copper	0.0042
Copper-manganese-iron	0.00012
Iron	0.005
Nickel	0.006
Platinum	0.003
Silver	0.003
Tantalum	0.003

14. The ampere. The **ampere** is the term used to express the rate at which electrons move past a given point in an electrical circuit. It is equal to 6.28×10^{18} (see Section 16) electrons per second. Since each electron carries a definite quantity of elec-

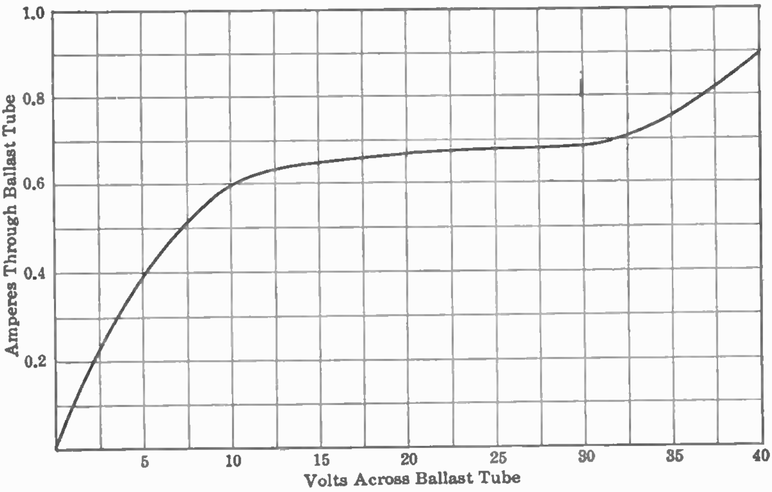


Fig. 3. Characteristic of iron wire in a gaseous atmosphere. Note that there is an appreciable region where the current through the wire is independent of the voltage across it. This is used to maintain a constant current through a transformer regardless of line voltage variations.

tricity, the total amount carried by 6.28×10^{18} electrons is a definite quantity and is known as the **coulomb.** The ampere, however, is the term used in electrical practice. It corresponds to the term gallons per second used in speaking of the amount of water transported through a pipe or hose. The term gallons alone conveys little meaning, since the same number of gallons will flow out of a small hose as out of a large one provided we do not consider the time involved, or the pressure. But "gallons per second" involves both time and pressure and is a term easily visioned. A current of 1 amp will convey through a circuit 1 coulomb of electricity per second.

The ampere as a quantity of electricity transported per second is a large unit if we compare it with the current flowing from the B batteries of a radio set. It is small compared with the currents encountered in power houses. The B batteries supply only thousandths of amperes or milliamperes, whereas in a small power house supplying power to a village one may have thousands of amperes flowing. A meter to measure the flow of current is called an ammeter, or milliammeter, or microammeter, depending upon the strength of current it can measure. Approximate currents flowing through commonly used devices are shown below.

Apparatus	Approximate Current in Amperes
50-watt lamp	0.5
250-watt lamp	2.5
2-hp motor	10.
Electric iron	5.
Filament of battery-type vacuum tube	0.05
Plate circuit of vacuum tube	0.005

15. The volt. The electrons are driven through the wires and apparatus composing the circuit by a force called an **electromotive force,** abbreviated to emf. The unit of force is known as the **volt.** It is the electrical force that will cause 1 amp of electricity to flow through a wire which has 1 ohm of resistance. The common dry cell used to ring door bells has a voltage of about 1.5; storage batteries when charged have a voltage of about 2.0, and thus a three-cell battery has a voltage of 6.0. The ordinary

B battery has a voltage of about 45, and if torn apart will be found to consist of thirty small cells, the voltage of which is 1.5 volts each. An instrument used to measure voltages is known as a voltmeter. A table of voltages is given below.

Apparatus	Voltage (Approximate)
Dry cell	1.5
Storage battery	6
B battery	45
House-lighting circuit	115
"Third rail"	500

16. Engineers' shorthand. Engineers have a simple shorthand method of working with large numbers well illustrated by the figures 6.28×10^{18}. This means 6.28 multiplied by a million million million. This many electrons flowing past a given point per second constitute the electric current known as an ampere. We shall have occasion to use this system many times in the course of the book and students are encouraged to master it as soon as possible. The table below will be helpful.

$$1 = 10^0 = \text{one}$$
$$10 = 10^1 = \text{ten}$$
$$100 = 10^2 = \text{hundred}$$
$$1000 = 10^3 = \text{thousand, etc.}$$
$$1 = 10^0 = \text{one}$$
$$0.1 = 10^{-1} = \tfrac{1}{10} = \text{one-tenth}$$
$$0.01 = 10^{-2} = \tfrac{1}{100} = \text{one-hundredth}$$
$$0.001 = 10^{-3} = \tfrac{1}{1000} = \text{one-thousandth, etc.}$$

The small number above the figure 10 is called the **exponent.** Numbers less than 1 have negative exponents. Thus three-thousandths may be expressed in these several ways:

$$0.003 = 3 \times 10^{-3} = \frac{3}{1000} = \frac{3}{10^3}$$

When numbers are multiplied, their exponents are added; when the numbers are divided, the exponents are subtracted.

Thus 100 multiplied by four-tenths may be done in shorthand as follows:

$$\begin{aligned} 100 \times 0.4 &= 10^2 \times 4 \times 10^{-1} \\ &= 4 \times 10^1 \\ &= 4 \times 10 \\ &= 40 \end{aligned}$$

Similarly, let us divide 3000 by 150.

$$\begin{aligned} 3000 \div 150 &= (3 \times 10^3) \div (1.5 \times 10^2) \\ &= \frac{3}{1.5} \times 10^{3-2} \\ &= \frac{3}{1.5} \times 10^3 \times 10^{-2} \\ &= 2 \times 10 = 20 \end{aligned}$$

The rules are few and simple:

1. To multiply, add exponents.
2. To divide, subtract exponents.
3. When any number crosses the line, change the sign of the exponent.

Example 1-1. Multiply 20,000 by 1200 and divide the result by 6000.

$$\begin{aligned} 20{,}000 &= 2 \times 10^4 \\ 1200 &= 12 \times 10^2 \\ 6000 &= 6 \times 10^3 \\ \frac{20{,}000 \times 1200}{6000} &= \frac{2 \times 10^4 \times 12 \times 10^2}{6 \times 10^3} \\ &= \frac{2 \times 12 \times 10^4 \times 10^2 \times 10^{-3}}{6} \\ &= \tfrac{24}{6} \times 10^3 \\ &= 4000 \end{aligned}$$

Problem 7-1. How many electrons flow past a given point per second when the number of amperes is 6? 60? 600? 0.1? 0.003?

Problem 8-1. The sun is roughly 90 million miles from the earth. Express this in "shorthand."

Problem 9-1. At 100 miles per hour, how many months would it take to reach the sun?

Problem 10-1. If light travels at 300 million meters per second and if a meter equals 3.3 ft, how long does it take the sun's rays to reach the earth?

Problem 11-1. How many amperes of current flow when 31.4×10^{15} electrons per second flow past a point?

In connection with such shorthand methods the following table of prefixes commonly used will be important.

Prefix	Abbreviation	Meaning	Shorthand
micro	μ	one millionth	10^{-6}
milli	m	one thousandth	10^{-3}
centi	c	one hundredth	10^{-2}
deci	d	one tenth	10^{-1}
deka	dk	ten	10
hekto	h	one hundred	10^2
kilo	k	one thousand	10^3
mega	M	one million	10^6

Thus a thousandth of an ampere is known as a milliampere, a million ohms is called a megohm, etc.; or, expressed in numbers, 1 ma $= 10^{-3}$ or 0.001 amp; 1 megohm $=$ 1,000,000 ohms.

Problem 12-1. How many cycles are 1000 kilocycles? How many kilocycles in 500 cycles?

Problem 13-1. How many megacycles are in 1000 kilocycles? How many cycles in 30 megacycles?

17. Mathematics in the study of radio. The amount of mathematics one needs varies with the intensity with which one intends to study radio. As in all other branches of science in which mathematics plays a part the easier it is to think mathematically the greater are the possibilities ahead of the student. In this book it is necessary to have only a rudimentary knowledge of algebra to work most of the problems. The student with no mathematics beyond arithmetic and common sense will be able to work his way through most of the examples.

18. Curve plotting. Many of the answers to radio problems can be seen visually if the problem is plotted in the form of a graph. Such graphs or curves are used frequently in this text, and it is essential that the student and experimenter shall be familiar not only with how to plot curves but also with how to interpret curves that other experimenters have drawn.

The simplest form of curve is a map. The map has two **coordinates or axes,** north-south and east-west. We say that a town is situated at so many miles east and so many miles south of some point that we take as the origin. We have now plotted the simplest mathematical equation, a point. A railroad runs straight north past a point, that is, so many miles east of this

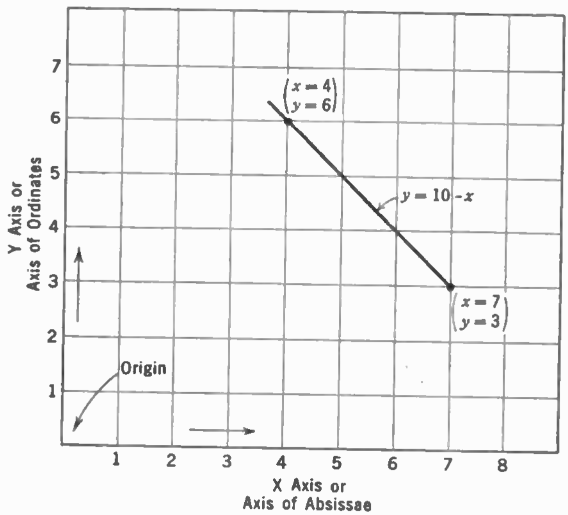


FIG. 4. Curves are usually drawn with some portion of them going through the 0–0 point as origin.

town. We can locate this railroad by giving two points through which it passes, or by giving one point through which it passes and its direction. By a point and a direction we have plotted another simple mathematical equation, a straight line.

In radio plots the axes may be called X for the horizontal and Y for the vertical, or current for one and voltage for the other, etc. A graph is a visual expression of the relation existing between two factors, X and Y, or current and voltage, etc. When one increases the other increases or decreases. Knowing the law connecting them (the equation or formula) we can tell what the current is at any given voltage. If the law expressed visually in the form of a graph is a straight line, we say the two factors, current and voltage, are proportional. If one increases and the other decreases, we say they are inversely proportional.

Curves are useful not only in giving us a visual picture of what is happening in a circuit, but also in telling us if the figures se-

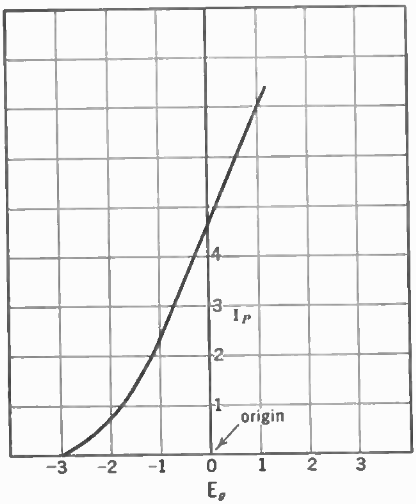


FIG. 5. The origin in the center.

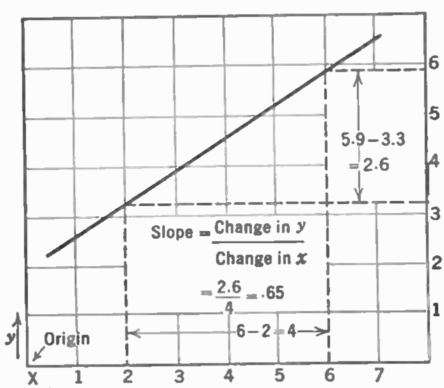


FIG. 6. How to calculate the slope of a curve.

cured in an experiment are correct. Thus we may calibrate a wavemeter in condenser dial degrees against wavelength in me-

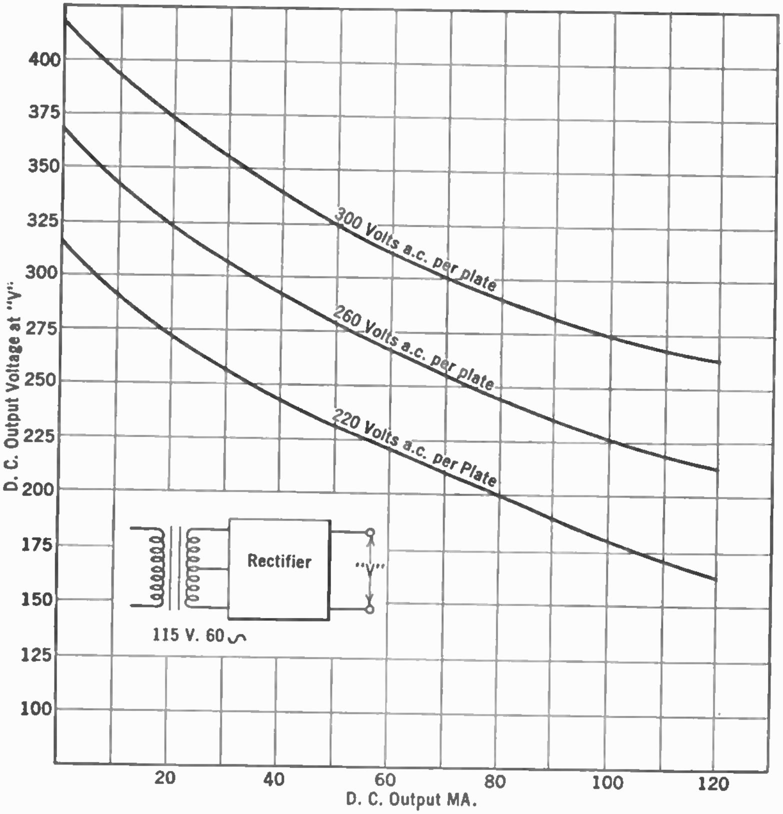


FIG. 7. A power supply device regulation curve.

ters. We plot this curve and one or more points do not seem to fall on the smooth curve that goes through the other points. Something in our laboratory experiment caused these points to be off the curve. They were incorrectly taken, and the measurement that gave us these points must be repeated.

Points which lie to the left of the vertical axis are negative; points which lie below the horizontal axis are negative. All others are positive.

The change in the vertical units with a given change in horizontal units is called the **slope** of the curve. If the curve goes through the origin this slope amounts to the ratio between the vertical and the horizontal values at any point. In Fig. 6 is shown the method of calculating the slope.

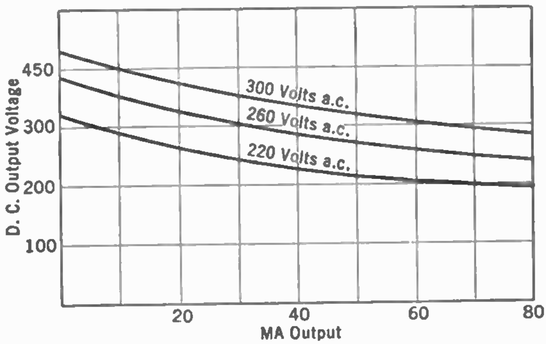
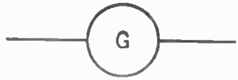


FIG. 8. The same data as in Fig. 7 but plotted to a different scale. Note how much flatter the curves appear.

The units in which a curve is plotted change its appearance. Thus in Fig. 7 is plotted the relation between the output voltage of a B eliminator as the current taken by the receiver is changed. Figure 8 shows the same data but plotted to a different vertical scale. The slope of these lines looks different but really is the same. If the slope is the factor in which we are interested, the more open scale should be used so that small changes will be visible.

Problem 14–1. Get some cross-section paper, or make some, like that used in the illustrations here. Plot on this paper the height of a road as it progresses from the bottom of a hill to the top using the following data. At the bottom of the hill it is 400 ft above sea level. At the end of a quarter mile it is 550 ft above sea level, at the ⅜ mile it is only 500 ft high, at ½ mile it is 700 ft, at ⅝ mile it has risen to 900 ft, at

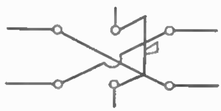
Headphones



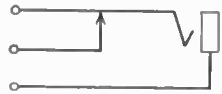
Galvanometer

Key

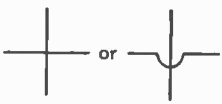
Wires Connected



Reversing Switch



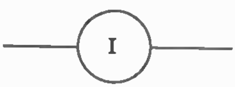
Closed Circuit Jack



Wires crossed
but not Connected

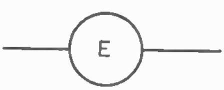
Single Pole
Double Throw Switch
"SPDT"

L = Inductance
C = Capacity
R = Resistance
ω = Ohms
Ω = Megohms
mh = Millihenries
μf = Microfarads
$\mu\mu$f = Micromicrofarads
μh = Microhenries

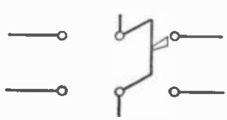


Ammeter or
Milliammeter

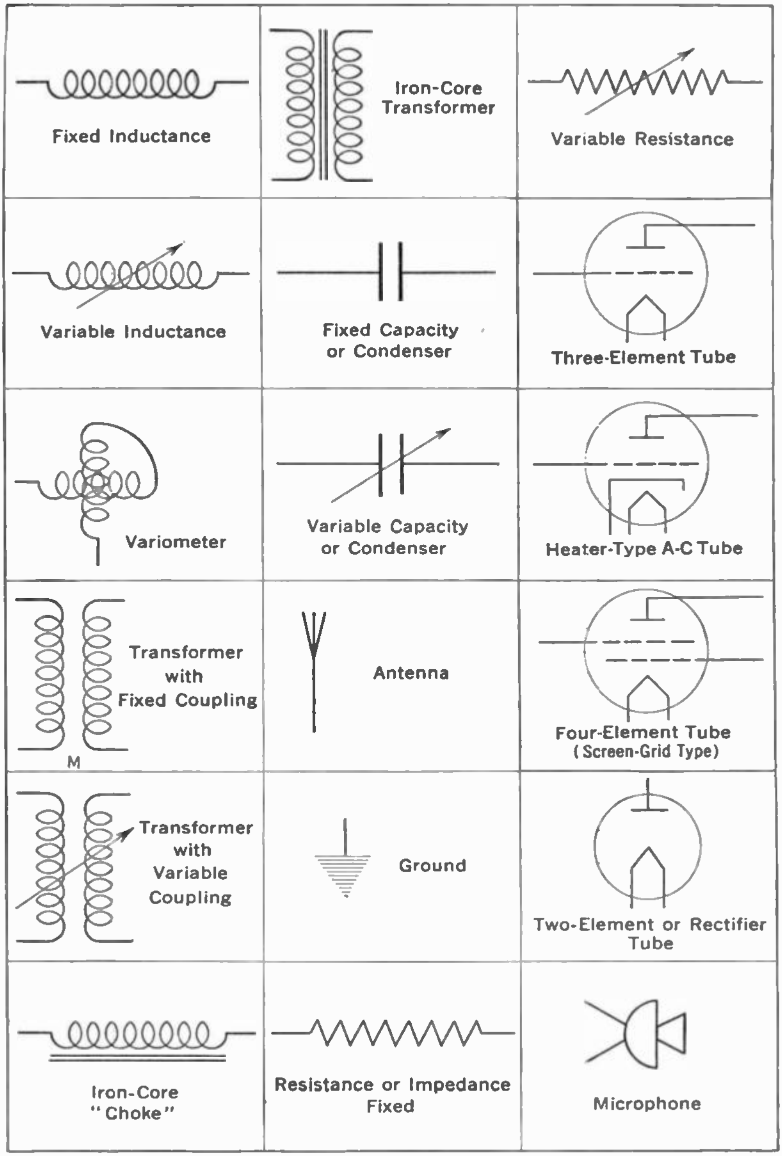
"SPST" Switch



Voltmeter



Double-Pole
Double-Throw Switch
"DPDT"


Fixed Inductance
Iron-Core Transformer
Variable Resistance
Variable Inductance
Fixed Capacity or Condenser
Three-Element Tube
Variometer
Variable Capacity or Condenser
Heater-Type A-C Tube
Transformer with Fixed Coupling
M
Antenna
Four-Element Tube (Screen-Grid Type)
Transformer with Variable Coupling
Ground
Two-Element or Rectifier Tube
Iron-Core "Choke"
Resistance or Impedance Fixed
Microphone

¾ mile it has dropped to 800 ft, at ⅞ mile it is 1000 ft high and at the end of a mile it is at the 1200 foot level. Mark off these points on the plotting paper, draw lines connecting the points, and then draw a line connecting the 400 and the final 1200-ft points. What is the average rate of climb (slope of the road) of a car traversing this road?

19. Symbols. In all technical literature a number of abbreviations are used to express parts of circuits. The symbols used in this book are shown on pages 21 and 22. A circuit is built up simply by connecting several of these symbols. Each piece of apparatus used in radio circuits has at least two terminals. Thus, there is a positive and a negative terminal to a battery; a pair of headphones has two terminals. When two pieces of equipment are in series, the current flows through one of them before it goes through the other. Thus if two coils of wire are connected in series, one terminal of one coil is connected to one terminal of the other coil. The two remaining terminals may be connected to the remainder of the circuit.

If, however, the components are connected in parallel, the current flows through the individual pieces simultaneously. The two terminals of one coil are connected to the two terminals of the other coil, and then these same paired terminals are connected into the remainder of the circuit.

Circuit diagrams are merely the engineers' pictorial system of showing the connections between the individual parts of an assembly of radio apparatus. An engineer can tell as much by looking at a circuit diagram about the equipment he is going to use as can an architect about a house by looking at a floor plan on a blueprint.

CHAPTER II

OHM'S LAW

In the previous chapter we stated that an electric current was a motion of electrons; that the force which caused the motion of the electrons was called an electromotive force (emf or a potential difference (pd), that the resistance of a circuit opposes the flow of current, and that the unit of the current which actually flows per second is called the ampere. We have then a very simple law which enables the engineer to calculate:

a. The current that will flow when the voltage and resistance are known.

b. The voltage necessary to force a certain amount of current through a known resistance.

c. The resistance that will restrict the current to a certain value under pressure of a certain emf expressed in volts.

20. Ohm's law. The law which governs all simple and many complex electrical phenomena is known as **Ohm's law.** This law states: Current in amperes equals emf in volts divided by resistance in ohms, or, as expressed in electrical abbreviations,

$$I \text{ (current)} = \frac{E \text{ (voltage)}}{R \text{ (resistance)}}$$

21. Ways of stating Ohm's law. There are three ways of stating this fundamental law.

$$(1) \quad I = E/R \qquad (2) \quad E = I \times R \qquad (3) \quad R = E/I$$

These three ways of stating the same law are determined from the first statement of Ohm's law by simple mathematical transformation, and make less difficult the solving of problems.

From these three expressions of Ohm's law, any one of the quantities can be obtained if the other two are known. Thus from (1) the current in a circuit can be determined if the voltage and the resistance of the circuit are known. From (2) the voltage required to force a desired current through a given resistance can be determined. Finally, from (3) the resistance of a circuit can be found provided we can measure the current flowing in it under the force of a known voltage.

Example 1–2. A radio tube filament producing the electrons which perform all the many useful functions of the tube is heated by current flowing through it. The current comes from a battery to which the filament is connected. The battery has a voltage of 5 and the resistance of the filament is 20 ohms. How much current will flow through the filament?

We use (1) dividing the voltage, 5, by the resistance, 20, to obtain 5/20 amp or 0.25 amp.

Now suppose we know the resistance (20 ohms) and that 0.25 amp is required to heat the filament sufficiently to cause it to produce the proper number of electrons. How many volts must be connected to the filament?

Here we use (2), multiplying the current, 0.25, by the resistance, 20, to get 5 volts required.

Finally if we know from experience that the proper voltage is 5 and that with this voltage 0.25 amp will flow through the filament, what is its resistance? Here we use (3) and the reader should work out this relation for himself.

NOTE. The fundamental units are amperes, volts, and ohms. We cannot use volts, milliamperes, and ohms without getting into trouble. First the milliamperes must be converted into amperes and then used in the formulas expressing Ohm's law.

22. Voltage drop. The second way of stating Ohm's law indicates that whenever a current flows through a resistance, a difference of potential exists at the two ends of that resistance. For every ampere of current that flows through an ohm of resistance, there is a volt lost. In other words it requires a volt to force an ampere through an ohm of resistance.

Consider Fig. 9, which shows the voltage divider between a radio receiver and a voltage supply system for feeding power to the receiver. The power tube may require 180 volts. Other tubes require only 90 volts or perhaps small negative voltages. If 36 ma of current flow through this voltage divider, whose resistance may be 5000 ohms, and if there are 180 volts across the entire resistance, there will be other voltages along the resistance as indicated in the illustration. If the negative terminal of a voltmeter were attached to the negative end of the voltage divider and the positive terminal of the meter touched to various points along the resistance on the way toward the positive end, greater and greater voltages would be measured. What is being measured at each point is the drop in voltage between that point and the negative terminal of the voltage divider.

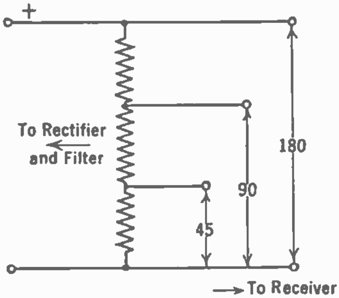


FIG. 9. The voltage divider of a receiver power apparatus.

Often in laboratories a voltage is needed so small that it cannot be measured with available instruments. A larger voltage can be measured easily, however; and if it is impressed across a voltage divider, any desired part of the total voltage may be utilized by tapping into this divider. (See Problem 4–2.) A voltage divider, consisting of a fixed resistor with a tap by which practically any value of resistance between zero and the maximum value can be obtained, is often called a potentiometer.

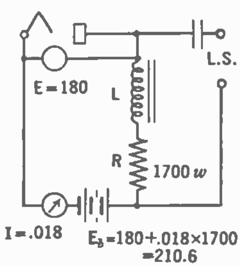


FIG. 10. A choke-condenser circuit connecting a loud speaker to a tube. The "choke" is a coil of wire of many turns.

These voltages appearing across a resistance because of current flowing through that resistance are known as *IR* drops. They may be calculated by multiplying the resistance in ohms by the current in amperes.

Example 2–2. In Fig. 10 is a symbolic representation of a radio tube connected to a battery through a coil of wire that has a resistance of 1700 ohms. The loud speaker is connected across this coil, but we will consider that it is temporarily disconnected from the circuit. The tube draws 18 ma from the battery, and 180 volts must be impressed between the "plate" of the tube and the negative terminal of the filament (which gets its current from another battery and is not involved in our immediate problem). The question is, how many volts must the plate battery have in order to impress this required 180 volts across the tube?

Now there is a rule (Kirchhoff) which states that the sum of the voltages appearing in a given circuit must add up to zero. That is, the voltage supplied by the battery must equal the sum of the voltage drops (current times resistance) appearing across the several circuit components. In this case the battery voltage minus the voltage drop across the resistance of the coil minus the drop across the tube equals zero. Thus

$$E_b - E_R - E_T = 0$$

or

$$E_b = E_R + E_T$$

where E_b = battery voltage;
E_R = voltage across resistance of coil;
E_T = voltage across tube.

In a series circuit the same value of current flows through all the parts; the voltage drops across each component are equal to this value of current multiplied by the resistance of the component. Thus

$$E_R = IR_c$$

$$E_T = IR_T$$

where R_c = resistance of coil;
R_T = resistance of tube.

The voltage across the tube is already given as 180. The voltage across the coil $E_R = IR_c = 1700 \times 0.018 = 30.6$ volts.

The battery voltage, therefore, is equal to 180 plus 30.6 or 210.6.

Note that the coil is represented in the diagram by two components, a coil plus a resistance. This is a convenient convention established among engineers whereby the individual parts of a circuit may be broken down into their electrical equivalents. A coil which has resistance, therefore, may be represented in a diagram as made up of two parts, the coil itself plus a resistance, although actually both the coil and its resistance reside in the same physical unit.

Problem 1-2. A piece of electrical apparatus having a resistance of 8 ohms is plugged into a 32-volt farm-lighting system. How much current will flow through the apparatus?

Problem 2-2. Suppose we desire to limit to 1 ma the flow of current in a circuit attached to a 45-volt battery. What must be the total resistance of the circuit?

Problem 3–2. What is the resistance of a 1C7-G tube filament taking 0.120 amp from 2-volt batteries?

Problem 4–2. Consider Fig. 11. How many milliamperes of current must be forced through the circuit in order to get 20 mv across the resistor *A–B?* How many volts in all will be needed?

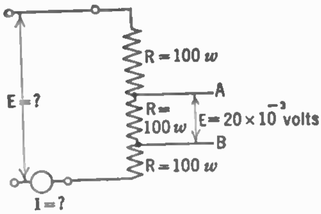


FIG. 11. Use of an *IR* drop as a source of voltage.

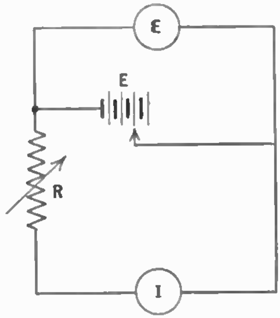


FIG. 12. A circuit for studying Ohm's law.

23. Graphs of Ohm's law. An interesting study of Ohm's law may be made by means of the circuit shown in Fig. 12 and several sheets of plotting or graph paper. The result of plotting current against voltage with constant resistance (Fig. 13); or resistance against current with constant voltage (Fig. 14); or

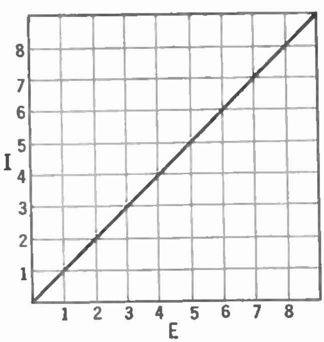


FIG. 13. In an Ohm's law circuit plotting current against voltage results in a straight line.

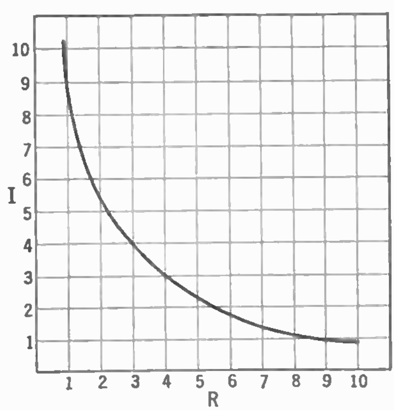


FIG. 14. The result of plotting current against resistance.

voltage against resistance with constant current—all give an accurate graphical picture of what Ohm's law means. In Chapter I the term conductance, K, was explained. It is equal to $1/R$. When conductance against current is plotted, a straight line results, as shown in Fig. 15. When voltage and current are

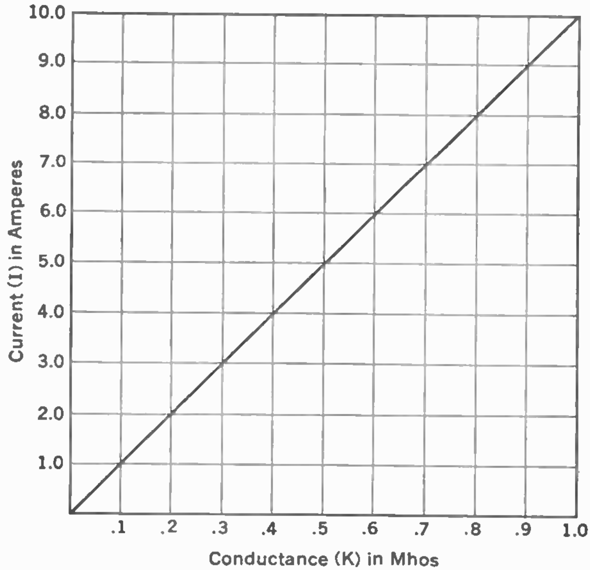


FIG. 15. Conductance $\frac{1}{R}$ plotted against current.

plotted with a fixed resistance in the circuit, the curve is a straight line if the circuit follows Ohm's law.

Experiment 1–2. If the apparatus is at hand, connect it up as in Fig. 12, using a 6-volt battery, a 40-ohm resistor, and an ammeter reading a maximum of about 0.5 amp. Connect the maximum resistance in the circuit and note the current as the voltage is changed from 2 to 4 and then 6 volts by tapping onto each of the three cells of the storage battery. Plot the data. Then use a smaller value of resistance and repeat.

Then use 2 volts and adjust the resistor until several current readings have been obtained. Calculate from Ohm's law what the resistance is and plot resistance against current.

Convert the resistances into conductances and plot against current. Calculate similar data, using 4 volts and then 6 volts, and plot the data.

Note in each case the shape of the curve has not changed, although the slopes of the straight lines vary with the resistance and the curved lines are displaced from each other.

Problem 5-2. In Fig. 16 is represented a radio tube in conventional symbols. The right-hand terminal represents the "plate" of the tube, the left-hand terminal the "grid" and the terminal next to the grid is the "cathode." The battery (known as the "B" battery) sends current through the tube from plate to cathode. The circuit is continued through the tube itself by means of electrons produced by the filament (terminals next to the plate). The current flows through the resistor and the voltage drop along this resistor is utilized to make the grid negative with respect to the cathode.

What must be the value in ohms of the resistor to make the grid 40 volts negative? There is no loss in voltage in the grid coil.

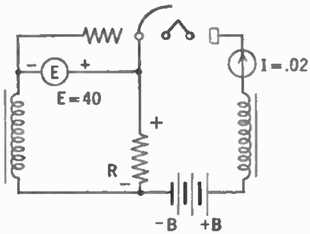


FIG. 16. A problem in Ohm's law—to determine the value of *R* to provide negative voltage for grid of tube.

24. Series and parallel circuits. There are two ways in which electrical apparatus may be connected.

When two or more pieces of equipment are connected as in Fig. 17 they are said to be in **series.** The same current flows through each unit. The voltage drop across each unit is controlled by its resistance, and if one of these units has twice the resistance of the other, the voltage drop across it will be twice as great. The sum of the voltage drops across the three resistances must be equal to the voltage of the battery, for there is no other source of voltage in the circuit.

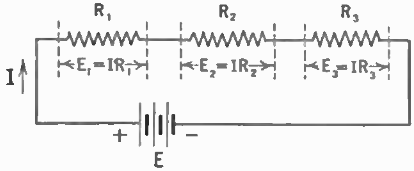


FIG. 17. A simple series circuit.

In a series circuit the total resistance is the sum of the individual resistances. The current in each unit is the same as in all other units. The current is obtained from Ohm's law (1).

If any of the units becomes "open" the current ceases to flow.

If, however, any unit becomes "shorted" the current will increase because the total resistance of the circuit has decreased.

Example 3-2. In Fig. 18 is a typical series circuit composed of a vacuum tube, a 6-volt battery, a current meter, and a rheostat or variable resistor whose purpose is to limit the flow of current through the filament of the tube. Note also Fig. 19 in which the same circuit is represented using electrical symbols. The arrow through R_1 indicates that it can be adjusted in value. R_2 indicates the resistance of the filament.

The question is, what current will flow through the circuit as the resistance of R_1 is varied? Suppose it is 4 ohms. We know the same current

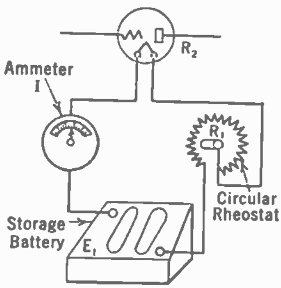


Fig. 18. A series circuit used in radio apparatus.

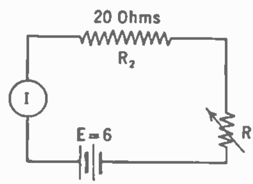


Fig. 19. The equivalent of Fig. 18.

will flow through both the filament and the rheostat. The resistance, then, in the circuit is equal to 20 plus 4 or 24 ohms, and by Ohm's law we know that the current will be the voltage divided by the total resistance, or

$$I = \frac{E}{R_1 + R_2} = \frac{6}{4 + 20} = \frac{6}{24} = 0.25 \text{ amp}$$

There are two resistances in this circuit. Current flows through them. There must then be two voltage drops. Let us calculate what they are. By equation (2) we multiply the resistance by the current.

$$\text{Voltage drop} = IR_1 = 0.25 \text{ ampere} \times 4 \text{ ohms} = 1 \text{ volt}$$
$$\text{Voltage drop} = IR_2 = 0.25 \text{ ampere} \times 20 \text{ ohms} = 5 \text{ volts}$$

In other words, of the 6 volts available at the terminals of the battery, 5 have been used up across the 20-ohm resistance and 1 volt has been used to drive 0.25 amp through the 4-ohm resistance.

Problem 6-2. In a "universal" ac–dc set there are 4 tubes of the 6.3-volt type connected in series. What resistance must be put in series with the filaments of those tubes if they are to be put directly across a 115-volt line? Each tube requires 0.3 amp.

Problem 7–2. Suppose you were going to use five 6.3-volt tubes in a series filament circuit. How many volts will be necessary?

Problem 8–2. What would be the resistance of the above tubes in series?

Problem 9–2. On a 32-volt farm system how many tubes of the 6.3-volt type (36, etc.) can be run in series? Six of the 2-volt, 0.06-amp type are to be run from this system. What series resistance is necessary if the tubes pass 0.06 amp?

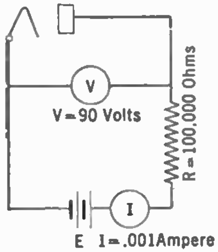


FIG. 20. A typical amplifier tube problem. What is the value of *E?*

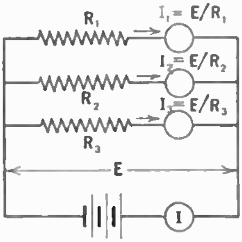


FIG. 21. A parallel circuit.

Problem 10–2. How much resistance would be necessary if one each 1R5, 1T4, 1S5 and 1S4 tubes are to be run from a 2-volt storage battery?

Problem 11–2. An incandescent lamp has a resistance, when hot, of about 55 ohms, and requires 1 amp to light at full brilliancy. How many could be run in series on a 110-volt circuit?

Problem 12–2. How many volts are required to force 1 ma through a circuit composed of a vacuum tube and a resistance, if the latter has 100,000 ohms and if 90 volts are required at the tube? (See Fig. 20.)

25. Characteristics of parallel circuits. A parallel circuit is represented in Fig. 21. It consists of several branches. The voltage across each branch is the same as that across every other branch and is equal to the voltage of the battery. The total current supplied by the battery is the sum of the currents taken by the branches. The resistance of the group may be found by

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

where R is the resultant or total resistance, and R_1, R_2, etc., are the individual resistances.

The resultant resistance of several units in parallel is less than the individual resistance of any of the components. If two equal resistances are in parallel, the resultant is one-half the resistance of one. Thus if two 10-ohm resistances are connected in parallel, the resultant resistance is 5 ohms. What would it be if they were connected in series?

If any number of equal resistances are in parallel, the resultant resistance is the individual resistance divided by the number of units.

If only two resistances are in parallel the resultant may be calculated by dividing their product by their sum:

$$R = \frac{R_1 \times R_2}{R_1 + R_2}$$

This simplified formula comes directly from that above by simple algebra, and the reader should prove it.

Example 4–2. What is the parallel resistance of two units which have resistances of 4 and 5 ohms?

This can be solved by either of the formulas given above.

$$\begin{aligned} \frac{1}{R} &= \frac{1}{4} + \frac{1}{5} \\ &= 0.25 + 0.20 \\ &= 0.45 \\ R &= 1/0.45 = 2.22 \text{ ohms.} \end{aligned}$$

Or,

$$\begin{aligned} R &= \frac{R_1 \times R_2}{R_1 + R_2} \\ &= \frac{4 \times 5}{4 + 5} \\ &= \frac{20}{9} = 2.22 \text{ ohms} \end{aligned}$$

Example 5–2. Suppose, as in Fig. 22, these two resistances in parallel are placed in series with a resistance of 1 ohm and across a battery of 6 volts. What current would flow out of the battery and through each resistance?

The total resistance is $2.22 + 1 = 3.22$ ohms. The current flowing, then, is $6 \div 3.22 = 1.86$ amp. This current through the combined resistance of the 4- and 5-ohm units produces a voltage drop of $I \times R$ or 1.86×2.22 or 4.14 volts. This voltage across 4 ohms produces a current of $4.14 \div 4$ or 1.035 amp, and across 5 ohms produces a current of 0.827 amp. These two currents added together are 1.862 amp, which checks our calculation above.

Problem 13–2. A radio receiver has five tubes of the a-c heater type, each taking 1.75 amp. What is their combined resistance, and how much

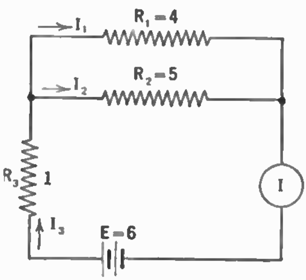


FIG. 22. Solve for the various currents.

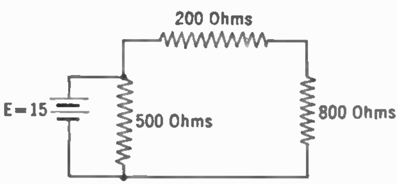


FIG. 23. What is the voltage drop across the 800 ohms?

current do they take from a 2.5-volt transformer secondary? If another load of the same voltage but half the previous current is added, what current is required? The tube filaments are connected in parallel.

Problem 14–2. A circuit has three branches of 4, 6, and 8 ohms. A current of 4 amp flows through the 6-ohm branch. What current flows through the other branches?

Problem 15–2. Consider the circuit of Fig. 23. What is the voltage drop across the 800-ohm resistor?

Experiment 2–2. Connect as in Fig. 22 several shunt resistances such as tubes, rheostats, fixed filament resistors in series with a battery and a rheostat. Measure the parallel resistance and individual resistances by reading the current through them separately and in parallel and the voltage of the battery. Test the relation $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$.

26. More complicated circuits. Some radio circuits are combinations of series and parallel circuits. A common form and its equivalent are shown in Fig. 24. Other more complicated circuits may arise in practice and may be solved by more complex algebra than is needed for simple Ohm's law cases. All such circuits can be reduced to more simple circuits by the application of certain rules which may be found in books on complicated networks of resistances, voltages, and current. In *Transmission Circuits for Telephone Communication,* by K. S. Johnson, may be found the equivalent circuits of many very complex arrangements of apparatus.

Problem 16-2. In Fig. 24, $R_1 = 20$, $R_2 = 30$, $R_3 = 60$ ohms, $E = 10$ volts. Solve for the three currents. Using the laws of series and parallel

$$I_1 = \frac{E(R_2+R_3)}{R_1R_2+R_1R_3+R_2R_3}$$

$$I_2 = \frac{ER_3}{R_1R_2+R_1R_3+R_2R_3}$$

$$I_3 = \frac{ER_2}{R_1R_2+R_1R_3+R_2R_3}$$

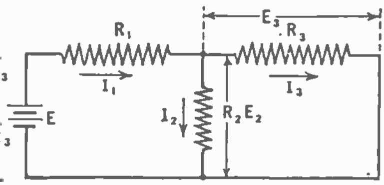


FIG. 24. A complex circuit and its solution.

circuits prove the equations in this figure by solving for currents and voltages indicated.

27. Detection and measurement of current. We cannot see or hear or smell the passage of an electric current through a circuit. It must be made evident to us by its effect upon the circuit. There are three kinds, a magnetic effect, a chemical effect, and a heating effect. Wire gets hot if too much current flows through it; two dissimilar metals (copper and zinc, for example) placed in a solution of one of them (copper sulphate) give off gas bubbles when a wire connects them externally; a wire carrying an electric current if brought near a compass needle will cause the needle to change from its habitual north-south position.

These are the three fundamental effects of electricity. Any of them can be used to detect the presence of a current or even to measure the rate at which the current flows. A hot-wire ammeter (Fig. 25), for example, is merely a wire which sags when it gets hot by passing a current through it. A needle is attached to the wire and moves across a scale as the wire gets hot. For another method, we might measure the quantity of gas given off per unit of time and thereby deduce the amount of current flowing through an electric cell.

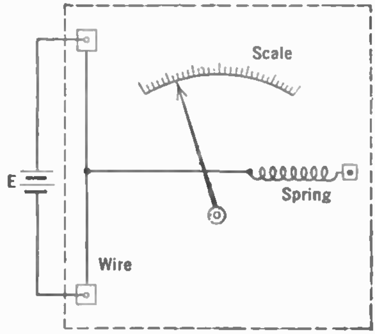


FIG. 25. Hot-wire ammeter.

Most measuring instruments use the magnetic principle. They consist of a permanent magnet near which is a coil of fine wire wound on a movable pointer. Current flowing through this coil makes a magnet of it. It changes its position with respect to the permanent magnet just as a compass needle does when brought near a wire carrying current. Such instruments can be made sensitive enough to measure currents as low as one-millionth of an ampere or to detect the flow of even smaller currents than this.

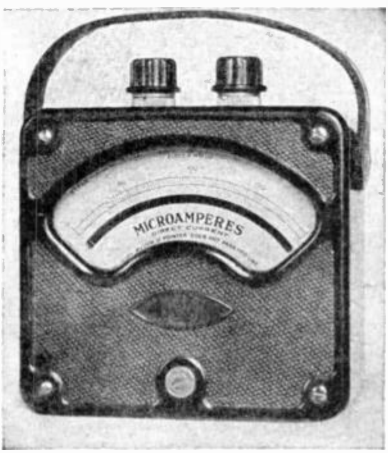


FIG. 26. A modern meter (Westinghouse type PX) which reads full scale 200 μa and which will indicate a current of less than 2 μa.

28. Ammeters. Meters to measure current are called ammeters. They are connected in series with the source of current and the device into which the current flows. They are made less sensitive—so they will measure large currents—by shunting them by copper wires so that only a small part of the total current flowing actually goes through the meter.

A very simple current-indicating device consists of a coil of wire through which the current flows and a compass placed in the center. A modern highly sensitive meter is a delicate instrument in which the compass needle is replaced by a carefully pivoted coil of wire carrying a pointer. Such an instrument is shown in Fig. 26. A meter measuring currents smaller than amperes is called a milliammeter or a microammeter for obvious reasons.

29. Voltmeters. Ammeters have low resistance. They are in series with the apparatus taking current from the source, as shown in Fig. 27. Voltmeters, on the other hand, must read the voltage across some part of the circuit. They must not permit much current to flow because this current would be taken away from the circuit. They have a high resistance. They are really high-resistance ammeters. Thus an ammeter, the Weston 0- to 1-ma meter, for example, can be made to read volts by putting it in series with a high resistance and across the circuit to be measured.

FIG. 27. Ammeters are connected in series with the resistance into which the current flows.

For example, 1 volt is required to give 1 ma of current through 1000 ohms. Thus if we have a 1.0-ma meter and we wish to measure a voltage of the order of 1 volt, we need a resistance of 1000 ohms. Then the figures on the meter scale will read volts instead of milliamperes. Such a series resistance is called a *multiplier*. The sensitivity of a voltmeter is often stated as its resistance per volt it will measure. Thus a meter to be used on circuits from which it is not permitted to take much current may have a resistance of 1000 ohms per volt. This means that a meter to measure a maximum voltage of 100 will have a resistance of 100,000 oms. It will require less current for full-scale deflection than a meter with a resistance of only 100 ohms per volt.

The manner in which ammeters may be adapted to read currents higher than originally intended may be shown by the following example. A given meter reading 1 ma full scale has a resistance of 28 ohms. Now if it is shunted by a resistance of 0.57 ohms the total current taken by the meter and its shunt will be 50 ma, but only 1 ma will go through the meter and 49 ma will go through the shunt. This is because the shunt has so much less resistance than the meter. If the shunt is properly designed with respect to the resistance of the meter, the original readings of the meter may merely be multiplied by a proper number to make it a measure of the total current flowing through meter and shunt.

Problem 17–2. What voltage is required to produce a full-scale deflection on a 1-ma meter having a resistance of 28 ohms? What current is required to produce a 25-volt reading on a meter having a resistance of 100 ohms per volt?

30. Sensitivity of meters. A sensitive current-measuring meter is one which will measure very small currents but which has a low resistance. A sensitive voltmeter is one which will give a large needle deflection through a very high resistance. Voltmeters which are used to measure the voltage of high-resistance devices such as plate supply units have high resistance in order that the current taken from the device shall not be great enough to lower appreciably the voltage of the device.

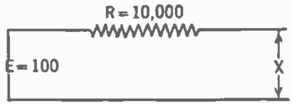


Fig. 28. A low-resistance voltmeter placed at X will not read the open-circuit voltage.

Example 6–2. Suppose we are to measure the voltage across the circuit at the point X in Fig. 28. The voltage at X depends upon the current taken by the meter. What is desired is the open-circuit or no-load voltage across X, that is, the voltage existing there if no current is taken by the meter. If no current flows, there is no voltage drop in the resistance R and hence the voltage at X is the voltage of the battery, or 100 volts. Suppose, however, the meter has a resistance of 1000 ohms. The current flowing through the meter is given by Ohm's law

$$I = E/R$$
$$= 100 \div (10{,}000 + 1000)$$
$$= \frac{100}{11{,}000} = 0.0091 \text{ amp or } 9.1 \text{ ma}$$

This current through the 10,000-ohm resistance R (which may be the internal resistance of the battery E, Section 49) causes a voltage drop across this resistance of $I \times R = 0.0091 \times 10{,}000 = 91$ volts.

The voltage actually recorded on the meter, then, is the difference between the battery voltage and the drop across the resistance R, or

$$\text{voltage at } X = E - (I \times R) = 100 - 91 = 9.0 \text{ volts}$$

If, however, the meter is a high-resistance meter, say 1000 ohms per volt, that is, 100,000 ohms for a meter designed to read 100 volts, the current taken from the battery would be

$$I = E/R = 0.00091 \text{ amp}$$

and the IR drop across the resistance R would be only

$$E = IR = (0.00091 \times 10{,}000)$$
$$= 9.1 \text{ volts}$$

and the voltage read at X would be 100 − 9.1 volts or 91.9 volts.

In other words the high-resistance voltmeter gives a reading much nearer the open-circuit or no-load voltage desired.

31. Ammeter-voltmeter method of measuring resistance. The example in the above section gives a clue to a good method of measuring the resistance of a device. The method consists in measuring the voltage across the device when a measured current flows through it. If the resistance of the voltmeter is high compared to that of the device, its own resistance need not be considered, and the inclusion of the ammeter into the circuit need not be taken into account aside from exceptional cases. If the voltmeter has low resistance, it will not read the true open-circuit voltage. One of the following indirect methods may then be used.

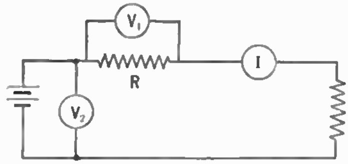


FIG. 29. Ammeter-voltmeter method of measuring resistance.

Example 7–2. Consider the circuit in Fig. 29. A voltmeter across the device whose resistance is unknown reads 75 volts, and the current meter, I, indicates a current of 0.05 amp. What is the unknown resistance?

$$R = E/I = 75 \div 0.05 = 1500 \text{ ohms}$$

32. Voltmeter method of measuring resistance. If the resistance of a voltmeter is known, a resistance can be measured by its use and a battery. Take two readings, one of the battery alone and one of the battery in series with the unknown resistance. Then the desired resistance may be found from

$$R = \left(\frac{E_b}{E} - 1\right) R_m$$

where E_b = voltage of battery alone;
E = voltage across battery and resistance;
R_m = resistance of meter.

33. Use of low-resistance voltmeter and milliammeter in high-resistance circuits. A high-resistance voltmeter is necessary when the voltage of any other device which has a high resistance, such as a power supply system for furnishing plate voltages to a radio set, is to be measured. The current taken by the meter is so low that the resistance drop, caused by this current flowing through the internal resistance of the device, is small compared with the voltage being measured.

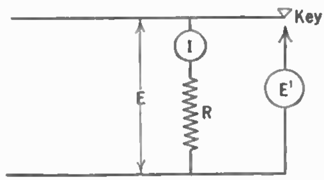


FIG. 30. A means of avoiding the use of a high-resistance voltmeter.

A method of using a low-resistance voltmeter and a milliammeter is shown in Fig. 30. Suppose the milliammeter is placed in series with the output resistance of the device across which the voltage is to be measured. Suppose the current without the voltmeter attached is I and the current with the voltmeter attached is I'. Let E' be the voltage indicated by the voltmeter when the key is pressed. The resistance in both cases is the ratio of the voltage and current. Thus,

I = current without voltmeter;
E = voltage without voltmeter;
I' = current with voltmeter;
E' = voltage with voltmeter;

$$R = \frac{E}{I} = \frac{E'}{I'};$$

whence

$$E = \text{desired voltage}$$

$$= E' \times \frac{I}{I'}$$

and

$$R = \frac{E'}{I'}$$

34. Resistance measurement. Resistances are often measured by what is known as the comparison method, that is, by comparing them with resistance units whose values are known. For example, we might measure the current through an unknown resistance, R_1, as in Fig. 31, and then adjust a variable resistance,

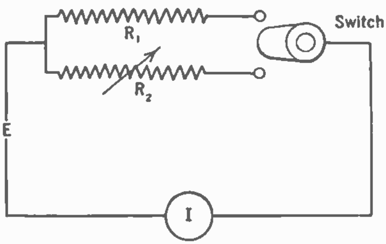


FIG. 31. Measuring resistance by comparison.

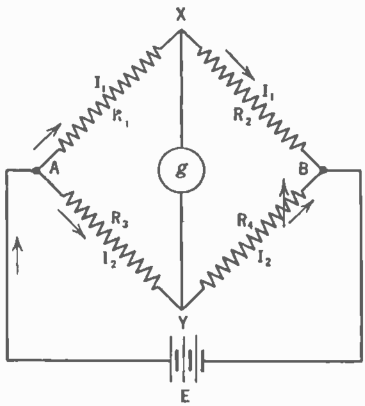


FIG. 32. Wheatstone bridge for measuring resistance.

R_2, whose values may be read directly until the same current flows under the same emf. The two resistances are then equal in value.

Another method employs a Wheatstone bridge. In diagrammatic form it is represented in Fig. 32, in which R_1 and R_2 are fixed resistances whose values are known, R_3 is the unknown resistance whose value is desired, and R_4 is a variable resistance to which the unknown is compared and the values of which are known. The method is as follows. A current is led into the bridge arrangement of resistances at the points A and B and a sensitive current-indicating meter is placed at the points X and Y. The values of R_1, R_2, and R_4 are adjusted until the meter, g, shows that no current flows through it, that is, there is no difference in voltage between the two points X and Y which would force current through the meter. In other words X and Y are at the same voltage.

The total current I divides at A and flows into the arms of the bridge forming the currents I_1 through R_1 and R_2 and I_2 through R_3 and R_4. If there is no potential difference between X and Y, the voltage drop along R_1 is equal to the voltage drop along R_3.

Thus

$$I_1R_1 = I_2R_3 \qquad [1]$$

Similarly

$$I_1R_2 = I_2R_4 \qquad [2]$$

Dividing (1) by (2)

$$\frac{R_1}{R_2} = \frac{R_3}{R_4} \qquad [3]$$

Suppose R_1 and R_2 are equal in value. Then equation (3) becomes

$$1 = \frac{R_3}{R_4}$$

or

$$R_3 = R_4$$

and to find the value of the unknown resistance R_3 we need only adjust R_4 (whose values are known) until no current flows through the meter. Then the two resistances are equal. Suppose, however, that the unknown resistance is much larger than any value we can obtain by adjusting R_4. For example, let it be ten times as large. Then it is only necessary to make R_1 ten times as large as R_2 when (3) becomes

$$\frac{R_1}{R_2} = \frac{R_3}{R_4} = 10$$

$$R_3 = 10R_4$$

and it is only necessary to adjust R_4 until no current flows through the meter and to multiply the resistance of this standard R_4 by 10 to get the value of the unknown resistance R_3.

The resistances R_1 and R_2 are called the **ratio arms;** R_4, the standard resistance, is usually a **resistance box,** that is, a box in which are a series of resistance units accurately measured and equipped with switch arms so that any value of resistance may be obtained. A simple slide-wire bridge is shown in Fig. 33. The unknown and known resistances are compared by means of a slider on a piece of resistance wire. The relative lengths of the wire provide the ratio arms R_1 and R_2.

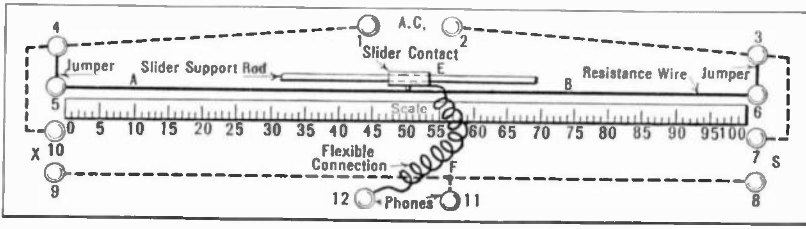


FIG. 33. A simple slide-wire bridge.

Problem 18–2. A soldering iron takes 5 amp when plugged into a 110-volt socket. What is its resistance? How much current will it take if the voltage is 115 volts?

Problem 19–2. A current of 50 ma flows through a resistance of 2000 ohms. What voltage would be measured if a high-resistance voltmeter were placed across the resistor?

Problem 20–2. A rheostat is a variable resistor, either with a contact arm riding on the resistance wire so that as the arm is moved by a handle any point in the resistance wire can be reached, or with definite connections to one or more points of the resistance. Suppose the total resistance of a rheostat is 30 ohms and that taps are brought out at the 12-ohm and 20-ohm points. If 1 amp flows through the entire resistance, what voltages are available at the taps?

Problem 21–2. A certain current-measuring instrument has a coil wound with wire that will burn up if more than 25 amp flow through it. It has a resistance of 0.06 ohms. What is the highest voltage that can be placed across it without danger?

Problem 22–2. A high-resistance voltmeter is not at hand and it is desired to measure the voltage output of a power supply system as in Fig. 30. When a milliammeter is in series with 20,000 ohms it reads 15 ma; when a voltmeter is shunted across the current meter and the resistance, it reads 270 volts and the milliammeter reads 13.5. What is the voltage output of the device?

Problem 23–2. Using the method in Section 32, a 10-volt full-scale Model 301 meter and a fully charged automobile battery (6.3 volts), the voltage across battery and resistor measures 5.42 volts. What is the unknown resistance? What is the current flowing through the battery, resistor, and voltmeter? The meter has a resistance of 62 ohms per volt.

Problem 24–2. Consider Fig. 28. E is a device (perhaps a rectifier tube) supplying voltage. It has an internal resistance, R, of 2000 ohms. It is desired to know the actual voltage produced by E. A voltmeter having a resistance of 1000 ohms per volt reading 250 volts full scale measures 240 volts at the point X. What is the value of E?

Problem 25–2. Suppose that R in this case is variable. When the 250-volt meter is placed at X, the terminals of the device, the needle goes off scale indicating that the voltage at X is greater than 250 volts. If, however, R is made equal to 2500 ohms, the needle of the meter indicates that just 250 volts appear across the meter. What is the voltage output of E?

NOTE. This is exactly the function played by a voltmeter multiplier—so to reduce the voltage actually appearing at the meter that it can be read on the meter scale without the needle going off scale.

Problem 26–2. What resistance must be put in series with a 250,000-ohm voltmeter reading 250 volts full scale if it is desired to make it measure 500 volts full scale?

Problem 27–2. A Weston Model 322 microammeter (25 μa full scale) has a resistance of 190 ohms. What voltage is required for full-scale deflection? What value of resistance shunted across it will make it possible to measure 250 μa?

Hint. A good starting point is to remember that the same voltage appears across the shunt resistance as across the meter resistance, and that the sum of the currents taken by these two resistances is equal to 250 μa.

CHAPTER III

PRODUCTION OF CURRENT

Electrical energy does not exist in nature in a form useful to man. It must be transformed from some other form of energy. For example, the mechanical energy of a motor or steam engine may be transformed into electrical energy by means of a generator.

The commonest sources of current useful to radio workers are the **battery** and the **generator.** The battery is a device which converts chemical energy into electrical energy; the generator uses up mechanical energy with the same result.

35. Batteries. A **battery** is made up of one or more units called **cells.** The essentials of the cell are three: two conductors called **electrodes,** usually of different materials, and a chemical solution known as the **electrolyte** which acts upon one of the electrodes more than it does upon the other. In this action, one of the electrodes is usually eaten up, and when this conductor, usually a metal, is gone, the battery is exhausted; it must be thrown away or the metal replaced. If the metal can be replaced by sending a current through the cell from some outside source, that is, by reversing the process through which the cell was exhausted, the cell is known as a **secondary** or **storage** cell. If the cell must be thrown away when one of the electrodes is eaten up, it is called a **primary** cell. The dry cell is a well-known example.

Experiment 1–3. If a plate of copper and a plate of zinc are placed in dilute sulphuric acid and a sensitive meter is placed across the terminals as shown in Fig. 34, a voltage of definite polarity will be indicated. The positive terminal of the voltmeter must be placed on the copper plate in order that the meter needle shall move in the proper direction. The copper plate is therefore positive; the zinc is negative. If a heavy external wire is attached to the plates, a current flows; the zinc is slowly dissolved, hydrogen bubbles appear at the copper plate, and finally the voltage of the cell falls off. Other combinations of metals should be tried.

The number of combinations of conductors and solutions that will make up a primary cell is very large; only a few of them are useful. Some deliver but small currents and low voltages, others give off noxious fumes, others do not last long enough to be practical.

The emf of such a cell depends upon the nature of the electrolyte and the materials from which the plates or electrodes are

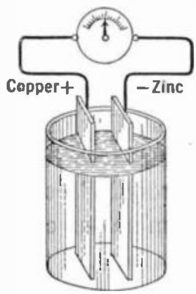


FIG. 34. A simple primary cell.

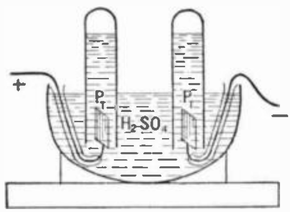


FIG. 35. An experiment in electrolysis.

made. Copper and zinc plates immersed in a solution of dilute sulphuric acid will give an emf of about 1 volt regardless of the size of plates or their distance apart. Zinc and carbon plates in chromic acid give an emf of about 2 volts.

Until the plates are connected externally by a conductor there is a difference of electrical potential existing between the two electrodes but no flow of current. This voltage is known as the emf of the cell. When the plates are connected and the cell is put to work the destruction of the zinc begins. When all the zinc is destroyed the cell is dead.

36. Electrolysis. The appearance of hydrogen bubbles at the copper electrode forms the basis of an interesting experiment which is illustrated in Fig. 35.

Experiment 2-3. Dip platinum electrodes into a solution of sulphuric acid and pass a current through them from a battery of about 10 or 12 volts. Hydrogen will be evolved at the electrode attached to the negative battery terminal and oxygen at the other. These gases will exert sufficient pressure to force the solution out of the inverted test tubes. If the volumes of the two gases are measured it will be found that the hydrogen always occupies just twice the volume required by the oxygen—which is one of the best proofs we have that water is made of two atoms of hydrogen combined with one of oxygen, whence arises the familiar chemical formula for water, H_2O.

The phenomenon whereby a chemical substance is decomposed by an electric current is known as **electrolysis.** In this case water made up of hydrogen and oxygen, is broken down into its two constituents. If two copper plates are placed in a solution of copper sulphate and if an electric current is passed between the plates the following events occur. The copper sulphate, $CuSO_4$, is broken down into copper, Cu, and sulphate, SO_4, ions. The copper ions move to the negative terminal and are deposited there in the form of "electrolytic" copper, while the sulphate ions move to the positive terminal or cathode. In this process the anode becomes $CuSO_4$ instead of pure copper and finally is "eaten" away.

37. Common dry cell. The common dry cell is illustrated in Fig. 36. The zinc container is the negative electrode, the carbon

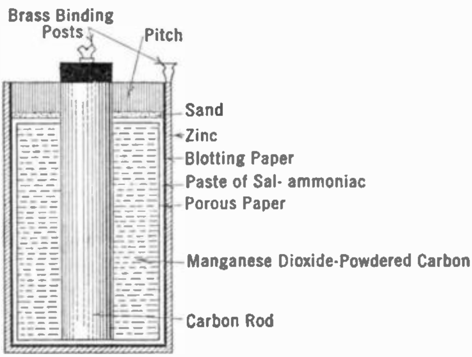


FIG. 36. Construction of dry cell.

rod in the center is the positive electrode. The electrolyte is a mixture of powdered carbon and manganese dioxide moistened with a solution of salammoniac. The voltage of the cell as measured by a voltmeter is about 1.5 volts. The ordinary B batteries used in radio are made up of many small 1.5-volt cells connected in series.

38. The storage cell. When the zinc container of the dry cell is eaten up, the cell must be thrown away. In the storage battery neither of the electrodes is eaten away, but the character of one plate is changed and when a current is sent through the battery from some external source this material is changed back to its original form, so that the cell is said to be charged and can be used again.

The storage cell has two electrodes, one of lead and one of lead peroxide immersed in a dilute solution of sulphuric acid. The usual storage battery is made up of three cells in series, producing a voltage of about 6 at the terminals. The positive terminal is usually marked, either with a red terminal, or a large cross, or in some other way. It is important to know the polarity of the battery when charging it. The positive post of the battery should be connected to the positive post of the charging line.

Experiment 3-3. If two lead plates about 6 in. square are immersed in a dilute solution of sulphuric acid—say one part of acid to ten of water—and connected in series with a battery of 6 or 8 volts and an ammeter, a current will be seen to flow, and the color of the plate attached to the positive terminal of the battery begins to change and the evolution of hydrogen bubbles at the other plate will be observed. The current soon decreases. Now replace the external battery with an incandescent lamp or an electric bell and note that current flows out of the lead cell and through the light or the bell.

39. Internal resistance. One might think that an unlimited current could be secured from a battery if it were short-circuited. Such is not the case. A very low-resistance ammeter placed across a dry cell gives a definite reading—it is not unlimited. Something must be in the circuit which has a resistance greater than that of the ammeter or the connections. For example, a new dry cell will deliver about 30 amp through wires of very low resistance.

This something which restricts the current to a limited value is the **internal resistance** of the cell. This resistance depends upon the construction of the cell, its electrode and electrolyte material, the distance apart of the electrodes, the condition of the cell—whether new or old. The older the cell the smaller the area of electrode in contact with the electrolyte and the greater the resistance. The current delivered by a cell is

$$I = \frac{E}{r + R}$$

when $r =$ internal resistance of cell;
$R =$ external resistance of circuit.

When a dry cell shows but a few amperes on short circuit, the chances are that its zinc case is badly eaten up. A voltmeter which requires very little current for a deflection will still read normal voltage, 1.5, because the small current through the cell does not cause appreciable voltage drop. The ammeter, however, draws all the current the cell can deliver. This current must flow through the cell as well as through the external circuit and hence there is a large voltage drop within the cell, leaving little voltage to force current through the meter.

Cells which have a large internal resistance deliver but small currents; low-resistance cells deliver large currents.

When one tests a dry cell with an ammeter, he is actually ascertaining the condition of the cell by measuring the internal resistance. When the cell gets old or has been exhausted because of too heavy currents, its internal resistance becomes high and an ammeter reads but small current when placed across it.

The storage cell is a very low-resistance device. Its terminal voltage when fully charged is about 2.1 volts and it has a resistance of about 0.005 ohm. Placing an ammeter across such a cell is dangerous. The meter will probably be ruined.

Example 1–3. A dry cell on short-circuit delivers 30 amp Its terminal voltage is 1.5 volts. What is its internal resistance?

By Ohm's law,

$$I = E/r$$

$$30 = 1.5/r$$

$$r = \frac{1.5}{30} = 0.05 \text{ ohm}$$

Example 2–3. The emf of a battery is 5 volts. When 100 ohms are placed across it the voltage V falls to 4 volts. What is the internal resistance of the battery?

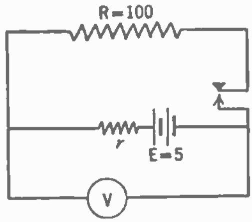


FIG. 37. A problem in internal resistance.

In Fig. 37, $R = 100$ ohms, $r =$ the internal resistance of the battery, the voltage drop across the 100 ohms is 4 volts, which leaves a 1-volt drop in the internal resistance of the cell. The current through the external 100-ohm resistance is, by Ohm's law,

$$I = 4/100 = 0.04 \text{ amp}$$

This current must also flow through the internal resistance of the battery and there it causes a voltage drop of 1 volt.

$$E = I \times r$$

$$1 = 0.04 \times r$$

$$r = 1 \div 0.04 = 25 \text{ ohms}$$

Note that the internal resistance of the cell is represented as being in series with the voltage and the external resistance. This is because the current must actually flow through the internal resistance of all such voltage generators, and hence the resistance of the device is represented in series with the remainder of the circuit. Care must be taken in such representations not to place the voltmeter in the wrong place. In Fig. 37 the voltmeter is actually placed across the battery and its internal resistance, which in turn are connected directly to the 100-ohm resistance.

The voltage of the cell on open circuit is its **emf.** Under load the voltage falls, and is now labeled as the **pd** (potential difference). The emf of high-resistance cells can only be measured by high-resistance meters, those that take but little current from the cell. When the voltage of a cell or battery is mentioned its emf is assumed unless otherwise labeled.

40. Polarization. In common with all other cells the zinc-copper sulphuric acid cell (Fig. 34) suffers from **polarization.**

The hydrogen bubbles which surround the copper plate decrease its surface in contact with the active liquid. This increases the cell resistance. In addition, a minute voltage is set up between the hydrogen and the copper. This voltage is opposite to the useful voltage and has the same effect upon the usefulness of the battery as an addition to the cell's internal resistance.

Various means are taken to overcome the bad effects of polarization. Chemicals may be placed in the cell to supply oxygen, which will combine with the hydrogen to form water; shaking the cell may remove the hydrogen bubbles and decrease the resistance of the cell. The manganese dioxide used in dry cell construction is a depolarizer. But these are only temporary remedies. Sooner or later the internal resistance of the cell becomes so high that the cell is no longer useful. A dry cell which has had large currents taken from it becomes polarized. If it is allowed to stand for a time, the chemicals put into the cell to do away with the polarization products have a chance to catch up with them and the cell is said to have recuperated. For this reason dry cells and others which tend to polarize are used only on intermittent service. Where a constant current is required a different type of cell is used.

41. Cells in series. Cells and batteries may be connected in several ways. When the positive terminal of one cell is connected to the negative terminal of the next cell, as in Fig. 38, they are said to be connected in **series.** Under these conditions, the voltage appearing at the two ends of the series of cells is the sum of the individual cell voltages. For example, if we connect four dry cells in series, each cell having a voltage of 1.5, a voltmeter across the two ends will register 6 volts. At the same time the total internal resistance is the sum of the individual resistances and whatever current flows must flow through this resistance.

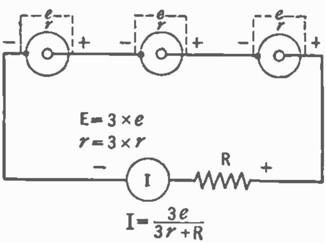


FIG. 38. Cells in series. Small letters indicate internal resistance and voltage of individual cells.

If the ends of the battery are connected with a wire of resistance R the current that will flow may be obtained by Ohm's law as

$$I = \frac{Ne}{Nr + R}$$

where N = number of cells;
e = voltage of each cell;
r = internal resistance of each cell.

42. Cells in parallel. When the positive terminal of one cell connects to the positive terminal of the next cell, and the negative terminals are connected together, as in Fig. 39, the cells are

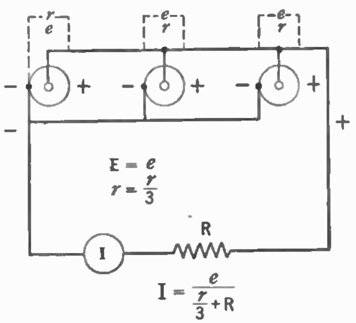


Fig. 39. Cells in parallel.

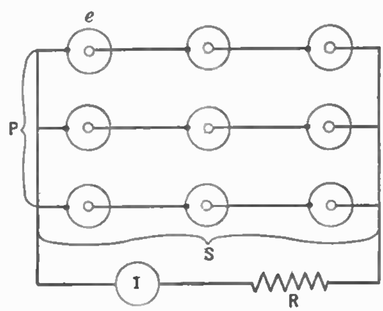


Fig. 40. Cells in series-parallel.

said to be connected in **parallel.** Under these conditions the terminal voltage of the combination is the same as the terminal voltage of each cell, but the internal resistance has been divided by the number of cells, N, and has become r/N.

If the ends of the battery are connected with a wire whose resistance is R, the current that will flow is

$$I = \frac{e}{\frac{r}{N} + R}$$

Cells may also be connected in what is called a **series-parallel** arrangement. In Fig. 40 are P sets of S cells in series, and the sets themselves are connected in parallel.

If the battery of cells shown in Fig. 40 is connected to a wire whose resistance is R, the current that will flow is

$$I = \frac{Ne}{RP + Sr}$$

where $N = P \times S$.

43. Magnetism. The second common source of electric currents is the generator. The magnet is the heart of the generator.

Magnets obey the same laws as the fundamental electrical charges mentioned in Section 3 of Chapter I. *Like magnetic poles repel each other, unlike poles attract.* Two magnets will repel each other if their North poles are turned toward each other, but will attract each other with considerable force when a North and a South pole are brought near.

44. Oersted's experiment. A Danish experimenter, Oersted, in 1819 made the first of a series of discoveries concerning the relation between electricity and magnetism which resulted in many modern applications of electricity. His experiment can be repeated by anyone who has a compass, a battery, and a wire.

Oersted's experiment demonstrated that a conductor carrying a current of electricity affects a compass needle just as a bar magnet does. Another experiment will teach us more about this important phenomenon known as *electromagnetism.*

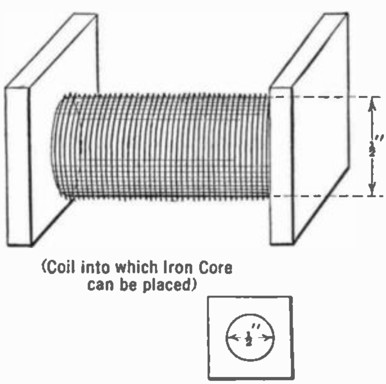


FIG. 41. A solenoid.

Experiment 4–3. Wind up about 1000 turns of rather fine wire, say No. 28 dcc, on a form about ½ in. in diameter or with a hole large enough that a bar magnet can be put in it easily, similar to that illustrated in Fig. 41. Connect it in series with a battery of about 6 volts, and bring a compass near its two ends. Reverse the current through the coil, and note change in direction of the compass needle motion. Note that the two ends of the coil act toward the compass needle just as a bar magnet would. Determine which of the coil ends is North and which is South by comparing their action on the compass with the action produced by the bar magnet whose poles are marked or by the position the needle takes with respect to the earth's poles.

Experiment 5-3. Scatter a quantity of fine iron filings on a piece of cardboard about 1 ft square. Place one end of a bar magnet under the cardboard, and tap the board until the filings assume a fixed position. Repeat, using the other end of the bar magnet, and then with a horseshoe magnet, and finally with the coil of wire through which a current is flowing. Place the bar magnet parallel to the cardboard and again scatter iron filings. Repeat with the coil magnet. Place the bar magnet inside the coil and remove from the cardboard to such a distance that, with no current flowing in the coil, the iron filings are affected but little. Connect the battery to the coil and note the increase in action among the iron filings. Repeat with battery connected and cardboard removed to such a distance that the filings are not affected. Then put the bar magnet inside the coil and note increased effect.

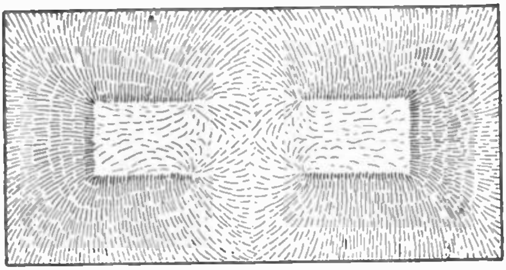


FIG. 42. How the lines of force about a bar magnet are located.

Such experiments demonstrate that coils carrying electric currents have much the same properties as iron bars which have been magnetized. The fact that such a coil or a magnet affects iron filings or compass needles even though some distance separates them, shows that in the space between them exists some force. The iron filings show the general distribution of this force. They tend to arrange themselves along lines which concentrate in strength at the two ends. These lines are called **magnetic lines of force.** The concentration points are called the **poles.** The space through which the lines pass is called the **magnetic field.**

The number of lines per unit of area, as in Fig. 43, is called the **field intensity** or **flux density**; and when one line goes through 1 sq cm the field strength is 1 **gauss.** The total number of lines through any given area is called the **flux,** and to find the flux it is only necessary to multiply the field strength, H, by the area, A. Thus

$$\text{flux } \theta = A \times H$$

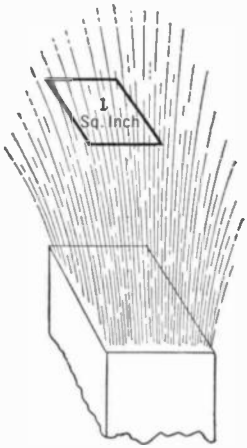


FIG. 43. The number of lines of force going through 1 sq in. or other unit of area is known as the flux density.

Magnetic lines of force may be set up in iron much more easily than in air. The ratio of the number of lines, under the action of a given magnetizing force, that exist in iron to those that would exist in air is called the **permeability** of the iron. If one line flows through 1 sq cm of air and one thousand through the same area of iron the permeability of the iron is 1000.

The field strength varies inversely as the square of the distance away from the pole as shown in Fig. 43. The nearer the unit area gets to the pole piece the greater the number of lines. As a matter of fact, halving the distance multiplies the number of lines by four.

The same magnetizing effect can be produced by a strong current acting through a few turns of wire as by a weak current through many turns of wire. If the product of turns and amperes, called the **ampere turns,** is the same in two cases the magnetizing effect will be the same.

It is because of the increased permeability, and of the consequent increase in flux density, that adding the iron core to the solenoid, or coil of wire in Experiment 5–3, is so effective. Soft iron is most easily magnetized, but loses its magnetism with the same rapidity. Permanent magnets are made from steel.

45. Faraday's discovery. The second important discovery on the way toward present-day electrical machinery was that of the celebrated English experimenter, Faraday. The experiment may be repeated by anyone who has a coil of wire, a bar magnet, and a sensitive current indicator such as the galvanometer used in Experiment 6–3.

Experiment 6–3. Construct a galvanometer made up of twenty-five turns of No. 14 bell wire, wound up in a coil with a diameter of about 6 in. Place an ordinary magnetic compass in the center of the coil and connect to the coil used in Experiment 4–3. Thrust a bar magnet into the coil quickly, and then remove it. Note the motions of the compass needle. Wind up another coil with about the same number of turns but of such a diameter that it can be placed around the first coil easily. Connect the second coil to a battery in series with a 30-ohm rheostat and place over the first coil and then remove with a quick motion. Note the compass needle variations.

In all the above procedure, note the relation between the compass needle movements and the rapidity with which the various changes are carried out.

Such was Faraday's experiment. When the bar magnet, or the coil carrying a current, was motionless, there was no motion of the needle. When a bar was thrust into the coil the needle moved in one direction, and when the motion of the bar was reversed the needle reversed its motion too. There was no metallic connection between the two coils, or between the coil and the bar magnet—and yet changing the position of one with respect to the other, or changing the direction or magnitude of current through one coil produced some electrical effect in the other circuit.

The facts underlying Faraday's experiment are these: An electric voltage was generated or **induced** in the coil when the bar magnet was thrust into it. A voltage of opposite polarity was generated when the magnet was removed. This voltage sent a current through the coil and the galvanometer so that the needle moved. The same explanation holds when two coils are used, one of them carrying a current taking the place of the iron bar. Whenever lines of force are cut by a conductor, a voltage is generated in that conductor. So long as the conductor moves so that it *cuts* the lines, that is, does not move parallel with them, a voltage is set up. The more lines per second and the more nearly the conductor cuts the lines at right angles, the greater the voltage. In Fig. 44, so long as the conductor *AB* moves in the direction of the arrow, no voltage is generated because its motion is parallel to the lines of force, but if *AB* moves up or down or in a direction through the paper, a voltage will be measured across its terminals.

This phenomenon is known as **electromagnetic induction,** and voltages and current in the conductor are called **induced,** and the electrical circuit in which they flow is usually called the **secondary;** the inducing circuit is known as the **primary.** There is no discovery in electrical science which has been so important. Almost every application of electricity to modern life depends upon this discovery of Michael Faraday.

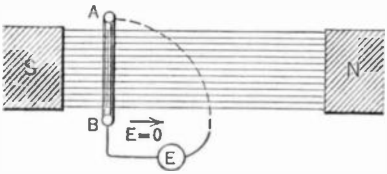


FIG. 44. So long as the conductor *AB* moves across the page, no voltage is generated. If it moves perpendicular to the paper, or up and down, a voltage is generated.

46. The electric generator. The essentials of a **generator** of electricity are first, a conductor, secondly an electric field, and third a motion of one relative to the other.

A generator converts mechanical energy into electrical energy. Figure 45 is a simple generator. It consists of a turn of wire which is mechanically rotated between two magnets. Remembering that no current due to the induced voltage flows when the conductor moves parallel with the lines of force, and that the maximum voltage is induced when the conductor moves perpendicular to the lines of force, because at this point the maximum rate of cutting takes place, let us see what happens as we rotate the coil.

In position (*a*), Fig. 45, the conductor is moving parallel with the field. No voltage is being generated. As the coil moves, however, it begins to cut the lines at a greater and greater angle until finally at (*b*) it is moving perpendicular to the lines and the voltage is a maximum. Now as the coil continues to move, the part *A-B* instead of moving upward across the lines of force moves downward across them. The induced voltage then has reversed its polarity and is increasing toward another maximum position, after which it returns to its original position, where the induced voltage is again zero.

In one complete revolution of the conductor there are two positions at which there is no induced voltage and hence no current

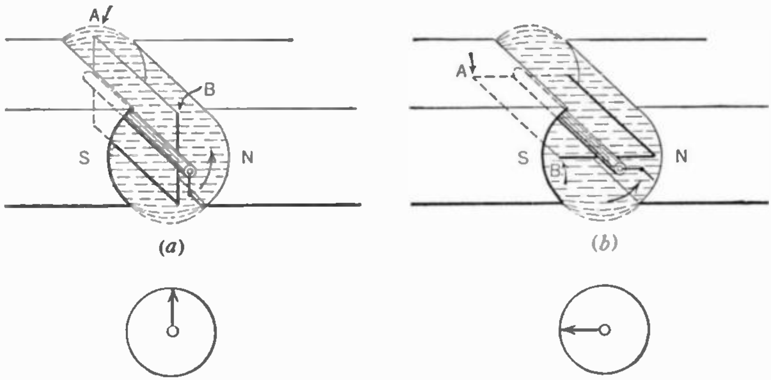


Fig. 45. In (*a*) the conductor *AB* is moving parallel or along the lines of force. In (*b*) the conductor is moving across or at right angles to the lines. At (*a*) the generated voltage is zero; at (*b*) it is a maximum.

in the external circuit, and two in which the voltage is at maximum. These two voltages have opposite polarities. At intermediate positions, the voltage has an intermediate value.

A complete circle, like a compass, may be divided into 360 degrees. Since the rotating coil moves in a circle, we can label the positions of the conductor in degrees of rotation instead of positions (*a*), (*b*), etc. At the beginning, (*a*), it is at 0 degrees —it has not started to move. Then at (*b*) it is at right angles to its original position (*a*), or it has gone through one-fourth of a complete revolution. It has therefore passed through one-fourth of 360 degrees or 90 degrees. When it is again parallel with the lines of force, it has passed through 180, and when it has gone through three-fourths of 360, or 270 degrees, the voltage is a maximum but in an opposite direction, and finally when it reaches its original position it has passed through a complete circle or 360 degrees.

Let us plot the current induced in the circuit against the degrees through which the coil has passed. Such a plot is shown in Fig. 46. When the current is flowing in one direction we call it positive, when it reverses we call it negative. If the conductor moves at a uniform rate, say one revolution in 360 sec, we can plot the current induced against time in seconds.

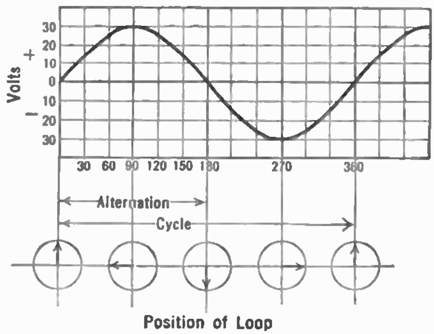


FIG. 46. Each position of the conductor as indicated by the arrows corresponds to some voltage as shown on the graph—called a "sine wave" of voltage.

One complete revolution is called a **cycle.** The number of cycles per second is known as the **frequency** of the induced voltage. The time required for one complete revolution is called the **period.** One-half cycle, or the part of the cycle during which the current flows in a given direction, is called an **alternation.**

Such is the current produced by an **alternating-current,** or a-c. generator. It flows first in one direction, then in another. The generator, of course, is a much more complex machine than we have illustrated here. The magnet is replaced by a heavy iron core covered with wire in which a direct current flows. This produces a strong unidirectional magnetic field. The moving coil is also wound on an iron form and consists of many turns of wire wound in slots.

The alternating current used to light our homes is usually of 60 cycles, or 120 alternations per second. In radio installations for use on shipboard and on aircraft, generators usually produce 500-cycle currents. At the high-power radio stations at Rocky Point, Long Island, are huge alternators which turn out radio frequencies of 20,000 cycles a second. By means of vacuum tubes, alternating currents having frequencies of many millions of cycles are generated.

47. Work done by alternating current. Some may wonder whether or not a current that is continually reversing its direction—never getting anywhere, so to speak—is useful. It is.

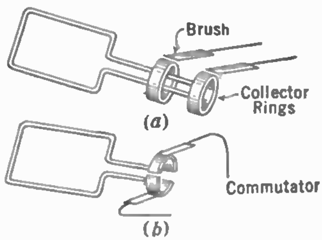


Fig. 47. Current is taken from an alternating-current generator by collector rings; a commutator serves the same purpose on a direct-current machine.

Consider a paddle wheel in a stream of water. To the paddle wheel are attached millstones. Grain is to be ground between the stones. It matters little whether the water flows continuously turning the millstones in a certain direction, or whether the water flows first one way and then another. So long as the millstones turn against each other, grain will be ground, work will be done. Current flowing through a resistance generates heat regardless of whether the current flows steadily in one direction or whether it reverses its direction periodically.

48. D-c generator. Current is taken out of a generator by **collector rings.** They are illustrated in Fig. 47. If current flowing continuously in the same direction is desired, the collector rings are not used, but instead a device called a **commutator** is used. It is a switch, or valve, which keeps the output current flowing in the same direction by reversing at the proper time the position of the leads with respect to the rotating wire. In this manner the current flows through the external circuit in a single direction, although the current in the conductor which cuts the lines of force must reverse each time the conductor passes through 90 degrees and reverses its direction with respect to the field.

The commutator serves the same purpose as a valve in a pump which keeps water flowing upward whether the pump handle is worked down or up. A machine which sends out current which flows in a given direction is called a **direct-current** generator, and naturally, the current is known as direct current, or dc.

49. Internal resistance. The generator too has an internal resistance so that the voltage measured at its terminals differs when different currents are taken from it. The voltage measured across the terminals on a meter requiring little current is called the **open-circuit voltage.** As the current taken from the generator increases, this voltage drops.

50. Electrical power. Throughout the previous discussion we have spoken of electrical energy in a rather loose way. What do we mean by energy? What is power? What is their relation to work?

Energy is the *ability to do work.* A body may have one of two kinds of mechanical energy, either **potential energy** or **kinetic energy.** The former is due to the position of the body, the latter is due to its motion. A heavy ball on top of a flag pole has potential energy because if it falls it can do work, useful or not. It may heat the ground where it falls, or it may be used to drive a post into the ground. A cannon ball speeding through the air has energy because it can do work, useful or otherwise, if it is stopped suddenly. The target may be heated thereby, converting the kinetic energy possessed by the ball into heat energy. The amount of damage done gives the eye a certain measure by which to judge the energy originally possessed by the cannon ball. This energy was originally possessed by the powder and was imparted to the ball when it exploded.

The **power** required to force a certain current of electricity through a wire at a voltage of E volts is the product of the voltage and the current. Thus,

$$\text{Power in watts} = \text{current in amperes} \times \text{volts}$$

or

$$P = I \times E$$

A horsepower is 33,000 ft-lb per minute. It is equal to 746 watts.

All expressions for power involve the factor of time. In other words, power is the *rate of doing work*. It requires more power to accomplish a certain amount of work in a short time than in a longer time. For example, a ton of material raised a foot in the air represents 2000 ft-lb of work. If it is accomplished by a crane in 1 sec of time it represents an expenditure of 2000 × 60 or 120,000 ft-lb per minute of power. Since 1 hp is equal to 33,000 ft-lb per minute, the crane has a power of 120,000 ÷ 33,000 or about 3.65 hp.

Now if a man raises the ton of material 1 ft in the air in an hour's time by going up a very long and gradual incline, his power is 2000 ÷ 60 or 33.2 ft-lb per minute, or roughly one-thousandth horsepower (0.001 hp). The amount of work done in the two cases is the same—the ton of material has been raised 1 ft in the air. The *rate of doing work* has changed.

Example 3-3. A generator is rated at 5 kw (5000 watts) output. How many amperes can it supply if its voltage is 110 and it has no appreciable resistance? How many horsepower is this?

Power equals $E \times I$

$$5000 = 110 \times I$$

$$I = 5000/110 = 45.6 \text{ amp}$$

Horsepower equals 746 watts.

$$5000/746 = 6.7 \text{ hp}$$

51. Power lost in resistance. According to the law called the conservation of energy, energy can neither be created nor destroyed. It comes from somewhere and goes somewhere. Similarly, all *power*, which is the rate at which energy is used, must be accounted for. The energy required to force current through a resistance must do some work. It cannot disappear. This work results in heating the resistance. Whenever current flows through a resistance, heat is generated and the greater the current the greater the heat. As a matter of fact, the heat is proportional to the square of the current. If the wire is heated faster than the heat can be dissipated in heating the surrounding air, the wire melts. Energy has been supplied to the unit at too great a rate.

A resistor used in a plate voltage power supply system is rated at so many ohms and as capable of dissipating so many watts. Thus a 1000-ohm, 20-watt resistor means that the resistance of the unit is 1000 ohms, and that 20 watts of electrical power can be put into it without danger of burn-out.

Problem 1–3. A voltmeter across a resistance measures 50 volts. Through the resistance flows 100 ma. What power is expended in it?

Problem 2–3. Assuming that 50 ma direct current flow through a resistor which has a d-c resistance of 750-ohms, what amount of heat in watts (I^2R) must be dissipated? What supplies this power?

52. Expressions for power. Just as there are three ways of stating Ohm's law, so there are three ways of stating the relation between power, volts, amperes, ohms. Thus,

$$(1)\ P = I \times E \quad (2)\ P = I^2 \times R \quad (3)\ P = E^2 \div R$$

Example 4–3. A plate voltage power supply system supplies 180 volts to a power tube of the 171 type which consumes 20 ma. How much power is taken? What is the resistance of the power tube?

The power supplied is $E \times I = 180 \times 0.02 = 3.6$ watts. The resistance into which this power is fed is equal to $P \div I^2 = 3.6 \div 0.0004 = 9000$ ohms or $E^2 \div P = 180^2 \div 3.6 = 32{,}400 \div 3.6 = 9000$ ohms.

The maximum current that can pass through one's body without serious results is 0.01 amp. The resistance varies with one's health and the surface in contact, etc. If the finger tips of the two hands are dry, the resistance from one hand to the other is about 50,000 ohms, and thus by Ohm's law the maximum voltage that can be safely touched is 500.

Problem 3–3. Assuming that a man can touch with his dry finger tips a 500-volt street car conductor, and that the resistance of his body is 50,000 ohms, how much power is used up in heating the body?

Problem 4–3. A voltage of 110 is to be placed across a circuit whose resistance must be such that 220 watts can be delivered. What is the resistance of the circuit?

Problem 5–3. How much power is taken from a storage battery which supplies five automotive radio receiver tubes each requiring 0.3 amp at 6.3 volts?

Problem 6-3. One milliampere of plate current flows through a 100,000-ohm resistor. How much power in heat must the resistor be capable of dissipating?

Problem 7-3. How much current can be sent through a 1000-ohm 20-watt resistor without danger of burning it up? What voltage is required?

Problem 8-3. In a plate voltage supply system the voltage divider has a total resistance of 5000 ohms. The receiver requires a maximum current of 30 ma. What must be the wattage rating of the resistor if all this current flows through it?

Problem 9-3. An automobile receiver of five 6.3-volt tubes consumes a plate current of 50 ma at 180 volts. Assume that the car battery supplies this load; what power is required?

Problem 10-3. Electric power is bought by the kilowatt-hour. Suppose your rate is 10 cents per kilowatt-hour. How much does it cost to run a flatiron on a 110-volt circuit if it consumes 6 amp?

53. Efficiency. Efficiency is a term that is loosely employed by nearly everybody. Anything which works is said to be efficient, and one's efficiency is often confused with his energy—his ability to do work whether the work is actually carried out or not. The term, however, has a very exact meaning when one uses it in speaking of mechanical or electrical systems of any kind. Efficiency is a relative term. It is a ratio showing how much *useful* work one gets out of a *total* amount of work done.

Let us consider a steam engine connected to a dynamo, a combination of machines for transforming mechanical energy into electrical energy. If the steam engine consumes 1 hp (746 watts) and delivers 500 watts of electrical energy, it is said to be more efficient than if it delivered only 250 watts. Let us consider two men, one of whom gets a lot of work done in a small amount of time and with an expenditure of little effort. The other gets the same amount of work done but with great effort, perhaps flurrying about from one thing to another instead of tackling his problem in a straightforward manner. The first man is more efficient. He *wastes* less time and energy.

Efficiency, then, is the ratio between useful work or energy or effect got out of a machine to the total energy or power or effort put into it. It is expressed in percentage. A machine that is 100 per cent efficient has no losses; there is no friction in its bearings, or, if it is an electrical device, no resistance in its wires.

There are no such machines in use today. Efficiency is the ratio of useful power one gets out of a device to the power put into it.

$$\text{Efficiency} = \frac{\text{useful output}}{\text{input}} = \frac{\text{useful output}}{\text{output plus losses}}$$

Problem 11–3. Seventy-five per cent of the ampere-hours put into a battery are returned by it on discharge. How many hours must a 100-amp-hr battery be charged at a 1-amp rate?

Problem 12–3. A motor generator or vibrator system supplies the plate voltage to an automobile receiver consuming 50 ma at 180 volts. If its efficiency is 40 per cent, what power and current are taken from the battery?

Problem 13–3. If a 5-hp motor operated from a d-c line is 85 per cent efficient, what current does it take from the power line?

Problem 14–3. A 200-amp-hr battery is taken into the field to operate a portable radio transmitter which requires 40 amp. It is keyed so that power is taken from the battery 75 per cent of the time. The transmitter consumes 50 watts, and in addition to this load there is a continuous load of 1.5 amp for a light. How long will the battery supply the transmitter and the lamp?

Problem 15–3. A broadcast transmitter radiates 10 kw in the daytime but is permitted to radiate only 5 kw at night. If the daytime antenna current is 15 amp, what is the nighttime current?

Problem 16–3. A transmission line made up of two wires transmits power from a radio transmitter to an antenna. At the transmitter end the current in the line is 5 amp; at the antenna end it is 4.7 amp. What power is lost in the line if 10 kw are delivered to the antenna?

Problem 17–3. If the strength of a radio signal at a distant point is proportional to the square root of the power at the transmitter, by how much must the transmitter power be increased to double the strength of the signal at the receiving end? How much should the transmitter antenna current be increased?

Problem 18–3. A generator delivers 42 amp at 440 volts at an efficiency of 82 per cent. What power is lost in the generator?

CHAPTER IV

INDUCTANCE

The experiments of Ohm, Oersted, and Faraday laid the foundation of modern electrical science. The experiments of the last chapter gave us some idea of what these investigators discovered, and gave us a background for the following fundamental facts.

54. Coupled circuits. Consider the two coils *P* and *S* in Fig. 48. They are said to be "coupled" when lines of force from one

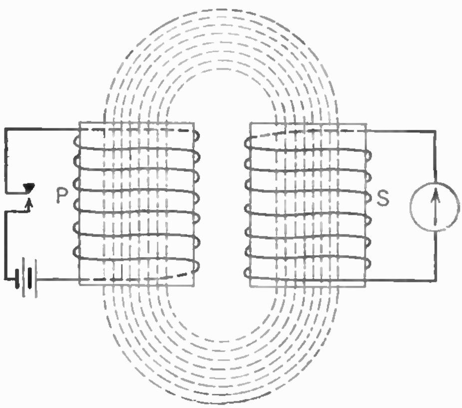


FIG. 48. If the coils *P* and *S* are coupled so that lines of force from *P* go through *S*, a current indicator will show a flow of current in *S* when the key in *P* is momentarily closed or open.

go through the other. When *P* is attached to a battery and the switch closed there is a momentary indication of the needle across *S*. When the switch is opened the needle moves again but in the opposite direction. So long as the current in the primary *P* is steady in value and direction, there is no movement of the needle across the secondary or coils. If a galvanometer is put across the secondary of an ordinary high-ratio audio transformer, and a battery is connected across the primary, the needle of the galvanometer will kick one way when the connection is made, and in the opposite direction when the battery connection is broken. This deflection of the needle indicates a momentary flow of current in the secondary coil; this current flows only when the primary current is changing, i.e., starting or stopping. not when the primary current is fixed in value or direction.

55. Lenz's law. There are two fundamental facts about this phenomenon of coupled circuits. The first is that when lines of force couple two coils together, and some change in these lines takes place, perhaps because of a change in the relative positions of the two circuits, a voltage is induced in the second circuit. The second fundamental fact is known as **Lenz's law:** the induced current is in such a direction that it opposes the change in position that produced it.

Thus when the battery is attached to P, lines of force thread their way across the turns of wire in S. This movement of the lines of force through S induces a voltage across this coil and a current flows in the coil and the apparatus connected to it. This current in the second coil is in such a direction that its field. that is, its lines of force threading through the primary, induces a counter-voltage in the primary opposite in direction to the battery voltage across it.

When the battery voltage is broken, the lines of force from the primary current collapse back on the coil, and, in crossing the secondary turns in an opposite direction to that taken when the current in the primary is increasing, induce a voltage in the secondary in such a direction that it tends to keep the primary current flowing.

The result is that it takes a longer time to build up the primary current to its final value at "make" and a longer time for the current to fall to zero at "break."

If it were not for the phenomenon expressed in Lenz's law, electrical equipment would burn up. If a current is induced in the secondary by a change in lines of force in the primary, a current will be induced in the primary by these changing secondary lines of force. This current would, in turn, induce more current in the secondary, which would produce more in the primary and soon there would be no limit to the currents that were flowing and the mechanism would be destroyed.

This phenomenon of induced current is of most fundamental importance. It is the basis of all our modern electrical machinery. Our motors, our dynamos, our radio signals, all are the result of our ability to produce changes in one circuit by doing something to another although the two circuits have no metallic connection whatever.

The fact that current takes longer to reach its final value in a circuit in which there is a coil of wire indicates that something about this coil tends to prevent any change in the current. If the current is zero, this property of the coil tends to prevent any current from flowing. If the current already exists, this coil property tends to prevent either an increase or decrease in this value of current.

56. Inertia—inductance. The property of an electrical circuit which tends to prevent any change in the current flowing is called its **inductance.** It has a mechanical analogue in **inertia.** A flywheel requires considerable force to get it up to speed; and after it is started it will continue to run for some time after the driving force is removed. It does not stop suddenly. As a matter of fact, it requires considerable force to stop it, and the more suddenly one wants to stop it, the more force he must apply.

Inertia is evident in a mechanical system only when some change in motion is attempted. It is not the same as friction, which is always present.

Inductance is a property of an electrical system in which changing currents are present. It is not to be confused with resistance, which is always present. Current flowing in a resistance circuit stops when the driving force (voltage) is removed. If inductance is added to the circuit, the resistance remaining the same, a longer time will be required for the current to reach its final value, zero, when the voltage is removed.

57. Self-inductance. Inductance is added to a circuit by winding up a wire into a compact coil. If, for example, 1000 ft of No. 20 copper wire is strung up on poles, it will have a resistance of about 10 ohms and the current into it would reach a final value very soon after a battery were applied. If, how-

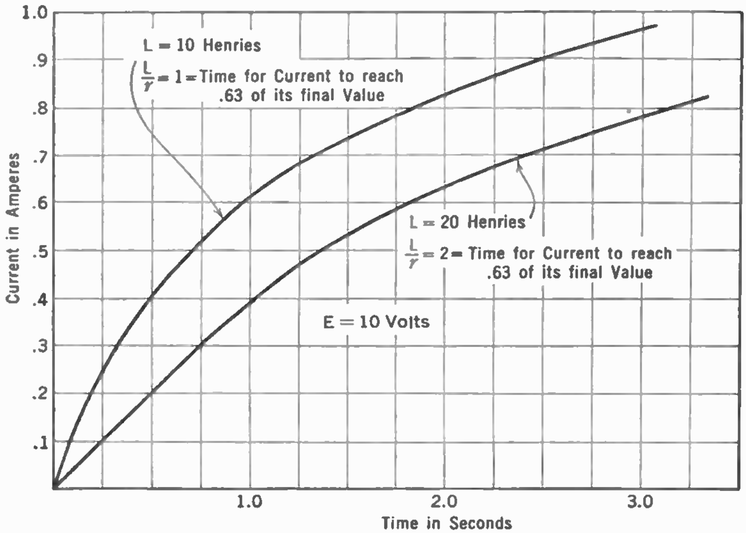


FIG. 49. Current in an inductive circuit does not rise instantaneously to its maximum value as these curves show.

ever, the wire were wound up on a spool with an iron core, the time required for the current to reach its final value would look like the curve in Fig. 49. Its resistance has not changed; we have merely added inductance.

When the switch is opened a fat spark occurs; this is not true when the wire is strung up on poles. The current seems to try to bridge the gap—to keep on flowing. It does not "want" to stop. This is because of the inductance of the coil.

A single coil can have inductance and can have a voltage induced across it just as though it were the secondary coil shown at S in Fig. 48.

When the current starts to go through the coil, lines of force begin to thread their way out through the coil, thereby cutting adjacent turns of wire, and according to Lenz's law inducing in each turn a voltage in such a direction that it tends to oppose the building up of the current from the battery. When the battery connection is broken, these lines of force fall back upon the coil and when cutting the individual turns of wire in the opposite direction they induce voltages in them which tend to keep the battery current flowing.

58. Magnitude of inductance and induced voltage. The greater the number of turns of wire in a small space, or the better the permeability of the core on which the wire is wound, the greater will be the inductance of the coil and the longer the time required for the current to reach its final value. The permeability of air is 1.0; that of iron may be as high as 25,000. This means that the inductance of a given coil may be increased 25,000 times by winding it on a core of high-permeability iron or alloy such as permalloy which, composed of nickel and iron, may have a permeability as high as 100,000.

The induced voltage across such a coil depends upon the rate at which the current is changing and the inductance of the coil. Since the current tends to keep on flowing when an inductive circuit is broken the voltage across the coil must be in the same direction as the battery voltage. Thus if a coil has 100 volts from a battery across it, and the current is suddenly broken, the voltage at the instant of break across the coil will be 100 plus the additional induced voltage. Breaking the current in a highly inductive circuit may set up a tremendous voltage across the coil and a severe shock can be felt by holding the ends of the wire at the moment of break. This is a practical demonstration of Lenz's law.

The inductance of a coil depends upon the number of turns, the manner in which the wire is wound, and the material on which it is wound. If the coil is wound on iron, the inductance will be greater because the lines of force will be concentrated into a smaller space; more lines per unit area will go through a given area of coil.

In radio circuits the coils are usually wound on non-magnetic cores. In audio * circuits iron is utilized to build up large inductances in small spaces and with a minimum of copper wire.

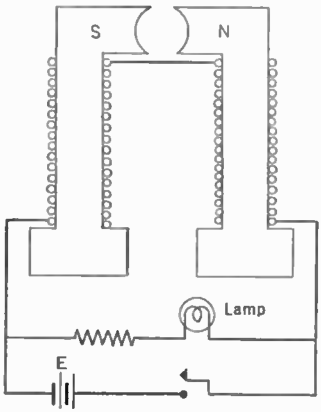


FIG. 50. An example of Lenz's law. The lamp will light when the key is opened even though insufficient current flows through it when the key is closed.

If an a-c voltage is placed across a coil, the current through the coil is much less than if a d-c voltage were placed across it. This is because of the counter- or back-voltage induced across the coil by the effects just described. The result is that a seeming decrease in voltage across the coil has taken place, although a voltmeter would indicate that the full-line voltage was across the coil.

Example 1–4. In Fig. 50 is an inductance across which is placed a flash lamp and a battery. The current is regulated so that insufficient current goes through the lamp to light it up. Now when the switch is opened the lamp will suddenly light (and may burn out) because of the added voltage across it.

59. The unit of inductance. When a current change of 1 amp per second produces an induced voltage of 1 volt, the inductance is said to be one **henry,** named from Joseph Henry, an American experimenter who discovered the phenomenon of electromagnetism at the same time as Michael Faraday. Coils added to circuits for the purpose of increasing the inductance of the circuit are properly called **inductors.**

60. Typical inductances. The coils used in radio apparatus vary from inductances of the order of microhenries to very large ones having over 100 henries in inductance. Broadcast fre-

* "Audio" circuits involve alternating currents which can be heard by the human ear, i.e., from 50 to 15,000 cycles. "Radio" frequencies are much higher and are inaudible.

quency tuning coils are of the order of 300 μh and may be from ½ to 3 in. in diameter wound with from No. 30 to No. 20 wire of from 50 to 100 turns or so. There are a number of complicated formulas by which one can calculate the inductance of coils of various forms and sizes. The ones in Fig. 51 are accurate enough for practical purposes.

These formulas show that the inductance increases as the square of the number of turns. Thus if a coil of three units in-

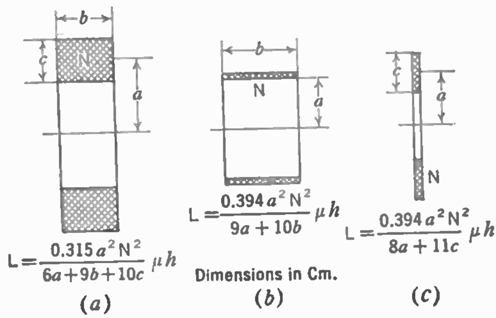


FIG. 51. Some typical coil forms and formulas on which the inductance may be calculated.

ductance has its number of turns doubled, the inductance will have increased four times or to twelve units. This is true provided there is good "coupling" between turns; that is, if the coil is on an iron core this rule is strictly true, but if the coil is wound on a core of air the rule is only approximately true. It becomes more nearly a fact the closer together the turns of wire.

Problem 1-4. A coil like that in Fig. 51*a* is called a **multilayer** coil. Such a coil is wound to have 1000 turns, in a slot 1 in. square. The distance from the center of the coil to the center of the winding (*a* in Fig. 51) is 2 in. What is the inductance of the coil in microhenries? Remember that the dimensions given in Fig. 51 are in centimeters and that 1 in. equals 2.54 cm.

Problem 2-4. A coil like that in Fig. 51*b* is called a **solenoid.** Calculate the inductance of such a coil composed of 60 turns of wire in a space of 3 in., the diameter of the coil form being 3 in. Coils used in modern broadcast receivers are wound on cores about 1 in. or less in diameter.

61. Coupling. The closer together the two coils, *P* and *S*, Fig. 48, the greater the number of the lines of force because of the primary current that links with the turns of the secondary, and the better the "coupling" is said to be. The better the permeability of the medium in which the lines go, the better the coupling.

The voltage across the secondary of such a two-coil circuit as that shown in Fig. 48 depends upon the sizes of both coils, their proximity, the permeability of the medium, and the rate at which the primary current changes. All the factors except the rate of change of the primary current are grouped together and are called the **mutual inductance** of the circuit.

The secondary voltage, then, is equal to

$$M \times \text{rate of change of primary current}$$

where M is the mutual inductance and is rated in **henries.**

62. Magnitude of mutual inductance. Formulas in Fig. 51 show that the inductance of a coil depends upon the square of

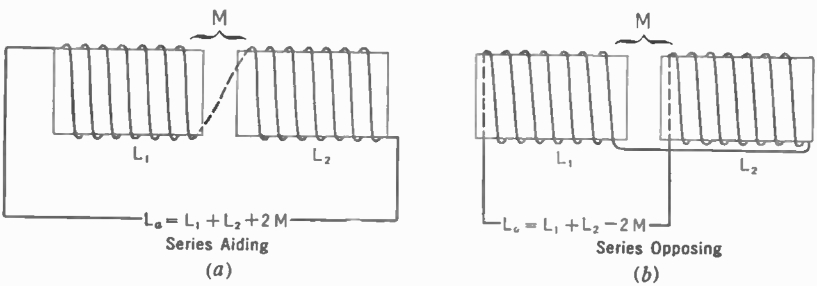


FIG. 52. Coils may be connected so that their fields aid or "buck." In one the total inductance is increased, and in the other the total inductance is decreased.

the number of turns. Doubling the turns increases the inductance four times. Consider two coils built alike and having the same inductance. If they are connected the total inductance will be equal to that of a single coil of double the turns. In other words, the total inductance of two coils connected "series-aiding" will be four times the inductance of a single coil. If the connections to one coil are reversed, the total inductance will be zero because the lines of force from one coil will encounter the lines of force from the other coil which are in the opposite direction. The coils are now connected "series-opposing."

Consider the series-aiding case, Fig. 52*a*. The total inductance is made up of the inductance of coil 1, that of coil 2, the mutual inductance due to the lines of force from coil 1 which go through coil 2 and the mutual inductance associated with the lines from coil 2 which go through coil 1; these two inductances are equal because the coils are identical. Thus,

$$L_a = L_1 + L_2 + 2M$$
$$= 2L_1 + 2M \text{ (because } L_1 = L_2\text{)}$$
$$= 4L_1 \text{ (by experiment or measurement)}$$

whence

$$M = L_1$$

Now if the coupling in both is less than perfect, if some of the lines from one coil do not link the other—and such is always true—the total inductance, L_a, in the series-aiding case is less than four times the inductance of one coil and in the series-opposing case is greater than zero. But in any case the total inductance of two coils of any inductance connected in series-aiding will be given by $L_1 + L_2 + 2M = L_a$ and if they are connected series-opposing the resultant inductance will be $L_1 + L_2 - 2M = L_o$. The following expression involving a new term, the *coefficient of coupling*, enables us to predict just what the total inductance in the circuit will be once we know how well the two coils are coupled.

$$\text{The coefficient of coupling } \tau = M/\sqrt{L_1 L_2}$$

The coefficient of coupling depends upon the total inductance in the primary and secondary circuits as well as upon the mutual inductance between inductances L_1 and L_2, Fig. 53.

The mutual inductance depends upon only the two coils, L_1 and L_2, and the coupling between them, or $M = \tau\sqrt{L_1 L_2}$; the coefficient of coupling between two circuits depends upon the total inductance in the circuits. The maximum possible value of τ is 1.0. This is called unity coupling, and approaches this value in iron-core transformers. In air-core coils and transformers the coupling may be very weak, that is, of the order of 0.1, and sel-

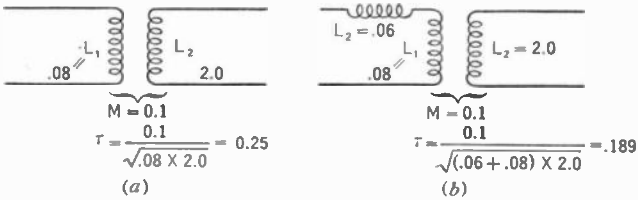


FIG. 53. Examples showing dependence of coefficient of coupling on series inductance.

dom reaches 0.7. In an iron-core transformer 98 per cent coupling ($\tau = 0.98$) is usual.

63. Measurement of inductance. Inductance is usually measured by means of a Wheatstone bridge (Section 34) just as resistance is measured. This is essentially a method of comparing the unknown inductance to a known inductance. Resistances are used as the ratio arms, as in Fig. 54. When there is no sound in the telephones the inductances are equal if the ratio arms are equal, or if the ratio arms are not equal the unknown inductance is given by the equation

$$L_x = L_s \frac{A}{B}$$

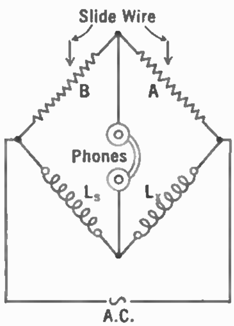


FIG. 54. If A and B are so adjusted that there is no sound in the phones,

$$L_x = L_s \frac{A}{B}.$$

Mutual inductance is measured on a bridge, or by the following method: The inductance of the individual coils may be measured first. Then they are connected series-aiding and the total inductance measured. This gives us the formula $L_1 + L_2 + 2M$, from which M can be calculated at once. Of course, the same result will be obtained by connecting the coils series-opposing. It is not even necessary to measure the individual inductances first, provided we can measure the inductance both series-aiding (L_a) and then series-opposing (L_o). Then

$$4M = L_a - L_o$$

$$M = \frac{L_a - L_o}{4}$$

Problem 3–4. If two identical coils are connected so that unity coupling exists between them, i.e., all the lines of force from one coil go through the other coil, what is the total inductance? If they are connected series-aiding?

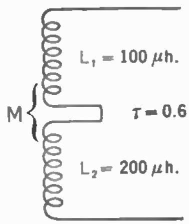


FIG. 55. A problem in coupled circuits.

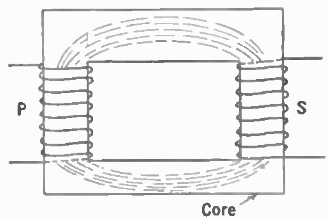


FIG. 56. A simple transformer.

Problem 4–4. In Fig. 55, when the coils are connected series-aiding, the inductance is measured as 400 μh. What is the mutual inductance?

Problem 5–4. In a screen-grid tube radio-frequency amplifier circuit the primary inductance is 350 μh, the secondary is 230 μh, the mutual inductance is 160 μh. Calculate the coefficient of coupling.

Problem 6–4. In Fig. 55, $L_1 = 100$ μh, $L_2 = 200$ μh, and $\tau = 0.6$. What is the mutual inductance? What is the total inductance ($L_a = L_1 + L_2 + 2M$)? What is it if L_2 is reversed (M is negative)?

64. The transformer. A transformer is a device for raising or lowering the voltage of an a-c circuit. It transforms one voltage into another. It consists of two windings on an iron core, as in Fig. 56. The purpose of the iron core is to insure that the magnetic field set up about the primary will flow through the secondary coil without loss. What few lines of force do not link primary and secondary are called **leakage** lines and the inductance associated with them is called **leakage inductance.**

The primary is attached to an a-c line, the secondary to the load, whether this is a house-lighting circuit, a motor, or any other device which requires electricity.

The continually changing lines of force from the primary flow through the secondary and induce voltages in it. The relation between the primary and secondary voltages is simple and definite—it depends upon the relative number of turns. If there are twice as many secondary turns as there are primary turns, the voltage developed across the secondary terminals will be double that across the primary. The following formula gives the relation between primary and secondary turns and the respective voltages:

$$\frac{e_p}{e_s} = \frac{n_p}{n_s} = N \quad \text{(turns ratio)}$$

By using the proper ratio of turns, voltages either greater or less than the primary voltages may be secured at the secondary terminals.

Example 2–4. A transformer is to connect a 110-volt motor to a 22,000-volt transmission line. What is the ratio of turns?

$$\frac{e_p}{e_s} = \frac{n_p}{n_s}$$

$$\frac{22{,}000}{110} = \frac{n_p}{n_s} = 200$$

Note. This does not give the number of turns in either primary or secondary windings. The absolute number of turns depends on several factors; the ratio of turns depends on the voltages to be encountered.

Problem 7–4. In electric welding a very low voltage is used. What would be the turns ratio of a transformer to supply a welding plant with 5 volts if it takes power from the standard 110-volt circuit?

Problem 8–4. A 2.5-volt transformer supplies 5 tubes with 1.75 amp for each filament. What are the turns ratio and minimum primary current? If the transformer is 90 per cent efficient what power does it take from the 110-volt line?

Problem 9–4. A primary consists of 200 turns of wire and is connected to a 110-volt circuit. The secondary feeds a rectifier circuit requiring 550 volts. How many turns will be on the secondary winding?

Problem 10–4. A certain transformer used in a radio-frequency amplifier has a secondary inductance of 240 μh. When the two coils of the transformer are connected series-aiding the total inductance has increased to 350 μh, and when connected series-opposing the inductance drops to 230 μh. What is the inductance of the primary? What :s the mutual inductance between them in the two cases, and what is the coefficient of coupling?

65. Power in transformer circuits. Since the transformer does not add any electricity to the circuit but merely changes or transforms from one voltage to another the electricity that already exists, the total amount of energy in the circuit must remain the same. If it were possible to construct a perfect transformer there would be no loss in power when it is transformed from one voltage to another. Since power is the product of volts times amperes, an increase in voltage by means of a transformer must result in a decrease in current, and vice versa. On the secondary side of a transformer there cannot be more power than in the primary and if the transformer is one of high efficiency, the power will be only slightly less than on the primary side. The product of amperes times volts remains the same. Thus the primary power is

$$E_pI_p \qquad [1]$$

and the secondary power is

$$E_sI_s \qquad [2]$$

and since there is no loss or gain in power

$$E_pI_p = E_sI_s \qquad [3]$$

whence

$$\frac{I_p}{I_s} = \frac{E_s}{E_p} = N \quad \text{(turns ratio)}$$

which shows that the secondary voltage increases as N increases; the secondary current decreases when N increases.

66. Transformer losses. Transformers are not perfect. There is some resistance in both primary and secondary coils. The current going through these resistances produces heat, which represents a certain amount of power lost. All the lines of force coming out of the primary coil do not go through the secondary (the transformer does not have "unity coupling"). Some of the magnetic field of the primary, therefore, is not used in inducing currents in the secondary. The iron core—which is a metallic conductor in the magnetic field of the primary, just as the secondary wire is—has currents induced in it and since the iron is a high-resistance conductor it heats up. All these losses must be supplied by the primary source of power, the generator. Large transformers, however, are very efficient, over 90 per cent of the input power being transferred to the secondary circuit.

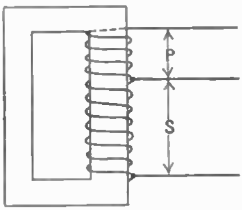


FIG. 57. An auto-transformer. The secondary can be the entire winding or part as shown.

67. The auto-transformer. It is not necessary for proper transformation of voltage that the primary and secondary windings shall be distinct. In Fig. 57 is a representation of what is known as an auto-transformer, in which the secondary is part of the primary. The voltage across the secondary turns, however, bears the same relation to that across the primary part as though there were two separate windings. The ratio of voltages is the ratio of the number of turns possessed by the secondary and primary.

A transformer is often used when both alternating and direct currents flow through a circuit and it is desired to keep the direct current out of the circuit to which the secondary is attached. No d-c current can go across the transformer when the two windings are distinct, although the a-c voltage variations occurring in the primary are transferred to the secondary by the effects already described. If no increase or decrease in voltage is desired the turns ratio is made unity; that is, the same number of turns will be on the secondary as on the primary.

An output transformer which couples a loud speaker to a power tube in a power amplifier serves this isolating purpose. The power tube has considerable direct current flowing in its plate circuit where the useful alternating currents also flow. The dc is undesirable in the loud-speaker windings, so a transformer is used to isolate the speaker from the direct current of the tube.

A good transformer of this type will transmit all frequencies in the audible range with an efficiency of about 80 per cent.

Problem 11-4. The line voltage in a certain locality is only 95 volts but a radio set is designed to operate from a 115-volt circuit. A transformer is to be used like that in Fig. 57. What will be the ratio of turns?

When no current is taken from the secondary of a transformer the primary acts merely as a large inductance across the line. The current will be rather small. The energy associated with this current is used in two ways, one of which is in heating the transformer and its core. The other part maintains the magnetic field of the primary. This consumes no energy from the line because at each reversal of the current the energy of this field is given back to the circuit.

When the secondary load is put on, however, it begins to draw current from the secondary and more power is taken from the line leading to the generator. This additional power is that required by the load together with the loss in primary and secondary resistance.

68. Variable inductors. A variable inductance may be used to regulate the current in an a-c circuit. This variation in inductance can be secured by means of a slider, as in Fig. 58, or by a fixed number of turns and a movable iron core. Variations in the position of the iron change the permeability of the core on which the wire is wound and thereby vary the inductance. This is often employed in power circuits.

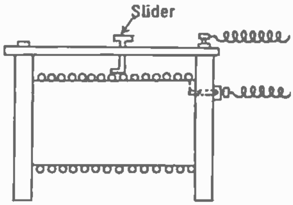


FIG. 58. An early form of variable inductance for radio purposes called a "single-slide tuning coil."

For radio-frequency work the variable inductance can take the form of a variometer, shown in Fig. 59, in which the inductance is continuously variable from a low value when the two coils are "bucking" each other, or are connected series-opposing, to the maximum value where they are connected series-aiding. The coils are always connected in the same manner, but by having one coil rotate within the other the variations in inductance result. The calibration of such a variometer is shown in Fig. 60.

69. Use of iron in inductances. If one were to measure the inductance of a coil of wire first without an iron core and then with an iron core, it would be found that in the latter case the

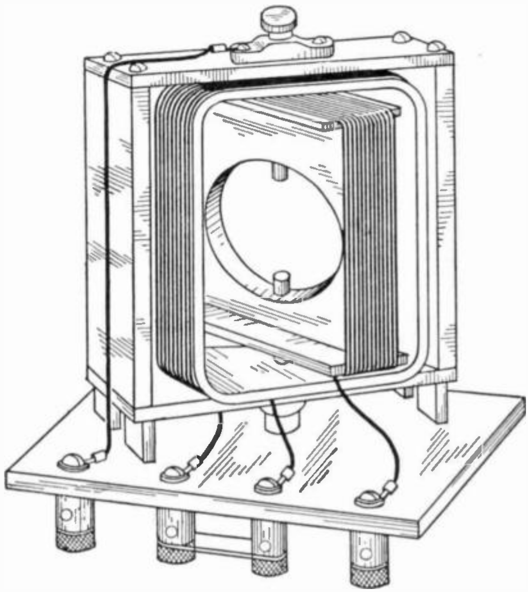


FIG. 59. Variable inductance made up of two coils, one rotating within the other.

inductance would have increased very materially. In Section 58 it was stated that the inductance depended upon the number of turns in the coil and the permeability of the core upon which the coil is wound. Now the number of turns has not increased; clearly it is the permeability that has increased.

Permeability is a measure of the ease with which lines of force can be concentrated in a small area. A highly concentrated field (many lines of force per unit area) is possible in iron or in one of the iron alloys used for this purpose. Iron, therefore, increases the inductance which one can secure with a given amount of wire wound in a given form.

The question arises, why not use iron in all our circuits where we want inductance? For a given amount of wire we can get more inductance with iron than without it, and for a given in-

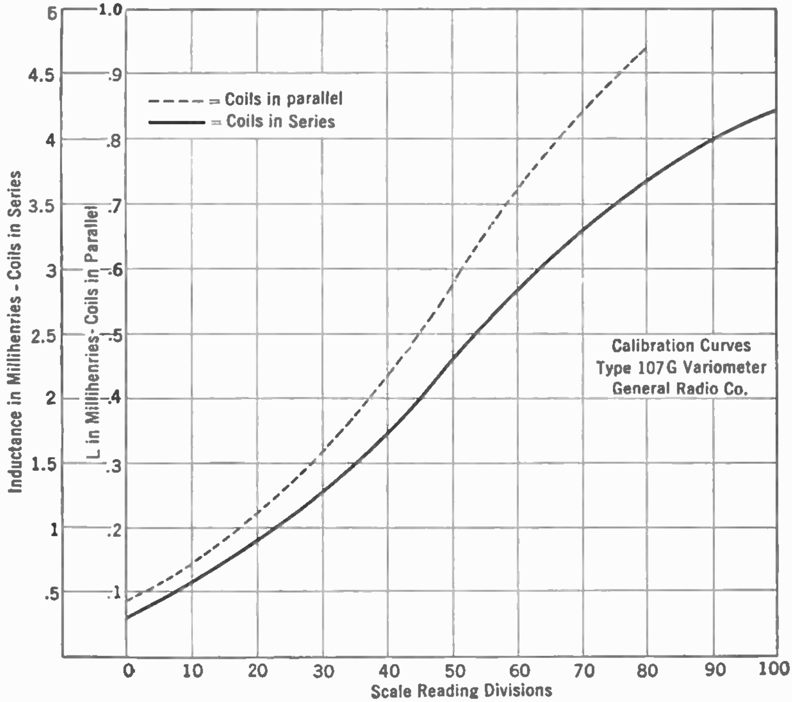


Fig. 60. Calibration of a standard variable inductance.

ductance we will need less copper wire and less space if we use iron.

There are several stumbling blocks, however, to this idealized situation. In the first case iron is a conductor. Lines of force flowing through it produce voltages and currents in it just as they do in a coil made up of copper wire. This current flowing through the iron core heats the core and this heat represents a waste of power. Furthermore, iron is rather cantankerous to deal with, magnetically speaking. The permeability of an iron core depends upon the amount of current flowing through the coil which surrounds the iron. This permeability does not increase or decrease in direct proportion to the amount of current. The power losses in the core depend upon the rate at which the lines of force change and thus as the frequency of the circuit in which the coil is operated increases, the losses increase, until finally a frequency is reached where the iron core is more wasteful than useful and one gets along better without it.

Consider a coil of wire wound on an iron core. Let us measure the inductance of this coil as the current through it is increased from zero up to some value and then decreased back to zero. It will be found that the inductance increases for a time and then that further increases in current do not produce any further increase in inductance. In other words, the core *saturates*. Now let us decrease the current. The curve plotted as successively lower values of current are put through the coil does not correspond to the curve secured when the current was increased. One curve is secured with increases in current; a different curve is secured when the current is decreased. The only points where the inductance values correspond are at zero current and at maximum current.

When direct current through an iron-core coil changes, the inductance changes because of the change in permeability of the core. In order to keep the inductance more or less constant a small air gap is placed in the core. The inductance of a coil to be used where both direct and alternating currents are to flow through it should always be rated by considering the number of d-c amperes that are to flow through it. Thus a coil may be said to have 30 henries inductance at a direct current of 30 ma. This is the current at which it is supposed to be used. At other currents it may have more or less inductance. In Fig. 61, note how the inductance steadily decreases as the direct current (magnetizing force) through it increases.

The effect of leaving a small air gap in the iron core is shown in Fig. 62. The air gap decreases the inductance at low values of direct current but brings it up at high currents and thereby flattens the curve of inductance versus direct current.

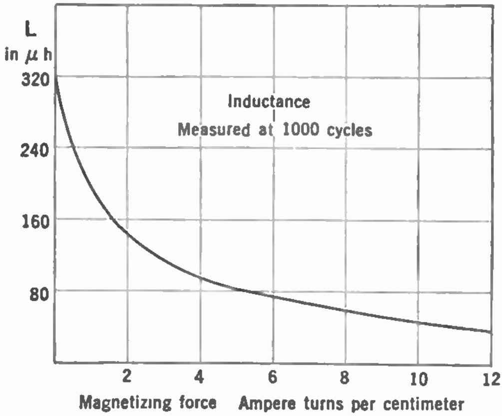


FIG. 61. Inductance of iron-core coils varies with direct current because of variation in permeability.

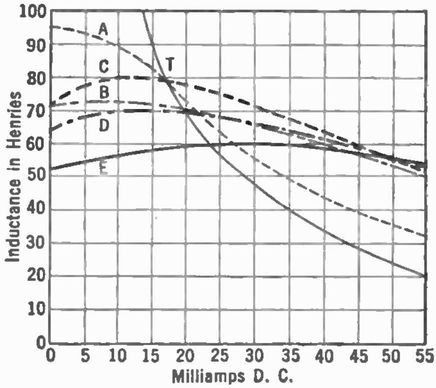


FIG. 62. Variation of inductance with air gap.

T. No air gap.
A. Average air gap.
B. Air gap at one end, 0.01 in.
C. Air gap at both ends, 0.005 in. each.
D. Air gap at both ends, 0.0075 in. each.
E. Air gap at both ends, 0.01 in. each.

Adding iron to an inductance greatly increases the difficulty of designing an inductance; increases the difficulty of measuring the inductance; increases the losses in the coil; and, in general, presents a situation widely at variance with that holding when the coils are wound on a core of air.

Of late years, however, new forms of iron (such as finely powdered iron bound together with certain insulated binders) or iron alloys have been developed which not only have fairly low losses but also fair permeability. They have made it possible to design transformers for power purposes which are efficient, and even at radio frequencies the general use of ferro-magnetic cores has come into general practice.

Iron is also used in permanent magnet loud speakers, in microphones, and wherever it is desired to get a high value of inductance in small space.

The design of such equipment has been developed by trial-and-error methods and by theoretical considerations until it has become an engineering science.

70. Coils for radio receivers. As will be learned later, coils used for tuning radio receivers should have a high inductance and a low resistance. The ratio of the inductance to the resistance may be taken as a figure of merit when comparing coils designed for the same purpose. In modern radio receivers, space is also a factor since it is desirable to make the receiver chassis as compact as possible. Therefore the volume of the coil is sometimes taken into account when comparing two coils.

Present-day tuning inductances are quite small. They are not single-layer solenoids but are multilayer coils wound in a manner known as "universal." They are wound in special machines which weave the wire back and forth over a given winding area so that the wire is literally woven into a coil. In this manner a high inductance with low resistance and low capacitance may be constructed. For a given length of wire the greatest inductance is obtained when the wire is wound as compactly as possible, that is, bank-wound with a cross section as nearly square as possible. These coils have higher resistance per unit of inductance, however.

A single-layer solenoid will have greatest inductance per length of wire when the diameter is approximately 2.46 times the length of the coil.

The trend is toward the use of powdered iron cores in inductances to be used in modern receivers because of their higher inductance per unit of resistance compared with air-core coils. Where it is necessary to get the maximum amplification or maximum selectivity in a small space or with a minimum number of tuned circuits, these coils wound on ferro-magnetic cores are very successful.

CHAPTER V

CAPACITANCE

There are two essential electrical quantities in every radio circuit. These are **inductance** and **capacitance** (or **capacity** in the every-day language of the engineer). They are represented in the circuit by the coils and the condensers. Upon their relative sizes depends the wavelength or frequency to which the receiver or transmitter is tuned. Resistance is always present too, but the effort of all radio engineers is to reduce the resistance and to overcome the losses in power due to its presence, just as mechanical engineers deplore the share of power wasted in mechanical friction.

71. Capacity. Inductance has been likened to inertia. In an alternating-current circuit, it tends to prevent changes in the current flowing. Inductance is a property of a circuit; so is capacity. It is not something one can see, or feel, or hear; one cannot see, or feel, or hear electricity. We are only aware of it by the work it does. Inductance in concentrated form is possessed by coils. Whenever a coil has an alternating current flowing through it, the inductance is one of its important qualities. Capacity in concentrated form exists in condensers formed by conductors which are insulated from each other. Electricity can be stored in a condenser. This capacity tends to prevent any change in the electrical pressure or voltage in the circuit to which the capacity is connected.

72. Capacity as a reservoir. In an electrical circuit, a condenser serves the same purpose that the familiar standpipe or water tower serves in the water supply system of a city. The water tower maintains a constant water pressure regardless of the number of small drains from it, and regardless of the fact that the pumps filling the tower put water into it in spurts, not in a steady stream such as comes from one's garden hose.

73. Capacity in a power supply device. Alternating current taken from the house-lighting wires may be put into a rectifier which cuts off half of the waves, as shown in Fig. 63. These spurts of current are forced through inductances which delay the rise of current to its final value on the half-cycle in which current flows from the rectifier. On the other half-cycle, in which no current flows from the rectifier the inductance tends to delay the decay of the current. The condensers which have been charged on the current half-cycle discharge during the no-current half-cycle. Current flowing into these condensers charges them to the voltage of the rectifier system. Then when the rectifier no longer passes current, the condensers begin to discharge and their voltage falls.

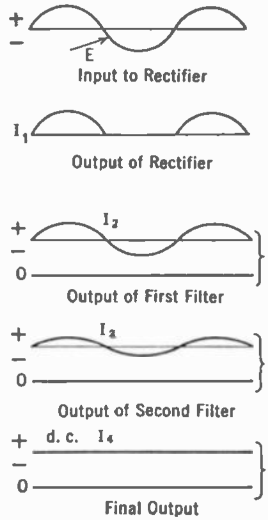


FIG. 63. How the current in a voltage supply system varies. The half-waves from the rectifier are smoothed out by series inductances and parallel condensers until at I_4 it is pure direct current.

A proper combination of inductance and capacity, called a **filter**, will keep a perfectly steady current flowing out although only spurts of current go into the system.

An inductance, then, opposes a change in current; it is like inertia in a mechanical system. Capacity opposes a change in voltage; it is like a reservoir. In an **inductive circuit** the current does not reach its maximum value until some time after the voltage has been applied. In a **capacitive circuit** the voltage does not rise to its maximum value until some time after the current has been flowing in it. A good condenser may remain charged with electricity for many hours after the charging voltage has been disconnected.

74. The charge in a condenser. A condenser is made up of two or more conducting plates separated by a non-conductor. The Leyden jar (Fig. 64) is a good illustration. This is a glass jar coated inside and out with metal foil. The inner foil is connected to a terminal in the cork stopper by means of a metal chain. Filter condensers used in radio circuits are made up of metal foil separated by waxed paper or some other insulator. The questions asked by everyone who looks at a condenser are: Can a condenser pass an electric current? What is this capacity possessed by a condenser? How much capacity is in a condenser? What is the spark that jumps when a condenser is discharged?

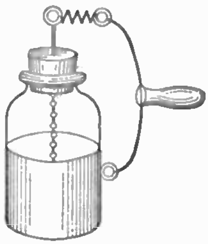


FIG. 64. A Leyden jar—an early form of condenser.

When a condenser is connected to the terminals of a battery, a 45-volt B battery, for example, there is a momentary rush of electrons on to one metallic condenser plate and an exit of electrons from the other. This constitutes a current flowing into the condenser, and if a voltmeter could be placed across it the voltage would be seen to rise in much the same manner in which the current builds up in an inductive circuit. As soon as the voltage of the condenser is the same as that of the battery, current no longer flows into it. It is now charged, and if the battery is disconnected the electrons remain on the one plate and there is a dearth of electrons on the other. Now if a wire is connected from one terminal to the other, these electrons jump across the gap in their effort to equalize the charge on the two plates. The momentary rush of electrons constitutes the spark. Once this spark has taken place the condenser is discharged.

So long as the condenser is charged it possesses energy, which is like the energy possessed by a ball on top of a flag pole. The kind of energy possessed by the ball is potential energy; it is due to the position of the ball. The energy possessed by the condenser when charged is also potential energy, due to the strain existing in the non-conductor. Nothing happens until the condenser discharges, then it may set fire to a piece of paper, may puncture a hole in a sheet of glass, or may give some person a severe shock. Thus the condenser, just as the ball on top of the pole, has the ability to do work—which is our definition of energy.

This is called **static** electricity, and is the same kind that produces sparks when we stroke a cat's back, or rub a comb on a coat sleeve, or the kind of electricity that jumps from one cloud to another on a hot summer day.

75. The quantity of electricity in a condenser. The quantity of electricity that rushes into a condenser when it is connected to a battery is a perfectly definite quantity and can be calculated or measured. This quantity, Q, rated in **coulombs,** depends upon two factors only, the capacity of the condenser and the charging voltage. The **capacity** of the condenser depends only upon the physical make-up of the condenser, that is, (a) the size of the conducting plates, (b) the nature of the non-conductor called the **dielectric,** and (c) the distance apart of the plates. The quantity Q is proportional to both these factors, and may be expressed as

$$Q \text{ (coulombs)} = C \text{ (capacity)} \times E \text{ (voltage)}$$

The unit of capacity is the **farad,** (f), named from Michael Faraday, and is the capacity of the condenser whose voltage is raised 1 volt when 1 coulomb of electricity is added to it; or vice versa, the capacity of the condenser to which 1 coulomb of electricity can be added by an externally applied voltage of 1 volt. This is a very large unit and in practice engineers have to deal with millionths of farads, or microfarads (μf). A smaller unit yet, micromicrofarad, ($\mu\mu$f), is used in some radio circuits. This is equal to 10^{-12} farads. Another unit is the **centimeter of capacity.** It is equal to 1.1124 $\mu\mu$f.

We can write the above expression as

$$C \text{ (farads)} = \frac{Q \text{ (coulombs)}}{E \text{ (volts)}}$$

This shows that the capacity of a condenser is the ratio between the quantity of electricity in it and the voltage across it.

The third way of stating the relation between capacity, quantity, and voltage, defines the voltage:

$$E \text{ (voltage)} = \frac{Q \text{ (quantity)}}{C \text{ (capacity)}}$$

A discharged condenser, of course, has no electricity, Q, in it and hence no voltage across it. When it is connected to a battery, a voltage is built up across the two plates, the value of this voltage being given at any instant by the ratio between the quantity, Q, and the capacity, C, of the condenser. The greater the quantity of electricity stored on the conducting plates, the greater the voltage. When the battery is removed the quantity of electricity remains and, of course, a voltage, E, exists between the two plates.

76. Time of charge. Since an ampere is a rate of flow of current, that is, 1 coulomb per second, one can calculate the rate at which current flows into a condenser provided the quantity, Q, and the time, t, are known. The amperes before the condenser is attached to the battery are zero, and at the completion of the charging process the amperes are zero. The average rate, then, is what one secures from the equation,

$$I = \frac{Q}{t}$$

The time taken to charge or to discharge a condenser depends upon the capacity of the condenser and the resistance through which the charging current flows. The "time constant" is the time required for the charge (or voltage) of a condenser to fall to 37 per cent of its original value and is equal to R in ohms multiplied by C in farads. RC circuits are often used to produce time delays.

Example 1-5. A condenser of 15 μf is attached to a 220-volt circuit. What quantity of electricity flows into it? If it requires 1/200 sec to charge it, what is the average current?

$$
\begin{aligned}
Q &= C \times E \\
&= 15 \times 10^{-6} \times 220 \\
&= 3300 \times 10^{-6} \\
&= 0.0033 \text{ coulomb} \\
I &= \frac{Q}{t} \\
&= \frac{0.0033}{0.005} \\
&= 0.66 \text{ amp}
\end{aligned}
$$

This is also the average rate of discharge if the time of complete discharge is 1/200 sec.

Problem 1–5. What is the capacity of a condenser that holds 0.0024 coulombs when attached to 220 volts?

Problem 2–5. In a radio circuit is a 0.0005-μf (500 $\mu\mu$f) condenser across a 500-volt source. What quantity of electricity will flow info it?

Problem 3–5. What voltage will be necessary to put 0.012 coulomb into the condenser of Problem 1?

Problem 4–5. The average charging current in Problem 1 is 2 amp. How long will it take to charge the condenser?

Problem 5–5. Suppose the average voltage across a condenser when it is being discharged is one-half the voltage when fully charged. Connect a 10-ohm resistance across the condenser of Problem 1. What average current flows? What is the average power used to heat the wire?

77. Energy in a condenser. The amount of energy that can be stored in a condenser in the form of static electricity can be computed from the formula:

$$\text{Energy} = \tfrac{1}{2}CE^2$$

This represents the work done in charging the condenser, and naturally represents the energy released if the condenser is discharged.

Similarly, the energy in the lines of force about a coil through which an alternating current flows is equal to $\frac{1}{2}LI^2$.

The unit of energy or work is the **joule.** It is the amount of work required to force one coulomb of electricity through one ohm of resistance. Thus if a 1-μf condenser is charged to a voltage of 500, the energy is

$$\tfrac{1}{2} \times 1 \times 10^{-6} \times 500^2 = 0.125 \text{ joule}$$

Since power is the rate of doing work, we can find the power required to charge such a condenser in 1 sec of time by dividing the above expression by 1 sec. Thus

$$\text{Power in watts} = \frac{1CE^2}{2t}$$

and if we attach the condenser to a secondary of a 500-volt transformer which charges the condenser 120 times a second (60-cycle current) the power will be $= \tfrac{1}{2}CE^2 \times 120$ provided the condenser is permitted to discharge each time it is charged. Thus the smaller the time, the greater the power required to charge the condenser.

A general expression for such a problem is

$$\text{Power} = \tfrac{1}{2}CE^2N$$

if N is the times per second the condenser is charged and discharged.

Example 2–5. A condenser in a transmitting station has a capacity of 0.001 μf and is charged with a 20,000-volt source. What energy goes into the condenser and what power is required to charge it 120 times a second (60-cycle source)?

Energy or work

$$\begin{aligned} W &= \tfrac{1}{2}CE^2 \\ &= \tfrac{1}{2} \times 0.001 \times 10^{-6} \times 20{,}000^2 \\ &= 0.2 \text{ joule} \end{aligned}$$

Power

$$\begin{aligned} P &= W \times N \\ &= \tfrac{1}{2}CE^2N \\ &= 0.2 \times 120 \\ &= 24 \text{ watts} \end{aligned}$$

As another example, consider the methods of making photographs at very high speeds utilizing a large condenser charged to a high voltage and then discharged through a gas-filled lamp.

The discharge condenser has a capacitance of 112 μf and is charged to 2000 volts. It is then discharged in a 30,000th of a second.

The total stored energy, $\frac{1}{2}CE^2$, is $\frac{1}{2} \times 112 \times 10^{-6} \times 4 \times 10^6 = 224$ joules, or watt-seconds. This work is done in a 30,000th of a second, however, and so is equivalent to a power of $3 \times 10^4 \times 224 = 6{,}720{,}000$ watts.

The quantity of charge, CE, is $2 \times 10^3 \times 112 \times 10^{-6} = 0.224$ coulomb. This quantity discharged in a 30,000th of a second results in an average current of $3 \times 10^4 \times 0.224 = 6{,}720$ amp.

Problem 6–5. If the generator in Example 2–5 were a 500-cycle generator, what would be the power taken from it?

Problem 7–5. How much energy can be stored in a condenser of 100 μf charged to 1000 volts?

Problem 8–5. How much power is required to charge a 1-μf condenser to a voltage of 220, 120 times a second?

Problem 9–5. A transmitting antenna has a capacity of 0.0005 μf. It is desired to transmit 1 kw of power. To what voltage must the antenna be charged from a 500-cycle source?

Problem 10–5. Suppose an antenna is to be supplied with 500 watts of power and that between the charging mechanism and the antenna exists an efficiency of 30 per cent. The condenser, which discharges into the antenna, has a capacity of 0.012 μf, and the generator which charges the condenser is a 500-cycle machine. A transformer is used to step up the voltage 110 from the generator to the value required by the condenser. What is the secondary voltage of the transformer and what is the turns ratio between secondary and primary? NOTE: Remember that a 500-cycle generator charges a condenser 1000 times a second.

78. Electrostatic and electromagnetic fields. The energy existing in an inductive circuit is said to exist in the electromagnetic field surrounding the inductance. This field is made up of lines of force and can be explored with a compass, or by sprinkling iron filings on paper as in Fig. 42.

The energy in a condenser is said to exist in the electrostatic field. This is the locality in which the electrical strain exists, that is, in the non-conductors in the vicinity of the conducting surfaces which are charged. This field cannot be explored with any magnetic substance, but can be discovered by any form of charged bodies or any container of static electricity.

Some circuits, an antenna system, for example, have both capacity and inductance and, if properly charged, have both a magnetic and a static field. Since the wire can be charged to a very high voltage with respect to earth, considerable energy can be fed into it.

Frictional electricity, such as that produced by rubbing a cat's back, is a form of static electricity. It is this kind of electricity that is produced in the tank of a truck carrying gasoline. The gasoline sloshing about in the metallic tank may raise the voltage of the tank to a considerable degree above the ground from which it is insulated by the rubber tires. Finally a spark may pass, and neutralize the charge—but in the process the tank and driver may be blown to bits. To prevent such accidents, all gasoline trucks trail an iron chain which connects the tank electrically with the ground and discharges static electricity charges as fast as they are produced.

79. Condensers in a-c circuits. A perfect condenser is one which is an absolute non-conductor to direct currents—that is, it is an infinite d-c resistance—and one which has no a-c resistance. All the energy that is put into it is used in setting up an electrostatic field. Unfortunately all condensers have some a-c resistance, and few have infinite d-c resistance. Otherwise a condenser once charged would keep its charge forever. The time it takes a condenser to discharge is proportional to the product of its capacity and its resistance. This is known as its **time constant,** and is also the time required to charge the condenser. The resistance to direct current is known as its **leakage resistance.** In a good condenser this may be as high as several hundred megohms. The time constant of a circuit containing capacitance and resistance is equal to RC in ohms and farads and is equal to the time for the current to fall from its initial value to 37 per cent of this value.

Experiment 1-5. Charge a filter condenser of about 2- to 10-μf capacity by connecting to a 110-volt d-c circuit. Then discharge by a heavy wire; then charge again and allow to stand for a half-hour and discharge. Charge again and permit to stand for an hour and discharge. The relative sizes of spark give an idea of how poor a condenser it may be from the standpoint of leakage. Then charge and place a 10-megohm resistance across it for a second or so. Then see if it can be further discharged by means of a wire.

A good condenser may retain its charge for many hours after being removed from the source of charging current. The leakage of condensers not only takes place across the insulating material through which its terminals are brought out but also through the wax filling, the container, and through the dielectric itself.

Example 3–5. In Fig. 65 is a coupling device used between tubes in a resistance-capacity coupled amplifier. A high-voltage battery is used at E_b. The purpose of condenser C is to keep these high d-c voltages from getting to the grid of the following tube. If this condenser has any leak-

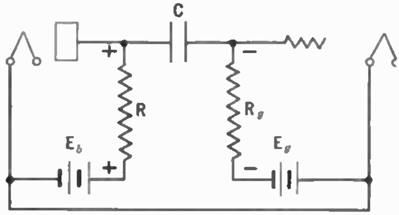


FIG. 65. Leakage of current through the condenser C causes a voltage drop across the input of the following tube.

age resistance, a direct current flows through it and impresses a voltage on the grid of the succeeding tube which is highly detrimental.

Suppose the condenser has a resistance of 100 megohms. What voltage will be impressed on the grid if the battery has a voltage, E_b, of 100?

Figure 66 represents the circuit. It has the battery in series with two resistances, the plate resistance of the tube R_p and the coupling resistor R. Across E_b and R is shunted the condenser resistance and a grid leak R_g in series. The problem is to find what current flows through this shunt circuit

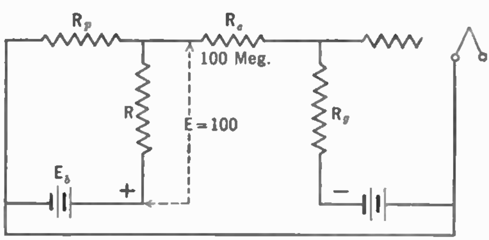


FIG. 66. The circuit equivalent of Fig. 65.

and what voltage drop this causes across the grid leak. Suppose 100 volts appear across the series circuit composed of R_c and R_g. This may be as represented in Fig. 67. One hundred volts across 100 megohms (the coupling resistance R and the grid leak resistance are negligible in comparison with the condenser leakage resistance) produces 1 μa of current. This 1 μa flowing through the grid leak of 1 megohm produces a voltage of 1 volt.

This voltage is of a polarity that is opposite to the grid voltage E_g and therefore decreases its value. In addition a certain amount of noise may be developed by the direct current flowing through this condenser and grid leak. This noise is directly impressed on the input to the amplifier tube and may assume large values when amplified by succeeding stages. Condensers used in resistance amplifiers must have a high resistance.

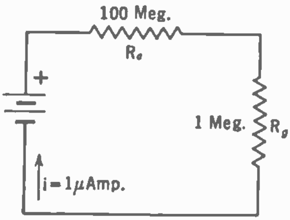


FIG. 67. The battery in this figure represents the voltage across R_c and R_g in Fig. 66.

80. Power loss in condensers. A pure inductance takes no power from an a-c line once the magnetic field is established. If, however, the coil has resistance, power is wasted in heating it. Similarly, a perfect condenser, that is, one having no resistance, wastes no power. If the condenser has resistance—and all have—power is wasted in heat when it is connected to a source of current, whether a d-c or an a-c source. This power in watts is the current squared times the resistance.

81. Condenser tests. If a voltmeter, a battery, and a condenser are connected in series a momentary deflection will be noted if the condenser is good. If the condenser is leaky, a constant deflection will be noted. If the condenser is fairly large, one or two microfarads, and no deflection is noted, the condenser is probably open. If the full battery voltage is read by the meter, the condenser is shorted.

If a condenser that has been determined to be not shorted is placed across a battery and then a pair of phones is placed across the condenser, a click will indicate that the condenser is good. The click is the discharge of the condenser through the phones.

82. Condensers in general. A condenser, then, is any object with two or more conducting plates separated by a non-conductor called the dielectric. A cloud filled with moisture is a good conductor. So is the earth. The cloud may be a mile or so above the earth and subjected to all sorts of electrical differences of potential. It may become charged with respect to the earth. When this charge becomes great enough to jump the gap, a spark passes, and the condenser is discharged. This is known to us as lightning. Small discharges between parts of a cloud or between two clouds may cause only small sparks and are made known to us by static.

The earth is considered as being at **zero potential.** All objects not connected to earth have a higher voltage than the earth. These objects have a capacity with respect to earth. This capacity will conduct electricity just as a 1-μf by-pass condenser in a radio receiver will, and may cause considerable embarrassment to the radio engineer or the experimenter who does not take it into consideration in his calculations.

In radio circuits the conducting plates of a condenser may be aluminum or brass or metal foil, depending upon the service which the condenser is to fill. The insulating material, called the dielectric, may be air, oil, mica, paper coated with beeswax or other insulating compound. The actual capacity of the condenser may be fixed, or it may be variable.

83. The nature of the dielectric. If two square metal plates 10 cm on a side are suspended in air and about 1 mm from each other, the capacity will be about 88.5 $\mu\mu$f. If a sheet of mica is between the plates the capacity will be increased about eight times. Other substances will give different values of the capacity. Each substance, in fact, will give a certain value of capacity depending upon what is called the **dielectric constant** of the substance. The table below gives the value of K, the dielectric constant, of several substances.

Material	Dielectric Constant K	Material	Dielectric Constant K
Air	1	Paraffin	2
Bakelite	4 to 8	Porcelain	5 to 6
Celluloid	4 to 16	Rubber	2 to $3\frac{1}{2}$
Glass	4 to 10	Pyrex	5.4
Mica	3 to 7	Shellac	3.5
Oil, castor	4.7	Varnished cambric	4
Oil, transformer	2.2	Wood	2 to 8
Paper	2 to 4		

This factor K has nothing to do with the ability of a substance to withstand high voltages without puncturing. Such ability differs not only with the substance but also with the condition of the substance at the time the voltage is applied, that is, the percentage moisture present, the pressure to which it is subjected, etc. Mica, for example, will withstand much greater voltages than paraffined paper.

84. Electrolytic condensers. Of late years the majority of condensers in radio-receiver power supply systems for filtering purposes have been of the electrolytic type. They provide high capacity in small space, but compared to air or mica dielectric units they have a high power loss. They must, usually, be connected to the circuit correctly; that is, they have a polarity and are used on circuits which have some direct current in them.

The electrolytic condenser is made up of an anode, almost always of aluminum, a cathode, of aluminum or copper, and a chemical substance between. On the surface of the anode is an extremely thin layer of a non-conducting chemical, say aluminum oxide. Thus in a small space may be the two conducting electrodes separated by this thin oxide layer. As will be seen in Section 85, the capacity of a condenser is increased when the area of the plates is increased and when the separation between the plates is decreased. Thus, if the intervening non-conducting layer is very thin, the capacity per square inch of conducting surface may be high.

These condensers are not adapted for high-voltage work, 600 volts being about the highest practicable voltage that may be applied. Furthermore, they consume energy because of the losses in the materials. If operated on low-voltage circuits, say 6 volts, as much as 4000 μf may be placed in a container of reasonable dimensions. At voltages of the order of 100 to 200, capacities may range up to 100 μf. Small leakage currents flow through these condensers in normal operation. This leakage current (which represents a wastage or energy loss) is about 0.2 ma per microfarad at 400 to 500 volts.

By etching the aluminum foil of which the condenser is made, the area of the surface may be increased, thus still further decreasing the cubic contents of the container into which a given number of microfarads is placed. An 8-μf 500-volt condenser (not etched) will be placed in a can 1⅜ in. by 4½ in.

In general there are two types of electrolytics—wet and dry. The wet type is more economical, will withstand high-voltage surges (self-healing), has greater internal losses, and can be built only in a limited range of capacities and voltages. The dry type does not suffer from these faults, and can be used on alternating current.

85. Condenser capacity formulas. Formulas have been worked out by which it is possible to compute the capacity of condensers of various forms. For example, the capacity of two flat conducting plates separated by a non-conductor may be computed from the formula

$$C = \frac{885 \times A \times K}{10^{10} \times d}$$

where C = capacity in microfarads;
A = area of the metallic plate in square centimeters;
K = dielectric constant of the non-conductor;
d = thickness of dielectric in centimeters.

Or

$$C = 0.0885 \frac{KA}{d}$$

where C = capacity in micromicrofarads;
d = thickness in centimeters;
A = area in square centimeters;
K = dielectric constant.

Formulas for other types of condensers may be found in the *Bureau of Standards Bulletin* 74, "Radio Instruments and Measurements," page 235.

In receiving sets the tuning condensers are variable. The important function of separating one station from another is performed by changing the capacity of the condenser, which is called tuning the circuit. The tuning condensers have air as the dielectric and plates of various metals, usually brass or aluminum.

The capacities range from 25 to 100 $\mu\mu f$ in a short-wave (high-frequency) receiver to 500 $\mu\mu f$ for broadcast-frequency receivers. The above values of capacity may be written as 0.0001 and 0.0005 μf. It is probably easier to express small capacities in micromicrofarads rather than in one of the larger units. Whenever an easy path for an alternating current is needed a fixed condenser is used. It is called a **by-pass** condenser.

Example 4–5. How many plates 16×20 cm in area and separated by paraffined paper ($K = 2.1$) 0.005 cm thick are required for a condenser of 24 μf?

$$C = \frac{885\,AK}{10^{10}\,d}$$

$$= \frac{885 \times 16 \times 20 \times 2.1}{10^{10} \times 0.005}$$

$$= 0.0119\ \mu f \text{ capacity per plate}$$

$$\text{Number of plates} = \frac{24}{0.0119} = 2200.$$

Problem 11–5. Express in micromicrofarads: $\frac{1}{1000}$ farad, 1 μf, 0.00025 μf. Express in farads: 500 μf, 0.01 μf, $\frac{1}{10}$ μf. Express in microfarads: 1 farad, 500 $\mu\mu f$, 0.01 $\mu\mu f$.

Problem 12–5. What is the capacity of two square plates suspended in air 0.1 mm apart, if the plates are 10 cm on a side?

Problem 13–5. A variable tuning condenser has a capacity of 0.001 μf when air is used as dielectric. Suppose the container is filled with castor oil. What is the capacity now?

Problem 14–5. Lead foil plates 2 in. square are separated by mica 0.1 mm thick having a dielectric constant of 6. What is the capacity of a condenser made up of 200 pairs of such plates?

Problem 15–5. How many joules of energy can be stored in such a condenser as in Problem 14 when 100 volts are impressed across it? How much power will it take to charge it to this voltage 120 times a second?

86. Condensers in series and parallel. When condensers are connected in parallel (Fig. 68) the resultant capacity is the sum of the individual capacities. When they are in series or parallel the resultant may be found as below:

$$C_{\text{parallel}} = C_1 + C_2 + C_3 \cdots$$

$$C_{\text{series}} = \cfrac{1}{\cfrac{1}{C_1} + \cfrac{1}{C_2} + \cfrac{1}{C_3} \cdots}$$

The resultant of two capacities in series is

$$C_{\text{series}} = \frac{C_1 \times C_2}{C_1 + C_2}$$

When connected in parallel the same voltage is across each capacity; when connected in series the voltage across each varies inversely as the capacity. If two equal capacities are in series, half the total a-c voltage is impressed across each condenser. If one condenser has half the capacity of the other, that one will

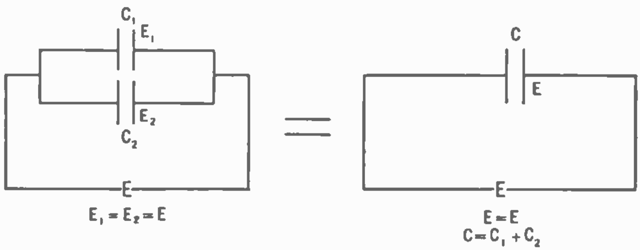


FIG. 68. Condensers in parallel.

have two-thirds the total voltage, whereas the other will have one-third the total voltage across it.

The resultant capacity of several condensers in parallel is always greater than any single capacity; in series the resultant is less than the capacity of the smallest of the group. In series the voltage across each condenser varies inversely as its capacity and is always less than the total voltage across the combination. When a condenser is placed in an a-c circuit whose voltage is more than the condenser can tolerate, it is only necessary to use two or more condensers in series so that the voltage across individual members of the group is below the danger limit, and so that the total capacity in the circuit is the value desired.

When condensers are used across d-c circuits, as in filter circuits, the d-c resistance of the condenser becomes of importance.

If two condensers in series across a certain d-c voltage have equal capacities but different d-c resistances, the voltage drop across the two condensers will differ. The voltage across one of them may be sufficient to destroy it.

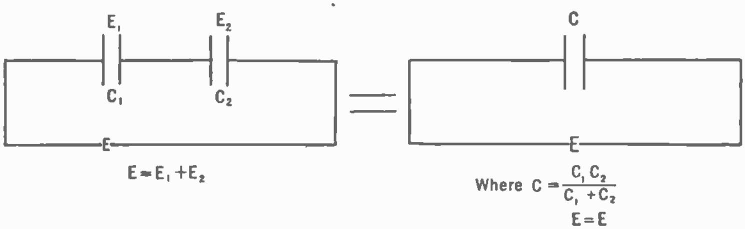


FIG. 69. Condensers in series.

Example 5-5. In a radio circuit a 0.0005-μf variable condenser is available but the circuit calls for a 0.00035-μf condenser. What fixed condenser may be used to reduce the maximum capacity in the circuit to the proper value? How shall it be connected?

Solution. Since the total capacity is to be reduced, the fixed condenser must be connected in series with the variable condenser. The total capacity is given as 0.00035 μf. This is equal, from the above equation, to

$$0.00035 = \frac{C_1 \times C_2}{C_1 + C_2}$$

$$= \frac{0.0005 \times C_2}{0.0005 + C_2}$$

whence

$$C_2 = 0.001166 \text{ or } 1166\ \mu\mu f$$

87. Padding condensers. In modern superheterodynes the tuning condenser has at least two sections, one of which tunes the oscillator and the other tunes the r-f amplifier. There must be a constant difference between the frequency of the oscillator and the frequency of the amplifier.

This constant difference of frequency (say 456 kc) is maintained by a combination of series and shunt capacities in the oscillator circuit. Since the oscillator is generally tuned higher than the r-f circuits, a smaller change in oscillator capacity is required to produce the desired variation in frequency than is required to tune the r-f circuit over the desired bands. The oscillator inductance is smaller than the r-f inductance, and the exact value is such that the two circuits tune properly (with 456 kc difference) at the middle of the tuning range, for example, at 1000 kc. Then at the two ends of the tuning range (1400 and 600 kc) the proper 456-kc intermediate frequency is attained by adjusting the series and shunt capacities—known as padders.

A typical circuit of the input to a superheterodyne is shown in Fig. 70. Here are the r-f and oscillator tuning circuits with the

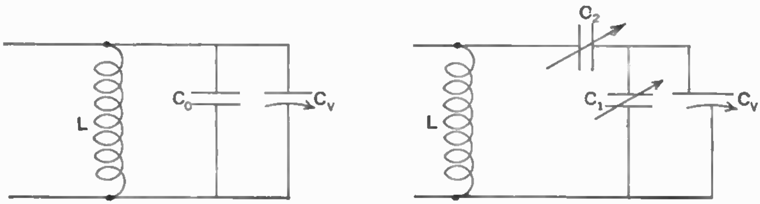


FIG. 70.

R-F Circuit
C_0 = distributed capacity.
C_v = tuning capacity.

Oscillator Circuit
C_1 = trimmer condenser.
C_2 = padding condenser.

padding condenser in series with the oscillator tuning condenser across which is a trimmer which is part of the aligning system to make certain that the two identical portions of the gang tuning condenser produce the required difference or intermediate frequency (say 456 kc) at each portion of the tuning range. Actually this exact correspondence does not take place, except at two or three portions of the range.

Problem 16–5. Paper condensers are made up of a thin foil pressed to a dielectric of paper which has the form of a long sheet about 6 in. wide. Suppose the dielectric constant of such paper is 2 and that it is 3/1000 in. thick. A condenser is to have a capacity of 1 μf; the metal foil is 5 in. wide. Two sheets of foil and three of paper are used. How long will each sheet of the foil be?

Problem 17–5. A "band spread" condenser is one in which many degrees of rotation of the movable elements of the condenser correspond to only a relatively small change in capacitance. One way to make such a band spread is to connect a fixed condenser in series with the variable condenser. Suppose a variable with a total capacitance of 500 $\mu\mu$f and a minimum of 50 $\mu\mu$f (a change of 10 to 1 in capacitance) is connected in series with a fixed capacitance of 1000 $\mu\mu$f. What capacitance variation is now secured by rotating the variable condenser plates?

Problem 18–5. A condenser of 1 μf has in series with it a resistance of 1 megohm. How long will it take the voltage across the condenser to fall to 37 per cent of its initial value if the circuit is shorted?

Problem 19–5. A resistanceless condenser is to be used in a 1000-volt circuit but the condenser will not stand this high a voltage. Another condenser is placed in series with it, so that the total voltage is divided between the two. One condenser will withstand 200 volts and the total capacitance is to be 1000 $\mu\mu$f. What will be the capacitances of the two condensers if the voltage across them is inversely proportional to their capacitances?

CHAPTER VI

PROPERTIES OF ALTERNATING-CURRENT CIRCUITS

The two kinds of current in common use are: **direct currents** (dc) which have a more or less constant value and which flow in the same direction all the time; and **alternating currents** (ac) in which not only is the magnitude constantly changing but the direction also.

88. Definitions used in a-c circuits. When the voltage (or current) has started from zero, risen to its maximum value in one direction, decreased to zero and risen to maximum value in the opposite direction and finally come back to its starting value, zero, it is said to have completed a **cycle.** Ordinary house-lighting current which has a frequency of 60 cycles per second goes through this cyclic change in magnitude and direction 60 times a second. The **frequency** is the number of times a second a cycle is completed. An **alternation** is half a cycle; that is, when the voltage has gone from zero to zero through one maximum it is said to have completed one alternation. In 60-cycle circuits there are 120 alternations per second. In a-c circuits we must consider the element of time; in d-c circuits time does not enter; the magnitude of the current is constant.

Alternating currents exist of nearly all ranges of frequencies. Sixty cycles is the common power frequency; tones generated by audio-frequency oscillators for testing purposes may go from almost zero frequency to as high as the human ear can hear, that is, about 15,000 cycles per second depending upon the person. Electric waves of frequencies as low as 15,000 cycles exist. They are generated in the long-wave high-power radio stations carrying on transoceanic communication. Radio frequencies up to about 600,000,000 cycles per second are now used. This corresponds to a wavelength range of from 20,000 meters to ½ meter.

89. Instantaneous value of alternating current. Since the voltage (or current) is continually changing in value it becomes expedient to provide a means of knowing what this value is at any time.

Let us consider the circle of Fig. 71 which is moved to the right at a constant rate. Within the circle is a rotating arm, representing the motion of the rotating part of an a-c generator, as well as the voltage E, it produces. It rotates at a constant speed such that one full rotation—one cycle—is completed in the time it takes the circle to move to the right a distance equal to the diameter. Now, when the arm is perpendicular to its starting position, the circle has completed one-quarter of its movement; when the arm is pointing in a direction opposite to its starting position the circle has moved through one-half of its motion, and so on. Now let us picture what the end point of the arm would trace out if we attached a crayon to it and let it go through its motion as the circle is moved to the right. Such a tracing will be an accurate representation of an alternating current or voltage.

In Fig. 71 the height of the arm above the horizontal axis, its starting position, represents the value of the voltage at the instant the generator winding is at the position in its cycle corresponding to the position of the rotating arm whose length is E. The position of the arm at any point is known as its **phase.** Since a cycle is represented by a complete circle of 360 degrees (360°), when the arm is vertical we speak of its position at the 90-degree phase. Now the height of this arm from the horizontal starting position is the value of the a-c voltage at that position or phase or instant of time. At 90 degrees this height is equal to the length of the arm itself, or the a-c voltage is at its maximum value; at any other point in that half-cycle or alternation the voltage is less than this value.

Now it is handy to have something with which to compare the value of the voltage at any phase, known as the **instantaneous** value—because this value is only temporary because of rotation of the alternator armature. This basis of reference is the **maximum or peak** value. The instantaneous value is always rated by stating its magnitude with respect to the maximum value. Fortunately there is a factor which relates the height of the arm

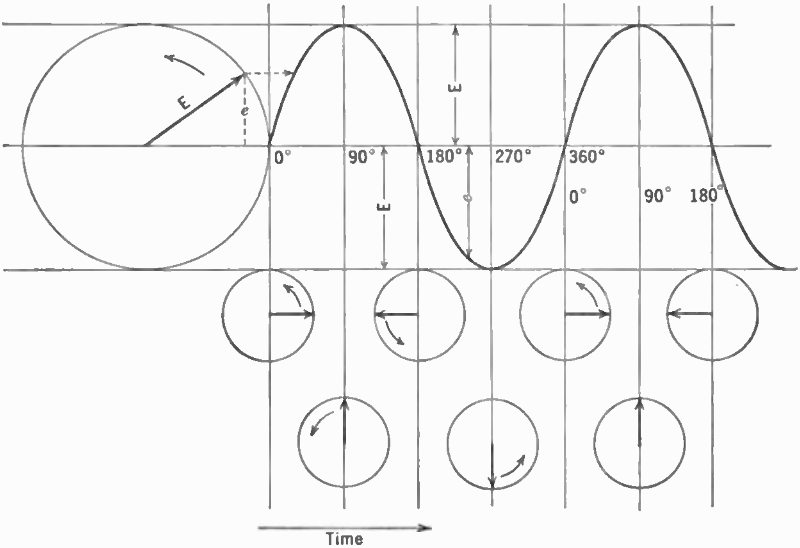


FIG. 71. As the vector E rotates, the vertical height, e, of the end of the vector varies according to the curve known as a sine wave. When the vector has the position as shown in the first small circle, the instantaneous value e is zero. At other times the instantaneous voltage has the other values as shown.

representing the instantaneous value and its length, or maximum value. This factor is known as the **sine** of the angle between the arm and the horizontal line. Knowing the maximum value of a-c voltage—the length of the rotating arm in Fig. 71—and the phase, or the angle through which the arm has rotated, to determine the instantaneous value of the voltage we need only multiply the maximum value by the sine of this angle which we may look up in a table made out for such a purpose. For example, the "functions" of several angles are given below. The angle itself (which is a means of expressing the time that has elapsed since the alternator arm started rotating) is called the **phase angle.**

Angle Degrees	Sine	Cosine	Tangent
15	0.259	0.966	0.268
30	0.500	0.866	0.577
45	0.707	0.707	1.000
60	0.866	0.500	1.732
90	1.000	0.000	∞
110	0.940	−0.342	−2.747
135	0.707	−0.707	1.000
175	0.087	−0.996	0.087
180	0.000	−1.000	0.000
220	−0.643	−0.766	+0.839
270	−1.000	−0.000	∞
300	−0.866	+0.500	−1.732
360	0.000	+1.000	0.000

90. Triangle functions. Considering the angle between CB and AB in Fig. 72 labeled as θ (the Greek letter theta), the side AC is called the **opposite** side, CB is called the **adjacent** side. Then these relations hold:

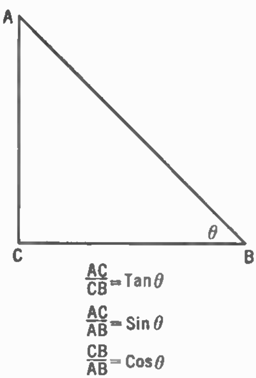


FIG. 72. Trigonometric "functions."

$$\frac{AC}{CB} = \tan\theta \qquad (1) \qquad \text{or} \qquad AC = CB\tan\theta$$

$$\frac{AC}{AB} = \sin\theta \qquad (2) \qquad \text{or} \qquad AC = AB\sin\theta$$

$$\frac{CB}{AB} = \cos\theta \qquad (3) \qquad \text{or} \qquad CB = AB\cos\theta$$

If we know any two of the three functions of the right-angled triangle and the angle involved, the other function may be found by means of the table in Section 89.

NOTE. The terms sine, cosine, etc., are called the **functions** of the angles. They are abbreviated as sin, cos, tan.

The function of angles greater than 90 degrees may be found from function $(N \times 90° + A)$ = function A, if N is even, e.g., $\sin 210° = \sin (2 \times 90° + 30°) = \sin 30°$. Function $(N \times 90° + A) =$ cofunction A if N is odd, e.g., $\sin 120° = \sin (1 \times 90° + 30°) = \cos 30°$.

91. Means of expressing instantaneous values. We may express the instantaneous value of an a-c voltage or current as follows:

$$e = E \sin \theta \quad \text{or} \quad i = I \sin \theta$$

where e or i = the instantaneous value;
E or I = the maximum value;
θ = the phase angle in degrees.

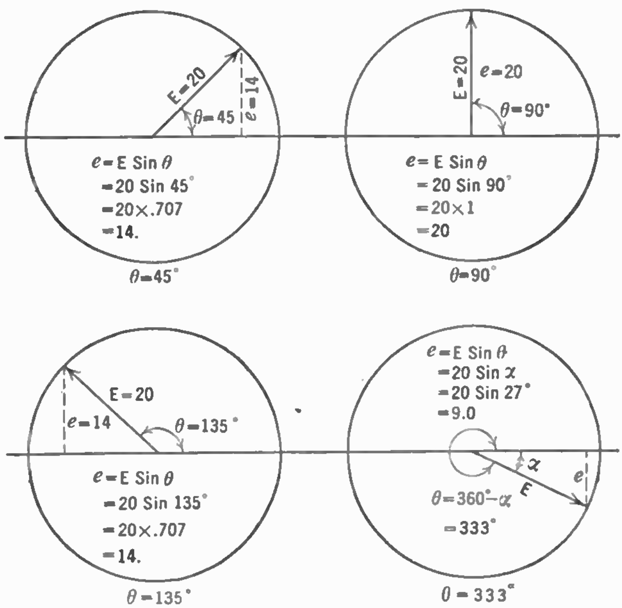


FIG. 73. At various times in the cycle the instantaneous value, e, of the vector E is as shown in these vector diagrams.

Small letters denote instantaneous values, capital letters denote maximum values.

Let us look at Fig. 73 which represents the rotating arm E and the vertical height e in four typical cases, 45, 90, 135, and 333 degrees. The actual height compared to the maximum length of the arm E may be calculated by means of the above table and formulas.

Since the sine of an angle of 0 degrees is zero, the instantaneous value of the voltage at 0 phase is zero; since the sine of an angle of 90 degrees is 1, the instantaneous value of the voltage at this point in the cycle is equal to the maximum value, and so on.

The three methods of representing an a-c voltage or current are:

1. By a graphical illustration such as Fig. 71, called a sine wave.

2. By an equation, such as

$$e = E \sin \theta \quad \text{or} \quad i = I \sin \theta$$

3. By the pictures shown in Fig. 73, known as **vector diagrams.**

Such a line as E in Fig. 74 which moves about a circle is called a **vector;** the vertical distances of its end point from the horizontal axis is called its **vertical component.** The angle θ between the horizontal and the vector is called the **phase angle;** the value of the vertical component may be found by multiplying the maximum value E by the sine of the phase angle.

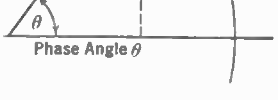


FIG. 74. The maximum value of the vector is E; the instantaneous value is $e = E \sin \theta$.

Example 1-6. Represent a voltage whose maximum value is 20 volts. Using graph or cross-section paper twelve divisions to the right equals one alternation and twenty divisions vertically from our horizontal line represents the maximum values of the voltage. The voltage starts at zero, increases to a maximum at 90° or six divisions, then decreases to zero at twelve divisions, etc. What is its value at other times? We can tell by using our table of sines in Section 89.

At the 30° phase the instantaneous value, or the height of rotating arm above the time axis, is $e = E \sin 30° = 20 \times 0.5 = 10$ volts. Other instantaneous values can be found similarly and the entire sine wave plotted similar to Fig. 71.

Lay off on cross-section paper a length say twenty divisions equal to the maximum value of the voltage. Then using this value as a radius draw a circle. Then the instantaneous value at any time in the cycle can be found by measuring the vertical distance of this point on the circle to the horizontal axis. Thus at the 30° phase the vertical distance is 10 because $\sin 30° = 0.5$.

A voltage of maximum value 20 may be represented mathematically as

$$e = 20 \sin \theta$$

Problem 1–6. The maximum value of an alternating voltage is 110. What is its value at the following phases: 30°? 60°? 110°? 180°? 270°? 300°? 360°?

Problem 2–6. The instantaneous value of an alternating voltage is 250 volts at 35°. What is its maximum value? What is its value at 135°?

Problem 3–6. The instantaneous value of an alternating voltage is 400 volts at 75°. Plot to some convenient scale its sine wave.

NOTE. In all this discussion voltages or currents can be spoken of with the same laws in mind. Thus the form of a sine wave of current looks exactly like the sine wave of voltage with the same maximum value. The vector diagram looks the same because it is only necessary to label the rotating arm I instead of E and the mathematical formula reads $i = I \sin \theta$ instead of $e = E \sin \theta$. The answers to the above problems will be the same numerically whether we speak of voltage or current.

A word should be said, too, about the terminology frequently used in speaking of the voltages and currents in an a-c circuit. Engineers use the expression "a-c voltage" or "a-c current" for simplicity, not stopping to think that such an expression really is an abbreviation for "an alternating-current voltage" or for "alternating-current current." Although one would not say the latter, one often uses the abbreviation. In many radio circuits there are both a-c and d-c branches and in some or all of them both direct and alternating currents and voltages exist. It is simpler to speak of an "a-c voltage" than of an alternating emf and in the interest of simplicity this terminology has been employed here whenever it is useful.

92. Effective value of alternating voltage or current. Since the voltage (or current) in an a-c system is rapidly changing direction, and since the needle and mechanism of an ordinary d-c measuring instrument require appreciable time for a deflection, they cannot follow the rapid changes of voltage or current and would only waver about the zero point of the meter even if they could follow the fluctuations. We can, however, compare direct and alternating currents by noting their respective heating effects. An alternating current is said to be equal in value to a direct current of so many amperes when it produces the same heating effect. This is known as the **effective value** of the alternating current and is equal to the maximum values multiplied by 0.707 or divided by $\sqrt{2}$. Thus

$$I_{\text{eff}} = 0.707\, I = I/\sqrt{2} \quad \text{or} \quad I_{\text{eff}} = \frac{I}{1.41}$$

where I_{eff} = effective value of an alternating current;
I = maximum value.

The effective value is also known as the **root mean square** or **rms** value for the following reasons. The heating effect of a direct current is proportional to the square of the current. Then if we take the instantaneous values of the current over a cycle of alternating current, square them, get an average of these values, extract the square root of this value, it will be equal to the direct-current value that will produce an identical heating effect. The value of current secured in this manner is 0.707 times the maximum value. Since it is the square root of the average or mean squares of several current values, it is abbreviated to the root mean square or rms. An rms voltage is one that will produce a current whose heating effect is the same as a given direct current as discussed above.

$$E_{\text{rms}} = E_{\text{eff}} = 0.707E_{\text{max}} = \frac{E_{\text{max}}}{\sqrt{2}}$$

and

$$E_{\text{max}} = \frac{E_{\text{eff}}}{0.707} = E_{\text{eff}} \times \sqrt{2}$$

Voltage or current is considered as effective unless otherwise indicated or stated.

Example 2–6. What is the effective value of an alternating voltage whose maximum value is 100 volts?

$$E_{eff} = 0.707 \times 100 = 70.7 \text{ volts}$$

Problem 4–6. The effective value of an alternating current is 12 amp. What is the maximum value?

Problem 5–6. The maximum value of an alternating voltage is 110 volts. What is the effective value?

Problem 6–6. At the 45° phase the instantaneous value of an alternating current is 10 amp. What is its effective value?

Problem 7–6. The effective value of an alternating current is 100 ma. What is the instantaneous value at the 60° phase?

93. Phase relations between current and voltage. Whenever an a-c voltage forces a current through a resistance, the wave

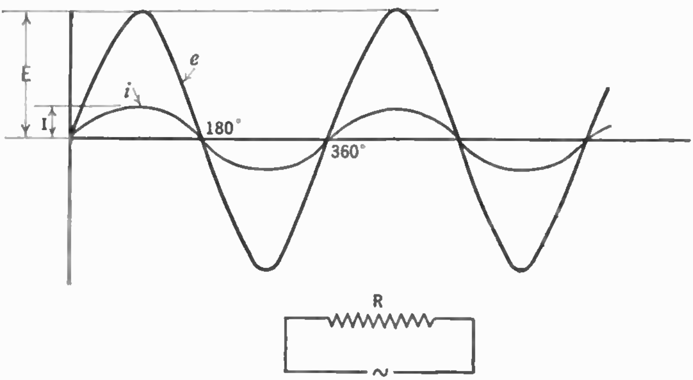


FIG. 75. Current and voltage in phase, true of a circuit containing resistance only.

forms of the voltage and the current look alike; so do their mathematical formulas and their vector diagrams. This is explained by the fact that the current and voltage start at the same instant, rise to a maximum value at the same instant and carry on throughout their respective cycles in perfect step, or **in phase.**

When an inductance or a capacity or any combination of these quantities with each other or with resistance is in the circuit, other phenomena take place differing entirely from what happens in a d-c circuit. For example, when an a-c voltage forces a current through an inductance, the current does not attain its maximum value at the same instant as the voltage, but at a later time; when the inductance is replaced by a capacity, the opposite is true, the maximum value of the current takes place before the maximum voltage is reached.

94. Case I. *Current and voltage in phase.* Figure 75 represents the current and voltage in phase, i.e., in a resistive circuit. Since the form of the voltage and current waves is exactly similar they can be drawn on the same horizontal axis, or in the vector diagram can be represented as in Fig. 76. They can be thought of as two vectors, which may or may not have the same length, rotating at the same speed in two different circles which move forward in the same direction at the same speed. Under these conditions, the end points of the vectors will trace out identical curves.

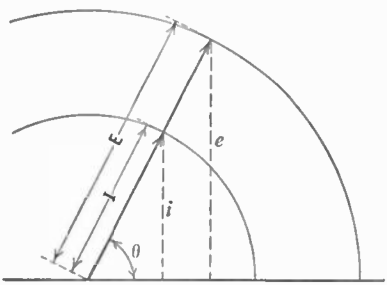


Fig. 76. Current and voltage in phase. The maximum value of voltage is greater (or is drawn to different scale) than the maximum value of the current.

In such cases, Ohm's law I equals E/R tells us the relations between current, voltage, and resistance, just as it does in a d-c circuit.

Example 3-6. Suppose a lamp of 55 ohms is placed across a 110-volt 60-cycle a-c line. What current will flow through it at the 30° phase?

We must first find the maximum value of the voltage.

$$E = E_{\text{eff}} \times \sqrt{2}$$
$$= 110 \times 1.41 = 155 \text{ volts}$$

Since there is no phase effect in the circuit due to the resistance, the current is given by Ohm's law

$$I = E/R$$
$$= \frac{155}{55} = 2.82 \text{ amp}$$

This is the maximum current. The current at any phase may be found by

$$i = I \sin \theta$$
$$= 2.82 \sin 30°$$
$$= 2.82 \times 0.5 = 1.41 \text{ amp}$$

Problem 8-6. A resistance of 10 ohms is in a circuit with an alternating voltage of 20 volts maximum. At what phases will the current through the resistance be 1 amp?

Problem 9-6. A certain alternating current has the same heating effect as a direct current of 8 amp. It flows through a resistance of 25 ohms. What is the effective and maximum voltage? At what phases will the instantaneous value of the voltage be equal to one-half the maximum value?

95. Case II. *Current lagging behind the voltage.* Let us consider the case where the current does not attain its maximum

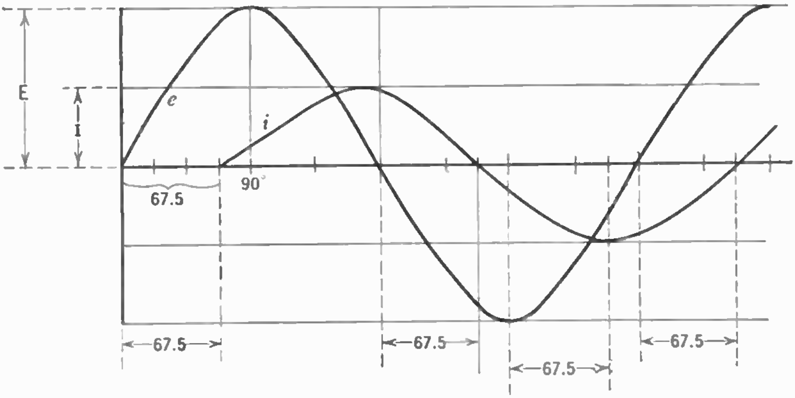


Fig. 77. Current and voltage in an inductive circuit where the current lags behind the voltage.

value at the same instant that the maximum voltage is reached, as is illustrated in Fig. 77. It will be noted that the current curve does not start until 67.5 degrees of the voltage curve has been completed, and therefore that the maximum value of the current is said to lag behind the voltage maximum 67.5 degrees. The current and voltage in such a case may be thought of as two vectors, or arms, moving in two circles one of which, the current circle, does not start until the other or voltage circle has completed 67.5 degrees of its total movement of 360 degrees.

The formulas for Case II where the current is lagging are

$$e = E \sin \theta$$

$$i = I \sin (\theta - \phi)$$

where θ = phase of the voltage in degrees;

ϕ = difference in phase between E and I or the angle of lag. (The angle ϕ is called phi.)

Example 4–6. The current lags behind the voltage by 60°. The maximum value of the current is 40 amp. What is the instantaneous value of the current at the 75° phase?

Solution. Lay off on graph paper the voltage at the 75° phase and 60° behind it the current which has a maximum value of 40 amp. The vertical component then is equal to the instantaneous value of the current at this phase.

The problem may also be solved by the mathematical formula

$$\begin{aligned} i &= I \sin (75° - 60°) \\ &= 40 \sin (75° - 60°) \\ &= 40 \sin 15° = 40 \times 0.26 = 10.4 \end{aligned}$$

Problem 10–6. If the maximum voltage is 110 what is the instantaneous voltage at the 110° phase? At the 90° phase? At 45°?

Problem 11–6. In an inductive circuit there is a phase difference of 25°. When the voltage is a maximum, the instantaneous value of the current is 10 amp. What is the maximum value of the current?

The cause of lagging current is inductance, which tends to make the maximum of current take place later than the maximum of voltage. If a circuit is purely inductive (the resistance is negligible) the difference between these maxima is 90 degrees. If there is appreciable resistance the difference is less than 90 degrees.

96. Inductive reactance. The opposition to the flow of current which inductance imposes on a circuit is called the **inductive reactance** and is measured in ohms just as resistance is. Its abbreviation is X^L. In any circuit in which there is only resistance, the expression which connects voltage and current is the familiar Ohm's law,

$$\text{Current} = \frac{\text{voltage}}{\text{resistance}} \quad \text{or} \quad I = \frac{E}{R}$$

Similarly, the expression when inductance is in an a-c circuit is

$$\text{Current} = \frac{\text{voltage}}{\text{reactance}} \quad \text{or} \quad I = \frac{E}{X_L}$$

and if the voltage is the maximum value the current will be the maximum value; if the voltage is the effective or rms value, the current will be the effective value; if the voltage is the instantaneous value the current will be the instantaneous value.

Inductive reactance is numerically equal to

$$X_L \text{ (ohms)} = 6.28 \times f \times L = \omega L$$

where f = frequency in cycles per second;
L = inductance in henries;
ω = Greek letter omega = $6.28 \times f$.

NOTE: The use of omega here as equal to $2\pi f$ should not be confused with the use of omega as an abbreviation for ohms. It is unfortunate that the same symbol has grown up in the art as standing both for resistance and for $2\pi f$.

Example 5-6. In an a-c circuit the following data are given: $E_{eff} = 100$ volts; inductive reactance, $X_L = 20$ ohms. Find the maximum and effective current and the instantaneous current at the 150° phase.

Solution. The effective current is found from

$$I_{eff} = \frac{E_{eff}}{X_L}$$

$$= \frac{110}{20} = 5.5 \text{ amp}$$

$$I_{max} = I_{eff} \times 1.41 = 7.8 \text{ amp}$$

The vector diagram in Fig. 78 shows the instantaneous current to be

$$i = I \sin (\theta - 90°)$$
$$= 7.8 \sin (150° - 90°)$$
$$= 7.8 \sin 60°$$
$$= 7.8 \times 0.866$$
$$= 6.75 \text{ amp}$$

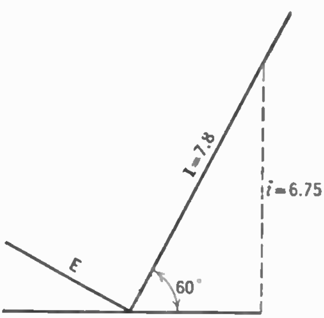


FIG. 78. Current lagging behind the voltage by 90 degrees.

Problem 12–6. In the above example find the instantaneous voltage when the instantaneous current is 6 amp. At what phase is this?

Problem 13–6. What inductive reactance is needed to keep the maximum current down to 75 amp in a 110-volt effective circuit?

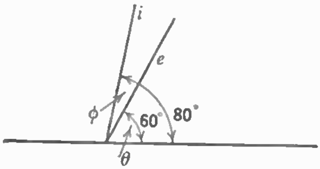


FIG. 79. Current leading the voltage by the angle ϕ at the 60° phase. The angle of lead is 20°.

97. CASE III. *Current leads the voltage.* In this case the maximum value of the current is reached before the corresponding maximum voltage is reached. The voltage lags behind the current, or as it is usually stated, the current **leads** the voltage. A vector diagram for such a case is shown in Fig. 79.

In this case the instantaneous values of voltage and current are:

$$e = E \sin 60°$$

$$i = I \sin 80° \quad \text{or} \quad i = I \sin (60° + 20°)$$

The formulas for Case III when the current leads the voltage are

$$e = E \sin \theta$$

$$i = I \sin (\theta + \phi)$$

where ϕ is phase difference between E and I or the angle of lead.

The current in such an equation will be the maximum current if the voltage is maximum, effective if the voltage is effective, etc.

Example 6–6. The effective current in an a-c circuit is 70 amp. The angle of lead is 30°. What is the instantaneous current when the voltage is at the 10° phase?

The maximum value of the current is found from

$$\begin{aligned} I_{max} &= I_{eff} \times 1.41 \\ &= 70 \times 1.41 \\ &= 98.7 \text{ amp} \end{aligned}$$

By the equation

$$\begin{aligned} i &= I \sin (\theta + \phi) \\ &= 98.7 \sin (10° + 30°) \end{aligned}$$

$$= 98.7 \times 0.643$$
$$= 64.5 \text{ amp}$$

Problem 14–6. The instantaneous value of current in a certain capacitive circuit is 8 amp. The instantaneous value of the voltage is 25. The maximum values of the current and voltage are 15 amp and 80 volts respectively. What is the angle of lead between them?

98. Capacity reactance. The opposition which a condenser offers to the flow of current in an a-c circuit is called its **capacitive reactance** and is measured in ohms just as resistance and inductive reactance are. The equation

$$\text{Current} = \frac{\text{voltage}}{\text{capacitive reactance}} \quad \text{or} \quad I = \frac{E}{X_c}$$

is similar in form to Ohm's law and the equation for current in an inductive circuit.

Capacitive reactance is equal numerically to

$$X_c(\text{ohms}) = \frac{1}{6.28 \times f \times C} = \frac{1}{\omega C}$$

where f = frequency in cycles per second;
C = capacity in farads;
ω = Greek letter omega = $6.28 \times f$.

Current leads the voltage in a capacitive circuit because capacity tends to prevent any changes in voltage and so the maximum of current in a purely capacity circuit takes place 90 degrees ahead of the maximum of voltage. If there is an appreciable resistance in the circuit the difference is less than 90 degrees; thus resistance tends to bring the current and voltage in phase.

Example 7–6. If a condenser which has a capacity reactance of 5 ohms, is in an a-c circuit the instantaneous value of the voltage at the 20° phase is 48 volts. What is the maximum current through the condenser? What is the instantaneous current through it at the 20° phase?

Solution

$$e = E \sin 20°$$
$$48 = E \times 0.342$$

$$E = 140 \text{ volts}$$

$$I = \frac{E}{X_c}$$

$$= \frac{140}{5} = 28 \text{ amp}$$

$$i = I \sin (20° + 90°)$$

$$i = 28 \sin 110°$$

$$= 28 \cos 20°$$

$$= 28 \times 0.940$$

$$= 26.32 \text{ amp}$$

Problem 15–6. If a condenser in an a-c circuit whose voltage is 110 passes a current of 3 amp what is the reactance of the condenser in ohms?

Problem 16–6. Condensers are usually rated at the maximum voltage at which they can be operated with safety. What should be the rating of a condenser to be used in a 220-volt a-c circuit?

Problem 17–6. An a-c circuit has a voltage of 115, and a current of 4.5 amp is flowing. It has a condenser in it. What is the reactance of this condenser? What is the instantaneous value of the current when the voltage is 80 volts? At what phase is this?

99. Comparison of inductive and capacitive reactances. Coils and condensers have opposite effects upon an alternating current. The reactance of an inductor increases as the frequency increases; the reactance of a capacitor decreases as the frequency increases.

A coil which may pass considerable current at 60 cycles may pass practically nothing at 1000 kc. On the other hand, a condenser which will pass considerable current at 1000 kc will pass practically nothing at all at 60 cycles.

Where it is desired to pass a low frequency through a circuit but to exclude a high frequency from it, a shunt condenser and a series coil are placed in the circuit. The series coil prevents the flow of the high-frequency current because of its high reactance while the capacitance shunted across the circuit provides an easy path for the high frequencies, but its high reactance to low frequencies prevents any of the low frequencies from leaking away through this shunt circuit.

Where it is desired to permit the flow of a high-frequency current through a circuit but to prevent a low-frequency current from flowing, the capacitor and the inductor are interchanged, the capacitor being placed in series and the coil in shunt to the circuit.

In both these cases, advantage is taken of the different effect of coils and condensers upon the flow of alternating currents of high and low frequencies.

Example 8–6. Assume an a-c circuit composed of an inductance of 1 mh. What current will flow if E is 100 volts and the frequency is 600 cycles?

$$\begin{aligned} X_L &= 6.28 \times f \times L \\ &= 6.28 \times 1 \times 10^{-3} \times 600 \\ &= 3.8 \text{ ohms} \end{aligned}$$

$$I = \frac{E}{X_L} = \frac{100}{3.8} = 26.3 \text{ amp}$$

Example 9–6. What is the reactance of a 500-$\mu\mu$f condenser to radio waves of a frequency of 600 kc?

$$\begin{aligned} X_c &= \frac{1}{6.28 \times 600 \times 10^3 \times 500 \times 10^{-12}} \\ &= \frac{10^9}{6.28 \times 600 \times 500} \\ &= \frac{10^5}{6.28 \times 30} = \frac{10^5}{188.4} = 530 \text{ ohms} \end{aligned}$$

Problem 18–6. What would the current be in an a-c circuit if the frequency were 6000 cycles? 60 cycles? If the inductance were 1 henry? One microhenry? Assume $E = 100$.

Problem 19–6. Calculate the reactance of 1 henry, 1 mh, 1 μh at the following frequencies: 100 cycles, 1000 cycles, 1,000,000 cycles.

Problem 20–6. What reactance is needed to keep the current into an electric iron down to 5 amp when it is placed across a 110-volt circuit (assuming the iron has no resistance)?

Problem 21–6. The inductance in an a-c circuit is 0.04 henry. At what frequency will the current be 3 amp if the voltage is 110?

Problem 22–6. Calculate the reactance of a 1-μf, 0.001-μf, 50-$\mu\mu$f condenser at 60 cycles, 60,000 cycles, 600 kc, 15,000 kc.

Problem 23–6. The capacity in an a-c circuit is 1.0 μf. At what frequency will the current through it be 415 ma if the voltage is 110?

100. By-pass condensers and choke coils. Condensers are shunted across a circuit to provide a low reactance path for the higher frequencies to follow and are called **by-pass** condensers; coils are used in series with a circuit to prevent the flow of the higher frequencies in that circuit; they are known as **choke coils.** When they are shunted across a circuit, they provide a path for lower frequencies to follow. The proper combination of inductors and capacitors will enable certain bands of frequencies to pass or to be excluded.

101. Measurements of capacities. Condensers may be measured for capacity by comparing them with a known capacity by means of a Wheatstone bridge. The unknown capacity may then be calculated from

$$C = \frac{B}{A} C_s$$

which differs from the formula when resistances or inductances are measured because of the fact that the reactance of a condenser decreases the larger it is. The formula when inductances are compared is

$$L = \frac{A}{B} L_s$$

The capacity of condensers from 0.01 to 10 or more microfarads may be measured by noting the current through them with a known voltage across them. The condenser is first tested for open or short as indicated in Section 81. Then, in series with a milliammeter, the condenser is plugged into a light socket (a-c, of course). Then the voltmeter may be put across the condenser, if the voltage of the line is not known. The capacity is

$$C\,\mu\text{f} = \frac{I\text{ ma} \times 1000}{6.28 \times f \times E}$$

102. Combinations of resistance with capacity or inductance. Coils and condensers are never pure reactances. They always have some resistance in them, although in most radio apparatus the resistance is negligible compared to the reactance. Since a reactance as well as a resistance impedes the flow of current, we must combine them to determine what current will flow through a piece of apparatus under a certain voltage and at a certain frequency.

Because an inductance has a different effect upon an alternating current than a resistance, and different from capacity, we cannot merely add their reactances in ohms to determine the resultant effect upon the circuit. They must be added *vectorially*, not *algebraically*.

103. Impedance. Combinations of resistance and reactance are called **impedances.** The value in ohms may be found as follows. Two factors whose effect is at right angles to each other may be combined and the resultant secured by the formula found in plane geometry which states that "the square on the hypotenuse of a right triangle is equal to the sum of the squares on the other two sides." Thus

$$Z^2 = R^2 + X^2$$

and if $R = 3$ ohms and $X = 4$ ohms,

$$Z^2 = 9 + 16 = 25$$

whence

$$Z = \sqrt{25} = 5$$

This is called getting the **vectorial** sum. The **algebraic** sum, obtained by simple addition—as when two resistances or reactances are combined—would be, in this case, 7 ohms whereas the vectorial sum is 5 ohms.

The resultant of combining a resistance and a reactance can be found graphically. Lay off on a horizontal line a number of units corresponding to the number of ohms resistance. Then if the reactance is inductive, erect a perpendicular and lay off on it a number of units equal to the number of inductive reactance ohms. The length of line connecting the extremities of these two lines is the resultant impedance in ohms.

The reasoning behind this procedure is as follows. Remember that in a resistive circuit the voltage and current are in phase; but that in an inductive circuit the current lags 90 degrees behind the voltage; and that in a capacitive circuit the voltage lags 90 degrees behind the current. Thus, comparing the resistive and the inductive circuits, we may see that in the latter the current lags 90 degrees behind the current in the former—there is a 90-degree phase difference between these two currents in the two circuits. Similarly, comparing a resistive and a capacitive circuit, the current of the latter is 90 degrees ahead of the current in the former.

Since the effects of inductance and resistance are at right angles to each other and since the effects of capacity and resistance are at right angles to each other, circuits combining resistance with either inductance or capacitance may be represented in this manner, using two vectors, one pointing at a 90-degree angle to the other. The effect upon the circuit of the two properties may be determined by drawing a diagonal to the parallelogram, two of whose sides are the resistance and the reactance due to inductance (or capacitance).

Because capacitive reactance has an opposite effect to that of inductive reactance, the line representing it should be pointed downward. Graph paper is of great aid in solving a-c problems in this manner.

Example 10–6. An alternating current of 8 amp maximum flows through a coil whose inductance is 0.043 henry and whose resistance is 5 ohms. What voltage is required if the frequency is 60 cycles?

The current in such a circuit is

$$I = E/Z$$

$$Z = \sqrt{R^2 + X^2}$$

and

$$X = 2\pi f \times L = 6.28 \times 60 \times 0.043 = 16.25 \text{ ohms}$$

$$Z = \sqrt{5^2 + 16.25^2} = \sqrt{289} = 17 \text{ ohms}$$

whence

$$E = IZ = 17 \times 8 = 136 \text{ volts.}$$

Example 11–6. What is the impedance in a circuit in which there is a condenser of 1.66 μf and a resistance of 800 ohms? The frequency is 60 cycles.

$$Z = \sqrt{R^2 + X_c^2}$$

$$X_c = \frac{1}{2\pi fC}$$

$$= \frac{10^6}{6.28 \times 1.66 \times 60} = 1590 \text{ ohms}$$

$$Z = \sqrt{800^2 + 1590^2}$$

$$= \sqrt{(64 \times 10^4) + (256 \times 10^4)} \quad \text{(approx.)}$$

$$= 10^2 \sqrt{320}$$

$$= 1790 \text{ ohms.}$$

104. General expressions for impedance. If an a-c circuit is composed of resistance and both inductive and capacitive reactance the impedance is figured as follows. Since the inductive and capacity reactances are opposite in effect, the negative sign is fixed to the capacity reactance, the positive sign to the inductive reactance. That is, a capacity reactance is a negative reactance of so many ohms; an inductive reactance is a positive reactance of so many ohms. Before they are combined with the resistance vectorially, their algebraic sum is obtained. Thus the general expression for impedance is

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

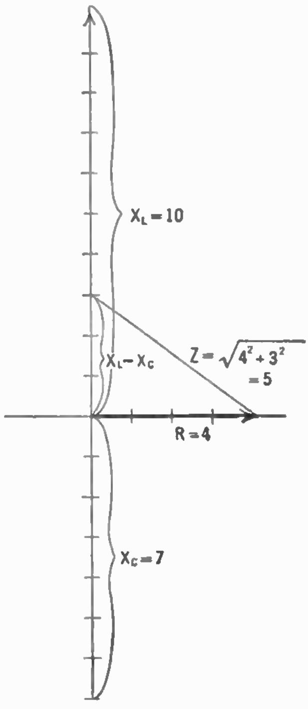


Fig. 80. Vector diagram of a circuit containing resistance (4 ohms) capacity reactance (7 ohms) and inductive reactance (10 ohms).

and after the capacity reactance has been combined with the inductive reactance (it is actually subtracted because the signs of the two reactances are different) the form of the impedance becomes as before.

$$Z = \sqrt{R^2 + X^2}$$

It will be noted that the sign before X^2 in the above equation is positive. This is always the case since two negative quantities multiplied together (or if a negative quantity is squared) result in a positive quantity. If, for example, the actual value of the capacity reactance in ohms was greater than the inductive reactance in ohms, the effective reactance in the circuit would be negative but X^2 would be positive.

Example 12–6. What is the impedance of a circuit consisting of a capacity reactance of 7 ohms, an inductive reactance of 10 ohms and a resistance of 4 ohms?

The vector diagram of such a case is shown in Fig. 80. Here we have X_L pointing upward at an angle of 90° from the resistance and X_c pointing downward at an angle of 90° from the resistance. The total effect of the reactances is $10 - 7$ or a positive 3 ohms which points upward.

If, however, the values of X_L and X_c are interchanged, so that the resultant of adding the reactances is a negative 3 ohms which points downward, then

If X_L is greater than X_c,

$$Z = \sqrt{R^2 + (X_L - X_c)^2}$$
$$= \sqrt{4^2 + (10 - 7)^2}$$
$$= \sqrt{4^2 + 3^2} = 5.$$

If X_c is greater than X_L,

$$Z = \sqrt{R^2 + (X_L - X_c)^2}$$
$$= \sqrt{4^2 + (7 - 10)^2}$$
$$= \sqrt{4^2 + (-3)^2}$$
$$= \sqrt{4^2 + 3^2} = 5$$

Problem 24–6. An antenna (Fig. 81) may be considered as an inductance, L_a and a condenser in series. If the voltage in Fig. 81 is 100 μv, $f = 1000$ kc, what is the current through the coil L_s in series with L_a? (There is no mutual inductance between L_a and L_s.)

Problem 25–6. What is the total reactance in a circuit which has 45 ohms inductive reactance, 70 ohms capacitive reactance and 20 ohms resistance? What is the impedance? What current would flow if the voltage were 110 effective?

Problem 26–6. What would be the values of capacity and inductance if in Problem 25–6 the frequency were 500 cycles?

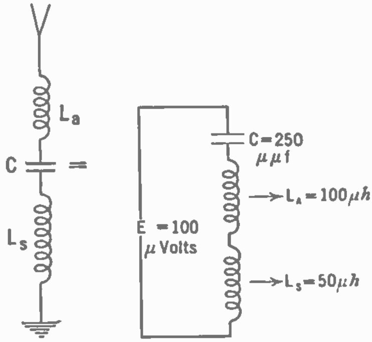


FIG. 81. An antenna and its equivalent.

Problem 27–6. What voltage is required to force 1 ma through the following circuit: resistance 8 ohms, inductance 300 μh, capacity 500 μμf, frequency 750 kc?

105. Series a-c circuits. In Fig. 82 is an inductance in series with a resistance. The current flowing in the circuit may be

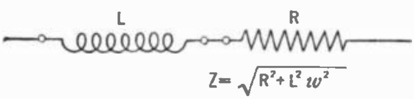


FIG. 82. A series circuit: $\omega = 6.28 \times f$.

found by dividing the voltage across the circuit by the impedance of the circuit, that is, $I = E/Z$, in which

$$Z = \sqrt{R^2 + X^2}$$

which is quite different in numerical value from $R + X$. For example, if $R = 3$ and $X = 4$, the vector sum $Z = 5$ whereas the arithmetical sum $= 7$.

As in a d-c circuit, the voltage across an impedance, a reactance, or a resistance is equal to that impedance, reactance, or resistance in ohms multiplied by the current in amperes.

Voltage across a resistance $E_R = I \times R$

Voltage across an inductance $E_L = I \times X_L$

Voltage across a capacity $E_C = I \times X_C$

Voltage across L and C $E_{L+C} = I\,(X_L - X_C)$

The voltage across two resistances or reactances is the *algebraic* sum of the individual voltages, remembering that a capacitive reactance has a negative sign and that the voltage across it is negative with respect to that across an inductance. The voltage across two impedances, however, must be determined by adding the individual voltages *vectorially*. This is because the impedance is a vector sum of a resistance and reactance.

Let us take a typical example. The current in the circuit of Fig. 82 is

$$I = \frac{E}{\sqrt{R^2 + X^2}}$$

or

$$E = I\sqrt{R^2 + X^2}$$

$$E^2 = I^2\,(R^2 + X^2)$$

or

$$E^2 = I^2R^2 + I^2X^2$$

$$= E_R^2 + E_X^2$$

whence

$$E = \sqrt{E_R^2 + E_X^2}$$

Therefore the resultant voltage across a resistance and a reactance is the vector sum of the individual voltages.

Example 13–6. If $E = 15$, $R = 3$, $X = 4$

$$I = \frac{15}{\sqrt{R^2 + X^2}} = \frac{15}{\sqrt{9 + 16}} = \frac{15}{5} = 3 \text{ amp}$$

$$E_R = IR = 3 \times 3 = 9 \text{ volts}$$

$$E_X = IX = 3 \times 4 = 12 \text{ volts}$$

$$E = \sqrt{E_R^2 + E_X^2} = \sqrt{81 + 144} = \sqrt{225} = 15$$

Experiment 1–6. To measure the capacitance of a condenser. Place a condenser of about 10-μf capacity in series with an a-c milliammeter and measure the current through it when placed across a 110-volt, 60-cycle line.

Then

$$E = IX_c = I \times \frac{1}{6.28 \times f \times C}$$

or

$$C = \frac{I}{E \times 6.28 \times f}$$

where E = line voltage or

$$C\ \mu\text{f} = \frac{I}{41.5} = I \times 0.024$$

when $E = 110$;
$f = 60$;
I = milliamperes.

106. Phase in series circuit. In a resistive circuit, the voltage and current are in phase, their maximum values occurring at the same instant. If the circuit is purely capacitive, or inductive, there is a 90-degree phase difference between current and voltage.

If, instead of a pure reactive circuit, we have some resistance, the angle of lead or lag (Sections 95, 97) is not 90 degrees but is some value less than this. To determine the phase angle, or the difference in phase, let us draw the vector diagram of the voltages as in Fig. 83. The voltage across the resistance, IR, is the horizontal line, and at an angle of 90 degrees with it is the voltage across the reactance, IX. The diagonal of the parallelogram represents the resultant voltage across the impedance, IZ.

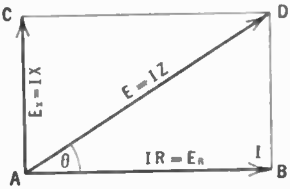


FIG. 83. The length of the line AD represents the vector voltage across an inductance and a resistance in series.

Because a resistance in an a-c circuit produces no phase difference between the current and voltage the current through and the voltage across a resistance are said to be in phase. Their directions may be represented along the same line, that is, along the horizontal line representing the voltage IR across the resistance. The direction of the diagonal represents the direction of the voltage across the entire circuit. Since, then, the direction of the IR line represents the direction of the current, I, and the direction of the IZ line represents the direction of the voltage, E, the angle between these lines represents the angular difference in phase between the voltage and current. The angle θ then is equal to the angle of phase difference between the voltage across the combination and the current through it. Thus, in Fig 83

$BD \div AB$ is the tangent of the angle θ, or

$$\frac{BD}{AB} = \tan \theta$$

and since $BD = AC = IX$ (or the voltage across X) and $AB = IR$ (or the voltage across R),

$$\frac{E_X}{E_R} = \frac{IX}{IR} = \frac{X}{R} = \tan \theta$$

Knowing the reactance and the resistance in ohms the tangent of the angle may be determined, and the angle itself looked up in a table. When the tangent of an angle is known but not the angle, the expression is written $\theta = \tan^{-1} \dfrac{X}{R}$ and is read "θ (theta) the the angle whose tangent is X over R."

The effect of a resistance in series with a reactance is to decrease the angle of phase difference between the current and the voltage, that is, to bring them more nearly in phase. In a pure reactance circuit, the angle is 90 degrees; when resistance is added this angle decreases. In a pure resistance circuit, there is no angle, the current and voltage are in phase; they reach their maximum values at the same instant.

Example 14–6. In an a-c circuit there is a resistance of 10 ohms and an inductive reactance of 8 ohms. A current of 8 amp is flowing. What voltage exists across each part of the circuit and across the entire circuit? What is the phase difference between the current and the voltage?

$$\text{Voltage across } R = IR = 8 \times 10 = 80 \text{ volts}$$

$$\text{Voltage across } X = IX = 8 \times 8 = 64 \text{ volts}$$

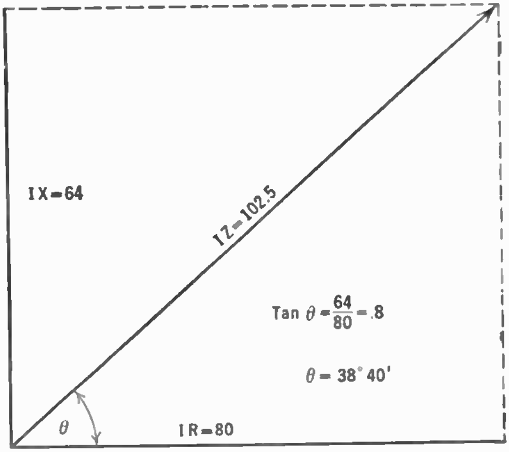


FIG. 84. A vector diagram of Example 14.

Draw the vector diagram to scale as in Fig. 84; then the diagonal $IZ = 102.5$ volts. (Note that the algebraic sum of the voltages across R and X is 144 volts.) The tangent of the angle of phase difference is equal to $X \div R$ or

$$\tan \theta = X/R = 8/10 \text{ or } 0.8$$

$$\theta = \tan^{-1} 0.8$$

or

$$\theta = 38° \, 40'$$

Note in Fig. 83 that the right-angled triangle has three sides respectively representing the voltage across the resistance, IR, across the reactance, IX, and across the impedance IZ. Now if each of these voltages is divided by the current, I, three sides of the triangle can be made to represent R, X, and Z. Then, if we know two elements of an impedance, or the impedance and one element, the third element can be found. Thus

$$\cos \theta = R/Z; \ \sin \theta = X/Z; \ \tan \theta = X/R$$

or $R = Z \cos \theta$

$X = Z \sin \theta$

$Z = R/\cos \theta$

$\theta = X/\sin \theta$

CASE I. X and R given, to find Z. Look in a table of trigonometric functions the angle whose tangent is X/R; find sine or cosine of this angle and divide into X or R.

CASE II. X and Z given, to find R. Note that the sine of an angle is equal to the cosine of 90° minus that angle. Thus sin 70° = cos 20°. Since the sum of the angles of a triangle is equal to two right angles (180°) and since one right angle exists between X and R, the other two angles must total 90°.

Now $R = Z \cos \theta$, but θ is not known. However, the angle $(90 - \theta)$ can be found since that is the angle between X and Z, and both are given. The cosine of the angle between X and Z is equal to X/Z. Therefore, if θ is not known, $R = Z \cos \theta$ cannot be solved, but $R = \sin (90 - \theta)$ is known.

Look up the angle whose cosine equals X/Z; at the same time find the sine of this angle and multiply it by Z; or in mathematical language

$$R = Z \cos \theta = Z \sin (90 - \theta) = Z \sin (\cos^{-1} X/Z)$$

CASE III. R and Z given, to find X. This situation resembles Case II and in mathematical language

$$X = Z \sin \theta = Z \cos (90 - \theta) = Z \cos (\sin^{-1} R/Z)$$

Example 15–6. A series circuit is made up of resistance = 46 ohms, inductive reactance = 26.6 ohms. What is the impedance?

Solution: $X/R = 0.577$. This is the tangent of an angle of 30°. The cosine of this angle is 0.866; and $Z = R \div 0.866$ or $46 \div 0.866 = 53$ ohms.

Suppose, however, that Z and X are given, to find R. $X/Z = 26.6 \div 53 = 0.5$. Look up the angle whose cosine is 0.5. Since it is 60° and the sine of this angle is 0.866, R, therefore, is equal to $0.866Z$ or $53 \times 0.866 = 46$ ohms.

Problem 28–6. Two resistances, one of 8 ohms and the other of 24 ohms, are in a 60-cycle 110-volt circuit. What current flows? What is the current if the frequency is increased to 500 cycles?

Problem 29–6. What current exists in the above-named circuit if the second resistance is replaced by an inductive reactance of 24 ohms? If the frequency is 60 cycles what inductance will be in the circuit?

Problem 30–6. In a circuit with 550 volts across the terminals are the following pieces of apparatus: A coil with 15 ohms reactance, a condenser with 7 ohms reactance, two resistances of 10 and 5 ohms. What current flows? What is the voltage across each part? What is the phase relation between voltage and current?

Problem 31–6. In an a-c circuit appear a voltage across a resistance of 34 volts and a voltage across a capacity of 66 volts. What is the voltage across the combination?

Problem 32–6. Two condensers are in series with two inductances and a resistance. The condensers have reactances of 8 and 10 ohms, the inductances 20 and 6 ohms, and the resistance is 4 ohms. What current flows, what voltage appears across each component and what is the phase between current and voltage? Assume $E = 110$.

Problem 33–6. What is the phase difference in the following cases: (*a*) pure resistance circuit; (*b*) pure inductive circuit; (*c*) pure capacity circuit; (*d*) 100 ohms resistance and 100 ohms inductive reactance; (*e*) 100 ohms resistance and 50 ohms inductive reactance; (*f*) 100 ohms resistance and 100 ohms capacity reactance; (*g*) 100 ohms resistance and 50 ohms capacity reactance; (*h*) 100 ohms inductive reactance and 50 ohms resistance and 25 ohms capacity reactance; (*i*) 100 ohms each inductive and capacitive reactance and 100 ohms resistance?

Problem 34–6. In a series circuit there are 45 ohms inductive reactance and 20 ohms resistance. It is desired to increase the phase angle between the current and voltage to 85°. How can this be done? How can the phase angle be decreased to 30°?

107. Characteristics of a series circuit. 1. The voltage across a series combination of resistance and reactance is the vector sum of the voltages across the separate units.

2. The combined resistance of several resistances in series is the algebraic sum of the individual resistances.

3. The combined reactance of several reactances, whether inductive or capacitive, is the algebraic sum of the individual reactances.

4. The impedance, or combined effect of a resistance and reactance, is the vector sum of their individual values.

5. The combined impedance of several separate impedances is the vector sum of the individual impedances.

Example 16–6. Suppose we combine two resistances, reactances, etc., of 3 and 4 ohms respectively. The table below shows the resultant values.

Combination	Sum		Resultant
1. $R = 3; X = 4$	$\sqrt{9 + 16}$	$= Z$	5
2. $R = 3; R = 4$	$3 + 4$	$= R$	7
3. $X_L = 4; X_c = 3$	$4 - 3$	$= X$	1
3. $X_L = 3; X_c = 4$	$3 - 4$	$= X$	−1
3. $X_L = 3; X_L = 4$	$4 + 3$	$= X$	7
3. $X_c = 3; X_c = 4$	$-4 - 3$	$= X$	−7
(1) $R = 3, X_L = 4\ X_c = 3$	$\sqrt{9 + (4 - 3)^2}$	$= Z$	3.16
(2) $R = 3, X_L = 3\ X_c = 4$	$\sqrt{9 + (3 - 4)^2}$	$= Z$	3.16
(3) $R = 3, X_L = 3\ X_c = 3$	$\sqrt{9 + (3 - 3)^2}$	$= Z$	3

Note in (1) and (2) above that the resultant is the same although the conditions are different. This occurs because a negative number when squared, or multiplied by itself, becomes a positive number. In other words, a negative reactance and a resistance always produce a positive impedance.

108. Resonance. Since reactances may be positive or negative in effect, a very important phenomenon can take place. When the capacity reactance of a series circuit equals the inductive reactance, their respective effects cancel out and the resultant impedance is the resistance in ohms alone. To a circuit possessing inductive reactance one can add a certain amount of capacity and thereby reduce the impedance of the circuit (at some particular frequency) to the value of the ohmic resistance. This is the phenomenon underlying all tuning in radio circuits; it is known as **resonance.**

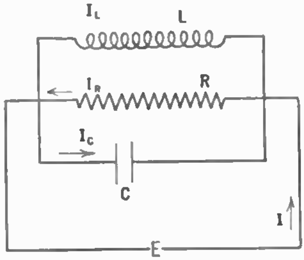


Fig. 85. In a parallel circuit the current I may be very small compared with I_L or I_C.

109. Parallel circuits. In a circuit like that of Fig. 85, in which several reactances or combinations of reactance and resistance may be connected in parallel, the following rules hold:

The *voltage* across each branch equals the voltage across the combination.

The total *current* taken from the voltage source is the vector sum of the currents through each branch.

The *impedance* offered to the flow of current by the combination is the voltage divided by the total current.

Thus in Fig. 85 the current through the entire combination may be found as follows, assuming $E = 120$; $X_C = 8$; $X_L = 5$; $R = 3$:

$$I_C = \frac{E}{X_C} = \frac{120}{8} = 15 \text{ amp through the condenser}$$

$$I_R = \frac{E}{R} = \frac{120}{3} = 40 \text{ amp through the resistance}$$

$$I_L = \frac{E}{X_L} = \frac{120}{5} = 24 \text{ amp through the inductance}$$

$$I = \sqrt{I_R^2 + (I_L - I_C)^2} = \sqrt{1681} = 41 \text{ amp}$$

$$Z = \frac{120}{41} = 2.92 \text{ ohms}$$

110. Phase in parallel circuit. The phase angle between the current and the voltage in a parallel circuit may be obtained from the expression

$$\tan \theta = \frac{I_L - I_C}{I_R}$$

or

$$\theta = \tan^{-1}\left(\frac{I_L - I_C}{I_R}\right)$$

111. Impedance of parallel circuit. Since the impedance is the ratio between the voltage across the circuit and the current through it, in order to find the impedance of several branches in parallel we must know the voltage and the current. Often we would like to know the impedance without knowing either the voltage or the current. The procedure then is to assume a voltage, find the currents that would flow, divide the voltage by the total current and get therefrom the impedance, or

$$Z = \frac{E}{I}$$

Example 17–6. What is the impedance of 630 ohms capacity reactance shunted by 100 ohms of resistance?

Assume a voltage of 100.

$$I_C = 100/630 = 0.159 \text{ amp}$$

$$I_R = 100/100 = 1.0 \text{ amp}$$

Total current

$$I = \sqrt{I_C^2 + I_R^2}$$

$$= \sqrt{0.159^2 + 1^2} = \sqrt{1.025}$$

$$= 1.015 \text{ amp}$$

$$Z = \frac{E}{I} = \frac{100}{1.015} = 98.5 \text{ ohms.}$$

112. Power in a-c circuits. In a d-c circuit the power is the product of the voltage across the circuit and the current through it. Thus, if one ampere is fed into a device under a pressure of 100 volts, the power used is 100 watts.

In a-c circuits the voltage and current are not always in phase. In fact in many circuits there is a decided difference in phase between the current and voltage. What is the power?

The power at any instant is the product of the instantaneous current and the instantaneous voltage. Thus in Fig. 86, where the voltage and the current are in phase, as in a resistance circuit, the height of the voltage line e above the horizontal, or time, axis multiplied by the height of the current line i above this axis gives the instantaneous power. This is plotted in the curve P.

When, however, the current and voltage are not in phase, as in an inductive (Fig. 87) or capacitive (Fig. 88) circuit, a different looking curve results although the instantaneous power is still the product of the instantaneous values of current and voltage. The part of the power curve marked B is interesting. It is

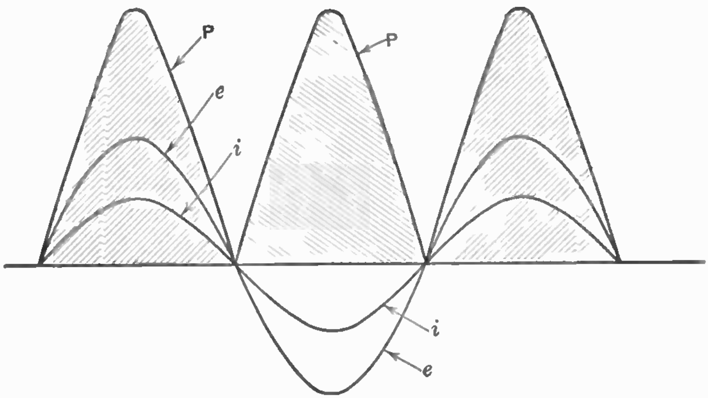


FIG. 86. All the power in a resistive circuit is used.

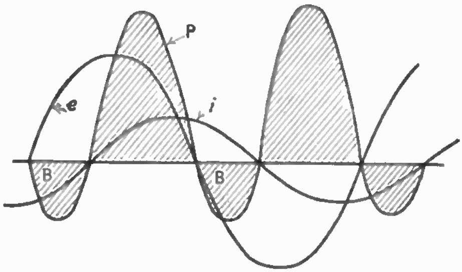


FIG. 87. In an inductive circuit some power is consumed and some (the shaded areas below the line) is returned to the generator.

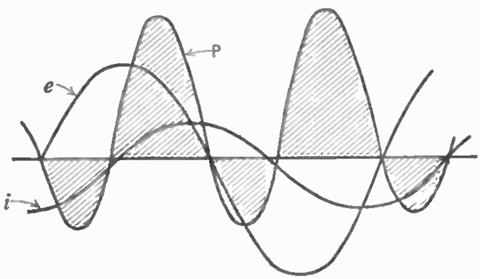


FIG. 88. Power in a capacitive circuit.

the result of multiplying a positive current (or voltage) by a negative instantaneous value of voltage (or current). The product is negative; so the power at that instant represented by this small loop must be considered as negative power.

Power consumed in a circuit is considered as positive power. Negative power is power that is returned to the generator from the line. Power is only returned to the generator when there is reactance in the circuit. A pure resistance circuit consumes the entire amount of the power fed it by the generator; a reactive circuit returns some of it to the generator.

The **effective power** in a resistance circuit is the product of the effective volts and the effective amperes. In a reactive circuit, however, the effective power is reduced by the power returned to the generator, so that the product of effective volts times effective amperes does not give the true measure of the power consumed in the circuit. The true power is given by

$$P = E_F I_F \cos \theta$$

where θ is the angle between the voltage and the current.

The product of the volts and the amperes is called the **apparent power.** Since this apparent power must be multiplied by $\cos \theta$, this factor is called the **power factor** of the circuit. When the current and voltage are in phase, that is, in a resistance or resonant circuit, the power factor, $\cos \theta$, is equal to 1.0, and the circuit is said to have unity power factor.

The power factor of a circuit, or of a piece of apparatus, is a measure of its resistance compared with its reactance, or vice versa. In radio circuits one is usually more interested in the reactance and there is every desire to keep the resistance low; but in power circuits the opposite is true, at least so far as the power companies are concerned. One uses a condenser or an inductor in a radio circuit because one wants a condenser or an inductor; whatever resistance the component has, in addition to its reactance, is a nuisance because it consumes power. A pure inductor or a pure capacity will not take any power from the line; thus, a pure capacity or inductance plugged into a light socket will not cause the electric meter to turn. The current the component takes from the line merely sets up a field which is given back to the line when the direction of flow of current changes. A flow of current through the line, however, is a positive thing; it flows through the resistance of the power line, resulting in a voltage drop and a power loss and it is a direct waste so far as the power company is concerned.

Power companies, therefore, do not like people to use apparatus on the line which has reactance because the current taken by the reactance does not turn the meter. Radio engineers, on the other hand, do not like apparatus to have resistance since it consumes power which must be supplied from somewhere and is a loss so far as the radio-frequency function of the apparatus is concerned.

Now $\cos\theta$ is equal to R/Z as shown in Section 106 and the power factor may be taken as a demerit of the apparatus so far as radio is concerned since a low power factor (values approaching zero) means that the impedance is high compared with the resistance; but in a power circuit a high power factor is a merit since in this case a high ratio of resistance to impedance is desired.

In a circuit containing resistance only the power factor is unity; in a purely reactive circuit the power factor is zero. All values of power factor lie between zero and 1 since all values of the cosine of an angle lie between these values.

Example 18-6. A 220-volt a-c motor takes 50 amp from the line; but a wattmeter in the line shows that 9350 watts are taken by the motor. The apparent power is the product EI or 11,000 watts; the power factor is true power divided by apparent power $= 9350/11{,}000$ or 0.85 or 85 per cent. What does this mean?

Power W taken by motor from line $= EI\cos\theta = 9350$
Current taken from line $= W/E\cos\theta$ $= 50$ amp
But the *useful* current $= W/E$ $= 42.5$ amp

Therefore, $50 - 42.5 = 7.5$ amp flow through the line and from the generator supplying the system, which would not be taken if the machine had unity power factor (like a pure resistance). This extra current represents a waste because of the voltage loss in the resistance of the lines and a power loss in the resistance of these lines.

Example 19–6. A single-phase induction motor with 440 volts across it, delivers 12 hp. The motor is 89.5 per cent efficient; and has a power factor of 84 per cent. What current is taken from the line and what power is taken from the line?

$$\text{Power taken by motor} = \frac{\text{power delivered}}{\text{motor efficiency}} = \frac{12 \times 746}{0.895} = 10{,}000 \text{ watts}$$

This is the real power taken from the line,

$$\text{Current taken from line} = \frac{\text{real power}}{E \cos \theta} = \frac{10{,}000}{220 \times 0.84} = 54.25 \text{ amp}$$

If the motor had unity power factor (no reactance) it would require W/E or 45.5 amp from the line. The difference, 8.75 amp, flows through the generator at the power plant, through the line and feeder transformers between the plant and the motor, through the wires in the factory using the motor, and finally through the wires of the motor.

Knowing the power factor, one can determine the ratio of the resistance to the impedance of the circuit; but one cannot find the absolute value of the ohmic resistance directly. For example, a motor may have a power factor which is more or less independent of the current drawn or the power delivered. That is, its ratio of resistance to impedance is a constant. The current taken from the line and the power taken from the line will depend upon the power the motor is called upon to deliver. If one can call the effective resistance of the motor the value of a pure resistance taking an equivalent amount of power from the line, i.e., R equals power divided by I^2, then one can determine this value of R, and since the ratio between R and Z is known (power factor) all three elements of the circuit, R, Z, and X can be found. However, not all this R will be made up of the ohmic resistance of the windings of the motor—in fact if much of it is, the motor is inefficient.

Problem 35–6. The reactance of a condenser is 300 ohms at 680 kc. What is its reactance at 1200 kc? HINT: Use simple proportion.

Problem 36–6. What current will flow through a 4-μf condenser when placed across a 400-volt source of 60-cycle voltage?

Problem 37–6. A resistance of 40 ohms is in series with a capacity of 60 $\mu\mu$f. What is the impedance at 28 Mc? If 100 volts is placed across this series circuit, what voltage will be across each element?

Problem 38-6. In a series circuit containing resistance and inductance, the values of these two components in ohms is equal at a certain frequency. What is the impedance at this frequency in terms of the resistance? What will be the impedance of the circuit at twice this frequency?

Problem 39-6. A series circuit composed of $R_p = 10{,}000$ ohms, $R_o = 20{,}000$ ohms, and $L = 100$ h has 100 volts at 100 cycles across it. What is the voltage across L and R_o in series? Assume $\omega^2 = 40$.

Problem 40-6. What is the impedance of 240 ohms resistance shunted by an equivalent value in capacity reactance?

Problem 41-6. Electric lamps with the transformers supplying them commonly operate at a power factor of about 95 per cent. What power is taken from a generator by eight 110-volt lamps each taking 5 amp?

Problem 42-6. A by-pass condenser across a 500-kc circuit has a capacity of 0.01 μf. If the voltage across the condenser is 100 and if the ratio of the reactance to the resistance is 40, what is the current taken by the condenser, what is its power factor, and how much power does it consume?

Problem 43-6. A certain loud speaker has an inductance of 1.5 h, a resistance of 3000 ohms. What power will it take from a 100-volt, 100-cycle source? What is its power factor?

CHAPTER VII

RESONANCE

The most important circuits in radio are those in which either series or parallel resonance occurs. In transmitting and receiving systems resonance is used to build up large voltages and currents at certain desired frequencies and to discriminate against undesired signal frequencies by keeping their voltages and currents low. When one tunes a radio receiver, he actually adjusts the a-c circuits within the receiver so that a condition of resonance occurs. Everyone who has operated a receiver has, in tuning it, performed one of the most interesting experiments in all a-c theory and practice. It is necessary that we look into the phenomenon of resonance very closely.

113. Series resonant circuit. Although a general idea may be obtained of what takes place in a resonant circuit when a radio receiver is tuned, a much more exact idea may be had as a result of a laboratory experiment.

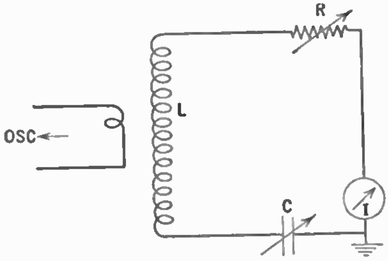


FIG. 89. When L is coupled loosely to an oscillator and C is varied, the current indicated at I will go through a maximum like that in Fig. 91.

Experiment 1–7. Connect, as in Fig. 89, a coil of about 200 μh inductance, a variable condenser of maximum capacity of 1000 $\mu\mu$f, a resistance of about 10 ohms, and a current-indicating device such as a current squared meter or a thermocouple and meter. Couple the circuit loosely to a radio-frequency generator and (*a*) adjust the condenser C so that resonance is obtained and then (*b*) adjust the frequency of the oscillator while the tuning condenser C of the external circuit is held constant. Plot the current in the circuit against condenser degrees or capacity and then against frequency. Change the value of R and repeat.

In either case the voltage across the condenser and across the coil and the phase between current and voltage should be calculated and plotted.

NOTE: If the experimenter possesses a short-wave transmitter which is equipped with an antenna meter he can carry out the same experiment by noting the antenna current as the antenna series condenser is adjusted, or as the frequency of the tank circuit is adjusted below and above resonance with the antenna. Such a curve is shown in Fig. 90.

Experiment 2–7. Connect in series with a lamp an inductance of several henries. Add sufficient resistance so that the lamp does not light when placed across a 110-volt 60-cycle line. Then put a condenser (of the filter type) in series with the resistance, the line, and the lamp. Add other capacity until the lamp lights up. Adding the capacity has brought the circuit to resonance so that the only hindrance to the flow of current was the lamp and the resistance. Adding something to the circuit actually made more current flow.

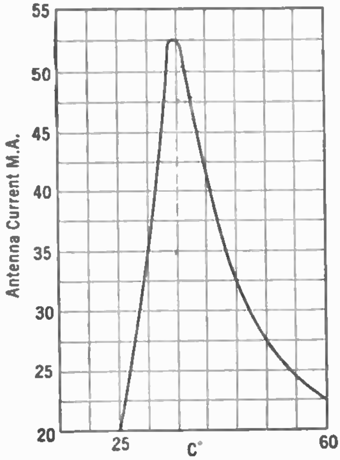


FIG. 90. How the antenna current of a radio station varies as the series antenna condenser is varied.

The curve in Fig. 91 shows what happens as the voltage across a series circuit is kept constant but the frequency is increased. At first the current increases slowly, then as the resonant frequency, 356 kc. is approached the current increases very abruptly and after passing through a sharp maximum at 356 kc falls very rapidly at first and then more slowly. The voltages across coil and condenser go through similar changes. The phase between current and voltage changes also, being a negative angle (current leading voltage) below resonance, being zero at resonance (current and voltage in phase), and becoming a positive angle above resonance (current lagging behind voltage).

At zero frequency, that is at direct current, the current in such a circuit would be zero because the condenser will not permit direct current to pass. At very low frequencies, the reactance of the condenser is very high, so that little current will flow. At very high frequencies the reactance of the coil becomes very great and therefore little current will flow. At intermediate frequencies more current flows.

When a series circuit is resonant, the current and voltage are in phase, the current is a maximum, the impedance is a minimum, the voltages across the condenser and the inductance are equal and opposite in sign and greater in value than the voltage across the combination.

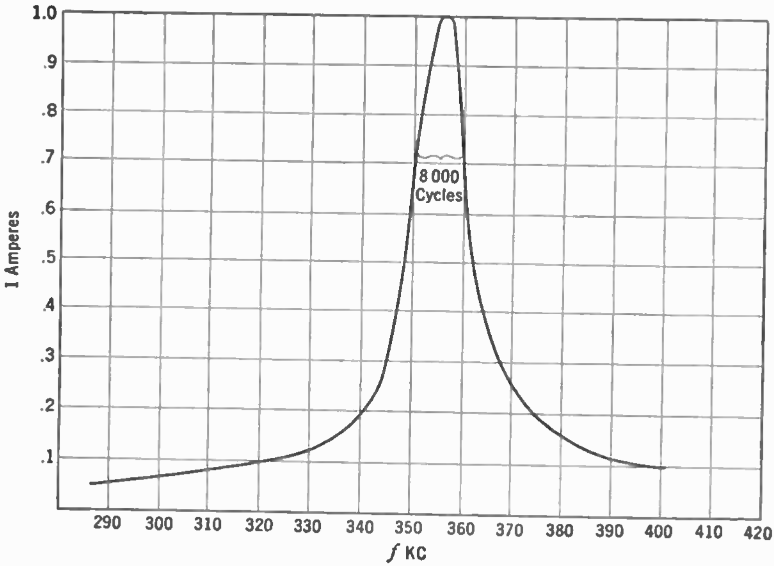


FIG. 91. The resonance curve of a circuit like that of Fig. 89.

In Fig. 91 note that from 340 to 356 kc, a change of 1.047 times, the current changes from 0.2 amp to 1.0 amp, a change of 5 times. The voltages across the condenser and inductance become much greater, at resonance, than the voltage impressed upon the circuit. This voltage may become so high that the condenser will be punctured. The voltage across the coil or the condenser at resonance is equal numerically to the voltage across the entire circuit multiplied by the factor X_L/R or X_C/R which are equal to $L\omega/R$ or $1/C\omega R$, often called the Q of the circuit.

A curve showing how the current in the circuit changes as the variable factors are changed, that is, a graph of I against the capacity, the inductance or the frequency, is called a **resonance curve** and is symmetrical about the resonant frequency if the circuit is adjusted by changing the inductance, and is dissymmetrical when the capacity or the frequency is the variable factor.

114. Characteristics of series resonant circuit. Below the resonant frequency the reactance is mainly capacitive; above this frequency the circuit is mainly inductive, that is, the capacitive reactance is the main deterrent to the flow of current below resonance; above resonance the inductance offers the greatest opposition to the flow of current. For a narrow band of frequencies in the neighborhood of 356,000 cycles in Fig. 91 the total impedance of the circuit is less than 100 ohms. Far from the resonant frequency the reactance is much greater and very little current will flow.

Below resonance, where the capacity reactance predominates, the current leads the voltage; at resonance the current is in phase with the voltage; above resonance the current lags behind the voltage. At resonance, therefore, there is an abrupt change in phase between the voltage across the circuit and the current taken by it from the generator.

At all frequencies the voltage across the inductance is 90 degrees ahead of the current and the voltage across the condenser is 90 degrees behind the current. Between the two reactive voltages, then, is a 180-degree phase difference. That is, they are exactly out of phase. Their resultant may be found by looking at Fig. 92 in which E_L and E_C are plotted as 180 degrees out of phase and of unequal magnitude. The resultant of combining them with the voltage across the resistance must be the voltage across the entire series circuit, which is the vector sum. Thus,

$$E = \sqrt{E_R^2 + (E_L - E_C)^2}$$

At any frequency but that of resonance, one of the two reactive voltages is greater than the other. At resonance, however, the two voltages are equal in magnitude and opposite in phase so that the resultant of combining the reactive voltages is zero. When added vectorially to the IR drop in the circuit, the resultant is the voltage which is impressed by the external source.

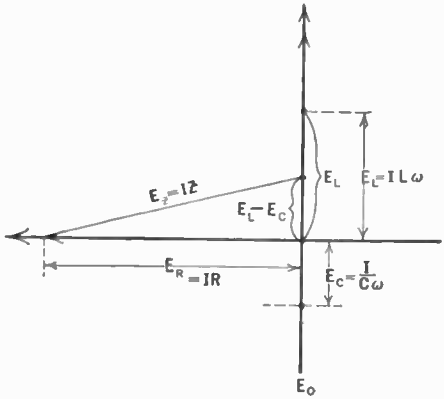


FIG. 92. Vector diagram of a series circuit in which inductance predominates.

The vector sum of the reactive and resistive voltages is equal to the impressed voltage.

Example 1-7. What are the voltages and phase relations in the circuit of Fig. 89 at a frequency of 370 kc?

$$I = 0.274 \text{ amp}$$

$$X_C = 430 \text{ ohms}$$

$$X_L = 466 \text{ ohms}$$

$$R = 10 \text{ ohms}$$

$$E_R = I \times R = 0.274 \times 10 = 2.74 \text{ volts}$$

$$E_C = I \times X_C = 0.274 \times 430 = 118 \text{ volts}$$

$$E_L = I \times X_L = 0.274 \times 466 = 128 \text{ volts}$$

$$E_{R+L} = \sqrt{2.74^2 + 128^2} = 128 \text{ volts (approx.)}$$

$$\phi_{R+L} = \tan^{-1}\frac{128}{2.74} = \tan^{-1} 46.6 = 88.46°$$

$$E_{R+C} = \sqrt{2.74^2 + 118^2} = 118 \text{ volts (approx.)}$$

$$\phi_{R+C} = \tan^{-1}\frac{118}{2.74} = \tan^{-1}43 = -88.38°$$

$$E_{L+C} = E_L - E_C = 9.6 \text{ volts} = E_X$$

$$E = I\sqrt{R^2 + X^2} = \sqrt{E_R^2 + E_X^2} = \sqrt{2.74^2 + 9.6^2}$$
$$= 10 \text{ volts}$$

$$\phi_{R+L+C} = \tan^{-1}\frac{X}{R} = \tan^{-1}\frac{X_L - X_C}{R} = \frac{466 - 430}{10} = 3.6$$
$$= 74° 30'$$

At resonance the reactances are equal to each other and equal to $\sqrt{L/C}$, i.e., $X_L = X_C = \sqrt{L/C}$.

For example the reactances of the condenser and inductance in the circuit of Fig. 89 may be found by

$$X_L = X_C = \sqrt{\frac{L}{C}}$$

$$= \sqrt{\frac{200 \times 10^{-6}}{1000 \times 10^{-12}}}$$

$$= \sqrt{0.2 \times 10^6}$$

$$= \sqrt{0.2} \times 10^3$$

$$= 0.447 \times 10^3$$

$$= 447 \text{ ohms}$$

At resonance the inductive reactance and the capacitive reactance in the equation for the impedance $Z = \sqrt{R^2 + (L\omega - 1/C\omega)^2}$ cancel out, that is, $L\omega - 1/C\omega = 0$ so that the resultant impedance is the resistance alone,

$$Z = R \text{ (at resonance)}$$

Problem 1-7. An inductance of 0.3 mh, a condenser of 0.0001 μf, and a resistance of 5 ohms are in series. Across the ends of this circuit is an alternator whose frequency is 910,000 cycles and whose voltage is 5. Calculate the current flowing, the phase between the current and voltage, the voltages across the coil and the condenser. What would the current be if the circuit were resonant? What is the impedance of the circuit at 900 kc?

Problem 2-7. What power is taken from the generator in Problem 1-7 at resonance?

115. Effect of resistance on series resonant circuit. At resonance the magnitude of the current in the circuit is controlled

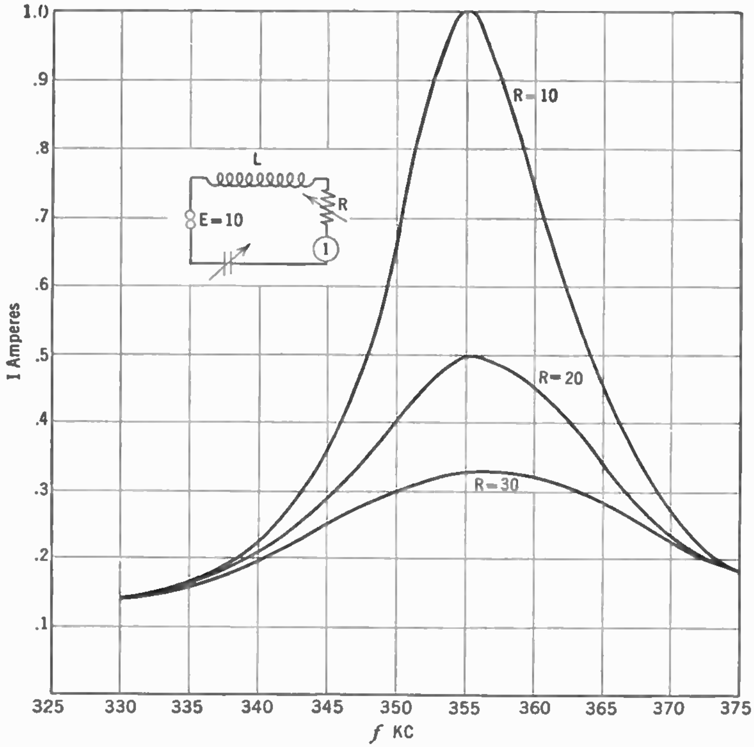


Fig. 93. Effect of resistance on a resonance curve. Note that the current far from resonance is not changed so much as the resonant current.

solely by the resistance. Its effect is most important in any radio circuits where resonance plays a prominent part. The curves in Fig. 93 show the effect of adding resistance to the circuit of Fig. 89. The voltages across the condenser and the inductance, too, depend upon the resistance of the circuit. They are greater the smaller the resistance. This is due to the fact that the voltage across these reactances is equal to the product of the reactance and the current. The latter, controlled entirely by the resistance at resonance, in turn produces greater voltages across the reactance when less resistance is in the circuit. If E is the voltage impressed on the whole circuit, the voltage across the condenser is $E \div C\omega R$ and that across the inductance at resonance is $E \times (L\omega/R)$. The voltage across either L or C is equal to EQ. Note how often the factor Q enters into radio circuits. Here it shows that the voltage rise in a low-resistance circuit may be very high at resonance.

116. Power into resonant circuit. No power is dissipated in heat in a pure inductance or capacity, but energy stored at one instant in a magnetic or electrostatic field is turned back into the circuit at another instant. Power is expended in the resistance of a circuit, but since at high values of resistance the current is small, the power in the circuit will be small. This power is equal, as usual, to

$$P = I^2 \times R$$

where R is the resistance of the circuit. In Fig. 89, where the resistance is 10 ohms and the current at resonance 1 amp, the power is 10 watts. Since at resonance there is no reactance effective in the circuit the power fed into it by the generator is the product of the current times the voltage, or 10×1 or 10 watts.

In other words, all the energy taken from the generator is used up in heating the resistance. None is necessary to maintain the magnetic and electrostatic fields of the coil and the condenser. The energy in these fields is transferred from one to the other, the sum at any one instant being equal to the sum at any other instant so long as the energy dissipated in the resistance is supplied from the outside.

In actual circuits the resistance is not isolated as in our demonstration problems. All coils have resistance; so do all condensers, although the resistance of modern variable capacities is quite small. These resistances take power from the generator and reduce the maximum height of the resonance curve.

117. The resonant frequency of the circuit. The condition for series resonance—that the reactances of the circuit add up to zero—is fulfilled when

$$X_L - X_C = 0$$

or

$$X_L = X_C$$

or

$$\omega L - \frac{1}{C\omega} = 0$$

or

$$\omega L = \frac{1}{\omega C} \quad \text{or} \quad \omega^2 = \frac{1}{LC}$$

and since $\omega = 2\pi f$,

$$(2\pi f)^2 = \frac{1}{LC} = 4\pi^2 f^2$$

$$f^2 = \frac{1}{4\pi^2 LC}$$

and so we arrive at the familiar expression for the **resonant frequency** of a circuit as

$$f = \frac{1}{2\pi\sqrt{LC}}$$

in which f = the frequency in cycles;
L = the inductance in henries;
C = the capacity in farads;
π = the Greek letter pi and is equal to $3.1416\cdots$.

Example 2-7. To what frequency will a circuit tune which has an inductance of 0.25 henry and capacity of 0.001 μf?

Let us write the above formula as

$$f^2 = \frac{1}{4\pi^2 LC} = \frac{1}{39.5\ LC}$$

$$f^2 = \frac{1}{39.5 \times 0.25 \times 0.001 \times 10^{-6}}$$

$$= \frac{10^9}{39.5 \times 0.25} = \frac{10^9}{9.87}$$

$$= \frac{10^3 \times 10^6}{9.87} = 101 \times 10^6$$

$$f = \sqrt{101} \times \sqrt{10^6}$$

$$= 10.1 \times 10^3 \text{ cycles}$$

$$= 10.1 \text{ kc}$$

Such an expression for the resonant frequency of a circuit shows that the frequency depends upon the product of L and C, and not upon either of them alone. If L is doubled, C can be halved and the resonant frequency of the circuit will not be changed.

118. Wavelength. The relation between frequency and **wavelength** is a simple one. The wavelength is equal to the speed at which the electric waves travel divided by the frequency in cycles. This speed is 300×10^6 meters a second and if we want the wavelength in meters we need only divide this quantity by the frequency.

$$\text{Wavelength} = \frac{\text{velocity of light}}{\text{frequency}}$$

$$\text{Wavelength in meters} = \frac{300 \times 10^6}{f \text{ in cycles}} \quad \text{or} \quad \frac{300 \times 10^3}{f \text{ in kilocycles}}$$

or

$$= 300 \times 10^6 \times 2\pi\sqrt{LC}$$

The customary symbol for wavelength in meters is the Greek letter lambda; so the above expression may be written:

$$\lambda = \frac{300 \times 10^3}{\text{kilocycles}} = 1.884\sqrt{LC}$$

where L = microhenry = 10^{-6} henry
L = micromicrofarad = 10^{-12} farad

Example 3–7. What wavelength corresponds to 1000 kc?

$$\lambda \text{ meters} = \frac{300 \times 10^3}{1000}$$

$$= \frac{3 \times 10^5}{10^3} = 300$$

Figure 94 is a graphical method of correlating L, C, and meters of wavelength. A table of LC products will be found inside of rear cover.

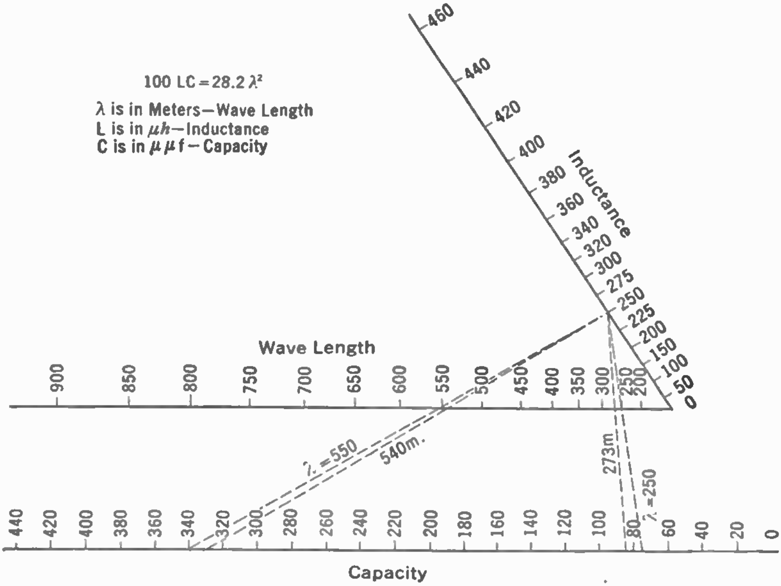


FIG. 94. Drawing a straight line through two points (L and λ, for example) and intersecting the third line give the unknown quantity desired (C).

Problem 3–7. What inductance must be placed in series with a 2-μf condenser to resonate at 60 cycles? If the voltage across the combination is 110 (effective) and the resistances in the coil and condenser add up to 200 ohms, what power is consumed in the circuit at resonance, what is the resonant current, and what voltage then appears across condenser and inductance?

Problem 4–7. A coil of 0.15 henry is in series with a condenser of 28.5 μf and a resistance of 5.8 ohms. The voltage across the circuit is 22 volts, the frequency is the resonant frequency of 80 cycles. What would the voltage across the condenser be if the resistance were doubled? What power would be wasted in heat at resonance?

Problem 5–7. A variable condenser has a range from maximum to minimum capacity of 9 to 1, that is, from 0.0005 to 0.0000555 μf. What frequency range will it cover with a given coil, that is, what is the ratio between the highest and lowest frequency to which it will tune the coil?

Problem 6–7. What happens to the voltage across the condenser of a series-resonant circuit if the capacity is reduced to half, resonance being maintained by other means which also keep the original current?

Problem 7–7. An antenna may be represented by an inductance of 50 μh in series with 0.00025-μf capacity and 30 ohms resistance. What is its resonant frequency? If a distant station transmitting on this frequency produces a voltage of 1000 μv across the ends of this antenna system, what current will flow? It can be seen that even fairly high voltages at the antenna (1 mv) produce only small currents.

Problem 8–7. Taking typical values of L, C, and wavelength, construct a chart like that in Fig. 94 for wavelengths shorter than 200 meters. As an example relabel the wavelength curve for values of L and C one-tenth those now on the chart. Since the factor of 10 is taken from each member of the product of LC, the value of LC will be decreased by a factor of 100. Therefore the wavelength line will be reduced by a factor of 10, because wavelength is a function of the square root of LC. This will leave a gap from 90 to 200 meters. Remake the chart to cover this band.

Problem 9–7. What can be done to increase the current at 150 meters in the antenna of Problem 7–7? At resonance, what voltage will appear across the 50-μh inductance, if the voltage across the antenna is 1 mv?

Problem 10–7. What power is being lost in this antenna at resonance?

Problem 11–7. The primary of an audio-frequency transformer has 100 henries inductance. In many circuits a condenser is placed across the primary so that high radio frequencies will not have to pass through the transformer. If this condenser has a capacity of 0.001 μf, what is the decrease in effective impedance of the circuit to a frequency of 10,000 cycles?

Problem 12–7. A loud speaker may be coupled to a power tube through a condenser as in Fig. 95. If the speaker has an inductance of 1 henry and the condenser is a 4-μf unit, to what frequency will the combination become resonant?

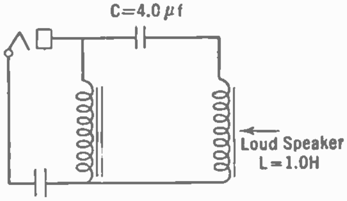


FIG. 95. To what frequency will the loud speaker and condenser tune?

Problem 13–7. Plot a curve of the reactance of the loud speaker in Problem 12–7 from 100 to 10,000 cycles.

Problem 14–7. In an amateur's short-wave transmitting station a 100-$\mu\mu$f condenser is in series with the antenna. What voltage has this condenser across it, if the frequency is 7100 kc and the antenna current is 1 amp?

Problem 15–7. In another transmitter an amplifier is used to raise the voltage coming from a 7500-kc oscillator. In the input circuit of the amplifier is an inductance of 4.5 μh. 80 volts are to appear across it. How much current must flow through this inductance? What capacity must be across it if it is to tune to 7500 kc?

119. Parallel resonance. Many of the circuits used in radio involve resonance in a branched or parallel circuit. Figure 96 shows a typical parallel circuit composed of an inductance shunted by a condenser, the combination forming what is sometimes called an anti-resonant circuit. The effects of varying the frequency of the voltage across the circuit are widely different from the effects in a series circuit. In the latter, the currents become very large at resonance and the resultant series impedance of the circuit becomes small. In the parallel connection the circuit at resonance offers a large impedance and the current from the generator becomes very small. In the series connection the same current flows through the condenser and the coil. The voltages across these units differ. In the parallel connection the same voltage is across each branch, but the currents through them differ.

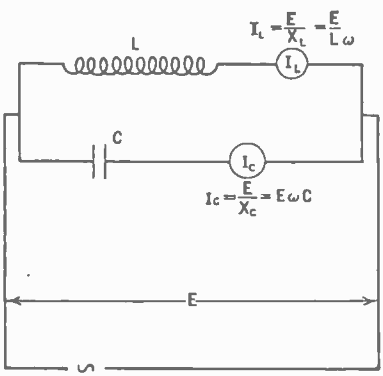


FIG. 96. An anti-resonant circuit.

Experiment 3–7. Connect as in Fig. 96 the coil and condenser used in Experiment 1–7. If sufficient meters are available read the alternating current in the two branches as well as the current from the generator as the frequency of the generator is changed. Then fix the generator frequency and adjust the condenser capacity until maximum response occurs. Plot the currents against frequency and against condenser capacity. The generator in this experiment may be a small oscillating tube. A 5-watt output is sufficient to produce currents in the branches of the circuit of 100 ma which can be read with a Weston Model 425 thermo-galvanometer.

If laboratory apparatus is not available, the current may be calculated after L, C, and E values have been chosen.

The same voltage exists across the branches and the circuit as a whole. The current taken by each branch is the ratio between the voltage and the reactance of that branch. Thus,

$$I_L = \frac{E}{X_L} = \frac{E}{L\omega}$$

$$I_C = E/X_C = EC\omega$$

$$I = I_L - I_C = E\left(\frac{1}{L\omega} - C\omega\right) = E\left(\frac{1 - CL\omega^2}{L\omega}\right)$$

As the frequency is increased, more and more current is taken by the capacity branch, less and less by the inductance branch. In the series case the voltages across coil and condenser are out of phase; their algebraic sum at any frequency combined vectorially with the IR drop is the voltage across the combination. In the parallel case the currents are out of phase; at any frequency their algebraic sum combined vectorially with the shunt resistance current (if any) gives the current taken from the generator. In the simple case where the resistance is neglected, the algebraic sum of the currents gives the generator current. Since these two currents are out of phase (the capacity current has a negative sign), adding them algebraically actually means subtracting I_C from I_L.

At resonance the currents taken by the two branches are equal and if there is no resistance in the circuit the current taken from the generator is zero, because it is the difference of the two branch currents which is read in the generator circuit ammeter.

The impedance of the circuit as a whole, that is, the impedance into which the generator must feed current, is the ratio between the voltage and current:

$$Z = E/I$$

Therefore, if no current flows, the circuit has infinite impedance. Actually there is always some resistance in the circuit. This may be in an additional shunt path, or resistance may exist in one or both of the other branches. Actually, then, the generator current does not fall to zero but passes through a minimum value. In most radio circuits by far the greater part of the resistance which is in the circuit resides in the coil since the resistance of the average well-constructed condenser used at radio frequencies is very small. The current taken by the circuit is not exactly in phase with the generator voltage, and so minimum-current resonance differs slightly from zero-reactance resonance.

The actual resistance of a resonant circuit is made up of two items: first, the ohmic resistance of the coil, condenser, and leads at the frequency to which it is tuned and secondly, any resistance which may be "reflected" into the circuit. That is, suppose the tuned circuit is coupled to another circuit, perhaps an antenna. This circuit takes power from the resonant circuit and this power must come from the resonant circuit. Suppose 5 watts is being fed into the resonant circuit at a current of 1 amp. Now if the circuit is coupled to the antenna, for example, and if 5 watts is taken by the antenna, the resonant circuit will act as though its resistance had been doubled, since twice as much power is now flowing into it as before. The coupling circuit acts as a transformer, across the secondary side of which is the antenna load and across the primary side of which appears the resonant circuit now acting as a source of power.

The current at resonance is

$$I_r = \frac{ER}{R^2 + \omega^2 L^2}$$

and the impedance presented to the generator is

$$Z = \frac{E}{I_r} = \frac{R^2 + \omega L^2}{R}$$

where R is the total resistance of the resonant circuit. This is the coil resistance unless more resistance is reflected into the circuit as discussed above.

There are several ways to tune the parallel circuit to resonance; that is, by adjusting the frequency, by adjusting the capacitance, by adjusting the inductance. Ordinarily the condenser is adjusted so that maximum impedance is attained, but the circuit can be adjusted by any of the variables so that unity power factor is attained. The differences in the several methods to attain resonance are not very great and may be neglected in practice.

If the condenser is adjusted for maximum impedance (minimum current taken from the source by the tuned circuit) the value of C for this condition is given by

$$C_{\text{for max } Z} = \frac{L}{R^2 + L^2\omega^2}$$

and under this condition the impedance is

$$Z = \frac{R^2 + L^2\omega^2}{R} = R(1 + Q^2)$$

Since under ordinary circuit conditions the square of the resistance is small compared with the square of the inductive reactance, the above expression for the impedance becomes

$$Z = \frac{L^2\omega^2}{R} = \frac{L}{CR}$$

When the circuit is tuned to resonance by varying the capacity, the current into the circuit is equal to

$$I = \frac{E}{Z} = \frac{E}{\left(\dfrac{L^2\omega^2}{R}\right)} = \frac{ER}{L^2\omega^2} = \frac{E}{QL\omega}$$

120. Effective resistance. The expression given above for the impedance of the parallel-tuned circuit (anti-resonant circuit) is also the effective resistance of the circuit since the impedance is almost entirely made up of resistance. This is true since the circuit is so tuned that the capacitive and inductive reactances are equal in numerical value but of opposite algebraic sign.

If the power fed into such a circuit is measured, it will be found to differ very little from the power fed into a pure resistance equal in value to

$$\frac{L^2\omega^2}{R} = L\omega Q = \frac{Q}{C\omega}$$

121. Resonant frequency. The condition for resonance under practical conditions is

$$\omega L = \frac{1}{C\omega}$$

or

$$f = \frac{1}{2\pi\sqrt{LC}}$$

The condition for resonance then is that the inductive and capacitive reactances are equal but opposite in sign—which is the same condition that holds for series resonance. Here, however, there are other conditions. The resistance must reside in the coil and must be small compared to the reactance of the coil.

For example, in the circuit in Fig. 96:

$$L = 200\mu\text{h}$$

$$\omega = 2\pi \times 356{,}000$$

$$R = 10 \text{ ohms (in the coil)}$$

$$X_L = L\omega = 200 \times 10^{-6} \times 2\pi \times 356{,}000$$

$$= 447 \text{ ohms}$$

Here we may neglect the effect of resistance and use the simple relation for resonant current and for impedance.

If

$$E = 10$$

$$I = \frac{ER}{\omega^2L^2} = \frac{ER}{(X_L)^2}$$

$$= \frac{10 \times 10}{447^2}$$

$$= 0.5 \times 10^{-3} \text{ amp} = \tfrac{1}{2} \text{ ma}$$

and

$$Z = \frac{\omega^2 L^2}{R} = \frac{447^2}{10} = 20{,}000 \text{ ohms}$$

At lower frequencies than resonance most current goes through the inductance because its reactance is low whereas that of the condenser is high. As the reactance of the condenser decreases with increasing frequency, and that of the inductance increases, and since the generator current is the actual difference between these currents, the generator current decreases as resonance is approached. At low frequencies the circuit is said to be inductive and at high frequencies is capacitive.

At resonance, the impedance or effective resistance presented to the generator is equal to Q times the reactance of either branch. The current taken from the generator is a minimum and equal to $E/\omega LQ$, and the current circulating in the tuned circuit is Q times the current taken from the generator.

122. Uses of series and parallel resonant circuits. Whenever it is desired to secure a large current and a low-impedance circuit, series resonance is utilized. When it is desired to build up a high impedance or a high-voltage circuit an anti-resonant circuit is used. Let us consider the antenna-ground system in Fig. 97. The antenna has in series with it an inductance across which a voltage is to be developed at a desired frequency. In series with this inductance are a capacity for tuning purposes and an anti-resonant circuit. Voltages of various frequencies, among them the desired frequency, are impressed on the antenna by distant transmitting stations. The maximum voltage is desired

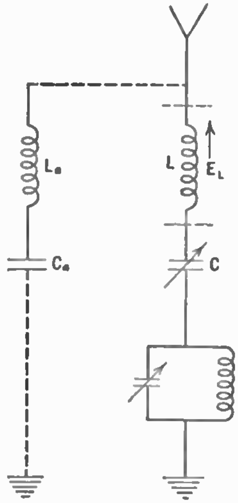


FIG. 97. The anti-resonant circuit in series with the antenna rejects undesired signals by making the series impedance to them very high.

across the inductance, L, at the desired frequency and the minimum at other frequencies. If there is an especially strong signal which is setting up a voltage across the antenna, then the anti-resonant circuit can be tuned to this interfering frequency when it will act as a rejector circuit.

The condenser, C, is adjusted until the antenna system as a whole is resonant to the desired signal. A large current flows through the series system, building up a large voltage across L. Voltages of other frequencies cause small currents to flow in the

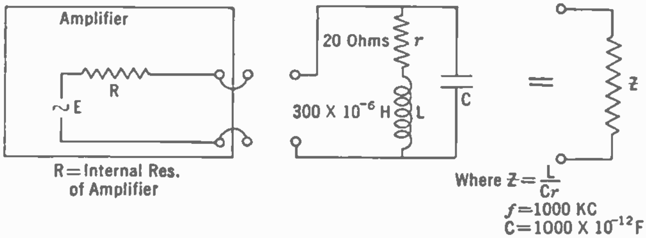


FIG. 98. A high impedance is desired for the amplifier to work into. A tuned circuit does the trick. Numerically it is equal to Z.

antenna system and consequently small voltages at these frequencies are built up across the coupling coil, L. The anti-resonant circuit being tuned to the unwanted signal makes the antenna system as a whole have a very high impedance at this frequency and so very small currents will flow through it, building up small voltages of this frequency across the coupling coil.

Such an anti-resonant circuit is often called a **rejector** circuit because it rejects signals of the frequency to which it is tuned. The series resonant circuit is called an **acceptor** because it accepts signals of the resonant frequency. The rejector used in this circuit is commonly known as a wave trap because it traps out unwanted signals.

Let us suppose signals are fed into the input of an amplifier which has an internal resistance, R, which is in series with an output circuit, as shown in Fig. 98. The voltage across this output, Z, is to be made as high as possible. The amplifier has available a certain voltage, E, which must be divided between the internal resistance of the amplifier and the output load. The proportion of the voltage that appears across this load increases as its ohmic impedance increases with respect to the amplifier's resistance. Thus, if the output impedance is equal to the internal resistance of the amplifier, one-half of the total voltage available will appear across it. If it is higher than this value, a greater proportion of voltage will be usefully applied across the load and less used up in the resistance.

In this case the anti-resonant circuit is used. At resonance its impedance becomes equal to $\frac{L}{CR}$ or

$$\frac{L^2\omega^2}{R} = \frac{(300 \times 10^{-6})^2 \times (6.28 \times 1000 \times 1000)^2}{20}$$
$$= 180{,}000 \text{ ohms}$$

If the amplifier's internal resistance is equal to 20,000 ohms, the voltage across the tuned circuit is 180/200 or 9/10 of the total available voltage. This is because the total voltage is divided between two resistances which add up to 200,000 ohms. The voltage across the 180,000-ohm tuned circuit is the useful voltage which is equal to 180,000/200,000 of the total voltage.

Problem 16-7. A screen-grid tube gives the greatest voltage amplification when worked into a very high impedance. A condenser of 1500 $\mu\mu$f is available. Calculating the size of the inductance required to tune to 30 kc and assuming it has a resistance of 30 ohms, what is the impedance ($L^2\omega^2/R$) that can be presented to the tube by shunting the coil and condenser?

Problem 17-7. A wave trap is to be put into an antenna and tuned to a station whose frequency is 750 kc. Convenient sizes of condenser and coil to use are 100 μh and 450 $\mu\mu$f. They are to be shunted across each other and the combination put in series with the antenna. If the coil has a resistance of 10 ohms and the condenser a resistance of 1.0 ohm at this frequency, what impedance will the trap offer to the offending signal?

Problem 18-7. In Problem 17-7, neglecting phase differences between the trap and the rest of the antenna, if the total impedance of the antenna to the offending signal is double that of the trap alone so that one-half of the total antenna voltage is across the trap, what current will flow through the condenser if the total 750-kc voltage across the system is 10 μv?

123. Sharpness of resonance. The effect of resistance is to reduce the maximum current flowing in a series resonant circuit, and to make less pronounced the minimum of current flowing into a parallel resonant circuit from an external source.

Since the maximum current is desired in a series circuit, and the maximum impedance in a parallel case, the inclusion of resistance in either is deleterious.

Let us consider the antenna illustrated in Fig. 97. Suppose that its inductance, L, is 200 μh and C at resonance (356 kc) is 1000 $\mu\mu$f. For the moment we shall neglect the presence of the wave trap. Assume a voltage of 10 volts. What is the effect on the resonance curve of this antenna system if it has a resistance of 10 ohms or of 40 ohms? The current at resonance in the 10-ohm case is 1 amp whereas at 370 kc the current is 0.274 amp, a ratio of 3.65. In this 40-ohm case, the resonant current would be only 0.25 amp—one-fourth of its value with the lower resistance—and the current at 370 kc, i.e., 14 kc off resonance, would be 0.188 amp. This is a current ratio between the resonant and the off-resonant current of only 1.33.

In other words, if the antenna had impressed on it from equally distant and equally powerful radio stations two voltages, one of 356 kc—the desired frequency—and one of 370 kc—the unwanted frequency—3.65 times as much current flows at the desired frequency as the unwanted. In the 40-ohm antenna, however, not only is the desired current cut to one-quarter of its other value but the ratio of wanted to unwanted current has been decreased to 1.33. The low-resistance antenna is said to be more selective and its selectivity is decreased when resistance is added to it.

124. Selectivity. The **selectivity** of a circuit is a measure of its ability to distinguish between wanted and unwanted signals. The steepness of the resonance curve is a direct measure of this selectivity.

Let us consider the parallel or anti-resonant circuit. At its resonant frequency it keeps currents of undesired frequency from flowing through the antenna because of its high impedance at those currents. This impedance, $L^2\omega^2/r$, increases as the resistance of the circuit decreases, so it behooves the designer to use low-resistance coils and condensers when building a trap or rejector circuit.

Since a circuit may be tuned to resonance by varying any one of three variable factors, the inductance, capacity, or frequency, we may express the sharpness of resonance in any one of three ways. It may be the fractional change in current for a given fractional change in either L or C. Naturally the sharper the resonance curve and the greater its height, the greater will be the current change for a small number of degrees of change in the tuning condenser. The circuit will tune "sharply"; it is called a sharp circuit. In practice the condenser is used as the tuning variable. If, then, the current at resonance I_r and the tuning capacity C_r are noted and then changed to give some other value of current, the sharpness of resonance may be found by substituting values in the following expression,

$$S_{res} = \frac{\sqrt{\dfrac{I_r^2 - I^2}{I^2}}}{\dfrac{C_r - C}{C}}$$

By some mathematical juggling of this cumbersome expression (see *Bulletin* 74, Bureau of Standards) a much simpler expression may be obtained. This has two forms,

$$\text{Sharpness of resonance } \alpha = \frac{1}{R\omega C_r} = \frac{L\omega}{R} = Q$$

where R = the resistance of the circuit;
C_r = the capacity at resonance;
L = the inductance of the circuit.

In other words, the sharpness of resonance is proportional to the ratio between the capacitive or inductive reactance to the resistance, and thus the resonance curve rises more abruptly the less resistance there is in the circuit.

Another expression for the sharpness of resonance is obtained by varying the frequency and noting how the current changes.

Thus an expression is worked out which shows the width of the resonance curve where the current is equal to $0.707 \times I_r$, where I_r is the resonant current.

Suppose, as in Fig. 99, we plot a resonance curve of current against capacity. Suppose the capacity is adjusted until the

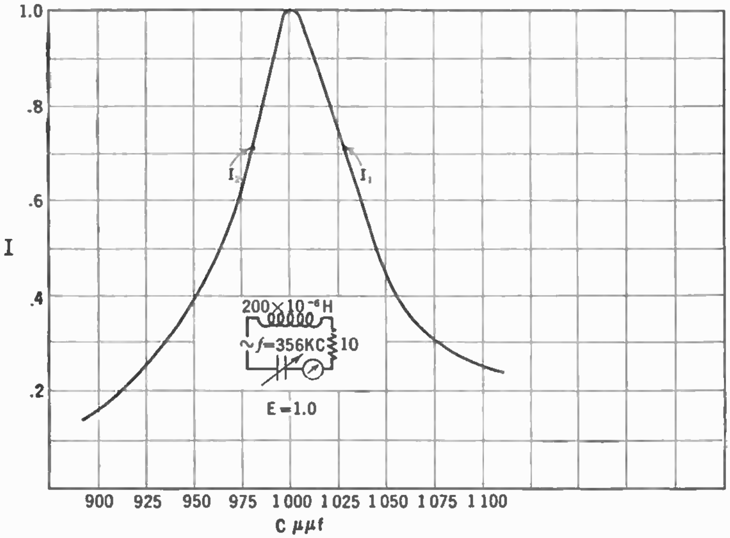


FIG. 99. If I_1 and I_2 are equal to 0.707 times the resonant or maximum current, the resistance of the circuit may be calculated.

total reactance in the circuit $(X_L - X_C)$ is equal to the resistance in the circuit, that is,

$$(X_L - X_C) = R$$

when

$$I = \frac{E}{\sqrt{R^2 + X^2}}$$

becomes equal to

$$\frac{E}{\sqrt{2R^2}}$$

and

$$I = 0.707\ I_r$$

where

$$I_r = \text{current at resonance}$$

and if

$$C_2C_1 = C_r^2$$

then

$$\frac{L\omega}{R} = \frac{2C_r}{C_2 - C_1}$$

in which C_r = the capacity at resonance;
C_1 and C_2 = the two values of capacity which makes $I = 0.707\ I_r$.

125. Width of resonance curve. If, however, the frequency of the impressed voltage is so adjusted that two currents are reached, above and below the resonant frequency f_r, which are equal to 0.707 I_r,

$$\frac{L\omega}{R} = \frac{f_r}{f_2 - f_1} = Q$$

whence the width of the frequency band

$$f_2 - f_1 = \frac{R f_r}{L\omega} = \frac{R}{2\pi L} = \frac{f_r}{Q}$$

Example 4-7. What will be the width in cycles of the resonance curve at a point where $I = 0.707\ I_r$ when $L = 200\ \mu\text{h}$, $R = 10$ ohms, $f = 356{,}000$ cycles?

$$f_2 - f_1 = \frac{10 \times 356{,}000}{447} = \frac{R \times f_r}{L\omega}$$

$$= 8000 \text{ cycles}$$

and if

$$\frac{L\omega}{R} = \frac{2C_r}{C_2 - C_1}$$

$$C_2 - C_1 = \frac{2C_r \times R}{L\omega}$$

$$= \frac{2000 \times 10}{447}$$

$$= 44.7\ \mu\mu f$$

This equals the change in capacity required to change the current from $I = 0.707\ I_r$ below resonance, to $I = 0.707\ I_r$ above resonance, or from I_1 to I_2 in Fig. 99.

Problem 19-7. In Fig. 99, suppose the resistance is 20 ohms instead of 10. Calculate the width of the band at the point where the current is 0.7 of its maximum value, and the change in capacity required to produce this change in current.

Problem 20-7. A certain coil-condenser combination has a resistance of 16 ohms at 400 meters. The inductance is 170 μh. What is the width of band passed at the point where the current is equal to 0.7 of its maximum value? What is the Q of this circuit?

Problem 21-7. A circuit is to pass only 0.707 of its maximum current at a point 2.0 kc off resonance, which occurs at 500 kc. The condenser to be used has a capacity of 0.0006 μf. Calculate the maximum resistance the circuit can have.

Problem 22-7. Suppose that increasing the size of an inductance by a factor of 2.0 increases the resistance in a circuit by a factor of 1.5. The circuit is to tune to the same wavelength. What has happened to the selectivity of the circuit?

Problem 23-7. If the expression $L\omega/r$ of a coil remains constant over a fairly wide band of frequencies, does the selectivity of a tuned circuit differ at different frequencies? Does the width of band passed differ at 1500 kc from what it is at 500 kc?

126. Effect of inductance and capacity on sharpness of resonance. Since the sharpness of resonance expression, $L\omega/R$ and $1/\omega CR$ both show that the inclusion of resistance tends to cut down the selectivity of the circuit in which the resistance exists, it behooves the experimenter and engineer to keep the resistance of his circuits at a minimum—when selectivity is his goal. What effect has changing the ratio of inductance to capacity, the product of $L \times C$ remaining constant?

Let us consider the ratio of inductive reactance to resistance, $L\omega/R$. If we can increase L without increasing R we shall increase the sharpness of resonance. Now considering the ratio of capacitive reactance to resistance, $1/C\omega R$, increasing C has the same effect as increasing the resistance—the sharpness of resonance is decreased, the selectivity of the circuit goes down.

In a series circuit, then, the selectivity increases as the ratio L/C increases. Some theoretical curves showing this effect are plotted in Fig. 100 showing that for selective circuits a large inductance and small condenser should be used. (R equals 10 ohms.)

The ratio of L to C occurs in many formulas dealing with the resonant circuit. For example, consider a long line with uniformly distributed capacity and inductance. The impedance of this line will be $\sqrt{L/C}$ ohms. Suppose that a tuned circuit is coupled to an antenna. The antenna resistance is a certain value; the tube resistance is a certain value. Maximum power

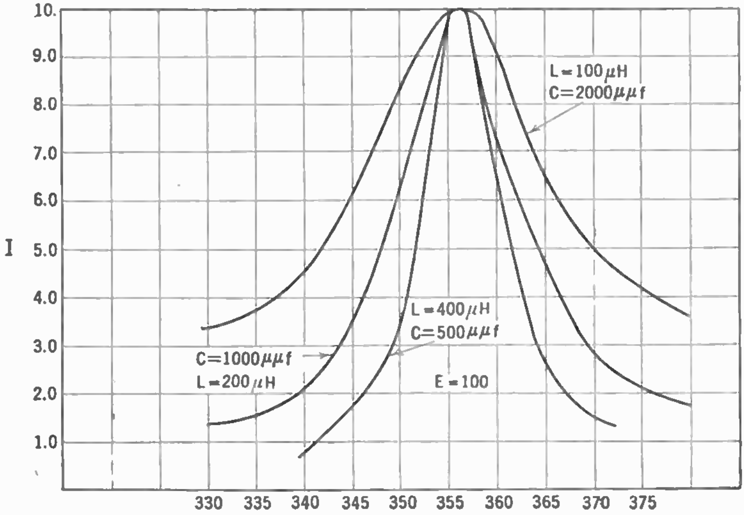


FIG. 100. Effect on sharpness of resonance of varying ratio of L to C.

will be transferred from the tube to the antenna via the tuned circuit when the antenna and tube resistances are equal. This may be accomplished by varying the ratio of L to C in the tuned circuit. This is why amateurs and others have found that the L/C ratio is important. There are other radio circuits in which this ratio of L to C occurs. The frequency to which the circuit tunes may be held constant (LC constant) although the ratio of L to C may be changed. When the L/C ratio is varied the effective resistance of a tuned circuit ($L^2\omega^2/R$) varies and thus the load presented to the amplifier tube may be adjusted by varying the ratio of L to C.

127. The resistance of coils. The curves in Fig. 100 were plotted on the assumption that the resistance of the coil did not increase as the inductance was changed. Unfortunately this cannot be carried out in practice unless very large and unwieldy coils are made. This means, simply, that a coil has a resistance to alternating current different from that which it has to direct current. For example, a very good coil used at broadcast frequency may have a resistance as low as 10 ohms at some medium broadcast frequency, but so little wire is used in making this coil that the d-c resistance will be perhaps a fraction of an ohm. Even straight wires have different a-c and d-c resistances.

Straight wires, however, have the least difference in resistance between high frequency and direct current. In laboratory work where small accurately known resistances are desired to be used at high frequencies, short lengths of high-resistance wire are employed. For example, manganin or one of the other high-resistance alloys may be cut into the proper lengths, soldered to copper lead wires and used as standards of resistance where a decade box could not be utilized at all.

Even with such wires it is often difficult to separate the reactance and resistance effects; if the lead-in wires are close together and of large size, appreciable capacity reactance may be added at high frequencies; if the lead wires are long, inductive reactance will be added.

128. High-frequency resistance. In all a-c problems the resistance that is considered is the resistance at the frequency under consideration. Thus at broadcast frequencies 550 to 1600 kc, a coil will have a certain a-c resistance; at 60 cycles its resistance will be different, and to direct currents its resistance may be still another figure.

A wire stretched out straight will have one resistance to d-c and another to a high-frequency current. Therefore the fact that the wire is coiled up in an inductance is not the cause of the additional resistance. The difference arises from the fact that the current in a conductor at high frequencies is not evenly distributed throughout the cross section of that conductor. Because of the rapid change of direction of flow and because the current within the cross section of a conductor changes rapidly, small emf's are generated in that cross section, and therefore all along the wire. These voltages are in such a direction, according to Lenz's law (Section 55), that of the total current flowing, more is along the surface of the wire and less along the inner parts of

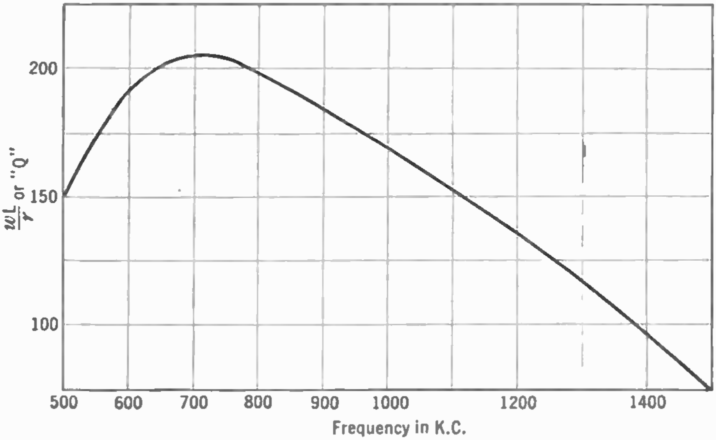


Fig. 101. How the $Q(L\omega/r)$ of a coil varies with frequency. Note that r is the coil resistance at the frequency to which it is tuned.

the wire. The result is a decrease in effective area of conductor and a consequent rise in resistance.

A table is given in *Circular* 74 (Bureau of Standards) showing the effect of diameter of wire, frequency, resistance, etc., upon this phenomenon known as **skin effect.** For our purposes it is sufficient to know that the resistance of a coil to high-frequency current is always greater than its resistance to a direct current.

The resistance of a coil over the range of frequencies at which it is used changes somewhat, increasing with increase in frequency.

The manner in which the expression $L\omega/R(Q)$ of a coil varies over the frequency range is plotted in Fig. 101. Knowing this factor for the coil in a series or shunt circuit we can calculate the width of the frequency band at a point where the current is

0.707 of its resonant value, we can plot a resonance curve, and we can calculate the equivalent impedance of the circuit at resonance to a generator which must feed current into it.

Let us, however, measure the resistance of the coil at higher and higher frequencies. What happens? Figure 102 shows that at higher frequencies the coil resistance becomes very high and

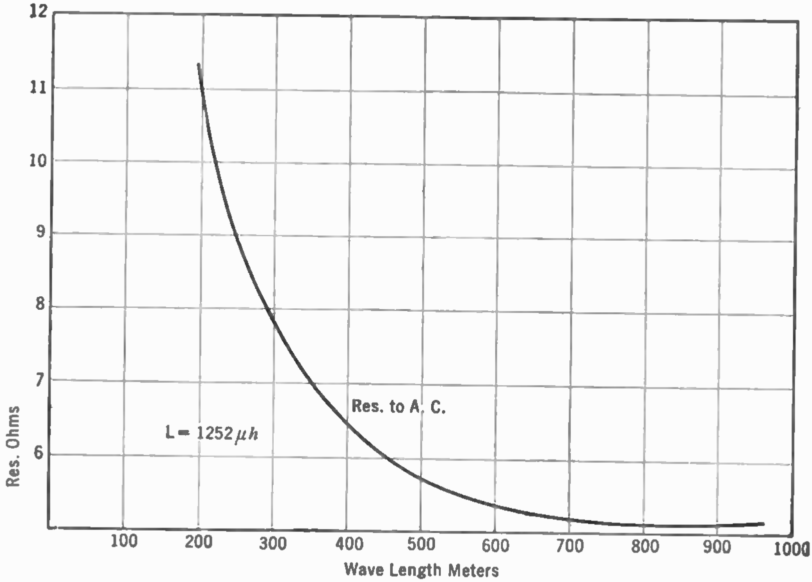


Fig. 102. High-frequency resistance of a coil.

finally the curve rises perpendicularly, indicating that at some nearby point the resistance is infinite. What is happening?

Problem 24-7. In the example cited in Sec. 121, what is the Q of the circuit?

Problem 25-7. A coil with a Q of 100, an inductance of 18 μh and a coil of 30 $\mu\mu$f are in series. To what frequency does the circuit resonate, what is the resonant impedance, and what is the resistance of the coil? How wide is the resonance curve at the points where the current is 0.707 of the maximum current?

Problem 26-7. At 1 Mc by how much must the frequency be changed to lower the resonant current to 0.707 of its value if the circuit Q is 200?

129. Distributed capacity of coils. Whenever two objects which conduct current are insulated from each other, they form a condenser. Electricity may be stored in it. Its capacity depends upon the proximity of the objects, the insulation between them, and their shape. In a coil of wire each turn is at a different potential from its neighbor, and is separated from it by the insulation of the wire. Thus every coil is not a pure inductance but may be thought of as a coil shunted by a capacity made up of the resultant capacity of a number of smaller capacities. At some frequency the coil shunted by its capacity becomes anti-resonant, and the circuit then becomes as shown in Fig. 103 where the tuning condenser is no longer in series with a coil but with a parallel-tuned circuit which at the resonant frequency has a very high impedance. The series impedance of the circuit, then, increases near the resonant frequency of the coil. Here its effective resistance becomes great.

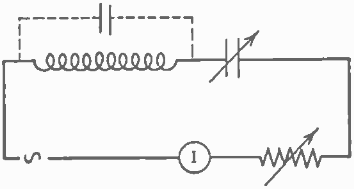


FIG. 103. When the dotted capacity across the coil tunes it to the frequency of the generator, the series impedance of the circuit becomes very high because it then acts as an anti-resonant circuit.

This capacity of the inductance is known as a **distributed capacity** since it is not concentrated in any one place or form but is more or less evenly distributed along the whole length of the inductance. Its effect is to lower the effective inductance of the coil and to increase its resistance somewhat. The capacity and inductance of a coil do not change much with frequency, but the apparent inductance of this anti-resonant circuit does change with frequency. It is equal to

$$L_a = \frac{L}{1 - \omega^2 C_o L}$$

in which C_o = the capacity of the coil;
L_a = its apparent inductance;
L = its true or low-frequency inductance;
$\omega = 6.28 \times f$.

Various attempts have been made to calculate the capacity of coils. It has been found by experiment that the radius of the coil and its shape control the distributed capacity to a large extent. Thus a coil of average proportions, i.e., the length about equal to the diameter, has a capacity of approximately $0.6R$ $\mu\mu$f where R is the radius of the coil in centimeters. As a rough rule it has been stated that the capacity in micromicrofarads is always less than the radius in centimeters in a solenoid of a single layer. Another experiment showed that the natural wavelength of solenoids was about 2.54 times the total length of wire on the coil.

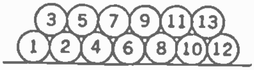


FIG. 104. Bank winding.

To obtain large inductance in reasonably small space it has become customary to make multilayer coils of peculiar types of winding called bank winding and universal winding.

Air cores have a permeability of unity; if coils could be wound on a core of higher permeability, the inductance per length of wire and per unit of space would increase. Permalloy is a kind of iron alloy dust on which coils may be wound with increased inductance at the medium frequencies. At higher frequencies one may use cores made up of finely powdered iron bound together with some sort of very fine binder. The permeability of this material may be as high as 12. With a given length of wire, therefore, of a given high-frequency resistance a greater inductance may be wound. The Q of such a coil will be higher because the ratio of inductance to resistance will be higher.

C. J. Franks has measured Q's of the following values: 456 kc litz wound universal coil, 80; same coil with powdered iron core, 145; transmitter coil for 5000 kc, 650; gang condenser, ceramic insulation, 1000 kc, 3000.

CHAPTER VIII

PROPERTIES OF COILS AND CONDENSERS

Coils and condensers form the nucleus of every radio circuit. Other apparatus is needed, of course, but for each of the other units needed there are several substitutes. There are no substitutes for coils and condensers. To understand what their role is in the reception of radio messages, either in code or voice or musical form, we must look at a simple receiving system.

130. Tuning a receiver. A simple receiving circuit consists of an antenna-ground system connected to a coil and a detector such as a crystal of galena, or silicon or other sensitive mineral which has the property of separating the audio tones from a radio wave. A pair of headphones may be put in series with the detector so that the audio tones which are filtered out of the radio wave by the detector may be made audible. A small condenser across the phones will pass the radio frequencies but not the audio frequencies which must go through the phones.

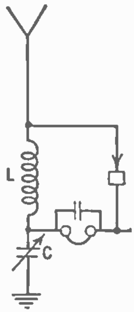


FIG. 105. A simple radio receiver.

One way to get louder signals is to tune the antenna-ground system to the frequency of the desired wave. This is done by varying C in Fig. 105. When the circuit is series resonant, a large current flows through the inductance. The voltage across it ($X_L \times I$) will be large and the response from the crystal will be greater.

The voltage across the inductance can be amplified and then impressed across the detector. This amplification may take place in several stages so that very weak signals may finally be heard with the strength of nearby strong signals which are detected directly from the antenna inductance. If desired, the signals may be amplified again after detection by means of audio-frequency amplifiers.

As we have already seen (Section 124), there is another advantage of tuning the antenna, the advantage of selectivity. Signals of low frequency find considerable impedance in the condenser of such a series-tuned antenna, signals of high frequency find impedance in the coil; signals of the desired or resonant frequency find a minimum of impedance, and so the filtering action of the tuned system is advantageous. If, in addition to the series-tuned circuit, we used an anti-resonant or parallel-tuned circuit as in Fig. 106, we impose more hardships upon unwanted signals. In this case when maximum current flows through L_1 maximum current is induced in L_2. If, then, C_2 is tuned so that L_2C_2 form an anti-resonant circuit, the impedance to the resonant frequency will be very high and any current through it will build up a large voltage across it so that the detector gets a high voltage at the desired frequency and a low one at all other frequencies—and the selectivity of the system as a whole is improved.

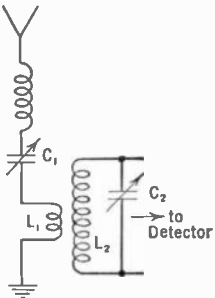


FIG. 106. Varying C_1 until the antenna system as a whole is series resonant increases voltage across L_1.

If, in addition, each radio-frequency amplifier stage is tuned to the desired signal, the selectivity of the entire receiver may become very great. In the present congestion of broadcast stations, the necessity for selectivity of a high degree is evident; as we shall see later it is a disadvantage.

131. The wavemeter. An instrument for measuring the wavelength or frequency of signals is called a **wavemeter** when calibrated in meters or a **frequency meter** when calibrated in cycles, kilocycles, or megacycles. It consists of a coil and a condenser and some means of indicating when this simple circuit is tuned to resonance with a radio wave. The indicator may be a current meter, a lamp which lights up at maximum current through it, or a crystal detector and a d-c milliammeter. It may be connected directly into the circuit, or, preferably, coupled loosely to it.

The circuit of a simple and effective wavemeter is shown in Fig. 107. The indicating device is a crystal detector and a meter which indicates the rectified direct current. If it is coupled loosely to the tuned circuit the resistance of this indicator will not broaden the response curve of the wavemeter. The inductance is usually fixed and the capacity varied to obtain resonance, but to cover a wide band of frequencies it is frequently necessary to have several coils which fit into the wavemeter by means of plugs and jacks. If the coils are arranged so that the larger coils have exactly four times the inductance of the next smaller the wavelengths to which the larger coil will tune will be twice those of the next smaller coil.

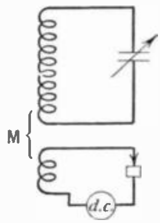


FIG. 107. A wavemeter in which the resistance of the indicator is removed from the tuned circuit and is coupled loosely to it.

A series of coils in which the same winding space is used but in which the number of turns in this space is doubled for each next larger coil will approximate very closely these conditions.

Sometimes the wavemeter is equipped with a buzzer so that it will send out a modulated wave. A receiver can be tuned to a desired frequency by starting the buzzer, tuning the wavemeter to the desired wavelength, or frequency, and adjusting the receiver until the buzzer tones are heard at maximum loudness.

132. Oscillating wavemeter. A most useful type of wavemeter uses an oscillating vacuum tube and a meter, usually connected in the grid circuit of the tube. The circuit diagram for such a meter is shown in Fig. 108. Tube 1 generates radio-frequency currents, which are modulated when desired by the low- or audio-frequency generator tube 2. The grid meter gives very sharp indications of resonance, and because the device is a small modulated source of radio-frequency energy it can be used to tune receivers to any desired frequency. It is a much more accurate instrument than the buzzer wavemeter. The data in Table I are those of an oscillator-wavemeter. The coils have dimensions as indicated. Similar coils may be wound by the reader.

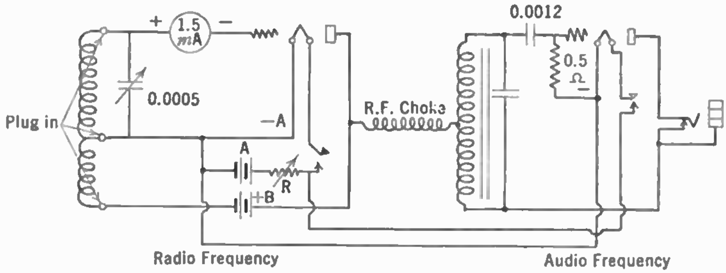


FIG. 108. Circuit diagram of a modulated oscillator useful as a wavemeter. The radio-frequency oscillator has a d-c meter in its grid circuit and employs a series of plug-in coils. The modulating oscillator may use an audio output transformer or other center-tapped inductance of the correct value. When the r-f oscillator is coupled to an external tuned circuit, a sharp dip in the grid current will occur when the two circuits are tuned to the same frequency.

TABLE I

Coil	λ	f	Kc per dial degree
15	45–120	2500–6660	31.6
30	80–210	1430–3750	23.3
60	165–400	750–1820	10.7
90	265–620	485–1130	6.5

Coil	Turns	Size Wire	Diameter	Length of Winding	L
A	15	21	$2\frac{11}{64}$	$1\frac{5}{8}$	0.014 mh
B	30	21	$2\frac{11}{64}$	$1\frac{1}{2}$	0.055 mh
C	60	21	$2\frac{11}{64}$	$1\frac{5}{8}$	0.217 mh
E	90	27	$2\frac{11}{64}$	$1\frac{3}{8}$	0.495 mh

133. Calibrating a wavemeter. A wavemeter, or frequency meter, to be most useful must be properly calibrated. This may be done in several ways. If the meter uses an oscillating tube all one needs is a source of known frequency and a receiver. The process is simple. Tune the receiver to a station whose frequency is known. Then turn on the oscillating tube wavemeter, and when a whistle is heard from the receiver, the known station, the receiver, and the wavemeter are all tuned to the same frequency. Next tune the receiver to another frequency and repeat the performance. A curve can then be plotted showing the calibration of the wavemeter.

The following description of how to calibrate a wavemeter over a wide range of frequencies by means of but a single accurately known frequency is an interesting experiment. It follows from the fact that an oscillating vacuum tube generates not only the frequency governed by the *LC* product of its circuit but also multiples (harmonics) of this frequency.

Experiment 1–8. To calibrate a wavemeter by harmonics. The necessary apparatus consists of:

(1) An oscillating wavemeter connected as in Fig. 108.

(2) An oscillating detector tube preferably followed by a stage of audio amplification.

Tune the oscillating detector to the frequency of some known station by listening in the headphones and bringing an antenna wire near the detector inductance. The condenser of the detector should be equipped with a vernier or worm gear so that very accurate settings are possible. Tune as nearly as possible to zero beat with the known station. As the tuning dial is adjusted near resonance with the known station, now acting as our frequency standard, a note will be heard in the phones which represents the difference in frequency between the known station and that of the detector tube. When this difference tone (or beat note) disappears, the two oscillations are at the same frequency. Since frequencies lower than about 100 cycles cannot be heard in the phones, it will not be possible to tune closer than this to the desired frequency. By estimating the two points at which the audible beat disappears and by finally setting the oscillating receiver detector at the mid-point between these two dial settings, a sufficiently accurate setting will be made.

We have now equipped ourselves with a local generator whose frequency is accurately known. For example, suppose it is 610 kc and that we are set to within 100 cycles of this frequency. We are within 100 parts in 610,000 of being exactly correct or one part in 6100, which is sufficiently accurate. It is much more accurate than the dial reading of the wavemeter we are to calibrate.

Now move away the antenna coupling and see if the beat note changes. If it does, again adjust for true zero beat. Then start up the oscillating-tube wavemeter and, after giving it a few minutes to warm up, tune its dial slowly until a whistle or beat note is heard in the headphones which are still plugged into the detector-amplifier. This means that the wavemeter is being tuned to the frequency of the oscillating tube.

If we use the broadcast band coil of the wavemeter we ought to get a very loud beat note when the two circuits are in near resonance and another loud note when the dial is tuned to the half wavelength, in this case 1220 kc. In between these points may be several other weaker beat notes.

TABLE II

Dial Degrees	Difference	Units Difference	f (approximate)	f (exact)
10.2*	....	...	1220	1220
34.0	23.8	2	1020	1016
47.0	13.0	1	920	915
60.0	13.0	1	820	813
85.0*	25.0	2	610	610

* Loudest beat notes.

Now turn the dial slowly and put down on paper each time a beat note is heard. For example, the table of such points may look like Table II, in which the loudest beat notes are marked with an asterisk. Then use another wavemeter coil and repeat, always marking down the loud notes.

Now prepare data like those in the next table, in which the numbers along the top are obtained by multiplying the detector frequency by whole numbers from 1 to 10, and the vertical numbers are obtained by dividing this frequency by whole numbers. Thus our fundamental frequency is 610 kc. Twice this is 1220 kc, one half is 305, etc.

Then make a list from this table of the frequencies that may be looked for from our calibration, namely, 610, 763, 813, 915 kc, etc.

What actually happens as we tune the wavemeter dial and hear beat notes? The oscillating detector and the wavemeter tubes are generating additional or harmonic frequencies as well as the fundamental to which they are set. These additional frequencies are much weaker than the fundamental. When we tune the wavemeter to 1220 kc it beats with the second harmonic of the detector and gives an audible note. But how are we to recognize the 1220 point? How do we know it is not the third or the fourth harmonic instead of the second?

Consider the data in Table II. We got loud notes at 10.2 and 85 degrees. We guess that these are the second harmonic and fundamental. We subtract the dial settings as in column 2. Then assuming that 13 degrees is a unit, we note that there are two units between the 10.2- and 34-degree beat notes. We see then that there are six units between 1220 and 610 kc. We guess again and say that each beat note represents about one-sixth of the difference between 1220 and 610 kc, or about 100 kc per unit. Looking in our list of expected frequencies we can pick out these frequencies exactly.

TABLE III

	1	2	3	4	5	6
1	610	1220	1830	2440	3050	3660
2	305	610	915	1220	1525	1830
3	202.5	406	610	813	1016	1220
4	152.5	305	457	610	763	
5						
6						

We might guess at these frequencies from the original assumption that the two loud notes were from the 1220 and the 610 kc frequencies and noting that between them—a difference of 610 kc—were 85 — 10.2 dial degrees or about 8 kc per degree.

When the smaller coils are to be used, care must be taken to see that no harmonics are missed. Fortunately, if the coils have the dimensions given in Table I, the harmonics will fall at almost the same points on the dial. Thus on the largest coil 610 kc is found at 85 degrees. On the next smaller coil the 1220 kc frequency will be found within a degree or two of 85 degrees. And so on until the entire set of coils is calibrated.

134. Standard frequencies. In this country standard frequency signals are sent out from a Bureau of Standards' station, WWV. These signals are on 5000 kc, modulated at 400 cycles and should be heard all over the United States. In addition there are many long-wave and intermediate-wave stations whose frequencies are kept within very close limits and which are on the air 24 hours of the day. The broadcasting stations themselves form good standards of frequency covering the band from 550 to 1600 kc, and above this are many short-wave stations whose signals may be heard the world over.

135. Calibrating by clicks. A method of calibration that is often used is the click method. When a tuned circuit is brought near the inductance of the oscillating wavemeter, a sharp dip of the grid-current needle will be noted as the two circuits are resonated to each other. If the same tuned circuit is brought near the inductance of an oscillating detector tube, a sharp click will be heard when the circuits are tuned to the same frequency, provided one listens in the plate circuit of this tube or behind a stage of audio amplification. This click is produced by a sharp change in grid current and a corresponding change in plate current.

Experiment 2-8. Calibration by clicks. This method requires an oscillating detector, a calibrated meter and the unknown meter to be calibrated.

Couple the calibrated meter to the inductance of the detector, and turn the dial until a sharp click is heard in the phones, indicating that the circuits are tuned alike. If the two inductances are closely coupled two clicks will be heard, one when the tube stops oscillating and one when it starts again. These two points may be several degrees apart. Loosen the coupling, and note that the two clicks approach each other. Keep on loosening it until a degree of coupling is reached when only a single resonance click is noticed. Note the dial setting of the standard meter. Now remove it from the tuned circuit and bring near the latter the wavemeter to be calibrated. Turn its condenser dial until a click is heard as before. Now the meter has the same frequency, or wavelength, as the standard. Other points for a calibration curve may be noted in the same manner.

This method really constitutes setting a generator or miniature transmitter (the oscillating detector) to a given frequency by means of the calibrated meter and then tuning the uncalibrated meter to resonance with this generator.

136. The properties of coils and condensers. We may investigate the properties of coils and condensers by performing the various parts of the following experiment.

Experiment 3-8. Wind up on a form about 3 in. in diameter, a coil of about 60 turns of rather large wire, preferably with silk or enameled insulation so the distributed capacity of the inductance will be rather large. Connect it across a condenser whose maximum capacity is about 500 $\mu\mu$f. Start at the maximum capacity of the condenser and measure the resonant frequency of the coil-condenser combination by clicking it into an oscillating receiver, or by coupling it to an oscillator. Then decrease the capacity and repeat until several readings are taken, say at 500, 400, 300, etc., $\mu\mu$f. Plot the result against C as shown in Fig. 109; that is (wavelength)^2 against capacity.

A straight line results because the formula

$$(\text{Wavelength})^2 = 3.54\, L \times C$$

where L is in μh and C in $\mu\mu$f

is the equation of a straight line and states that the wavelength squared is proportional to the capacity in the circuit. The slope of the line divided by 3.54 is the inductance of the coil, that is

$$L = \frac{1}{3.54} \times \frac{\lambda^2}{C}$$

It will be noticed that the straight line crosses the wavelength squared axis at some distance above the zero point. This gives us the natural wavelength squared of the coil itself and therefore the resonant wavelength to which the coil with no additional capacity will tune. The point where the line crosses the capacity axis gives us the distributed capacity of the coil. This value multiplied by the inductance as obtained above gives the LC product which when fitted into the proper formula gives the natural wavelength of the coil.

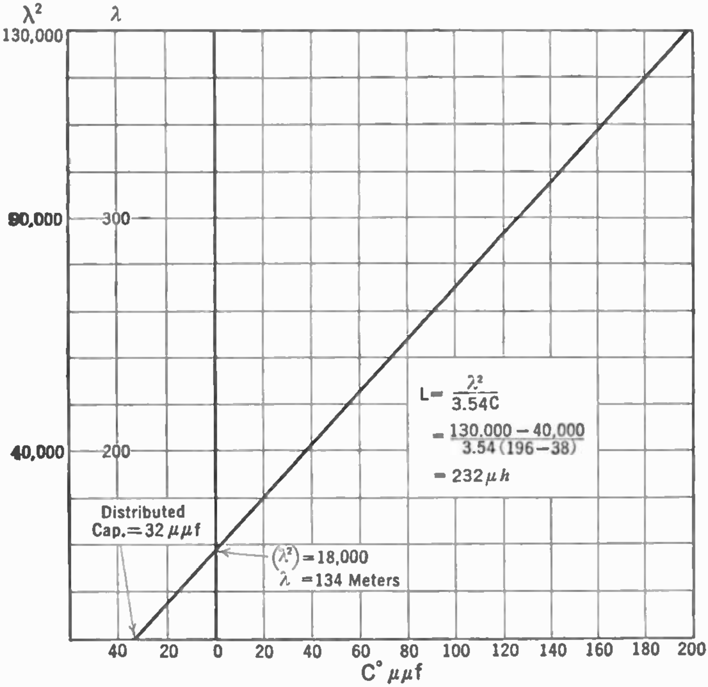


FIG. 109. A method of determining the distributed capacity of a coil.

Thus, in one experiment we can determine not only the frequency or wavelength to which a coil-condenser combination will tune, but we can determine the coil's inductance, its distributed capacity, and its natural wavelength.

As a check on these data (*a*) calculate the inductance from the formulas given in Fig. 51. (*b*) Disconnect the condenser from the coil and determine the natural frequency of the coil alone by means of an oscillating wavemeter.

137. Measurement of coil resistance. The effect of resistance upon the sharpness of resonance and the selectivity of the circuit has been mentioned (Section 115). The **resonance curve** gives us one method of measuring the resistance in a given circuit, provided we know the inductance of the coil—which can be calculated from the formula in Fig. 51.

Experiment 4-8. To determine the resistance of a coil. Couple a series circuit composed of a coil, condenser, and indicating meter to a generator of about 5-watts output. Adjust the frequency of the generator through resonance with the series circuit. If the generator has a constant output over this frequency range the accuracy with which the coil resistance is determined will be greater. Pick out the two frequencies (f_2 and f_1) above and below resonance where the current in the circuit is 0.707 of its value at resonance (f_r) and calculate the width of frequency band at this point and the resistance of the circuit, from the equation

$$R = \frac{L\omega\,(f_2 - f_1)}{f_r}$$

Subtract from this value the resistance of the current meter. For example a model 425 Weston thermo-galvanometer will read currents of 115 ma and has a radio-frequency resistance of 4.5 ohms. The value of resistance remaining is the resistance of coil, leads, and condenser. Most of this resistance resides in the coil.

Experiment 5-8. To determine resistance of a circuit. Another method of determining the resistance of a coil is as follows: It necessitates the use of a decade resistance box or series of accurately known resistances of negligible inductance and capacity and a variable condenser.

Small lengths of high-resistance wire (manganin) are to be preferred for frequencies higher than 1000 kc. Their d-c and high-frequency resistance is practically the same.

Connect the apparatus in series and couple to an oscillator.

With the resistance box short-circuited ($R = 0$), tune the circuit to resonance. Then add enough resistance to the circuit to halve the current, retuning to resonance, if necessary. Then since we have halved the current, Ohm's law tells us that we have doubled the resistance. In other words the added resistance is equal to the resistance already existing in the circuit. Again subtract the resistance of the current-indicating meter. What remains is the resistance of coils, condensers, and leads.

Repeat at several different frequencies and calculate the Q and plot against frequency and wavelength.

If only one or two resistance units are available, say 5 or 10 ohms and not a continuously variable standard of resistance like a decade box, the resistance of the circuit above may be determined by noting the current at resonance, and the current when some resistance has been added, retuning to resonance after adding the resistance if necessary. Then the current, according to Ohm's law, is

$$I_1 = \frac{E}{R_1}$$

$$I_2 = \frac{E}{R_1 + R_2}$$

where I_1 = current at resonance and no added resistance;
I_2 = current at resonance and R_2 added;
R_1 = resistance of circuit;
R_2 = added resistance;

whence

$$R_1 = \frac{R_2 I_2}{I_1 - I_2}$$

If a current-indicating meter is used whose deflections are proportional to the current squared, such as a thermogalvanometer or a hot-wire meter, it is only necessary in this experiment to add sufficient resistance to quarter the deflection of the instrument. This is equivalent to halving the current, and the added resistance is equal to the resistance already in the circuit.

The lower the resistance of the current-indicating device, the greater will be the accuracy with which such measurements may be carried out. For example, if the indicator has a resistance of 4.5 ohms and the circuit a resistance of 5 ohms, great accuracy cannot be attained, but if the circuit resistance is double or treble that of the indicator, much greater accuracy results. In any case the meter resistance must be subtracted from the measured resistance to get the resistance due the circuit alone.

138. Condenser capacity. We will now investigate by means of an experiment the capacity of a condenser.

Experiment 6–8. To determine the capacity of a condenser. Connect a variable condenser whose calibration is known across a coil and click into an oscillating receiver or into an oscillating wavemeter; attach the unknown condenser across the variable condenser and retune the latter to resonance with the wavemeter. The difference in readings of the calibrated condenser is the capacity of the unknown condenser. For example, suppose resonance is obtained by the variable condenser alone when set at 400 $\mu\mu$f. Connecting the second condenser across the variable forces us to reduce the capacity of the latter to 340 $\mu\mu$f. The difference $400 - 340 = 60$ $\mu\mu$f is the capacity of the unknown. Such a method enables the experimenter to disregard the capacity of the coil itself or of the leads since these are connected across the variable at all times and do not change when the unknown is attached to the circuit.

139. Antenna wavelength.

We will proceed to determine the wavelength of an antenna by means of the following experiment.

Experiment 7–8. To measure the natural wavelength of an antenna. Connect in series with the antenna an inductance which can be adjusted in even steps, say a coil of 20 turns with taps at each turn. Measure the frequency to which the antenna tunes with the entire coil in the circuit by coupling the coil to an oscillating wavemeter. Then reduce the inductance by one turn, and repeat. Repeat until accurate readings are no longer possible. Plot wavelength, or frequency, against added turns of wire. Where the line crosses the wavelength or frequency axis is the natural wavelength or frequency of the antenna.

140. Antenna capacity.

The capacity of an antenna may also be determined by experiment.

Experiment 8–8. To measure the capacity of an antenna. Measure the wavelength of an antenna attached to an inductance, as in Fig. 110. Then replace the antenna-ground connections by a variable condenser (Fig. 110*b*) and tune the condenser until resonance with the wavemeter is indicated. The capacity of the condenser at this point is the capacity of the antenna.

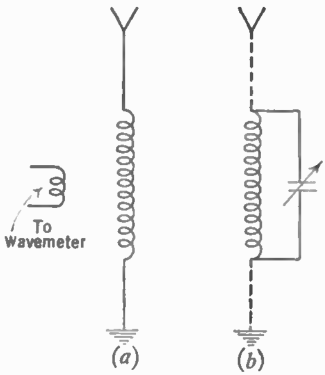


FIG. 110. To measure capacity of an antenna.

141. Antenna inductance. By the following experiment we can determine the inductance of an antenna.

Experiment 9–8. To determine the inductance of an antenna. Connect a known inductance, L_1, in series with the antenna and measure the frequency f_1. Repeat using a different inductance L_2 and get frequency f_2. The two frequencies are related as follows:

$$f_1 \propto \frac{1}{\sqrt{(L_1 + L_a)C_a}}$$

$$f_2 \propto \frac{1}{\sqrt{(L_2 + L_a)C_a}}$$

where L_a = antenna inductance;
C_a = antenna capacity;
$\propto$ indicates is proportional to.

Squaring both equations and solving for L_a we get

$$L_a = \frac{f_1^2 L_1 - f_2^2 L_2}{f_2^2 - f_1^2}$$

Problem 1–8. A wavemeter is being calibrated from a standard. At resonance the capacity of the standard is 400 $\mu\mu$f, the capacity of the other meter is 500 μf. What is the ratio of their inductances? If the inductance of the standard is 300 μh, what is the inductance of the other wavemeter? At what frequency are they now set? What is the wavelength?

Problem 2–8. In calibrating a wavemeter from a source of 1000 kc which has many harmonics, the fundamental is received when the condenser capacity is 253 $\mu\mu$f. Another indication is received when the capacity is approximately 65 $\mu\mu$f. What harmonic is this?

Problem 3–8. In an experiment to determine the resistance of a coil by the change of total resistance method (Experiment 5), the current without added resistance is 100 ma and with 12 ohms added it is 60 ma. The resistance of the meter is 5 ohms. What is the resistance of the coil and condenser in series?

Problem 4–8. A certain coil condenser (LC_1) tunes to a frequency, f_1. The condenser is changed by adding another to it so that the value is C_2. The circuit now tunes to a frequency, f_2. Prove that $f_2/f_1 = \sqrt{C_1}/\sqrt{C_2}$.

Problem 5–8. Using the formula in Problem 4, what must be done to the capacity to make a circuit tune to twice the frequency, half the frequency, double the wavelength, one-half the wavelength?

Problem 6-8. A coil-condenser combination tunes to 450 kc when the condenser is 600 $\mu\mu$f. When an unknown condenser is placed in series with the 600-$\mu\mu$f capacity the circuit tunes to 600 kc. What is the unknown capacity?

Problem 7-8. An antenna tunes to 1000 kc when 100 μh are in series with it, and 750 kc when 300 μh are in series. What is the inductance of the antenna? Remembering that the two inductances, L_1 or L_2, and the inductance of the antenna L_a are in series, and can be added to get the total inductance, what is the capacity of the antenna? What is its natural wavelength?

Problem 8-8. A radio receiver tunes to 600 meters (500 kc) with a 500-$\mu\mu$f condenser. What maximum capacity must be put in parallel with this condenser in order to receive 800-meter (375-kc) radio compass signals and ship-to-shore traffic on 2200 meters?

142. Coil-condenser applications. Combinations of coils and condensers in circuits perform useful services throughout the electric communication art. Not only is the selectivity of a radio receiver produced by the properties of a resonant circuit, but such circuits may also be used to eliminate undesired frequencies or frequency bands. Resonant circuits may also be used to change the response of a system to frequencies of certain values.

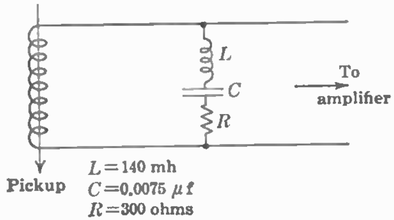


FIG. 111. Use of series-resonant circuit as a low-impedance trap to reduce noise from needle scratch.

For example, a "scratch" filter may be used with a phonograph amplifier to reduce the noise caused by needle scratch. This filter is a series-resonant circuit placed across the circuit between the phonograph pickup and the amplifier it feeds into, as shown in Fig. 111. This circuit tunes to about 4500 cycles and since it is a series-resonant circuit, its impedance to frequencies near 4500 cycles will be very low. It will provide a low impedance path for these frequencies and since needle scratch is of this order of frequency, the scratch noise will be reduced. Of course, any music frequencies in this region will be reduced also.

Problem 9-8. Let the reader calculate the impedance of the filter of Fig. 111 at 3000, 4000, 5000, and 6000 cycles and plot the results in terms of the impedance at 3000 cycles. From this judge how much the scratch-frequency voltages will be reduced in strength.

A parallel-resonant circuit, on the other hand, will be shunted across a line if the response of a system is to be increased at some frequency. Thus in Fig. 112 note that it is the characteristic of the telephone line to fall off at the higher frequencies.

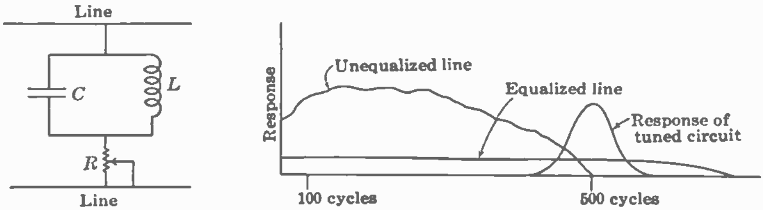


FIG. 112. Resonant circuit and result of using it across a telephone line.

This is due to the capacity of the line which lowers the line impedance at the higher frequencies. Now if a parallel-resonant circuit is shunted across the line, and if the resonant frequency is at the point where the line response is practically zero, the effect will be as shown in the figure. The resonant circuit will have low impedance at frequencies lower than resonance and will reduce the voltages on the line below this frequency. At the resonant frequency, however, the circuit will have high impedance and no voltage will be lost in it. Therefore the voltages in the line will be reduced below resonance, but will not be reduced at the resonant frequency. The resonant circuit will tend to pull up the voltage of the line at this resonant frequency, and the increase in voltage will be a function of the Q of this coil-condenser circuit and the resistance that is placed between it and the line.

CHAPTER IX

THE VACUUM TUBE

The most important single device known to radio science is the **vacuum tube.** Although it is true that early receivers used no tubes at all, and that those which are within a very short distance of broadcasting stations and which use only headphones can get along with a coil, a condenser, and a crystal detector, all modern receivers use tubes, some of them as many as twelve or more.

143. The construction of the vacuum tube.[1] As we know the tube today it consists of a glass or metal wall within which are three or more metallic parts known as the elements. In the center is the **filament,** which may be made of tungsten, carbon, tungsten covered with thorium, platinum or nickel coated with oxides of barium, strontium, cesium, or other chemical elements. Next to the filament is the **grid,** an open mesh of molybdenum (frequently) wire screen; finally there is the **plate,** a sheet or screen of metal, often of nickel. Some tubes have only two elements, the filament and the plate; many have additional grids; the mechanical construction differs according to type of tube, its use, and its manufacturer.

After the various elements are placed within the tube, the glass or metal wall is attached to a pump and the gas is removed. During the pumping process the wall is heated in an electric oven to drive out the gas, and later the elements are heated by means of an "induction furnace" so that various gases bound up in these metals may be pumped out. The modern tube is a high vacuum tube. Early types were poorly pumped and were really gaseous

[1] In this preliminary study of the vacuum tube, only the simplest tube is considered, i.e., a three-element tube with a filament supplying electrons. In some tubes the filament serves only to supply heat to an emitter of electrons called the **cathode.**

tubes, tubes which would be rejected by modern testing methods. When the pumping or "exhaustion" process is complete the wall and its contents are sealed. Then the tube goes through several electrical tests and inspections before it can be labeled, packed, shipped, and again unpacked and put in use.

144. The purpose of the filament. In Chapter I of this book we discussed the electron, that elementary constituent of matter which carries electricity. Little has been said about the electron in preceding chapters; now it enters again and assumes an important role. The filament is the heart of the vacuum tube; the electrons which rush about in this filament are the life blood. When the filament is dead—due to age or crossed wires—the electrons no longer move in the proper manner; the tube is dead and might as well be broken up. If a filament of tungsten is heated so that an individual electron gets up a speed of 1×10^8 centimeters per second (620 miles per second) it can break through the surface tension of the filament. Since it is negatively charged it will be attracted toward any positive body near by.

145. The purpose of the plate. When the electron is released from the filament it goes shooting out into the void in which the elements are situated. When it leaves the filament, it takes with it a negative charge, and thereby leaves the filament positively charged. If there is no body at a positive potential within the bulb other than the filament, the electron will eventually find its way back to the source whence it came. If, however, a plate is within the tube and is more positive than the filament, the electron will be attracted to it. Even when the plate is at the proper positive potential to attract many electrons, some go back to the filament, and others congregate somewhere between the filament and the plate and constitute what is called the **space charge.** This is a cloud of electrons, negatively charged, of course, and presents a barrier through which electrons must go if they are to reach the plate. If there were no space charge, all emitted electrons would reach the plate.

Every electron which hits the plate constitutes a minute electric current and when enough of them arrive per second a measurable current is attained. This current carried by the electrons from the filament constitutes the tube's plate current which is used in so many ways. Plate current, the symbol for which is I_p, is usually measured and expressed in milliamperes.

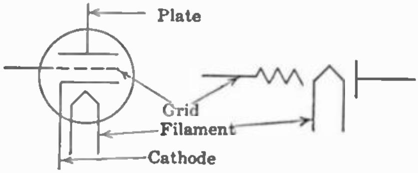


Fig. 113. New and old symbols for vacuum tube.

The source of the electrons is usually called the cathode, which may be a filament or a coated cylinder heated by an internal filament. This filament is heated by a battery, called an **A battery,** or by a step-down transformer from the a-c lighting circuit. A battery inserted between part of the cathode system and the plate maintains the plate positive with respect to the cathode. It is called the **B battery.** In a-c operated receivers and transmitters the B battery is replaced by a rectifier-filter system which produces direct current from alternating current.

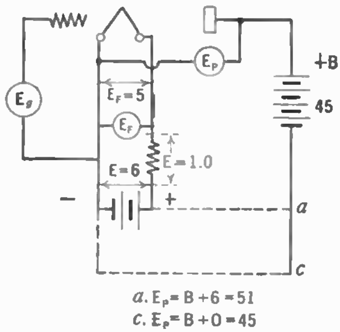


Fig. 114. If the B battery is connected as at (a) the voltage on the plate is 51 volts; if connected as at (c) the voltage is 45.

When the cathode is heated to a proper temperature a copious stream of electrons is emitted. In a filament-type tube some electrons are attracted to the positive part of the filament, i.e., to the side of the filament attached to the positive end of the A battery. If the plate is insulated from the filament, a few electrons will get through the space between them but if the plate is at a higher potential than the filament, it attracts many more electrons. It is usually so maintained by means of the B battery which in power tubes may be as high as 10,000 volts above the potential of the filament. This B battery may be attached to the filament in several ways. Its negative end may be connected to the negative end of the A battery or to the positive end of the A battery. It is common practice to connect the two negative leads together. The most negative part of the filament in d-c tubes, or the center of the filament or the cathode sleeve in a-c tubes, is considered as the point to which all other voltages are referred. (See Fig. 114.)

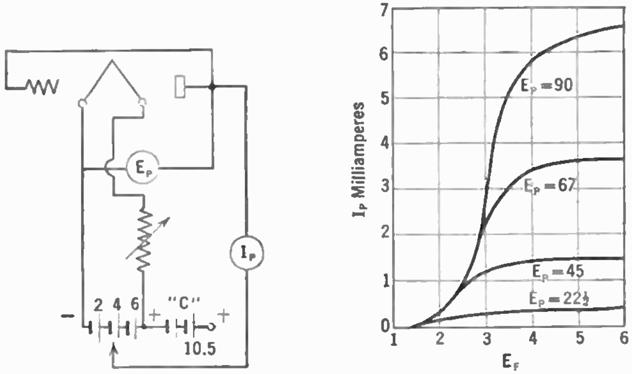


FIG. 115. Circuit for testing effect of plate voltage on emission and saturation curves made with the circuit.

Experiment 1–9. Effect of plate voltage on a two-element tube. Connect together the grid and plate of a receiving tube and connect into a circuit as shown in Fig. 115. Use a plate current meter reading about 5 ma. Light the filament and read the plate current as the plate is connected to the negative end of the battery and then to plus 2, 4, and 6 volts by connecting it to the first, second, or third storage cell in the battery. Connect the negative terminal of a 4.5-volt C battery to the positive end of the A battery and the positive terminal of the C battery to the plate. Read the plate current. The plate is now plus 10.5 volts above the potential of the negative part of the filament. Explain why.

146. Effect of filament voltage. The experiment above shows that the effect of increasing the positive potential of the plate is to increase the flow of electrons. The filament temperature, too, has an important effect upon the flow of electrons. The hotter the filament the more electrons per second will be released into the space surrounding the heated element. If, however, the voltage on the plate is low, there will soon be reached a definite plate current which cannot be exceeded no matter how hot the filament becomes. In other words the plate is taking all the electrons it can get through the space charge. It is true that more electrons leave the filament at higher temperatures but they simply add to the space charge or return to the filament. If the plate battery voltage is increased, a greater plate current will flow, but again a point will be reached where passing more current through the filament ceases to increase the plate current. Typical saturation curves for a 5-volt tube are shown in Fig. 115. Whenever the space charge (negative) is more effective in repelling electrons than the plate (positive) is in attracting them the plate current curve flattens off as shown in Fig. 115.

Experiment 2-9. Effect of filament-voltage on a three-element tube. A study of many of the tube's characteristics may be made with a setup of apparatus like that in Fig. 116 which consists simply of a board upon

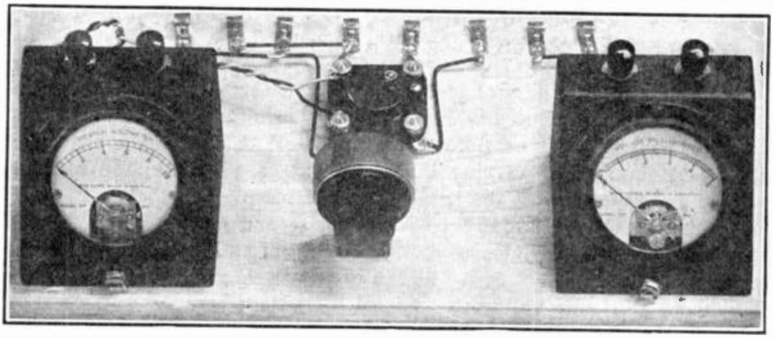


Fig. 116. An experimental setup for measuring tube characteristics.

which are connected several Fahnestock clips to which may be attached meters and batteries of the proper potential. A good voltmeter is a two-range Weston Model 506 reading on the low scale up to 7.5 volts and on the upper to 150 volts. These will read the ordinary ranges of filament and plate voltages. A plate current meter may be any milliammeter reading from 5 ma upward.

Connect up a tube as shown in Fig. 117 and after reading the plate voltage, place the meter across the filament. Use at the start about 22.5 volts of B battery. Turn on the rheostat slowly and read the filament voltage and plate current. If either meter should read backwards, reverse it. Plot as in Fig. 115 the relation between E_f (filament volts) and I_p (plate current). Increase the plate voltage and repeat.

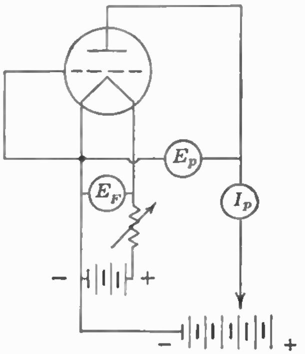


FIG. 117. Circuit for apparatus of Fig. 116.

147. Saturation current. With a given filament voltage (which produces a certain filament temperature) more and more electrons will be drawn to the plate as the voltage of the latter is increased—up to a certain point. But beyond this point additional plate voltage has little effect on plate current and the plate current curve flattens out. All the electrons emitted by the filament are being taken by the plate and increasing the plate voltage has no effect upon the number of electrons emitted. Increasing the filament temperature produces an additional supply of electrons, and the plate current will again increase.

Experiment 3–9. Effect of plate voltage on a three-element tube. Connect up the apparatus used in Experiment 2 as shown in Fig. 117. Set the filament voltage at some fixed value and take data showing the effect upon plate current of varying the plate voltage. Increase the filament voltage and repeat. Plot the data in a manner similar to that in Fig. 115. Remembering that 6.28×10^{18} electrons per second flowing past a certain point in a circuit constitutes an electric current of an ampere, calculate the number of electrons that arrive at the plate per second for several values of filament and plate voltage.

The experiments and curves above show

1. The relation between plate and filament voltage and plate current.

2. The saturation effect at low filament and plate voltages. Saturation due to insufficient plate voltage is known as filament saturation; that due to insufficient electron supply is called plate saturation.

3. The fact that little is to be gained by increasing the filament voltage above the rated value.

4. The curve connecting plate current (I_p) and filament voltage (E_f) is not a straight line.

This shows that Ohm's law is not being followed; the law in fact is much more complicated. The plate current is zero at zero filament voltage, and as the latter is increased the plate current begins to rise too, but not in a straight line. Soon, however, the negative space charge built up by the electrons which do not get to the plate prevents any more electrons getting to the plate. The plate current then is limited, and may be increased only by increasing the plate voltage so that it is again more positive than the space charge is negative. Various means are used to overcome this space charge which shall be discussed later.

148. The purpose of the grid. The third element, for which DeForest is famous, is the grid, the mesh of wires between the filament and plate. It has several important uses. It may be used to neutralize the space charge so that greater plate current may flow with a given filament temperature and given plate voltage.

Suppose the grid is made positive with respect to the source of the electrons. Since it is physically nearer the filament than is the plate, a small positive potential will have the same effect as a large positive potential on the plate. A positive potential near the filament speeds up the escape of electrons and prevents the building up of a high negative space charge and then the plate has a greater ability to attract the carriers of electric current.

Suppose, however, we make the grid negative. Its negative potential, near the filament, will be more powerful than the positive potential on the plate, farther from the filament. Therefore a small negative voltage on the grid will prevent the plate from getting electrons even if the plate is at a positive potential. Since there is no time lag in the flow of electrons, the grid takes instantaneous control and affects the plate current which is made up of the sum total of the minute charges carried to the plate by the electrons. The grid is a **control** electrode.

The relative ability of plate voltage and grid voltage to control flow of electrons is called the **amplification factor.** This important tube constant is actually the ratio between the grid's ability and the plate's ability to control electron flow.

149. Characteristic curves. In the simplest receiving tube there are three electrodes. The cathode has already been mentioned, and the manner in which its temperature affects the plate current has been tested. The plate and the effect of its voltage

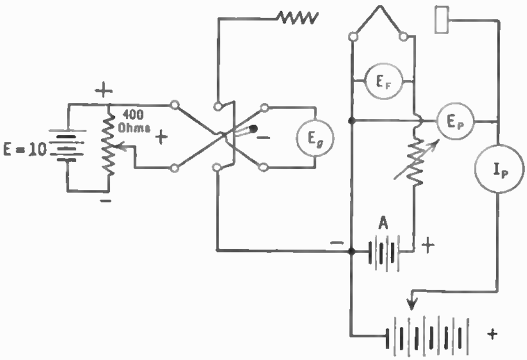


FIG. 118. Complete apparatus for measuring characteristics. The double pole-double throw switch reverses the grid voltage.

on plate current have been qualitatively mentioned; so has the effect of grid voltage. Under ordinary conditions the cathode is operated saturated, that is, at such voltage that there is little use in raising it farther. Its voltage is then fixed; it is not varied.

If the cathode voltage is considered as fixed, we still have the plate current depending upon two variable quantities, the grid and the plate voltage (E_g and E_p). The manner in which these variables affect the plate current controls the characteristics of the tube. When plotted in graphs, they are called **characteristic curves.**

Experiment 4–9. Effect of grid bias upon plate current. Set up the apparatus as shown in Fig. 118, using in succession several of the common types of tubes. Set the filament at the proper voltage. Fix a small voltage, say 22.5 volts, on the plate of the tube and take down data showing how the plate current changes as the grid bias is varied from a point where the plate current is zero to a grid voltage of about positive 10 volts. The DPDT switch in the grid circuit makes possible changing the polarity of the grid without changing the meter (E_g) connection. Then raise the plate voltage and repeat. Plot these data like those in Fig. 119.

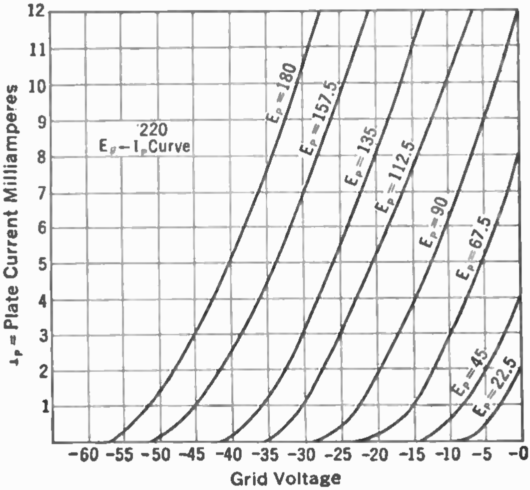


FIG. 119. A family of E_g–I_p curves.

150. Grid voltage–plate current curves. Several interesting and important facts may be discovered by looking at such curves which we shall call the E_g–I_p curves. At large negative grid voltages there is little or no current in the plate circuit. As this negative voltage is decreased, some electrons get past the grid and through the space charge and to the plate. The current begins to flow, increases at a rather slow rate, then more rapidly, then in a steep and straight line, and finally, if the experiment is carried far enough, the curve flattens out. Increasing the plate potential and again varying the grid potential produces a new curve which is essentially parallel to the first, but moved to the left. Increasing the plate voltage a like amount again produces a new curve displaced an equal distance to the left of the second line. Such a graphic collection of data is known as a family of curves and tells all we need to know of the effect of grid voltage upon plate current. Grid voltages may be secured from a battery known as a C battery and the voltage itself is frequently called a **C** or grid **bias.**

If we place a meter in the grid circuit at the same time the plate current is measured, we shall see that a very small grid

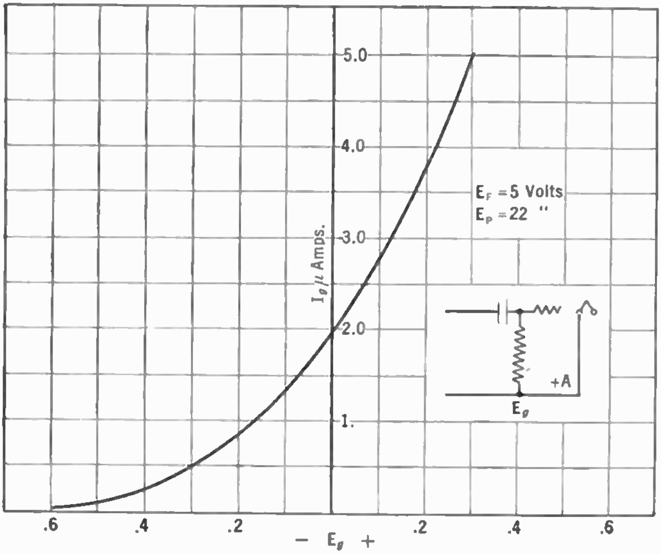


FIG. 120. Grid current curve of a three-element tube.

current flows when the grid is positive. This current in ordinary practice is very small, seldom over one-tenth of the plate current, and in all amplifiers in which the minimum distortion is desired the current in the grid circuit is kept as low as possible by making the grid highly negative. The grid current curve for a typical case is shown in Fig. 120.

151. The effect of plate voltage upon plate current. To determine this effect we will resort to experiment.

Experiment 5-9. Set up the apparatus as in Experiment 4. Set the grid voltage at some value, say minus 5 for an ordinary receiving tube, and note down the plate current as the plate voltage is changed from 0 to perhaps 100 volts in 10-volt steps. Then change the grid voltage to minus 10 and repeat; then at minus 15 and 20; 0, and plus 5 and 10, etc.

These data may be taken from the E_g–I_p curves plotted in Experiment 4 by picking off the curves the proper values of current, and plate and grid voltages.

152. Plate voltage–plate current curves. Here again (Fig. 121) the plate current curves are essentially parallel over the

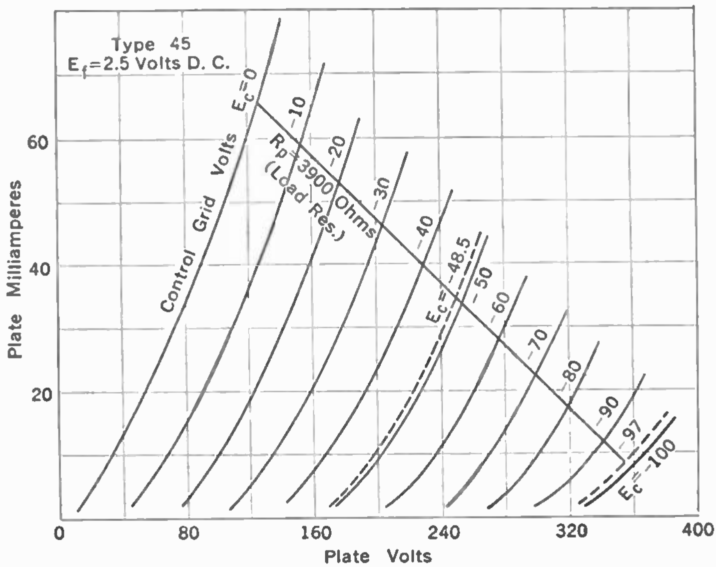


FIG. 121. Plate current–plate voltage curves.

straight parts. If the grid voltages chosen are in equal steps, the plate current curves will be equal distances from each other.

From characteristic curves of this type, we may calculate all the tube constants, and foretell nearly all the properties of the tube when connected into a circuit with other apparatus whose electrical constants we know.

153. Amplification factor. For example, we know that the grid potential is relatively more important in controlling plate current than is the plate voltage. Why? Because it is nearer the source of electrons. How much? We can tell from the E_p–I_p curves in

Fig. 122. Looking at the line marked $E_g = -22.5$, we see that at a plate voltage of 180 the plate current is 16 ma but that if E_p is decreased to 140 volts the plate current decreases to 8.2 ma —a change of 7.8 ma for 40 volts or a net change of 0.195 ma per

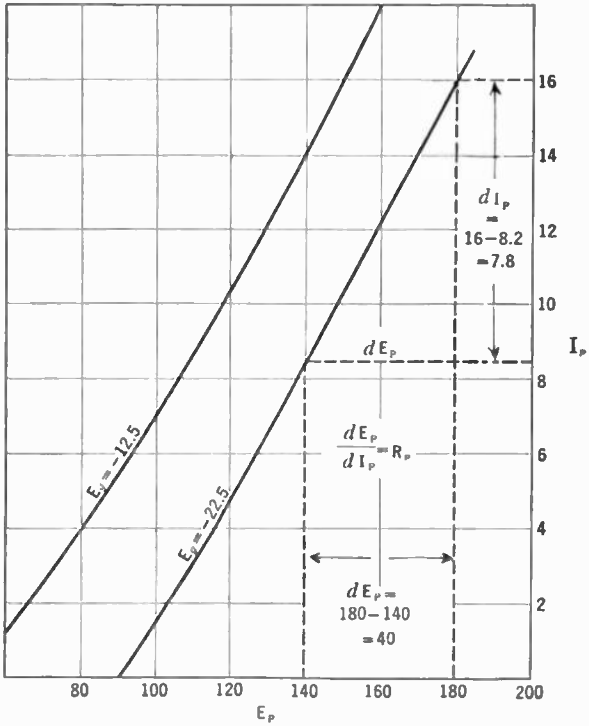


FIG. 122. Detailed E_p-I_p curve showing how to calculate R_p.

volt. This is the slope of this particular line and, as we shall see later, it gives us another important tube constant without further calculation.

Now looking at the two curves marked $E_g = -12.5$ and $E_g = -22.5$ at the points where they cross the 140-volt E_p line, we see that at this value of plate voltage the plate current is respectively 14.0 and 8.2 ma at these two values of grid voltage.

This means that changing the grid voltage by 10 volts causes a change of 5.8 ma in the plate current, a net change of 0.58 ma per volt. Dividing the change per volt caused by E_g variations by the change per volt produced by E_p variations gives us the relative ability of the grid and plate potentials to influence the plate current. Thus,

$$\frac{\text{Ability of grid voltage to control plate current}}{\text{Ability of plate voltage to control plate current}}$$

$$= \frac{0.58 \text{ ma/volt}}{0.195 \text{ ma/volt}} = 3.0$$

This ratio is defined as the **amplification factor** of the tube. It is the ratio between the plate voltage change required to produce a certain plate current change and the grid voltage change required to produce the same change in plate current. The Greek letter mu, μ, is the symbol used in the literature for the amplification factor of a tube. Thus,

$$\mu = \frac{\text{plate voltage change to produce a given plate current change}}{\text{grid voltage change to produce the same plate current change}}$$

The amplification factor for a given tube does not vary much under the conditions under which the tube is ordinarily used. It is controlled largely by the mechanical construction of the tube and the nearness of the grid to the filament. A grid composed of many wires close to the filament produces a high amplification factor; a tube with a wide mesh and not so close to the filament produces a tube with a low amplification factor.

The student should note that the amplification factor is *not* the ratio between plate and grid voltages, but is the ratio between *changes* in these voltages. It may be expressed in more mathematical language as

$$\mu = \frac{dE_p}{dE_g} \quad \text{to produce a given } dI_p$$

where the prefix *d* signifies "a change in" (a differential).

The amplification factor may be obtained from the E_g–I_p curves in Fig. 122 in a manner similar to that outlined above. It is also equal to the change in I_p produced by say 20 volts change in E_g divided by the change in I_p produced by 20 volts change in E_p. Thus in Fig. 121 changing E_g from -40 to -20 (with $E_p = 160$) produces a variation of 32 ma whereas along the $E_g = -40$ line a change of E_p from 200 to 220 volts produces a variation of approximately 11 ma.

Then

$$\mu = \frac{32}{11} = 3 \text{ (approx.)}$$

154. The meaning of the amplification factor. If the amplification factor of a tube is 3, for example, adding 30 volts to the plate will increase the plate current a certain amount. Adding only 10 volts (positive) to the grid will produce the same plate current change or adding 10 volts negative to the grid will bring the plate current back to its value before the plate voltage had been increased. In other words, any voltage placed on the grid of such a tube has the same effect as a voltage in the plate circuit multiplied—or amplified—by the μ of the tube. A voltage E_g on the grid becomes equal to μE_g when it gets to the plate circuit.

155. Equivalent tube circuit. Since a change in plate voltage may be replaced by a smaller change in grid voltage multiplied by the μ of the tube, we may replace the entire tube by a fictitious generator whose voltage is μE_g and whose internal resistance is equal to the resistance of the tube. In fact in all problems the tube is so considered, and is indicated symbolically as in Fig. 123.

Problem 1-9. With a 20-volt bias the plate current of a tube under a given value of E_p is 55 ma, and when the bias is increased to 30 volts the plate current is reduced to 28 ma. If, however, at this value of grid bias (-30) the plate voltage is increased from 180 to 210 volts the plate current comes back to its original value, 55 ma. What is the amplification factor of the tube?

Problem 2-9. The amplification of a tube is 8 and when the grid is -3 volts the plate current is 3 ma. If the bias is reduced to zero the current increases to 8 ma. Both these current values were read when the plate voltage was 90 volts. How much would the plate voltage have to be reduced (at zero grid bias) to bring back the current to its 3-ma value?

Problem 3–9. Changing the plate voltage of a power tube from 100 to 300 volts changes the plate current from 10 to 55 ma. If the bias is zero at the latter figure what must be done to it to reduce the current to its former value if the amplification factor is 7.8?

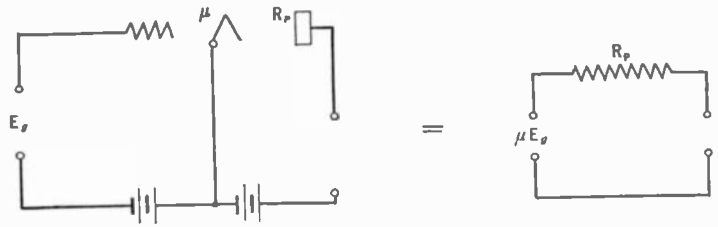


FIG. 123. The tube and its equivalent circuit; a voltage μE_g in series with R_p and the load.

156. D-c resistance of a tube. Since a certain plate current flows under the pressure of a certain plate voltage, the ratio

$$R = \frac{E_p}{I_p}$$

in which E_p = the d-c voltage on the plate,
I_p = the direct current in the plate circuit,
R = the d-c resistance of the tube,

gives the d-c resistance of the space between the filament and the plate. The d-c power used up by the electron current may be found by multiplying the plate voltage by the plate current, or

$$P = I_pE_p \quad \text{or} \quad \frac{E_p^2}{R} \quad \text{or} \quad I_p^2R$$

This power is the rate at which the kinetic energy possessed by the moving electrons is given up to the plate. When the electron leaves the filament it is attracted toward the plate, increasing in speed as it gets closer and closer to the positive potential which is the attracting force. When the electron hits the plate its kinetic energy due to its motion is given up. In a transmitting tube the number of electrons that arrive per second may be so high that the plate becomes red- or white-hot.

157. Internal resistance of the tube. This d-c resistance is not what is popularly known as the **impedance** of the tube, or more properly called its **plate resistance,** or **differential or internal resistance.** The latter is the ratio between a *change* in plate voltage and the *change* in plate current produced by this change in plate voltage. It is the resistance offered to the flow of alternating currents in the plate circuit and is not the same resistance as is offered to the flow of direct current from the battery. Then

$$R_p = \frac{\text{change in plate voltage}}{\text{change in plate current}} \quad \text{or} \quad \frac{dE_p}{dI_p}$$

For example, changing the plate voltage from 180 to 140 volts (Fig. 122) produced a plate current change of 7.8 ma (0.0078 amp)

$$R_p = \frac{dE_p}{dI_p} = \frac{180 - 140}{0.016 - 0.0082} = \frac{40}{0.0078} = 5200 \text{ ohms (approx.)}$$

Problem 4-9. Make a table showing the d-c resistance of various tubes in general use at the conditions they ordinarily work, that is, a 6P5 at $E_p = 250$ volts and $E_g = -13.5$, a 45 with $E_p = 180$ and $E_g = -31.5$. Use values of plate current in the tube chart. Compare the d-c resistance with the a-c resistance as given in the manufacturer's data.

Problem 5-9. The plate current of a tube is 4.5 ma when $E_p = 90$ volts, and is equal to 0.9 ma when $E_p = 40$ volts. What is the plate resistance?

Problem 6-9. The plate resistance of a tube is 12,000 ohms. At $E_p = 140$, $I_p = 14.5$ ma. What is I_p when $E_p = 100$ volts?

Problem 7-9. Calculate the d-c resistance of the tube under the two conditions of E_p and I_p in Problem 6, and the power used in heating the plate.

The internal resistance changes with plate and grid voltages and so the conditions of both must be considered when the resistance is mentioned. Thus the 2A3 tube has an internal resistance of 800 ohms when the plate voltage is 250 volts, and the grid voltage is 45 volts negative. Its internal resistance changes if either E_p or E_g is varied.

The student should note that R_p is not the ratio between a plate voltage and a plate current but is a ratio between *changes* in both plate current and plate voltage. Thus a 2A3 tube at a plate voltage of 250 has a plate current of 60 ma. The ratio $\frac{250}{0.060} = 4150$ ohms is the d-c resistance; R_p is equal to about 800 ohms under these conditions.

158. Transconductance of a tube.[1] There is one more important tube constant, the **transconductance.** This is the factor which tells us how much plate current change is caused by a given grid voltage change. (This is not the plate conductance $1/R_p$.) Thus

$$g_m = \frac{\text{change in plate current}}{\text{change in grid voltage}} = \frac{dI_p}{dE_g}$$

Thus if a change of one grid volt produces a change of plate current of 1 milliampere, the **transconductance**

$$g_m = \frac{1 \times 10^{-3}}{1} = 1 \times 10^{-3} \text{ mho or 1000 micromhos}$$

The mho is the unit of conductance. Note that it is ohm spelled backwards.

The transconductance is numerically equal to the ratio between the amplification factor and the plate resistance. Thus

$$g_m = \frac{dI_p}{dE_g} = \frac{\mu}{R_p}$$

because

$$\mu = \frac{dE_p}{dE_g}$$

and

$$R_p = \frac{dE_p}{dI_p}$$

Therefore

$$\frac{\mu}{R_p} = \frac{dE_p \div dE_g}{dE_p \div dI_p} = \frac{dI_p}{dE_g}$$

[1] In the older literature this tube constant is called "mutual conductance." Transconductance is the term to be preferred now.

Problem 8-9. A tube has a plate current of 7.75 ma at zero grid bias and 3.8 ma at $E_g = -4$. What is the transconductance?

Problem 9-9. The transconductance of a tube is 800 micromhos. What change in plate current is produced by a 1-volt change on the grid?

Problem 10-9. The transconductance of a tube is 775 micromhos. The plate current at $E_g = -6$ is 2 ma. What is the plate current at $E_g = -2$?

159. Importance of transconductance. The tube is ordinarily so worked that small variations in the input a-c voltage (grid voltage) produce variations in output (plate circuit) a-c current, and it is important that the transconductance of a tube be high. Tubes are in general use which have amplification factors as low as 3 and as high as 100 for simple three-element tubes with plate resistance varying from 800 to 66,000 ohms or higher, and with transconductances of the order of 1000 to 4000 micromhos.

When one is comparing two tubes of the same type, say two triodes, the transconductance is a measure of their relative merits, the one having the greater transconductance being the better tube. This is because this tube will produce a greater plate current change with a given grid voltage change than the tube with lower transconductance. One cannot compare two different types of tubes this way, however, because the two tubes may be designed for entirely different service.

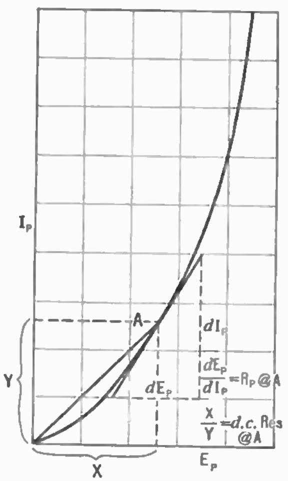


FIG. 124. Note how R_p is obtained. It is not E_p divided by I_p, which gives the d-c resistance.

160. Slopes of characteristic curves as tube constants. Since the plate resistance of the tube is defined as

$$R_p = \frac{dE_p}{dI_p}$$

and the transconductance as

$$g_m = \frac{dI_p}{dE_g}$$

these values may be taken directly from the curves showing the relation between plate voltage and plate current and between grid voltage and plate current. The transconductance is the slope of the E_g–I_p line. When changing the grid voltage produces no change in plate current (saturation) the transconductance is zero, that is, the E_g–I_p curve no longer has any slope or steepness and it flattens out, as for high positive values of grid bias. On the other hand, when the E_p–I_p curve flattens out the plate resistance becomes infinite—and so the steeper the E_p–I_p curve the

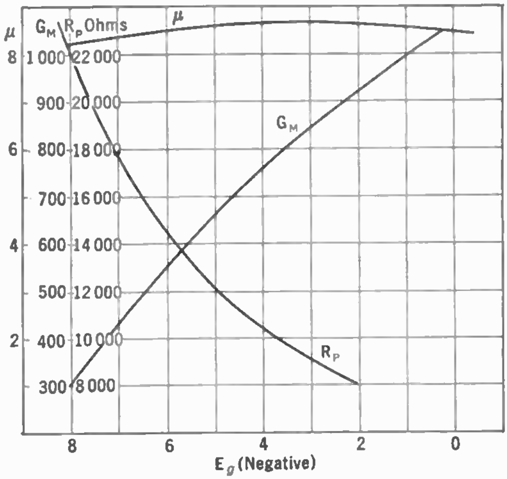


Fig. 125. Effect of grid voltage on tube characteristics.

lower the plate resistance. Care should be taken that the plate resistance is obtained properly from the E_p–I_p curve. Figure 124 shows the correct and incorrect methods.

Experiment 6–9. From the curves plotted in Experiments 4 and 5 measure the slopes at various values of E_p and E_g and calculate the plate resistance, transconductance, and amplification factor. Plot these values against grid voltage for one curve and against plate voltage for another curve. Such data for a typical tube are shown in Fig. 125.

161. "Lumped" voltage on a tube. An expression in England for the voltage on the plate of a tube is very useful. It involves the expression,

$$E = E_p + \mu E_g$$

where E = the effective or "lumped" voltage on the plate;
E_p = the plate voltage due to the B battery;
E_g = the voltage on the grid, due to a C bias;
μ = the amplification factor of the tube.

For example, we know that adding a negative C bias to a tube grid reduces the plate current. The same value of plate current may be attained without the C bias by reducing the plate voltage. Then for every value of plate current there are several combinations of grid bias and plate voltage that will produce it, the actual values being given by the above expression.

If, then, we plot the single curve showing the plate current at various plate voltages but with the grid at zero bias, we can easily calculate what the plate current will be under some other condition of B and C voltage. Thus with zero bias and 90 volts on the plate, the plate current may be 10 ma. That is,

$$E = 90 + \mu \times 0 = 90$$

Now suppose

$$\mu = 8 \quad \text{and} \quad E_g = -3$$

$$E = 90 + 8 \times (-3) = 90 - 24 = 66$$

To get I_p, it is only necessary to look at our E_p–I_p curve for $E_g = 0$ and find what I_p is when $E_p = 66$. This is the value of current desired, and is one point on the new curve $E_g = -3$. Then assume some other value of E_p and find the new I_p and place a mark on the graph paper for this point which is the second for the $E_g = -3$ curve. Other points may be obtained for other values of E_p and E_g and thus any number of curves may be drawn which will be parallel to the first or $E_g = 0$ curve.

When alternating voltages are placed upon the grid, they are the equivalent of μe_g volts in the plate circuit. On the negative half-cycles, this μe_g voltage must be subtracted from the plate voltage. Then when $\mu e_g = E_p$, the effective voltage on the plate is zero.

Problem 11-9. The μ of a tube is 3; what is the lumped or effective plate voltage when $E_p = 180$ and $E_g = -40$?

Problem 12-9. The plate voltage E_p on a tube is 120 but the plate current corresponds to a plate voltage of 40 at zero grid bias. If the value of E_g is 10, what is the μ of the tube? Do you see a simple way of measuring the amplification factor of a tube by this method?

Problem 13-9. If the plate current of a tube is 2 ma when $E_p = 90$ and $E_g = -4.5$ and $\mu = 8$, at what value of E_p will it be equal to 2 ma when $E_g = 0$?

162. Measurements of vacuum tube constants. The various factors which define all characteristics of a tube—μ, R_p, and g_m—are known as the **tube constants.** It is very important that means be handy for measuring these constants at various values of plate and grid voltage so that a full knowledge of a tube's characteristics may be had.

Such calculations may be made by means of the characteristic curves. This is slow work, however, and the engineer has no time for such processes. A simpler method will be described.

(*a*) *To measure the plate resistance of a tube.* This is the ratio between the change in plate voltage and the change in plate current: dE_p/dI_p. Set the grid bias at the value desired, for example —5 for a 37, and choose the plate voltage at which the tube will operate in practice at this bias. Then set the plate voltage at values somewhat higher and then somewhat lower than this median value, measure the plate currents, set down the data below in which the currents and voltages will be values secured by testing a 37.

$$R_p = dE_p/dI_p = \frac{150 - 100}{0.011 - 0.004} = \frac{50}{0.007} = 7150 \text{ ohms}$$

This means that at a grid bias of $E_g = -5$, the average plate resistance between the values of $E_p = 100$ and 150 volts is 7150 ohms.

This method will not work with screen-grid tubes and similar tubes because the plate current curves are almost flat over the working voltage range.

(*b*) *To measure the transconductance.* This is the ratio between plate current change dI_p and the grid voltage change dE_g

that produced it. Set the plate voltage at the value at which the tube will operate, for example, 150 volts. If the bias under operating conditions is to be 10 volts (a 37) set the grid at —15 and then —5 and read the plate currents. Set down the data as follows, assuming the plate currents are respectively 1 and 11 ma:

$$g_m = \frac{dI_p}{dE_g} = \frac{0.011 - 0.001}{15 - 5} = \frac{0.010}{10} = 0.001 \text{ mho} = 1000 \text{ micromhos}$$

(c) *To measure the amplification constant.* The value of the amplification constant may be calculated directly from the results obtained in (*a*) and (*b*) above. Since

$$g_m = \frac{\mu}{R_p}$$

or

$$\mu = g_m \times R_p$$

it is only necessary to multiply the plate resistance by the transconductance. Thus, if

$$R_p = 7150 \text{ ohms}$$

$$g_m = 1000 \times 10^{-6} \text{ mhos}$$

$$\mu = 1000 \times 10^{-6} \times 7150 = 7.15$$

The amplification constant may be determined in the following manner, which makes it unnecessary to determine first the transconductance and the plate resistance.

Set the plate voltage at a certain value, say E_{p_1}, read the plate current, I_{p_1}; change the plate voltage to E_{p_2}, note plate current I_{p_2}. Then bring the current I_{p_2} back to its original value I_{p_1} by varying the grid voltage. The ratio of the corresponding plate and grid voltage changes is the amplification constant, as indicated in Section 153, that is,

$$\mu = \frac{E_{p_1} - E_{p_2}}{E_{g_2} - E_{g_1}}$$

163. Bridge methods of determining the tube factors. A number of meters have been devised to measure the three tube constants by the methods outlined above—meters which read them directly and in a very simple manner. Other methods of obtaining the tube constants are in common use in laboratories. These methods involve balancing out one voltage by another.

For example, let us consider the circuit in Fig. 126. An alternating current flowing through R_1 and R_2 in series produces two voltages, one across each resistance. The IR voltage drop across

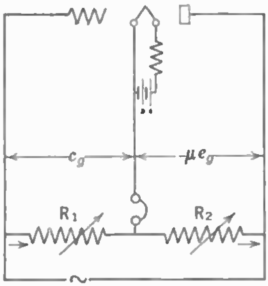


FIG. 126. Bridge for determining amplification factor.

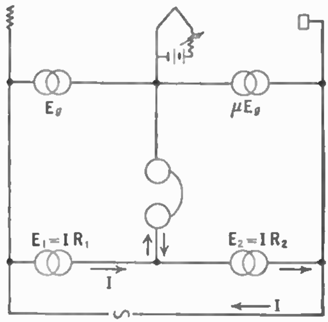


FIG. 127. Equivalent of Fig. 126.

R_1 is applied to the grid-filament path of the tube. The IR drop across R_2 appears across the plate-filament circuit of the tube. The grid voltage (here e_g is used to indicate an a-c voltage) is amplified in the tube and appears in the plate circuit as μ times e_g.

This is, in effect, a bridge circuit in which one voltage is compared to another. If the arms of the bridge, R_1 and R_2, are properly adjusted no sound will be heard in the telephones. Then the bridge is balanced. Under these conditions two currents are trying to flow through the headphones, one due to the voltage in the grid circuit, another due to the plate circuit. If these two currents have the same value, but are of opposite directions of flow, no current will flow through the phones, there will be no voltage across the phones and no sound will come from them.

This will be true when the voltage across R_1 and which is impressed upon the tube, is just equal to the voltage across R_2 which is equal to the grid voltage of the tube multiplied by the amplification factor of the tube, or

$$\mu IR_1 = IR_2$$

$$\mu R_1 = R_2$$

$$\mu = \frac{R_2}{R_1}$$

It is only necessary to adjust the relative values of R_1 and R_2 until the headphones give forth no sound, then μ is found by the equation above. In practice the source of voltage impressed upon the bridge comes from a buzzer, or a tone generator of some sort, usually having a frequency of about 1000 cycles.

In this bridge, R_1 may be fixed at 10 ohms and R_2 varied. Thus if $R_1 = 10$ ohms, and at balance $R_2 = 134$ ohms, the μ of the tube is $134 \div 10$ or 13.4.

164. To measure the plate resistance. A bridge circuit may be set up to measure the plate resistance. There are several such bridges; one of them is shown in Fig. 128. Let us consider Fig. 129 which is equivalent to Fig. 128 (neglecting L) in which R_p represents the internal plate resistance of the tube. Current I from the alternator divides: part flows through R_1 and R_2 and part through R_p and R. Here again the resistances are varied until no sound is heard in the headphones. If, therefore, there is no voltage across the phones, the points between R_1 and R_2 and between R_p and R to which the phones are connected must be at the same potential. This means that the IR drop through R_1 is equal to the drop through R_p, and similarly the drop across R_2 must be equal to the voltage drop along R, or

$$IR_1 = IR_p \quad \text{and} \quad IR_2 = IR$$

By dividing one equation by the other

$$\frac{IR_1}{IR_2} = \frac{IR_p}{IR} \quad \text{or} \quad R_p = R \times \frac{R_1}{R_2}$$

If $R = 10{,}000$ ohms,
$R_2 = 100$ ohms,
$R_p = 100\ R_1$.

Bridges of this type are seldom used except in the laboratory. Instead, circuits are arranged so that the actual alternating current in the plate circuit is measured when 1 volt alternating voltage is put on the grid of an amplifier. This measures the

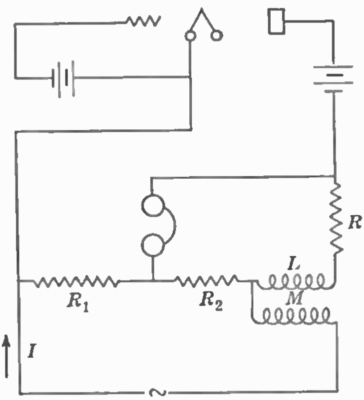


FIG. 128. A bridge measuring R_p.

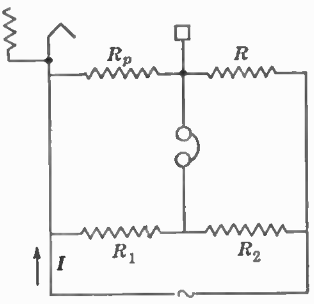


FIG. 129. The equivalent of Fig. 128.

transconductance of the tube, and in ordinary service this is the tube constant that is most important.

The inductance L is useful in balancing out certain capacity voltages. It is not necessary and its reactance can be neglected in calculating the tube constant being measured.

It is essential that small variations of voltage be used. Since the E_p–I_p curve is not straight, its slope differs at different points and is only a "constant" over a limited part of the curve. If a large variation, dE_p, is used to measure the plate resistance, or a large grid variation, dE_g, when the transconductance is measured, the values obtained will not be very accurate.

165. An a-c tube tester. A simple tester which the diagram in Fig. 130 describes pictorially will be useful for quick tests to determine whether or not a tube should be thrown away. It comprises an a-c transformer which provides the proper filament voltages for standard tubes, and a resistor divided into two parts through which the plate current flows. Across this resistance appears a voltage which may be used as C bias. The operation of the tester is as follows. It is plugged into a lamp socket (ac, of course), the tube is inserted, and the reading of plate current noted. Then part of the grid-bias resistor is shorted, thereby changing the plate current and the C bias. The ratios between the corresponding plate current changes and the grid bias changes give an indication of the transconductance of the tube. In actual tests it would determine the transconductance of several types of tubes within 80 per cent or better of the value as measured upon an accurate bridge.

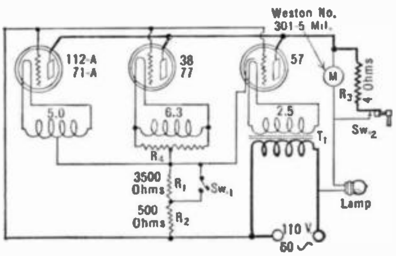


FIG. 130. An a-c tube tester.

Suppose for example that the plate current is 0.001 amp when the bias resistor is 4000 ohms and 0.003 amp (3 ma) when the bias resistance is reduced to 500 ohms. We set the data down as

$$g_m = \frac{dI_p}{dE_g} = \frac{0.003 - 0.001}{0.001 \times 4000 - 0.003 \times 500} = \frac{0.002}{4.0 - 1.5} = \frac{0.002}{2.5}$$

$$= 0.0008$$

$$= 800 \text{ micromhos}$$

166. Types of electron emitters. Certain types of vacuum tubes get along without a thermionic (heated) emitter, but by far the greater number in service get their supply of electrons by heating a filament or a surface which emits these electricity carriers. In general there are two types of emitters today, the true filament type and the indirectly heated cathode. The first type consists of a wire made of certain emitting metals or coated with certain emitting compounds. The second type consists of a cylinder, whose outside is coated with electron-emitting materials and whose inside is a filament which is heated, and which in turn heats the cylinder called the cathode.

Filament-type tubes are more adapted for battery operation since they produce hum when operated with alternating current; the heater-type tube may be used on a-c, d-c, or battery power. The coated filaments are much more efficient than the pure tungsten filaments, for example, since they emit much more copiously at a given temperature than the pure metal filaments.

Pure metallic emitters are made of tantalum or tungsten. If the pure tungsten wire is coated with a thin layer of thorium the emission increases greatly. In practice, thorium oxide is introduced into the tungsten when it is made, and at first was added to improve it physically. Then it was discovered that emission also improved. After the tube is made, the filament is activated by raising the temperature of the filament to 2500 degrees absolute temperature (Kelvin). This converts some of the thorium oxide to thorium which diffuses to the surface of the metal. Tubes using thoriated tungsten filaments may be reactivated if they are accidentally exhausted of their supply of thorium by being placed across too high a voltage. Emission can be improved by flashing them at a higher voltage than normal. This repeats the original activation process.

Coated cathodes are made up of a core of metal such as nickel or alloys of nickel, on which are coated carbonates of strontium and barium. These carbonates are converted to oxides in the process of manufacture. By far most of the receiving tubes used today have cathodes coated in this manner.

167. Screen-grid tubes. So far we have discussed only very simple tubes, i.e., triodes, or three-element tubes. In modern circuits, however, simple triodes are practically useless except as power amplifiers at audio frequencies. In radio-frequency amplifiers, triodes cannot be used effectively. This is due to the following difficulty.

Between grid and filament, grid and plate, and plate and filament of a vacuum tube exist electrostatic capacities. These capacities are made up of the inherent capacity of the tube and its elements plus the socket and wiring capacities. An amplifier tube works effectively, and under perfect control, only when it is a one-way device, voltage being applied to the input (grid-filament path) and voltage being taken from the output (plate-cathode path). If some of the output voltage gets back into the input in any way, the effective input voltage is either increased (regeneration) or decreased (degeneration). If either of these unwanted effects get out of control, the amplifier is no longer useful.

If the amplification of the tube and its circuit is ten, and if one-tenth of the output gets back into the input in some way, as much unwanted input voltage is placed upon the grid-cathode circuit from the output as was put there by intention. Soon the tube and circuit break out into uncontrollable oscillation and therefore are worthless for the purpose intended.

The capacity existing between grid and plate forms a bridge for some of the output voltage to get back to the input. This capacity may be reduced by structural design, but cannot be reduced to near zero except by the intervention of a shield between grid and plate. This produces what is known as the screen-grid tube.

The shield or screen between grid and plate consists of a grid of wires or some such structure. This is grounded as far as radio-frequency voltage is concerned and is maintained at a positive d-c voltage with respect to the grid. The positive voltage draws electrons away from the cathode toward the plate. Some of them hit the screen and form a screen current, which is wasted, but most of them get to the plate. Since the screen is at ground potential with respect to radio-frequency voltages on the grid, there is a very much reduced capacity between grid and plate. The ability of the grid to control flow of electrons to the plate is as great as ever; and at the same time a marked change takes place in the E_p–I_p curves. Changes in plate voltage produce very small changes in plate current, compared with those occurring in a triode.

If, therefore, plate voltages have little effect upon the plate current, and if grid voltages have a considerable effect upon plate current, it follows by definition, that the amplification factor of the tube is very high. This is a fact, and values of 1000 or more are not uncommon. At the same time the plate resistance of the tube is much higher than is attainable in triodes. Although this might seem to be a disadvantage, it is not so for the purpose for which the tubes are used, i.e., voltage amplification.

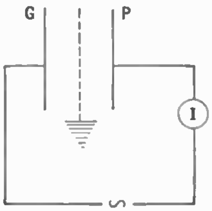


FIG. 131*a*. Capacity current from plate to grid is nullified by grounded shield or screen.

Characteristic curves of the screen-grid tube are shown in Fig. 131*b*. Note the fairly flat portion of the curves to the right of the $E_p = 90$ line. This is the useful region of the characteristic. To the left of this 90-volt line something very interesting happens. Over a small region the plate current actually decreases as the plate voltage is increased. How does this happen?

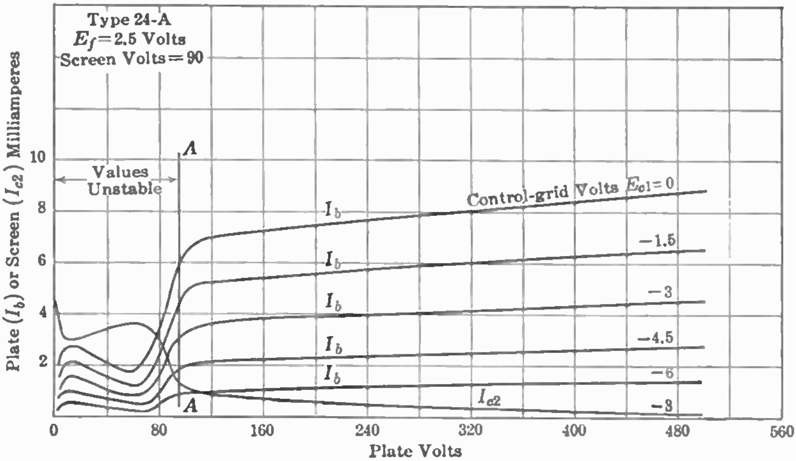


FIG. 131*b*. Characteristic curves of typical screen grid tube.

Consider the screen grid biased at +90 volts. An electron leaves the cathode and is impelled onward by this positive voltage on the screen. It gets through the mesh of the screen and may strike the plate. If the plate is positive enough, say 10 volts or so, the velocity of the electron as it hits the plate may be high enough to knock an electron out of the plate. Since the screen is at a higher positive potential than the plate it has greater attraction for the electron than the plate, and the electron will naturally turn around and go back to the screen. This new electron is called a secondary electron, and the emission of electrons under these conditions is known as **secondary emission.**

If the plate voltage is raised higher than that of the screen, the electrons will prefer to go to the plate and the characteristic curve straightens out like an ordinary law-abiding tube. As will be seen later, when tubes are operated with a-c input voltages, the actual voltage on the plate varies from instant to instant, under some circumstances going from zero to twice the battery voltage impressed upon the plate-cathode path. A circuit operated so that the plate voltage might be lower than the screen voltage would be unstable and, therefore, the useful operating region of the E_p–I_p characteristic is limited. This means that the voltage and power output of the tube are less than if this unstable region of the characteristic did not exist.

168. Pentode tubes. How can this unwanted falling-plate current region be eliminated? By the simple placement of another shield or screen in the tube, this one being placed between the screen grid and the plate. It is connected to the cathode and therefore is negative with respect to the plate. Now an electron may strike the plate hard enough to knock some electrons out of it, but these electrons find the zero-potential screen (negative compared with the plate) an insuperable barrier and cannot go through it to get back to the screen grid. They are turned around and fall back into the field of the plate. This third grid is called a suppressor grid because it suppresses secondary emission. Note the curves in Fig. 132 and compare them to those of the screen-grid tube of Fig. 131*b*. The tube itself has become a five-element tube, or pentode, and as a class the pentode has taken over functions formerly performed by screen-grid tubes or tetrodes. Pentode power amplifiers such as the 2A5, 1A5-G, and 47 produce a considerable output with low grid voltages:

voltage amplifiers like the 6J7 produce very high amplification compared with that possible in triodes.

Pentode tubes are of two general types, those used for power output and those used for voltage amplification. In either the third grid acts as suppressor grid to push secondary electrons back to the plate. In the output tube the useful part of the

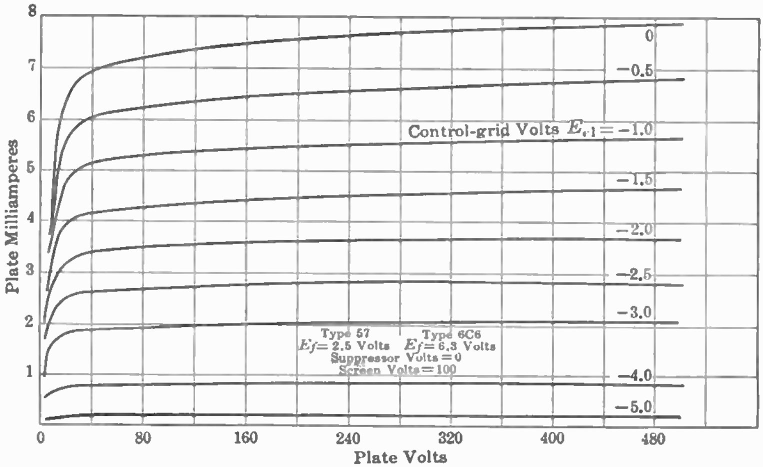


FIG. 132. Characteristics of a typical pentode tube used for voltage amplification.

characteristic is increased and more output can be attained. Tubes for voltage amplification also employ the suppressor grid and make possible higher degrees of voltage amplification than in four-electrode screen-grid tubes.

169. Beam power tubes. Although the pentode is an advance over the screen-grid tetrode, there is need for improvement. At the lower plate voltages, there is still considerable curvature to the characteristic, and this produces distortion unless the tube is limited severely in its output. It would be an advantage to straighten out the plate voltage, plate current curves. This is done in the beam power tubes in a most ingenious way.

Instead of placing an actual grid-like electrode within the tube structure, electrons are forced to travel in prescribed paths

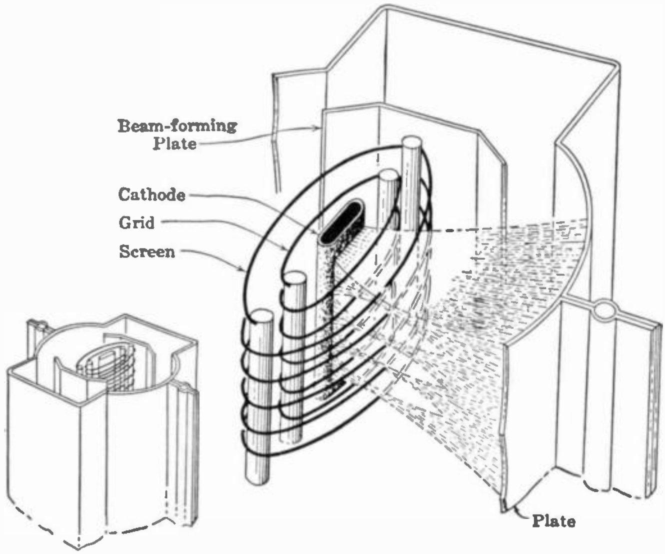


FIG. 133. Construction of beam power tube showing beam effect on electron flow.

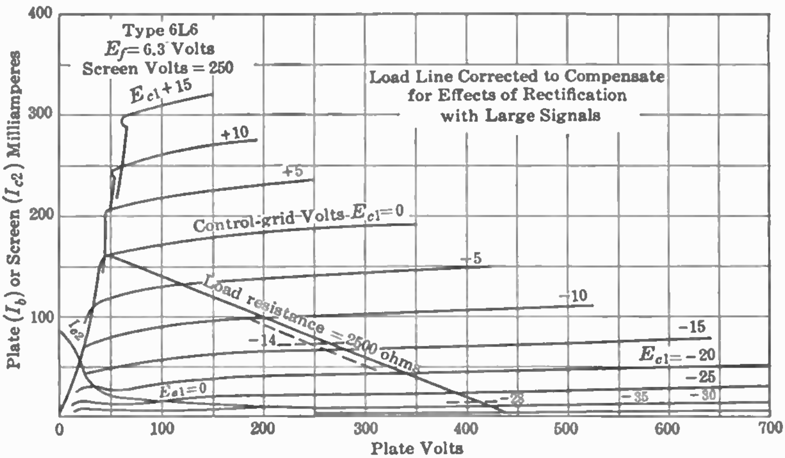


FIG. 134. Plate voltage–plate current characteristics of beam-type power tube.

and with such density that a "virtual" low-voltage electron-repelling screen is produced in the desired region. The screen, therefore, which repels secondary electrons back to the plate does not exist in the form of wires, but rather in the form of a collection of other electrons. The second grid, corresponding to a screen-grid tube, is spiral-wound like the control grid and each turn is shaded from the cathode by a turn of the control grid. For this reason electrons do not often hit the screen and therefore very little screen current flows. The beam power tube is very efficient since so little loss of current exists in the screen circuit, and has very high sensitivity, which means that a large amount of power is delivered for a small input grid voltage.

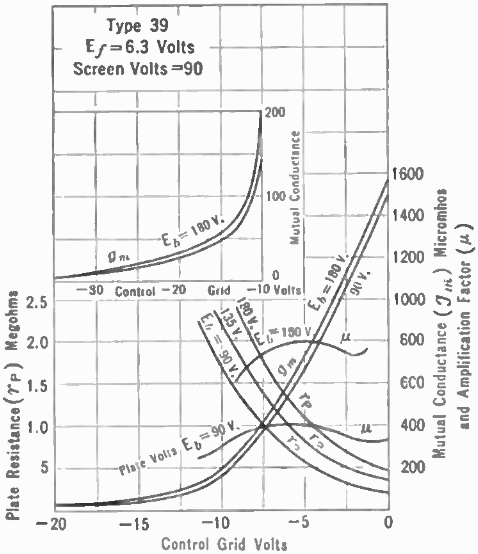


FIG. 135. Characteristic of variable-mu or super control tube.

170. Variable-mu tubes. Early receivers utilizing screen-grid tubes suffered from many troubles. Among others was the production of cross modulation or cross talk by strong undesired signals. These tubes had such a short range of grid voltage over which they could work that a strong signal would force the grid voltage to the point where the alternating plate current would cut off. This resulted in severe distortion, evidenced by blurbs or gasps of undesired modulation crashing through the desired program, or by hum entering from the power supply.

Late in 1930 a new screen-grid tube made its appearance and became quite important in the following year. This was the variable-mu or super control tube. It had a very long, fairly

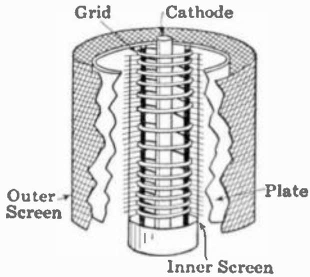


FIG. 136. Note how the grid winding has variable pitch from top to bottom.

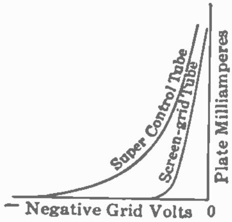


FIG. 137. Difference between variable-mu and sharp cut-off tube. Variable-mu tubes are said to have a "remote" cut-off.

flat characteristic at the bottom of its E_g–I_p curve. In other words, strong negative voltages on the grid did not force the plate current to zero, and cross modulation was prevented.

Because of the very long even characteristic, the tube was nicely adapted for automatic volume control, for radio- and intermediate-frequency amplifiers, and for recording signal strength, or loud-speaker output, or other measurements where large ranges of current or voltage, etc., were to be measured.

The tube gets its characteristic from the way the grid is wound, not perfectly regular or even along the length of the winding space, but with a wide spacing at one portion and close spacing at another. The characteristic may be controlled in manufacture by varying the pitch of the winding or the manner in which the wide and close spacing is put on the grid-wire supports.

171. Multi-unit tubes. It is possible to put two tubes in one mechanical structure and to put the combination in one envelope. Some tubes are entirely distinct with separate cathodes and means to prevent electrons from straying from their desired paths; other tubes share a cathode; and in still other tubes extra grid structures are added to exercise additional control functions, as in converter tubes.

Putting two tubes in one envelope conserves space, shell material, and bases but rarely does a circuit which needs two tubes work as well if the tubes are combined in this way.

In the 6L7, for example, there are seven electrodes. This tube is employed as a mixer tube in a superheterodyne circuit. It mixes signals coming from the antenna with signals generated in an oscillator within the tube. These two signals are at different frequencies, and in the output of the tube occur signals of still another frequency.

172. Metal tubes. The tube elements may be mounted with a glass or a metallic envelope. Modern receivers use both types. The metal-envelope tubes are smaller and better shielded than glass-envelope tubes. They are more expensive to make which may explain why they have not superseded the glass types. Fundamentally they perform exactly as their counterparts in glass envelopes.

Several kinds of bases and sockets are utilized, but since the tube operations are not controlled by the kind of base, this matter will not be discussed here.

173. Tube operation. In practice, then, tubes may be operated from batteries, from d-c or a-c lines. The tubes may have filaments which produce the electrons or a metallic cylinder to produce the electrons. Inside this cylinder is a heater filament to bring the cathode (cylinder) to the emitting temperature. The heater-type tube may be operated either on alternating or on direct current without danger of hum appearing in the output. Filament-type tubes cannot be operated on alternating current except in the final output stage, since otherwise hum produced in the filament will be amplified by succeeding stages and cause noise in the output.

If several tubes are to be operated in a circuit, the electron-emitting filaments or the heater filaments may be wired in series or in parallel. If the source of filament power is of low voltage, a battery, or a step-down transformer, the filaments are wired in parallel. Each tube gets the same voltage and the current required from the source is the sum of the currents taken by the individual tubes. If the source of filament power is of high voltage, a house-lighting circuit, for example, the tubes are frequently wired in series. Each tube, then, gets the same current and the total voltage required to heat the filaments properly is the sum of the voltages appearing across each tube.

Filament voltages vary from 1.4 to 50. The 1.4-volt tubes are designed to operate directly from a dry cell: the 2-volt tubes operate directly from a single storage cell; the 6.3-volt tubes may be operated directly across a 6-volt storage battery. If these tubes are to operate from higher-voltage sources some means must be provided to limit the flow of current through the filaments. Thus if a 1.4-volt tube is to be operated from a 2-volt battery, a series resistance must be provided. If several tubes are to be operated with their filaments in series across a line whose voltage is greater than the sum of the tube voltages required, a voltage-dropping resistor must be employed.

The required resistance may be calculated from this formula:

$$\text{Required resistance} = \frac{\text{supply volts} - \text{voltage required by tube}}{\text{current required by the tubes}}$$

Thus if two 32's, two 30's, and two 31's are to be operated from two dry batteries in series, the resistor is equal to $(3 - 2)/0.56$, approximately 1.8 ohms.

If one 6SA7, one 6SK7, one 6B8, one 25A6, and one 25Z6 are to be operated from a 117-volt line, the resistance equals $(117 - 68.9)/0.3$, or 160 ohms.

174. Grid-bias arrangements. A tube operated from batteries may get its proper grid-bias voltage from a battery. This is known as a C battery. A battery, however, is inconvenient and every means are taken to avoid their use except in those circumstances where batteries are the only practical source of power. Then the grid bias is obtained in other ways.

One of the simplest manners of placing a steady negative voltage on the grid is by means of a resistor through which the plate current of the tube flows. The voltage drop ($I \times R$) along this resistor is of such a polarity that the negative end can be con-

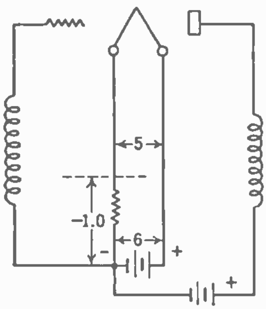


FIG. 138. Obtaining grid bias by means of filament current flowing through a resistance.

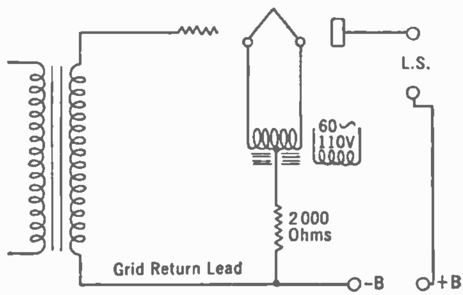


FIG. 139. Obtaining grid bias by means of plate current flowing through a resistance.

nected to the grid and thus give the grid a negative bias with respect to the filament or cathode. This resistor is usually connected between the negative end of the plate supply voltage and the cathode, although the voltage drop along a resistor between battery and filament in battery-operated circuits may be used. Thus in Figs. 138 and 139 may be seen the two methods of providing bias. In one case the plate current flowing through the "cathode-bias resistor" provides the voltage; in the other the resistance required to lower the battery voltage to the voltage required by the tube filament is utilized.

Although any current flowing through any resistance can be used, and therefore the plate currents of several tubes flowing through a common resistor may be utilized as bias, it is common practice to have each tube provide its own bias and thus to isolate its plate current from that of other tubes.

In series filament circuits, benefit may be taken of the voltage drop across tube filaments to bias one or more grids. Thus in Fig. 140 the filaments are wired in series. The same current flows through each filament and the total voltage required is the sum of the individual tube filament voltages, plus the voltage drop across the 10-ohm resistors. If each tube requires a quarter am-

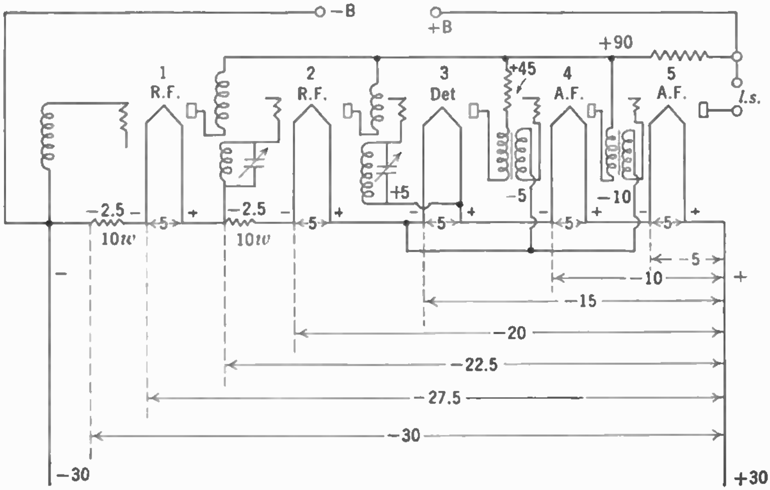


FIG. 140. A series filament circuit in which the voltage drop across a tube filament is used as another tube's grid bias, etc.

pere, then this current (250 ma) must be provided and the voltage is 5 times 5 or 25 volts (since each tube filament requires 5 volts) plus the voltage drop across the bias resistor for the first and second tubes. The current enters one end of the string of filaments and leaves at the other.

As we go along the series of filaments there is a series of voltage drops and these voltage drops may be used as biases.

For example, suppose the final tube (No. 5) is a power tube requiring a C bias of 10 volts. We note that the negative terminal of the filament of tube 3 is 10 volts more negative than the negative terminal of tube 5 because there is a 5-volt drop across the filament of tube 4 and an additional drop of 5 volts across tube 3. We attach the grid circuit to this point in the circuit. If tube 4 requires only 5 volts C bias we can attach its grid circuit to the same point in the circuit because so far as tube 4 is concerned this point is only 5 volts negative. If the detector tube 3 requires a C bias of positive 5 volts we can attach its grid circuit to the positive leg of its own filament.

Suppose the first two tubes in the set do not require 5 volts bias but some value less than this. All that is necessary is to insert a resistor in the circuit ahead of that tube so that the negative drop in voltage in this resistance will be utilized. Thus in Fig. 140 the 250 ma through a resistance of 10 ohms will produce a drop of 2.5 volts. The grid circuit should be attached as shown.

175. Modern series filament receivers. The "Universal" circuit. For years the series filament style of wiring was dormant; then it blossomed forth again and became of tremendous importance. The heater-type tube made the new circuits possible; the circuits themselves made new tubes of high efficiency necessary and stimulated the tube designers to improve their product.

The new circuits were built around the idea that a truly universal set could be made, i.e., one which would work interchangeably on alternating or direct current. Although the number of homes in the United States having direct current is few, nevertheless the idea took hold and hundreds of thousands of these receivers have been built. They are, in general, small sets selling at low prices. Early models suffered from many mechanical and electrical faults. They brought radios to many homes which could not afford the more expensive models, and thus served a very useful purpose.

All the tubes in present-day a-c–d-c receivers have heater-type cathodes. The filaments for the heaters are wired in series and in series with the string of filaments is a resistor designed to lower the line voltage to the value required by the series of filaments. Tubes with higher heater voltages have been produced so that the voltage to be lost in the series resistance is decreased or eliminated. Instead of dropping the resistance by means of a single concentrated resistance, the cord which connects the receiver to the light socket had the resistance contained in it. This extended the surface from which the heat generated in the resistance could be dissipated.

176. Screen voltages. Voltages for screen grids, which are usually at lower potential than that of the plates of the tubes, are obtained by connecting a voltage-dropping resistor to the positive end of the power supply. The screen current flowing through this resistor produces a drop in voltage. The power supply voltage minus this *IR* drop is the desired screen voltage.

All such voltage-dropping resistors are by-passed with condensers so that any a-c voltage flowing in the grid or screen circuits will not flow through the resistors but will be returned directly to the cathode of the tube.

177. Cathode-heater connections. In heater-type tubes, it is common practice to connect the cathode to the center tap of a transformer winding supplying heater voltage or to the center of a 50-ohm resistor across this winding. It is sometimes desirable to have the heater somewhat positive with respect to the cathode to prevent any electrons from flowing from heater to cathode and thereby producing a-c hum. This voltage is of the order of 10 volts. In general, however, it is desirable to have no high potential difference between cathode and heater.

CHAPTER X

THE TUBE AS AN AMPLIFIER

The essential property of a vacuum tube with a control grid in it is the ability to amplify voltages or currents. Small voltages put on the input (grid-cathode path) appear in an output circuit (plate-cathode path) in amplified form. How does the tube amplify?

We have already learned how to gather data and from the data to draw the characteristic curve of an amplifier tube. These data consist of the relation between the plate current as a function of the grid voltage when the plate voltage is held fixed in value (I_p–E_g curves) and the relation between plate current and plate voltage when the grid voltage is held fixed at some constant value (I_p–E_p curves). These curves do not tell us, directly, how the tube amplifies.

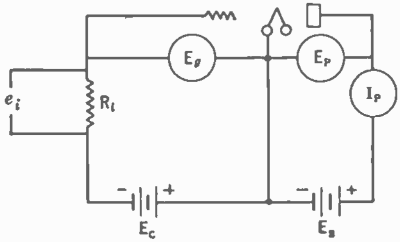


Fig. 141. When e_i is applied, I_p consists of an alternating current as well as steady plate current.

Suppose, however, we draw a single I_p–E_g curve, as in Fig. 142. This is done by collecting data as follows. Fix the plate voltage at some value as indicated by the tube manufacturer's data. Then read the plate currents with various values of grid voltage (dc) and plot these values, drawing a line through the points. This curve shows that if the grid voltage is —5 the plate current is 3 ma; if E_g equals —4, I_p equals 3.6; and if E_g equals —6, I_p equals 2.4. Note that the higher negative values of grid voltage permit less current to flow in the plate circuit.

Now, let us place two voltages on the grid-cathode path, one from a battery (C bias) in such a direction that the grid is negative with respect to the cathode by some fixed amount, say 5 volts. The plate current is now 3 ma. The other voltage will be

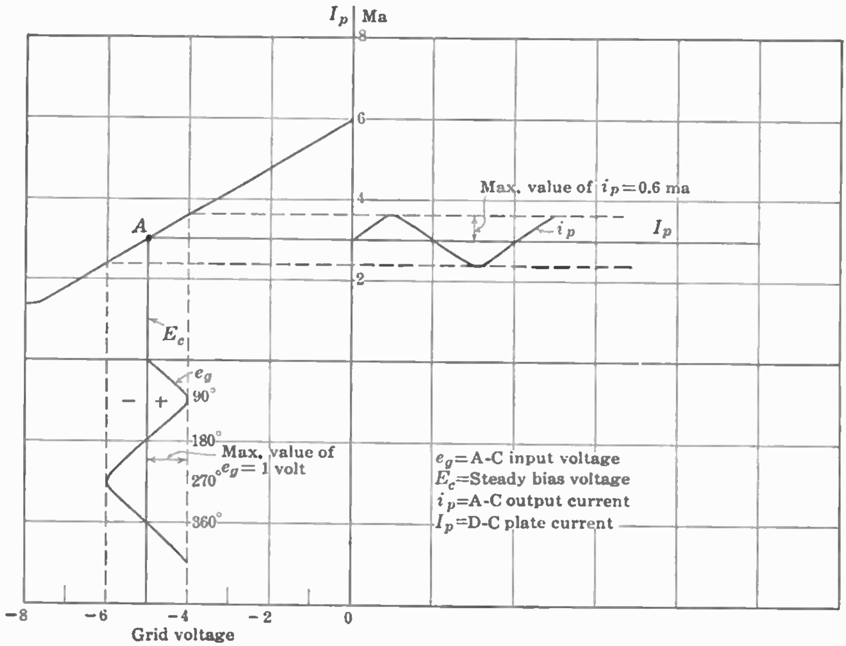


FIG. 142. What happens in the plate circuit of an amplifier tube when an alternating voltage is applied to the grid—an alternating current appears which may be used to produce an amplified voltage in the plate circuit load.

an a-c voltage with a peak value of 1 volt. Remembering that an a-c voltage goes through cycles of maximum and minimum values we can see that at some instants this a-c voltage adds to the negative C bias and at other instants (from 0 to 180°) subtracts from this C bias, because in those instants it is on the positive half of its cycle. At other instants the a-c voltage is zero and therefore adds to or subtracts nothing from the steady C-bias voltage obtained from the battery.

If the total grid voltage (the dc plus the ac) is changing, the plate current will change, increasing and decreasing from its steady value of 3 ma obtained when there is no alternating current. There is, in the plate circuit, therefore an alternating current as well as a direct current and both can be measured by appropriate instruments. This can be looked at in another way. The plate current can be considered as an alternating current with a maximum value of 0.6 ma. A d-c meter will read 3 ma, and an a-c meter $0.6 \times 1/\sqrt{2} = 0.42$ ma rms.

The point A on the curve corresponding to the C-bias point is called the operating point and the C bias determines this point on the characteristic curve about which all the tube operations take place.

If the a-c input voltage is a 60-cycle voltage, the a-c plate current will be a 60-cycle current; and if the frequency is 1000 cycles the plate current will be at 1000 cycles.

Now a note on nomenclature. Since there are two grid voltages and two plate currents, it is important to be able to tell them apart in any discussion of the tube. In the rest of this book we will use large letters (E, I) to indicate d-c values and small letters (e_g, i_p) to indicate a-c values, and these values will represent the maximum value instead of the effective value unless otherwise indicated.

178. How the tube amplifies. Still we have not discovered how the tube amplifies; but this is very simple.

Suppose we place a resistance in the plate circuit and place an a-c voltmeter across this resistance. Naturally if the only voltage in the grid circuit is the C bias, no voltage will be measured across the resistance with the a-c meter because there is no alternating current in the plate circuit. If, however, we turn on the a-c source in the grid circuit, a-c current will flow in the plate circuit, this a-c current flowing through the resistance will produce a voltage drop along this resistance (IR drop) and the a-c meter will indicate it.

If the conditions under which the tube operates are properly chosen the a-c voltage measured across the resistor will be greater than the a-c voltage placed upon the grid-cathode circuit. The input voltage has been amplified.

The resistance is called the **load** of the tube, and the value of this resistance in relation to the resistance of the tube has much to do with the kind and amount of amplification secured.

179. Resistance output load. If we put a resistance R_o in the plate circuit of a tube we may adjust conditions so that distor-

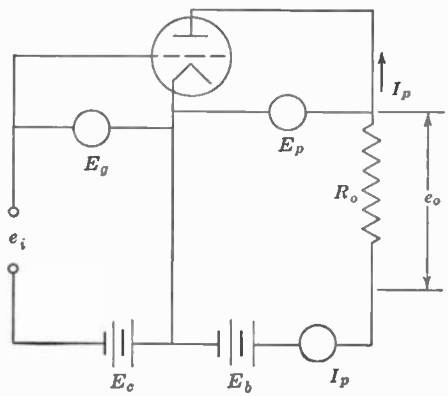


FIG. 143. Amplifier tube with a resistance load. Under proper conditions, e_o will be a magnified replica of e_i.

tionless amplification results, that is, the wave form of the output voltage is exactly like that of the input voltage. These conditions are: (*a*) the C bias and the magnitude of the input a-c voltage must be such that only the straight part of the characteristic curve is utilized; and (*b*) the load resistance R_o must be high in value compared to the tube resistance.

Let us look at the circuit in Fig. 143 rather critically. It is the fundamental amplifier circuit. The plate voltage, E_p, as measured by a voltmeter connected from plate to the negative filament lead is no longer the voltage across the B battery. It is less than this value by the voltage drop in the resistor R_o, i.e., the *IR* drop caused by the plate current. The voltage actually on the plate then is

$$E_p = E_b - I_p \times R_o \quad [1]$$

If, for example, the B battery voltage equals 180 volts, R_o equals 100,000 ohms, I_p equals 0.5 ma, $I_p \times R_o$ equals $0.0005 \times 100{,}000$ or 50 volts, and E_p equals 180 — 50 equals 130 volts.

Now it can be seen that any variation in I_p causes a variation in the IR drop across R_o, and hence the plate voltage E_p must change according to equation (1). For this reason any variation in the grid bias will cause a variation, not only in the plate current of the tube but also a variation in the plate voltage as well. We cannot use the "static" characteristic to determine what the output voltage looks like, because the plate voltage is no longer constant, but changes in instantaneous value with each instantaneous value of the grid voltage. We must employ a new kind of characteristic curve, known as a "dynamic" characteristic curve.

180. Dynamic characteristic curves. A series of dynamic curves is shown in Fig. 144. They were taken by placing resistances in series with the plate battery and a 71-A power tube maintaining the voltage on the plate equal to 180 when the C bias was 38.5 by increasing the plate battery voltage (E_b in Fig.

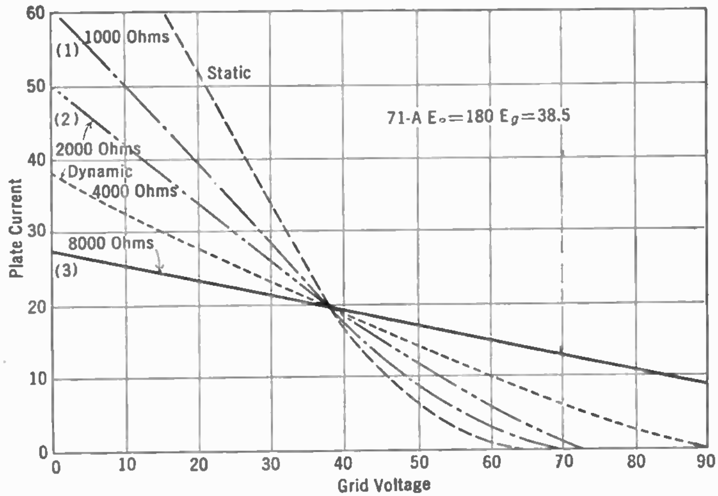


FIG. 144. Dynamic characteristic curve secured by placing various resistances in the plate circuit.

143) to compensate for the loss in voltage across R_o. It will be noted that these curves are much flatter and longer than the static curves. This means that plate current variations are much smaller in magnitude under the same grid voltage variations. The transconductance of the circuit is not as high as the value for the tube alone—but the slope of the curve tells us the alternating current which will flow through the resistor when a given a-c voltage is applied to the grid, and these curves are therefore more useful than the static curves.

Experiment 1–10. Connect as in Fig. 142 a tube of the 37 type, a plate battery, and a resistance. Short-circuit terminals for e_i. Measure and plot the current in the plate circuit as the grid voltage is varied. Then change the resistor and repeat. Use values of 8,000, 16,000, 24,000, and 48,000 ohms.

181. Phase of e_g, e_p, and i_p. When the grid of the tube is made more negative the plate current decreases; when the grid is made less negative the plate current increases. When the plate current increases, however, the voltage drop, I_pR_o, across the resistor, R_o, increases and for this reason the voltage E_p actually on the plate decreases. That is, the plate *current* increases when the grid voltage increases (becomes less negative), but on the contrary the plate *voltage* decreases when the grid voltage increases. Thus we may say that the plate current variations are in phase with the grid voltage variations whereas the plate voltage variations are out of phase with the grid voltage variations. These phase relations are shown in Fig. 145.

182. Magnitude of the amplified voltage. There are several variable factors in a one-stage resistance-coupled amplifier, as shown in Fig. 142. The grid bias, E_c, the plate battery voltage, E_b, the load resistance, R_o, all may be changed as desired. With a fixed value of E_c and E_b, the plate resistance of the tube, R_p, is fixed. If we go into the laboratory and measure the voltage across a load resistance with a given value of a-c voltage on the grid we shall determine the voltage amplification of the stage. Then if we change the load resistance and measure the output voltage across R_o, we shall get data for a curve which shows that the amplification increases as the load resistance increases.

but which finally comes very near a certain fixed value numerically equal to the amplification factor of the tube. Increasing the load resistance beyond this point has little effect on the amplification.

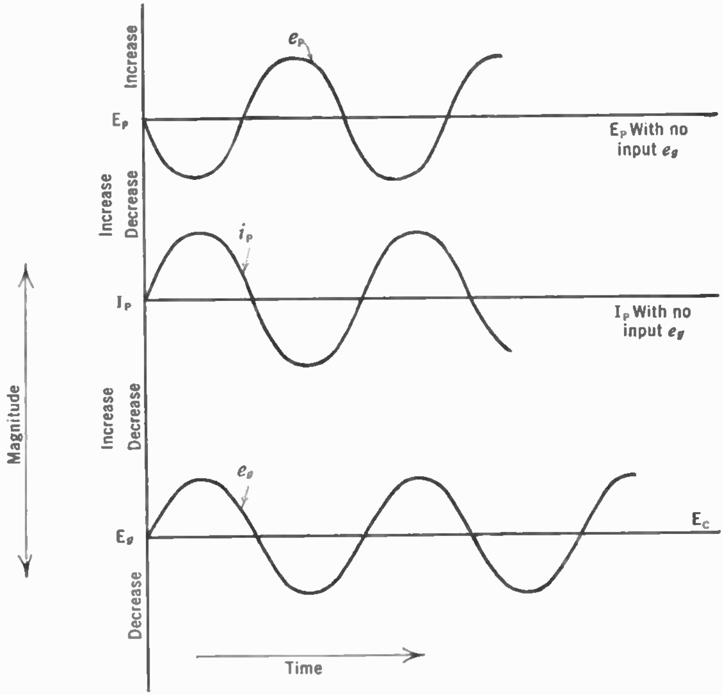


FIG. 145. Phase relations between a-c grid and plate voltages and plate current.

Because each change in R_o will change the plate current, we must adjust the plate battery each time so that the voltage actually on the plate (E_b minus the voltage drop along the load resistance) is the same.

The amplification that will be realized in a laboratory experiment of this kind may be calculated from this formula.

$$\frac{\mu R_o}{R_o + R_p} = G \quad \text{(voltage amplification)} \qquad [2]$$

and the alternating plate current from

$$\frac{\mu e_g}{R_o + R_p} = i_p \qquad [3]$$

and the a-c voltage across the load from

$$\frac{\mu e_g R_o}{R_o + R_p} = Ge_g = i_p R_0 \qquad [4]$$

where e_g equals grid voltage.

The student should derive these equations by using the equivalent circuit of Fig. 123 in which R_o is connected to the output terminals.

The maximum voltage amplification takes place when the external resistance, R_o, is infinite. Practically, however, 75 per cent of the maximum amplification is obtained when R_o is three times as great as R_p. For example, if R_p is 10,000 ohms, a load resistance of 30,000 ohms will realize 75 per cent of the μ of the tube. The maximum possible value is the amplification factor of the tube. Thus if a tube especially made for resistance-coupled amplifiers having an amplification factor of 30 is used, the maximum possible amplification will be 30, but under actual operating conditions the voltage amplification, G, of the complete circuit is about 20.

183. Power output. The a-c power in the load resistance is calculated as follows.

$$P = i_p^2 R_o$$

$$i_p = \frac{\mu e_g}{R_o + R_p}$$

$$P = \frac{(\mu e_g)^2 R_o}{(R_o + R_p)^2} \qquad [5]$$

This is a maximum when the two resistances are equal, that is, when

$$R_p = R_o$$

Then the power

$$P = \frac{\mu^2 e_g^2}{4R_p} \qquad [6]$$

where e_g = rms input voltage; and

$$P = \frac{\mu^2 E_g^2}{8R_p} \qquad [7]$$

where E_g = peak or maximum input voltage.

This power which is fed into the load resistance must come from the plate battery, because the tube itself generates no power—it acts merely as a transformer or valve which takes small voltages and currents on its input and turns out larger voltages and currents to its output circuit. The power in the input circuit must come from the circuit to which the tube is attached. The power in the output must come from the batteries. The tube therefore releases power from the batteries in a form which is an exact replica of the power utilized in the input circuit to which the tube is attached. The tube itself consumes power from the battery. This power heats the plate and is wasted power. It is equal to I_pE_p.

184. Power amplification. Ordinarily the grid of a tube is biased so highly negatively that practically no current flows in the grid circuit. The tube input circuit itself then draws little or no power. If, however, the a-c voltages are fed into the tube through a resistance, some power is expended in this input resistance. If the values of resistance and current are known the power may be calculated. The power amplification will be the output power divided by the input power. The fact that a tube is a power multiplier distinguishes it from a transformer which is merely a power transmitter, taking power at one current and voltage and passing it on at another current and voltage. The transmitted power is never more than or even equal to the input power. It is always less; unlike a tube, the transformer cannot amplify power or release it from local batteries. The power output in a tube amplifier is proportional to the square of the voltage on the grid. Thus doubling the input a-c voltage quadruples the output a-c power.

Example 1–10. Four ma of current at 1000 cycles are fed through a 10,000-ohm resistance in series with the grid of a tube and its C battery. In the output is a 2000-ohm resistor. The amplification factor of the tube is 3, its internal plate resistance is 2000 ohms. What is the power output, what is the voltage across the output, what is the voltage and power amplification, and what power is lost on the internal resistance of the tube?

Let the input voltage $e_i = i_i R_i = 0.004 \times 10{,}000 = 40$ volts rms

$$\text{voltage amplification } G = \frac{\mu R_o}{R_o + R_p}$$

$$= \frac{3 \times 2000}{4000} = 1.5 \text{ times}$$

The output voltage $e_o = e_i \times G = 40 \times 1.5 = 60$ volts rms

$$\text{Power output } P_o = \frac{\mu^2 e_i^2}{4R_p}$$

$$= \frac{9 \times 40^2}{4 \times 2000} = 1.80 \text{ watts}$$

$$\text{Power input } P_i i_i^2 R_i = (0.004)^2 \times 10{,}000$$

$$= 16 \times 10^{-6} \times 10{,}000$$

$$= 0.16 \text{ watt}$$

Power amplification $= P_o/P_i = 1.8/0.16 = 11.25$ times.

Since i_p flows through both R_o and R_p and since $R_p = R_o$, a-c power lost in R_p = power lost in R_o = 1.8 watts.

Total power taken from batteries = 3.6 watts.

$$\text{Efficiency} = \frac{\text{useful power}}{\text{total power}} = \frac{1.8}{3.6} = 50 \text{ per cent}$$

Problem 1–10. Assume a tube with a load resistance of 12,000 ohms and an a-c grid voltage of 3 volts (peak). The μ of the tube is 8, its R_p is 12,000 ohms. What is the maximum value of the alternating plate current? (Use formula 3.) What is the rms value? What a-c power is developed in the load resistance? What voltage appears there?

Problem 2–10. What is the voltage amplification in the above circuit? (Use formula 2.) How much would it be increased if the load resistance were increased to 36,000 ohms? How much would this change the power output?

Problem 3–10. The plate resistance of a certain "high μ" tube is 60,000 ohms and its amplification factor is 20. What plate resistor value in ohms must be used to realize a voltage amplification of 15?

Problem 4–10. A certain tube has an internal plate resistance of 5000 ohms, its amplification factor is 8; it is worked into a load of 5000 ohms. Plot the output power in the load resistance as the input a-c voltage is increased from 1 to 8 volts (peak). (Use formula 7.)

Problem 5–10. What is the voltage amplification in Problem 4.

Problem 6–10. The power output of a tube when worked into a load whose resistance is equal to the tube resistance (when the input grid voltages are maximum volts) may be written as $\frac{\mu^2}{8R_p} \times e_g^2$. If we divide this expression by e_g^2 we shall have a figure which gives us the power output in watts per (volt input)^2. Make a table of such values for representative tubes used at the present time, getting the data from manufacturers' information.

Problem 7–10. The normal C bias for a certain tube is 9 volts. What is the largest rms voltage that may be applied to its grid before the grid goes positive?

185. Amplifier overloading. The conditions for undistorted amplification are: (*a*) the C bias and magnitude of the a-c input voltage must be such that only the straight part of the tube characteristic load, and (*b*) the load resistance must be large with respect to the internal resistance of the tube R_p. Let us examine these conditions. Suppose first that the C bias is too great, as in Fig. 146*a* so that a curved part of the characteristic is used. Suppose, at the start that there is no a-c voltage on the grid. The plate current I_p will be as indicated on the drawing. Now let the a-c voltage be impressed on the grid. The instantaneous plate current, i_p, will increase when the negative bias is decreased by the addition of the positive half of the input a-c wave to the negative steady bias. Similarly, i_p will decrease from the steady no-input-signal value as the grid bias is increased by having added to the steady C bias the negative half of the a-c input wave. Note, however, that at the most negative portion of the input voltage cycle, no current at all flows in the plate circuit. The plate current has been *cut off*.

The current flows longer on the positive portion of the cycle than it does on the negative part of the cycle, and the average value will be something between zero and the maximum value attained. This will be greater than the current which flows when no input voltage is applied. A meter in the plate circuit will show an increased current when a-c voltage is applied to the grid under these conditions compared with the current that flows

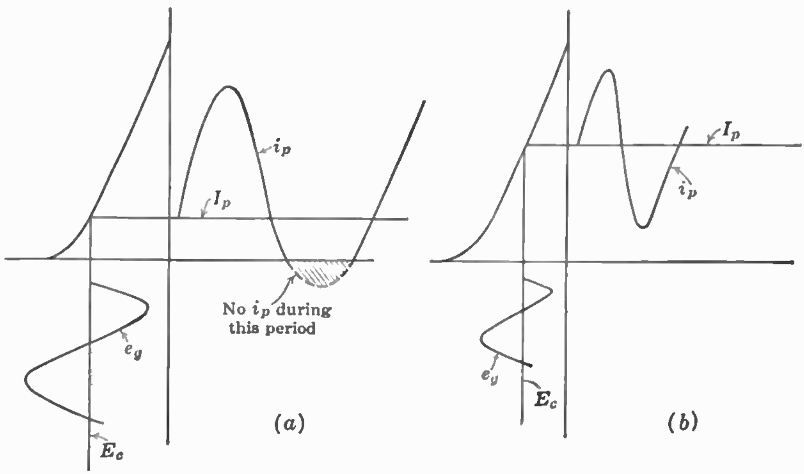


FIG. 146. Effect of using too great bias voltage causing distortion. Correct bias is indicated in (*b*).

without an input signal (or without *excitation,* as the engineers say).

This is a sure sign of distortion—an increase or decrease in plate current as read by a d-c meter when the grid is excited. A glance at the plate current curve in Fig. 146*a* is all that is necessary to prove that distortion is present: the plate current wave does not resemble that grid voltage exciting wave. In this case the remedy is to decrease the C bias, permitting more no-signal plate current to flow (Fig. 146*b*).

Distortion may be caused if the C bias is correct, say at the center of the E_g–I_p curve, but if the input a-c voltage is so great that the grid is still forced so negative, at times, that no instantaneous plate flows.

The C bias may be too low so that on the positive half cycles of input voltage, the grid is forced positive. The remedy in this case it to reduce the voltage applied as excitation, or to increase the C bias. In the latter case the negative part of the input voltage may force the operating point down onto a curved part of the characteristic and distortion again occurs. The remedy now is to increase the plate voltage. This may cause such a large steady plate current to flow that the plate of the tube heats.

Thus there are a number of conditions that must be met in designing and operating correctly an amplifier.

186. Distortion due to curved characteristic. When a load is in the plate circuit of a tube its characteristic becomes flatter and its straight part longer, but at the lower part of the curve there is still a bend and throughout the E_g–I_p graph there is considerable curvature unless the load resistance is high. Large input voltages, therefore, may cause distortion because of these curved parts of the characteristic.

Although the maximum power output is obtained from a tube when the load resistance is equal to the internal tube resistance, the maximum *undistorted* power output is attained when the load resistance, R_o, is twice as great as the tube resistance, R_p. Some power is sacrificed under these conditions but, as the curve in Fig. 147 shows, the loss is not great until the output load resistance is several times the tube resistance. If the load resistance is lower than the tube resistance distortion due to curvature of the characteristic is bound to occur. Even with a load equal to twice the tube resistance there is considerable curvature at the bottom of the characteristic and so input voltages high enough to drive the plate current too low must not be applied. The power output when R_o equals $2R_p$ is

$$P = \frac{2}{9} \times \frac{\mu^2 e_g^2}{R_p} \qquad [8]$$

where e_g is rms input voltage.

Distortion frequently occurs at low audio frequencies. There are two reasons for this. In the first place the excursions of the operating point may be somewhat greater on these frequencies because of the greater power in them than in high tones. In the second place, the loud speaker may have an impedance which varies with frequency, becoming low at low frequencies, probably

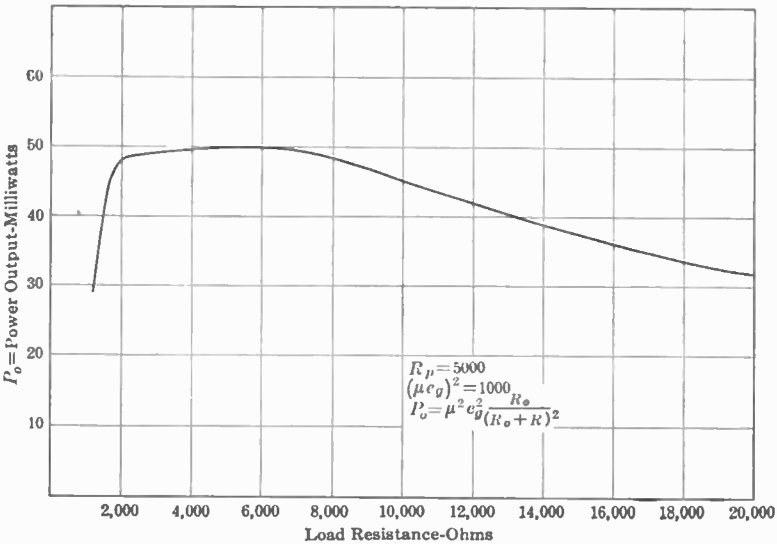


FIG. 147. Relation between load resistance and power output. Maximum power is transferred from tube to load when load and tube resistances are equal.

lower than the tube resistance. Thus distortion due to curvature as well as loading distortion may occur on low notes.

The solution is to use a power tube which will easily handle the greatest input grid voltages that will be encountered, and secondly, to use a power tube with a low internal resistance so that the load impedance will, at the lowest frequency, be larger than the tube resistance, or to use an output transformer with a turns ratio such that the impedance of the speaker at the lowest audio frequency is higher than the tube resistance.

187. Distortion due to positive grid. Why does distortion occur when the grid of an amplifier tube is permitted to swing positive on loud signals? If we plot the plate current against grid voltage, as the C bias, E_c, in Fig. 143 is changed, we find that, when the grid goes positive, the plate current curve no longer is straight; it slumps off and soon becomes almost horizontal. Distortion will occur on the portions of the input voltage cycle when the grid is instantaneously positive.

The reason is as follows. When the grid becomes positive with respect to the negative side of the filament, it begins to attract electrons to it and these electrons constitute a flow of current. Current flows in the grid circuit, and must go through the input resistance R_i. (See Fig. 141.) There is, then, an IR drop in the grid circuit, so that the voltage actually on the grid is not the applied grid voltage e but this value minus the drop in the input resistance—just as the plate voltage is not the voltage of the B battery but this voltage minus the drop in the output load resistance. The greater the input voltage the more the grid goes positive, the greater the voltage drop in this resistance and the greater the bias voltage that is actually on the grid because of the fact that the grid draws current.

The grid must never be permitted to go positive in ordinary circuits. Some circuits have been developed in which the grid is not only permitted to go positive but is forced to do so with a consequent greater power output. Such circuits (Class B) are used where high efficiency is desired, i.e., a high ratio of output power to power lost in the tube.

188. Amount of distortion caused by overloading. What is the result of operating amplifier tubes over a curved part of the characteristic? The result is an output wave form different from the input wave. Distortion is taking place whenever the magnified output voltage is not exactly, in all respects, like the input voltage. When the direct plate current of an amplifier tube changes under the action of an input a-c grid voltage, distortion is taking place; the form of the wave in the output circuit does not look like the form of the input wave. This output wave may be very complex.

When a tube distorts, it adds certain frequencies to the output circuit which were not present in the input. All these frequencies added together at any instant produce a wave form which looks unlike the original wave form.

How can we tell the amount of distortion to be expected with given tube and circuit constants? It is not difficult to determine

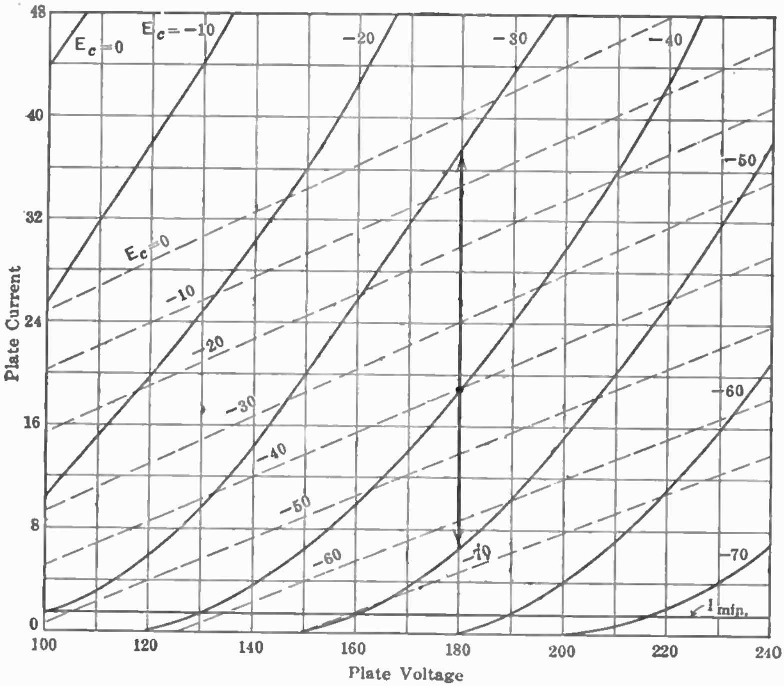


FIG. 148. Static characteristic of power tube. Dashed lines represent characteristic with a load in the plate circuit.

what percentage of distortion will occur. Here is another place where the characteristic curves come in handy; this time the E_p–I_p curves are used.

Let us look at Fig. 148 which gives the characteristic of a 71-A type of power output tube with zero load in the plate circuit. The vertical 180-volt line is the working line for this tube. The intersection of this line with the 40-volt grid-bias line gives the plate current, 19 ma. If an a-c voltage is placed on the grid

—in addition to the 40-volt d-c bias voltage, of course—say of a maximum or peak value of 10 volts, the actual grid voltage will vary 10 volts up and 10 volts down from the 40-volt bias, that is, at one instant it will be —30 volts and at another —50 volts. Looking at the appropriate curves in Fig. 148 we see that when the grid voltage E_c is —30 the plate current is 38 ma and when the voltage is —50 the plate current is 6 ma. These represent changes of 19 ma (38 — 19) and 13 ma (19 — 6) respectively. Although the input voltage is symmetrical about the 40-volt bias voltage, the plate current is obviously not symmetrical—there is a greater change in current (19 ma) in one direction than there is in the other (13 ma). The output curve would not be a magnified replica of the input curve. Harmonics would appear in the output.

Now when a load resistance is placed in the plate circuit, the straight part of the curve becomes longer and flatter as shown in the dashed lines of Fig. 148, and as more and more resistance is added the actual working lines rotate about the intersection of the 180-volt plate voltage line and the grid-bias line which for this curve was 40 volts. The plate current changes are no longer as great but they occur symmetrically about the normal plate current value which is governed by the plate voltage and the bias voltage. Thus for a given value of load resistance such that the dotted lines in Fig. 148 represent the plate current as controlled by plate and grid voltages, the same input voltage 10 (peak) causes the plate current to increase from 19 to 24 ma in one direction and to decrease from 19 to 14 ma in the other—a symmetrical variation.

It is a simpler process to determine the plate current variations with a given plate load resistance by the method of plotting the "load line." To do this a family of E_p–I_p curves is necessary as in Fig. 149. The load line gives the plate current at any given set of E_c and E_p values and with a given resistance load. It is determined as follows: It must pass through the intersection of the $E_p = 180$ and $E_c = -40.5$ lines, or A in the figure, because these are the recommended values for this tube, a 71-A. Through this point A draw a line parallel with the plate voltage axis. Make it any convenient length. Then at the end of this line erect a perpendicular line of such length that $YX/AY = 1000/R_o$ where R_o is the plate load resistance, in this case 3900 ohms. Through X draw a line through A and extend to the $E_c = 0$ line and the $I_p = 0$ line as in the figure.

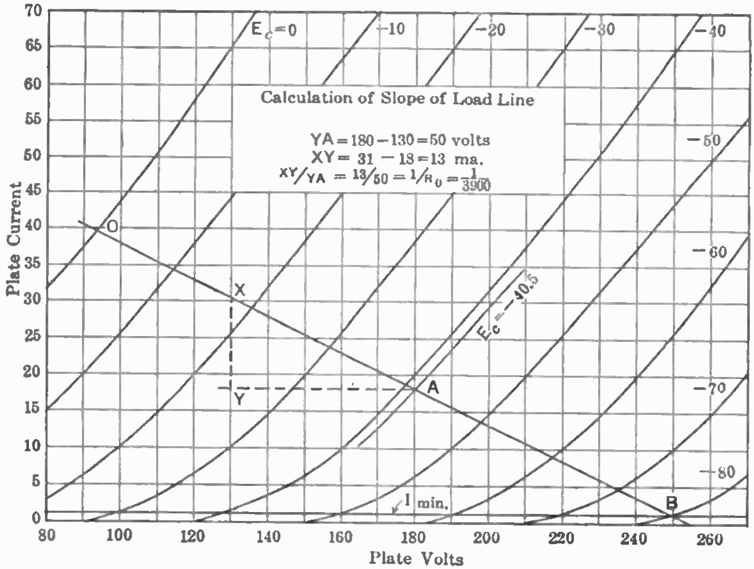


FIG. 149. Method of plotting "load line" of a power tube. From such a curve the entire performance of an amplifier can be determined.

The reasons for this bit of apparent sleight-of-hand are as follows. The slope of this load line must be the reciprocal of the load resistance, i.e., if the load resistance, R_o, is 3900 ohms, the slope of this line must be 1/3900 ohms. The slope of the line will be equal to the vertical side of a triangle divided by the horizontal side of this triangle which has for the third side either the load line, or a shorter line parallel to the load line.

Thus, slope of load line:

$$\frac{\text{Vertical}}{\text{Horizontal}} = \frac{1}{R_o} = \frac{I\ (\text{amp})}{E\ (\text{volts})} = \frac{I \times 1000\ \text{ma}}{E\ \text{volts}}$$

The value of plate current corresponding to any set of E_p and E_c values with this particular load resistance may be found from this line. Thus with $E_c = 0$ and $E_p = 92$ volts, $I_p = 39$ ma, with $E_c = -60$ and $E_p = 218$, $I_p = 9$ ma. Thus if the bias voltage is 40.5 and the peak voltage applied to the grid is 10, the actual grid voltage varies from 40.5 — 10 or 30.5 to 40.5 + 10 or 50.5 and the corresponding plate currents will be 24 and 13 approximately, or approximately 5.5 ma up and 5.5 ma down from the 18.5-ma value.

Now the grid must not go positive, and the plate current must not become so low on strong signals that the curved part of the characteristic is used. Thus 1.0 ma is about the lowest the plate current should go, or the value when $E_c = -80$. From —40.5 to —80 is 39.5 volts which is the peak alternating current that should be put on the grid. This input will cause the plate current to vary between 39 ma and 1 ma.

Not only does the load-line type of curve show the plate current for any instantaneous value of grid voltage, but it also will show the actual plate voltage under these conditions. Since the actual plate voltage is equal to the plate battery voltage minus the voltage drop in the load resistance, the load-line curve will also show the voltage across the load for any instantaneous value of grid voltage.

In Fig. 149, 18 ma of plate current flows when the grid voltage is —40.5 and the plate voltage is 180. But since there are also 18 ma flowing through the load resistance and causing a voltage drop there, the battery voltage must be higher than the 180 volts on the plate of the tube. As a matter of fact, the battery volts required must be the sum of the voltage drops across the load and the tube. The diagram shows that 250 battery volts must be available to insure that the tube draws its 18 ma of plate current at a bias of —40.5. Then 180 volts will be across the tube and 250 — 180 or 70 will be across the load.

The actual plate voltage for any other value of grid voltage may be found from the curve in Fig. 149. For example, with a less negative grid voltage, say —30, the plate current will rise, causing a larger voltage drop across the load. Therefore there will be less voltage on the plate. In this case, at —30 on the grid, the plate current is approximately 23 ma, and the plate voltage is approximately 156 volts.

From a load-line curve, one can determine how much less the plate current changes with grid voltages when there is a load in the plate circuit than if no resistance exists in the plate circuit. For example, without load, if one considers the portions of the curves where they are straight and parallel to each other, a change of 10 volts on the grid produces a plate current change of approximately 17 ma. This is determined by reading the plate current for any given plate voltage, by noting where the —30 and the —40 grid-volt lines cross this value of plate voltage, say 180 volts. In this case the plate currents will be approximately 38 and 20 ma.

Now consider the load line. At —40 grid volts the plate current is 20 ma, and with —30 on the grid the plate current is 23 approximately. This is determined by following the load line until it crosses the grid voltage lines in question.

Problem 8-10. If with 20 ma flowing in the plate circuit the actual plate voltage is 172 volts, although the battery voltage is 250, what is the resistance of the load?

189. Power output calculation. More can be determined from the load line. Let us consider Fig. 150 in which a tube is to be operated under the following conditions. The grid bias will be —80, with a plate current 22.5 ma, a plate voltage 350 (at 22.5 ma), a load resistance of 6800 ohms and with a peak voltage of 40 ac on the grid. What is the battery voltage requirement, what peak voltages will occur across the load, what power will be taken from the battery, what power will be fed into the load?

The battery voltage required will be the value indicated at the point where the load line crosses the plate voltage axis, i.e., about 500 volts. This can be checked by noting that at the bias point of —80 the current is 22.5 ma, and that this current flows through the 6800-ohm load resistance causing a voltage drop there of 153 volts. This must be added to the 350 required on the plate producing a net required voltage of 503 volts.

Now suppose we impress upon the grid an alternating voltage of 40 volts peak value. The grid voltage actually on the tube, therefore, will vary 40 volts up and down from the —80-volt value. The instantaneous plate current will vary from 33 to 12

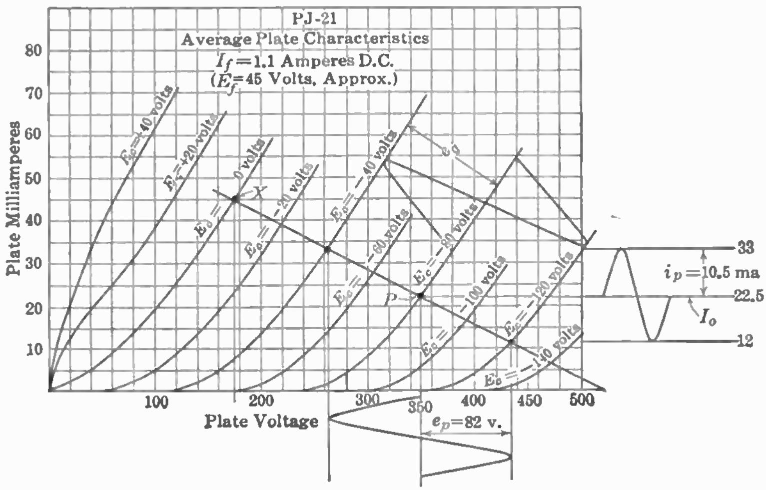


FIG. 150. Determination of all amplifier qualities from a set of I_p–E_p characteristics and a load line.

ma, with a peak value of 10.5 ma. The instantaneous plate voltage varies up and down from the 350-volt value, with the upper and lower limits given by the values of plate voltage at which the load line crosses the grid voltage lines —120 and —40. These limits in plate voltage are 432 and 262, and the peak value of the alternating plate voltage is approximately 82 volts.

The power into the load resistance is the useful tube output. It may be calculated from the formula:

$$P = \frac{1}{8}\,[(E_{p_{\max}} - E_{p_{\min}}) \times (I_{p_{\max}} - I_{p_{\min}})]$$
$$= \frac{1}{8}\,(432 - 262) \times (0.033 - 0.12)$$
$$= 0.445 \text{ watts or } 445 \text{ mw}$$

This is the a-c power conveyed to the load by the tube—not the steady d-c power lost in the load resistance whether a-c voltage is fed to the grid or not.

190. Harmonic distortion calculation. The amount of distortion produced in such an amplifier may be calculated from this load-line curve. The distortion is produced when the non-linear parts of the tube characteristic curve are used, when the load resistance is wrongly calculated (and used) for the tube in question, and when the a-c input to the grid is incorrect with respect to the steady grid bias. The distortion increases as the input excitation to the grid (a-c voltage) increases, and it is very low for low inputs and may become quite evident to the ear if the grid is over-excited.

The second harmonic distortion may be calculated from:

$$\frac{I_{p_{\max}} + I_{p_{\min}}}{2} - I_o \left(\frac{\frac{(I_{p_{\max}} + I_{p_{\min}})}{2} - I_o}{I_{p_{\max}} - I_{p_{\min}}} \right) \times 100\%$$

where I_o is the steady plate current when no signal is applied to the grid. In Fig. 150 where the excitation is low compared with the grid bias, distortion will be very low. Consider, however, the case if the grid is excited with an a-c voltage whose peak value is equal to the grid bias, —80 volts. Substitute in the above expression the values from Fig. 150.

$$\frac{\frac{0.045 + 0.0065}{2} - 0.0225}{0.045 - 0.0065} \times 100\% = \frac{0.02575 + 0.0225}{0.0385}$$

$$= \frac{0.00325}{0.0385} = \frac{3}{38.5} = 0.078 \times 100 = 7.8\%$$

This means that for every signal put on the grid having a peak value of 80 volts, there will be in the output a second harmonic of this input signal frequency equal to 7.8 per cent of value of the fundamental. Since it is generally considered that 5 per cent second harmonic distortion is readily audible to the average listener, this amount of distortion is too great for high-quality reproduction. The solution is to reduce the input voltage, to increase the plate voltage, to increase the load resistance, or some combination of these possibilities.

Problem 9-10. Let the reader choose other load lines, such as one representing a low resistance, say 4000 ohms as in Fig. 150, and calculate the power output and percentage second harmonic distortion for several values of input voltage. A curve might be plotted showing percentage distortion as a function of the load resistance for a given input a-c voltage, or as a function of input voltage with a constant load resistance.

A method somewhat simpler than that used above for drawing the load line is as follows. The load line must go through the zero-signal bias point P. It must also cut the zero-volt grid-bias curve. The point X at which it cuts this curve is equal to twice the zero-input signal-plate current.

$$\text{Zero-signal bias } P = \frac{0.68 \times E_b}{\mu}$$

where E_b is the d-c plate voltage at which the tube is to operate and μ is the amplification factor of the tube.

Thus in Fig. 150, $0.68 \times E_b/\mu = 0.68 \times 350/3$ or 80, approximately. At this grid bias the tube draws 22.5 ma, and therefore point $X = 45$ ma.

191. Power diagrams. To review the tube with a resistance load as a power amplifier, and to gather a few additional facts, let us draw the E_p–I_p curves as shown in Fig. 151, which is a purely theoretical case—the curves and values of current and voltage represent no particular tube now available; they were chosen at random. Let us assume that the voltage actually on the plate is 160 volts when the steady plate current is 20 ma. That is, $E_p = 160$, and $I_p = 20$ ma. Let us assume a load of 5000 ohms, find the slope, and draw the load line through the intersection of the $I_p = 20$-ma line with the $E_p = 160$-volt line, and find that the bias on the grid to maintain such a plate current is 20 volts. Let us assume that on the grid is put a sine wave whose maximum value is 10 volts, so that the actual grid voltage varies between —10 and —30 volts. The corresponding I_p variations are from 30 to 10 ma.

We note that the load line crosses the battery voltage line at about 260 volts. This, then, is the battery voltage necessary to insure that the plate of the tube gets its 160 volts. In other

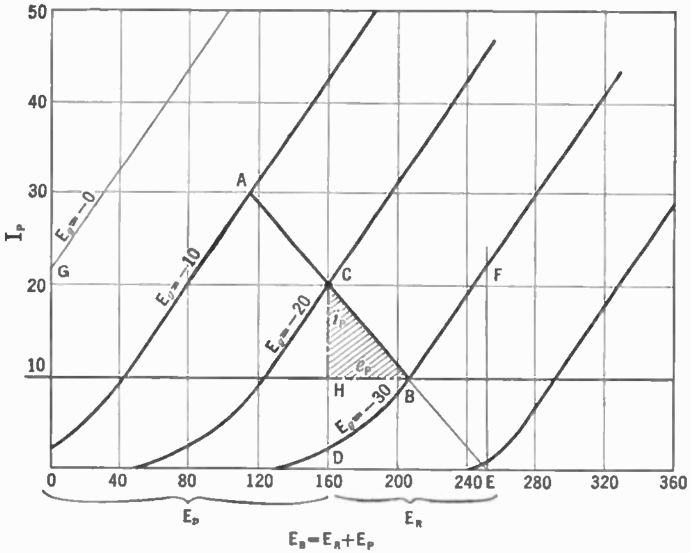


FIG. 151. Power diagram. The area of shaded triangle represents a-c power used in load.

words there is a drop of 100 volts (5000 × 0.02) in the resistance of the load R. Under normal conditions of no a-c input to the grid, the voltage across the tube is 160 volts, across the load is 100 volts, and the plate current is 20 ma.

Now the d-c power lost in the load is the product of the voltage across the resistance R and the current through it, and the power lost on the plate of the tube is the product of the voltage across the tube and the current flowing. Thus,

$$\text{Power lost in load} = E_R \times I_p = DE \times CD$$

$$\text{Power lost in tube} = E_p \times I_p = OD \times CD$$

and the total power supplied by the battery must be the sum of these powers, that is

$$\text{Power from battery} = E_B \times I_p = OE \times CD$$

Now the area of the rectangle $CDEF = DE \times CD =$ power in load, and the area of the rectangle $ODCG = OD \times CD =$ power lost in tube, and the area of the rectangle $OEFG = OE \times CD =$ total power from battery.

When an a-c input is applied to the tube so that the grid is operated about its mean or average value of —20 volts, the peak value of the alternating current through the load is given by the line HC and the peak value of the a-c voltage across the load is given by the line HB. Let us call these values of current and voltage

$$e_R = \text{peak a-c voltage across load} = HB$$

$$i_p = \text{peak alternating current through load} = HC$$

Since a-c power in a resistance circuit is the product of the rms current and the voltage, to obtain the a-c power in the load we must first get the rms values of the above values and then multiply them

$$e_R \text{ rms} = e_{R_{\max}} \times \frac{1}{\sqrt{2}}$$

$$i_p \text{ rms} = i_{p_{\max}} \times \frac{1}{\sqrt{2}}$$

whence a-c power in load $= e_R i_p$ (rms)

$$= e_R \times i_p \times \frac{1}{\sqrt{2}} \times \frac{1}{\sqrt{2}}$$

$$= \frac{e_R \times i_p}{2}$$

$$= \frac{HB \times HC}{2} = \text{area of triangle } HCB$$

This power is dissipated in the load resistance in addition to the d-c power lost there due to the voltage drop across it and the current through it. Since the average current drawn from the battery has not changed, the power taken from the battery has not changed—and yet the load has an additional amount of power used up in it. Where does this power come from? Clearly it must come from the power used up on the plate of the tube. *When an a-c voltage is placed on the grid, then a-c power is developed in the load, less power is wasted on the tube plate, and the tube will actually run cooler when it is delivering power to the load than when standing idle, that is, with no a-c input grid voltage.*

Let us see what these values of power are. We can take them directly from the graph in Fig. 151.

d-c power lost in load (no a-c grid voltage)

$$= DE \times CD = (260 - 160) \times (20 \text{ ma})$$
$$= 100 \times 0.02 = 2 \text{ watts}$$

d-c power lost in tube (no a-c grid voltage)

$$= OD \times CD = (160) \times (20 \text{ ma})$$
$$= 160 \times 0.02 = 3.2 \text{ watts}$$

d-c power taken from battery

$$= OE \times CD = 260 \times 0.02 = 5.2 \text{ watts}$$

max a-c voltage across a load (a-c grid voltage = 10)

$$= HB = 210 - 160 = 50 \text{ volts}$$

max ac through load (grid ac = 10)

$$= HC = 10 \text{ ma} = 0.01 \text{ amp}$$

a-c power in load (grid ac = 10)

$$\tfrac{1}{2} \times HB \times HC = 0.5 \times 50 \times 0.01 = 0.25 \text{ watt}$$
$$= 250 \text{ milliwatts,}$$

which is subtracted from d-c power in tube.

In Section 183 the formula for the power output of a tube was stated to be

$$\text{Power output} = \frac{\mu^2 e_g^2 R}{(R_p + R)^2}$$

and in order to check the above calculations we must find the tube constants from the curves in Fig. 151. The plate resistance of the tube is simply the reciprocal of the slope of the E_p–I_p line, and noting that a change of 160 − 100 volts on the $E_g = -10$ line produces a change in plate current of from 42 to 25 ma we calculate

$$R_p = \frac{160 - 100}{0.042 - 0.025} = \frac{60}{0.017} = 3500 \text{ ohms}$$

and from the two curves, $E_g = -10$ and $E_g = -20$ we ascertain that a change of 10 volts on the grid produces a change in plate current of from 42 to 20 ma when the plate voltage is 160, we calculate

$$g_m = \frac{0.042 - 0.020}{10} = 2200 \text{ micromhos}$$

whence

$$\mu = R_p \times g_m = 3500 \times 2200 \times 10^{-6}$$
$$= 7.7$$

whence power output

$$= \frac{(7.7 \times 7.07)^2 \times 5000}{(5000 + 3500)^2}$$
$$= 0.206 \text{ watt} = 206 \text{ mw}$$

This value agrees closely enough with our data secured from the characteristic curves in Fig. 151.

Thus from a collection of the E_p–I_p curves of any tube we may obtain all the necessary data upon which to build an amplifier and calculate its power output, the losses in the various tubes, the percentage distortion, etc.

192. Power output for pentode and beam power tubes. The general procedure for obtaining power output and distortion from pentodes and beam power tubes is much the same as for triodes just described. The calculations are made from a special plate voltage-plate current family of curves. In Fig. 152 from a point A just above the knee of the zero-bias curve draw arbitrarily selected load lines to the zero plate current axis. These lines should be on both sides of the operating point P whose position is located by the desired operating plate voltage, E_o, and one-half the maximum signal plate current. Along any load line AA_1 measure the distance AO_1. Along this load line lay off line O_1A_1 equal in length to AO_1.

For best operation the change in bias from A to O_1 and from O_1 to A_1 should be nearly equal. If they are not, select some

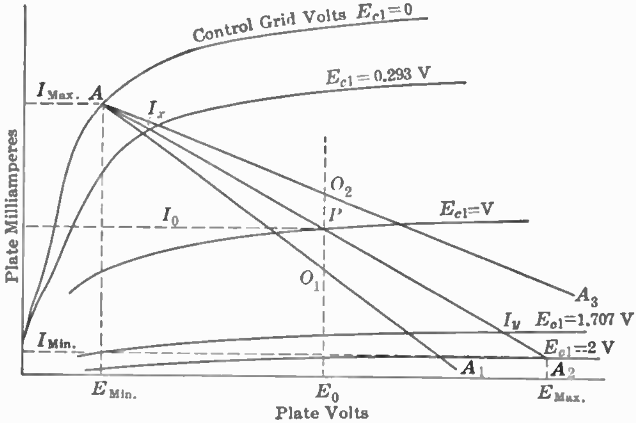


FIG. 152. Method of determining correct load resistance for a pentode power tube.

other load line arbitrarily, until one is found which makes the equal-bias change a fact. The load resistance for the tube may then be found by

$$\text{Load resistance } R_p = \frac{E_{\max} - E_{\min}}{I_{\max} - I_{\min}}$$

This value of load resistance may be substituted in the following formula and the power output obtained.

$$\text{Power output} = \frac{[I_{\max} - I_{\min} + 1.41(I_x - I_y)]^2\, R_o}{32}$$

In these formulas, I is in amperes, R is in ohms, E is in volts, and W is in watts.

193. Distortion calculation from pentodes and beam power tubes. The following formulas will be useful in calculating distortion from tubes of the pentode or beam power output type.

$$\text{Second harmonic distortion} = \frac{I_{max} + I_{min} - 2I_o}{I_{max} - I_{min} + 1.41(I_x - I_y)} \times 100\%$$

$$\text{Third harmonic distortion} = \frac{I_{max} - I_{min} - 1.41(I_x - I_y)}{I_{max} - I_{min} + 1.41(I_x - I_y)} \times 100\%$$

194. Gain from high-mu tubes. Since the plate resistance of screen-grid tubes may run as high as 1 megohm, a better method must be found for estimating the voltage amplification than the formulas used with low-mu tubes. Such a formula is

$$G_{sg} = g_m R_{e_q}$$

where g_m is the transconductance (in mhos) of the tube at the operating values of grid, screen-grid, and plate voltages

R_{eq} is the equivalent resistance of the plate resistance of the tube and the load resistance is parallel.

Since the tube resistance is very much greater than any load resistance likely to be used with the tube, and since the effective resistance of a small resistance shunted by a large resistance is not very much different from the small resistance unshunted, a good approximation of the voltage gain of a screen-grid tube, or of any similar tube having high amplification factor and high plate resistance is

$$G_{sg} = g_m R_o$$

where R_o is the load resistance.

Problem 10–10. Remember that the equivalent resistance of two resistances in parallel is the product over the sum of the resistances and calculate the gain of a circuit using a 6K7 tube operated as a pentode with $E_B = 250$, $E_{sg} = 125$, and $E_c = -3$, working into a load resistance of 100,000 ohms. Then calculate the gain, disregarding the shunting effect of R_p upon the load resistance.

An amplifier of three such stages is required to deliver an output of 1 volt. What input voltage is required?

Problem 11–10. In the plate circuit of a tube with a plate resistance of 10,000 ohms and an amplification factor of 10, is an inductance of 20 henries and a Q of 10. What alternating voltage e_o will appear across this inductance if 10 volts at 100 cycles are placed on the grid? NOTE: $e_0 = i_p \sqrt{R_0^2 + X_L^2}$ and $i_p = \mu e_g \sqrt{(R_p + R_0)^2 + X_L^2}$.

Problem 12–10. In a receiver to be operated from a-c or d-c lines is one tube requiring 25 volts for the filament and four others requiring 6.3 volts each. They require 0.3 amp each and the filaments are in series. If the receiver is to be operated from 115-volt circuits, what value of resistance is to be used between line and the filaments?

Problem 13–10. What loss in power is experienced in operating a tube under the conditions of maximum undistorted power as compared with the maximum output power? Assume any reasonable tube values and calculate power under both conditions and express the loss in percentage of the maximum power.

CHAPTER XI

AUDIO AMPLIFIERS

So far we have not spoken of the frequency or band of frequencies at which the vacuum tube and its associated apparatus will amplify. The theory up to the present point deals with amplifiers in general. It is necessary now to consider the types of amplifiers and their differences.

195. Need of an audio amplifier. All radio receivers in use at the present time have an audio amplifier of more or less amplification. The principles of such amplifiers underlie the whole phenomenon of amplification.

Let us think of the broadcasting studio in which originate the signals which we must amplify. A microphone stands in front of a musician or a speaker. This microphone is made up of a small coil of wire suspended in a strong and steady magnetic field. When voice or music waves in air strike this coil they deflect it from its steady no-signal position. This coil cutting the lines of force from the permanent magnets about it has voltages set up in it, much as a generator produces alternating currents when rotated in a steady magnetic field. These microphone currents are very minute and are increased in strength by amplifiers which will transmit the range of frequencies that will be encountered in practice. Here then is the first need for amplifiers. They must increase the microphone currents to a more usable value.

The frequencies normally transmitted over telephone lines range from 250 to about 2500 cycles. These are complex audio-frequency alternating currents. Most of the energy of the voice occurs in the frequencies below 1000 cycles, most of the intelligibility above that frequency. Therefore, if in the telephone line is placed a filter which passes only frequencies below 1000 cycles, we would hear a sound but it would be unintelligible. On the other hand, if the filter cut out all the low tones and transmitted only those above 1000 cycles, we could understand what the speaker was saying, but the sound would not carry, it would be weak.

For best intelligibility and carrying power—naturalness, we say—all the frequencies from about 120 to 2500 are necessary for transmission of speech.

Music, however, is more complex and for realism and naturalness a much greater frequency range must be transmitted, not only by the microphone but also by the amplifiers, the radio broadcasting station, the ether, the receiver, the amplifier, and finally the loud speaker in one's home. Music requires the transmission of all frequencies between 100 and 5000 cycles per second, and many critics desire that a still greater range shall be transmitted. At the present time, in the United States, the best broadcasting stations and connecting circuits transmit from below 100 to above 5000 cycles per second. After a certain amount of amplification these tones are mixed with a radio-frequency wave which is emitted from the antenna of the transmitting station. The radio-frequency wave of the station is said to be modulated by these amplified audio-frequency tones. The program then becomes inaudible and remains so until some demodulating device separates the program from the radio-frequency voltages.

Even though considerable power is used at the broadcasting station, there is an enormous loss in signal strength as we go away from the transmitter. These radio-frequency waves modulated at audio frequencies are greatly reduced in strength owing to absorption and dissipation in the medium through which they travel. Furthermore, the energy spreads in all directions from the transmitter and, as it spreads, the energy available at any particular place becomes smaller the farther the place is from the transmitter.

An audio amplifier has nothing to do with radio at all, and can be used to amplify any voice- or music-frequency modulated electric currents that are placed upon its input. Its job is to build up the strength of a minute electric current to the point where the audio modulations on this current are of useful strength.

From the moment the sound in the studio enters the microphone, it ceases to exist as sound, and becomes an electric current. The amount of voltage amplification necessary depends, of course, upon the ultimate strength of the desired signal and the strength of the signal which is to be raised to this level. No sound is emitted again until some translating device is used, a device that will have electric currents in its input and sound or air waves in its output. Then, and only then, is sound emitted. Nowhere along the line from microphone to loud speaker can the signal be heard, unless some translating device is "plugged in." After demodulation the currents of audible frequency are amplified as much as desired by an audio amplifier.

The voice-frequency currents that can be amplified by an audio amplifier may come from a phonograph "pick-up," a telephone transmitter mouthpiece, or the plate circuit of a detector tube in a radio receiver. The radio link is, then, only an incidental and extremely inefficient part of the whole system—better results could be secured by eliminating the radio link completely and using wire lines between the receiver and the transmitter. The advantage of radio is the ability to "broadcast" in all directions, and to eliminate the need of a metallic circuit between the person broadcasting and the person listening.

Let us forget all about the radio part of our receiver, temporarily, and consider only the audio-frequency amplifier.

196. The requirements of an audio amplifier. An amplifier to accept, transmit, and amplify audio-frequency tones has several requirements:

(1) The amplifier must transmit all the tones required, in their proper proportion. It must not discriminate against some frequencies and favor others.

(2) The amplifier must amplify all frequencies properly whether the input voltage is high or low.

(3) It must have an over-all amplification which added to the radio-frequency amplification will make up for the enormous loss

of power between the input to the microphone and the output from the loud speaker.

Let us consider, for the moment, only the amount of amplification necessary. This value of over-all amplification varies, of course, with the input signals available and the output power required. For home reception an output of several watts of electrical power into a loud speaker of average efficiency—perhaps 5 per cent—is sufficient, although many people get along with much less than this value, and some require much greater power outputs.

Suppose the amplifier works out of a detector tube from which the maximum voltage available without distortion is 0.3 volt. If the speaker has a resistance of 4000 ohms and if the required output is 0.7 watt, and tube resistance is 2000 ohms, there must be the following amplification:

W_o =	power into load	= 700 mw
R_o =	resistance of load	= 4000 ohms
e_o =	voltage across load	$= \sqrt{W_o \times R_o} = 53$ volts rms
e =	total a-c voltage in plate circuit of last tube	$= 53 \times 3/2 = 79$ volts*
e_i =	input voltage to amplifier	= 0.3 volt rms
G =	voltage amplification	$= 79/0.3 = 260$ times

It is better that the amplifier shall have considerably more gain than this figure so that the detector may be worked at a safe distance below its overloading point—to have a good factor of safety—and so that weak signals from distant stations can "load up" the amplifier and its speaker.

Let us say, then, that the minimum gain for our amplifier is 300 times. How can we secure this amplification? There are several ways and we have already discussed the various types of amplifier arrangements. It is only necessary so to design each stage or to add a sufficient number of stages that the over-all voltage amplification will be sufficient. The next problem is to see if the required frequency characteristic can be secured to prevent distortion due to over emphasis or discrimination at some frequencies.

* See note on page 263.

Example 1-11. An amplifier has a voltage gain, up to the grid of the last tube, of 200. The last tube has a μ of 8 and a plate resistance of 5000 ohms. It works into a resistance of 10,000 ohms. The input to the amplifier is 0.1 volt rms. Calculate the power into the resistance, the voltage across it and the ratio between this voltage and the input voltage to get the over-all voltage amplification.

The a-c voltage on grid of last tube $= e_g \times G = 0.1 \times 200 = 20$ volts.
The a-c voltage in plate circuit of last tube $= 20 \times 8 = 160$ volts.
The a-c voltage across 10,000-ohm load $= 2/3 \times 160 = 106$ volts.*
Power into load $= e^2/R = 106^2/10{,}000 = 1.2$ watts.
Voltage amplification $= E_o/E_i = 106/0.1 = 1060$ times.

Problem 1-11. What voltage gain must an amplifier have to deliver 1.5 watts to a 4000-ohm load in the plate circuit of a tube whose plate resistance is 2000 ohms if the input voltage to the amplifier is 0.3 volt rms?

Problem 2-11. The load of an amplifier is a 2000-ohm resistor. The plate resistance of the last tube is 2000 ohms and its μ is 3. The gain in voltage up to the grid of this last tube is 100. What input voltage is required to deliver 50 mw of power?

Problem 3-11. Prove that if the load resistance is double the tube resistance, the voltage across the load is two-thirds of the total a-c voltage in the plate circuit of the tube and the voltage amplification is equal to the amplification up to the grid of the tube times the μ of the tube times 2/3.

Problem 4-11. If the load resistance is twice the tube resistance and the a-c voltage across the load is 100 volts, what must be the total a-c voltage in the plate circuit? If the μ of the tube is 8, what must be the grid a-c voltage? If this is the rms voltage, what must be the minimum C bias of the tube to keep its grid from going positive?

Problem 5-11. The voltage gain per stage is 8. How many stages will be needed to produce an over-all gain of 500? Remember that voltage gains are multiplied, not added. Estimate the gain as the total a-c voltage in the plate circuit of the last tube divided by the input voltage.

Problem 6-11. The voltage gain per stage is 10. What is the total voltage gain (total a-c plate voltage divided by input voltage) in three stages?

197. Cascade amplifiers. It is usually necessary to use more than one stage of amplification, whether this is at high (radio), at intermediate, or at low (audio) frequencies, that is, an a-c voltage is applied to the grid of one tube and amplified; this

* These factors of 3/2 and 2/3 arise from the fact that only part of the total plate alternating voltage appears across the load resistance—part of it is lost in the tube resistance.

amplified a-c voltage is used to drive the grid of another tube where it is again amplified. This voltage may again be amplified or used to drive the grid of a power tube whose function is not voltage amplification but the delivery of power to a loud speaker. There may be an actual loss in voltage between the last voltage amplifier and the power amplifier, as in case of Class B amplifiers. The first tube in a two-stage amplifier is designed to amplify the voltage alone, and the transfer of power either at maximum efficiency or at maximum output is not a consideration. The second tube, or the third in a three-stage amplifier, is designed solely for the purpose of delivering power to the load, whether this is a loud speaker, or group of speakers, or a telephone line where it may be again amplified and put into the loud speakers. When two or more amplifiers are connected in series they are said to be connected in "cascade."

198. Frequency characteristic of resistance amplifier. Let us look at the circuit in Fig. 153 which gives two tubes coupled by

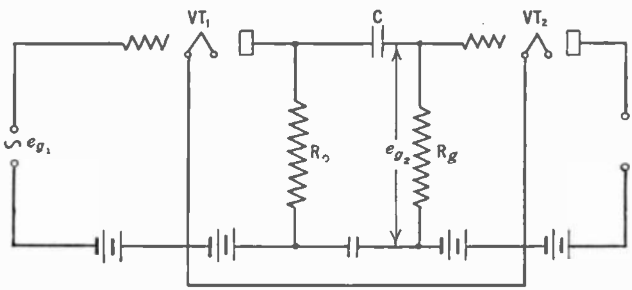


FIG. 153. Two tubes coupled by a resistance-capacity network.

means of a resistance-capacity unit. Voltage is fed to the grid of the first tube VT_1, is amplified there, and reappears across R_o. This amplified voltage is applied to the grid of the second tube and amplified, whence it reappears across whatever load is in its plate circuit. The voltage gain of such an amplifier stage is the ratio between the voltage on the second grid and the voltage on the first grid, that is,

$$G = \frac{e_{g_2}}{e_{g_1}} \qquad [1]$$

We have already spoken about the conditions that result in maximum amplification in such a system, that is, the impedance in the plate circuit of the first tube must be large compared with the plate resistance of that tube, that is, the equivalent impedance of R_o shunted by C and R_g in series must be large compared to R_p (Fig. 154).

Now the only part of this circuit which has a different impedance at different frequencies is the condenser. To get a good frequency characteristic, then, it is necessary to choose a value of C which will transmit the lowest frequency desired, because all other frequencies above this limit will find less impedance than this value. (The reactance of a condenser decreases with increase in frequency.)

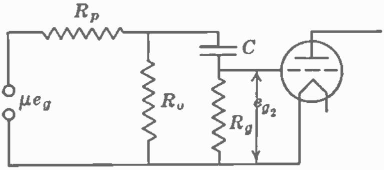


FIG. 154. Equivalent circuit of Fig. 153.

The voltage that is developed in the plate circuit of VT_1 is divided between the plate resistance of that tube and the load in the plate circuit. The voltage across this impedance is the output voltage, and is divided between that lost on the condenser reactance X_c and the grid resistance R_g of the following tube. The only useful part is that appearing across R_g.

The purpose of the condenser is to prevent the positive plate voltage of the first tube from being impressed upon the grid of the second tube. It is an isolating condenser and must have high d-c resistance. Any current flowing (dc) through it will cause a voltage drop in such a direction that the grid will be unfavorably biased. The purpose of the grid leak, R_g, is twofold: one is to provide a means of biasing the second tube grid, as by putting a C battery between the lower terminal of this resistor and the cathode of the tube, and secondly, to provide a high impedance in series with the low impedance of the capacity to be bridged across the plate coupling resistor of the first tube.

In modern resistance-coupled amplifiers the value of capacity C is of the order of 0.1 μf. The grid resistor is 0.5 to several megohms. With care in construction, seeing that stray capacities which shunt the two resistors do not become large enough to reduce the effective impedance of those resistors at the desired frequency, a resistance-coupled amplifier will provide uniform amplification over a very wide frequency range.

At the high frequencies the stray capacities which shunt the resistances so reduce the effective impedance of the load in the tube plate circuit that little amplification, and hence little volt-

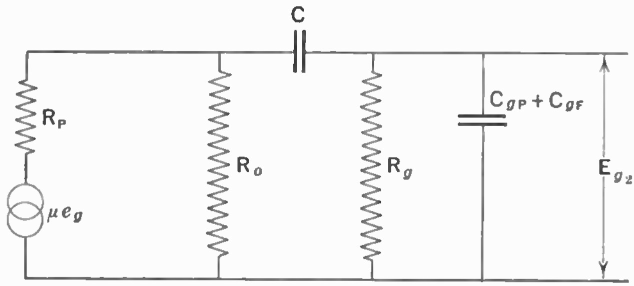


Fig. 155. Equivalent of tube and load and shunting capacities.

age, is developed. These stray capacities are made up of the plate-to-filament capacity of the first tube, the grid-to-filament (or cathode) capacity of the second tube, the capacity in the wiring, etc. These may be lumped together to form an equivalent capacity across the grid resistor as shown in Fig. 155.

At 1000 cycles or so, where the reactance of the coupling condenser will have no effect, the maximum possible amplification is obtained. It is equal to the mu of the tube multiplied by the ratio between the effective load resistance to the sum of this resistance and the plate resistance of the tube. Thus

$$G = \frac{\mu R_{eq}}{R_{eq} + R_p} \qquad [2]$$

where R_{eq} is equal to the load resistance shunted by the grid resistance of the following tube. The circuit is shown in Fig. 155. At these middle frequencies the reactance of C may be neglected. Therefore the tube has, as its load, two resistances in parallel.

Therefore to calculate the amplification it is first necessary to calculate the equivalent resistance which the tube works into, i.e., the shunt circuit composed of the coupling resistor and the grid resistor. Then calculate the amplification as in formula 2.

At *low* frequencies the effect of the coupling condenser cannot be neglected. Across its reactance will appear a voltage which cannot be impressed upon the following grid-cathode input circuit. It is a voltage that is supplied by the previous tube and is then lost. The load, then, of the tube is more complicated than at middle frequencies. At a low frequency it consists of the load resistance R_o shunted by a condenser and a resistance in series. It is not difficult to calculate the effective load resistance in this case but it is rather tedious.

The low-frequency characteristic depends upon the value of the coupling capacitor and upon the value of the grid resistor as well. If the grid resistor is low in value the capacity must be low in reactance (high in capacity) whereas if the grid resistance is high, the coupling capacity may be lower in value. Actually, if the reactance in ohms of the coupling capacity is equal to the value of the grid resistance in ohms the voltage amplification will be equal to 70 per cent of the value obtained by equation 2. This means that if 70 per cent or more of the maximum amplification is desired at some low frequency compared to, say, 1000 cycles, the reactance of the condenser must be equal to or less than the value of the grid resistance in ohms. If the reactance is equal to twice the grid resistance in ohms, then the amplification at the frequency for which this is true will be equal to 50 per cent of the amplification at the frequencies at which the reactance of the condenser are negligible. If X_c (condenser reactance) equals $\frac{1}{3}R_g$, 95 per cent of the maximum amplification may be obtained.

Higher amplification will be obtained if the grid resistance is high, but then another phenomenon begins to become important.

The limit to the high-frequency amplification is controlled by capacitances which *shunt* the load resistance of the tube. These may be made up of the wiring, the socket, the inherent capacities within the tube. They shunt the grid resistance and lower the effective impedance into which the tube works. The lower this impedance, the lower the resistance, and the lower the voltage amplification, the higher the grid resistance, the more important become the shunting capacities.

The actual amplification at a high frequency (which is where the reactance of shunting capacities becomes effective) compared to the amplification at, say, 1000 cycles, may be found from

$$\frac{\text{Gain at high frequency}}{\text{Gain at 1000 cycles}} = \frac{1}{\sqrt{1 + (R/X)^2}}$$

where R is the effective resistance of the grid leak, the coupling resistance, and the plate resistance all in parallel, and X is the reactance of the stray capacities shunting the three resistances in parallel.

At the frequency which makes the stray shunting capacities have a reactance equal to three times the value in ohms of the effective resistance of the three resistances in parallel, the amplification will be 95 per cent of the amplification at, say, 1000 cycles. If the frequency is raised until the reactance is equal to the effective resistance of the circuit the amplification will be 70 per cent of the maximum attainable at, say, 1000 cycles.

Problem 7-11. Suppose the amplification of a single pentode stage working into 100,000 ohms at 1000 cycles is 100. The grid leak is ½ megohm, the plate resistance of the tube is 1 megohm. Stray capacities plus tube capacities add up to 25 $\mu\mu$f. What is the voltage gain at 3 megacycles?

199. Over-all amplification. Let us consider a three-stage amplifier, having resistances, tubes, etc., as shown in Fig. 156.

The first two tubes have an amplification factor of 30, the final or power tube has a μ of 3. What is the over-all voltage amplification? If the values of R, C, and R_g are properly chosen, the amplification per stage will be 75 per cent of the μ of the tube, and what the first tube amplifies will be amplified again by the second, that is, if an input of 0.1 volt is applied to the grid-filament input of the first tube a voltage of $0.1 \times 0.75 \times 30$ or 2.25 volts will be applied to the second, and a voltage of $2.25 \times$

30×0.75 or 50.5 volts to the third input; and if the resistance into which this tube works has twice the value of the plate resistance of the tube, two-thirds of the total a-c plate voltage of the last tube will be applied to the load. That is, the load will have across it a voltage equal to $50 \times 3 \times 2/3$ or 100 volts.

The over-all voltage amplification in such a case will be 100 divided by 0.1 or 1000. This is equal numerically to the product of the voltage gain of the individual stages. Thus if each stage has a gain of G, two stages will have a gain of G^2, three stages

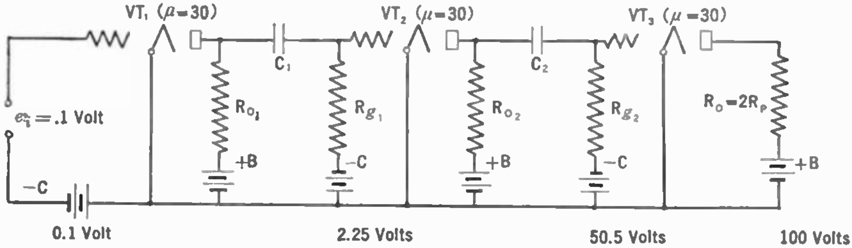


FIG. 156. Three-stage resistance-coupled amplifier.

a gain of G^3, etc. In this case it will be $(22.5)^2 \times 3 \times 2/3 =$ 1000 (approximately).

200. Plate battery requirements. One of the objections to the resistance amplifier is the excessive plate battery voltages that are necessary. The voltage on the plate of a tube in whose plate circuit is a high resistance is not the voltage of the battery but this voltage minus the voltage drop across the resistor in the plate circuit. We want the a-c voltage drop across this resistance to be high but the d-c voltage drop to be low. As an example, suppose a tube has a plate resistance, R_p, of 60,000 ohms when the plate voltage, E_p, is 100 volts. To get 75 per cent of the μ of the tube as the over-all amplification from grid input voltage to the voltage output across the resistor, we need a resistance in the plate circuit of 180,000 ohms. Suppose under these conditions the plate current is 1 ma. What plate battery voltage is necessary if 100 volts are required on the plate?

The plate voltage may be found from

$$E_p = E_b - I_pR_p$$

$$100 = E_b - 0.001 \times 180{,}000$$

$$E_b = 280 \text{ volts}$$

Now the tube will amplify with fewer volts on the plate than this, but the difficulty lies in the following fact. The plate resistance of a tube is a function of the plate voltage, that is, at low plate voltages the plate resistance is high, which in turn necessitates a higher value of load resistance to get the 75 per cent of the μ of the tube, which means that the voltage drop will be high across this resistor and so on. A high plate battery is always needed.

To get 100 volts on the plate of this tube requires a plate battery of 280 volts. This is inefficiency, of course. What can be done about it?

201. Inductance-load amplifier. Suppose instead of the resistor in the plate circuit we substitute a low-resistance inductance with a high value of reactance at the frequencies at which the amplifier is to work, for example, a 100-henry choke coil with a d-c resistance of 1000 ohms. The circuit looks like Fig. 157. Now the direct plate current encounters no appreciable opposition in the 1000-ohm resistance. In fact, the voltage drop is 1 volt per milliampere of plate current. The alternating current, however, must flow through the high inductance and the resistance in series. Across this impedance $\sqrt{R^2 + L^2\omega^2}$ will appear the amplified a-c voltage which may be used to drive another amplifier stage if desired.

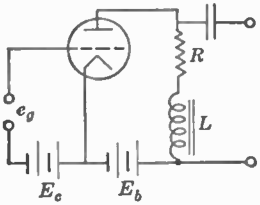


FIG. 157. Inductance-capacity or impedance-coupled amplifier.

Such an amplifier is commonly called an **impedance** amplifier: The loss in d-c voltage between the plate battery and the plate itself is 1 volt per 1000 ohms per milliampere current, and if the plate current is 2 ma only 102 volts of B battery will be required to put 100 volts on the plate of the tube.

Problem 8-11. An amplifier is to be used at audio frequencies. What must be the impedance of the choke coil at 100 cycles to secure an amplification of 7.5 from a tube whose μ is 10 and whose plate resistance is 15,000 ohms? What will be the amplification at 1000 cycles?

Problem 9-11. If the resistance of the choke coil used in Problem 8 is 500 ohms, what is the inductance required?

Problem 10-11. A tube has a load resistance of 100,000 ohms. The plate current is 2 ma and the plate voltage required is 90 volts. What plate battery voltage is necessary?

Problem 11-11. A tube draws 0.5 ma from the B batteries whose voltage is 180 volts. A coupling resistance of 100,000 ohms is used. What is the voltage actually on the plate?

202. Capacity effects at high frequencies. We have already explored the resistance-coupled amplifier at middle and low frequencies. The same maximum amplification formula will apply to the impedance amplifier. The lower frequencies in this amplifier are not amplified as well as the median frequencies because of the fact that the choke used as the load of the first tube does not have a uniform reactance at all frequencies. This reactance is low at low frequencies and therefore the extent to which these tones are amplified depends upon the magnitude of this reactance.

The choke consists of some resistance, a large inductance, and some capacity since there are many turns of wire insulated from each other, and just as in a solenoid this coil has distributed capacity. At some intermediate frequency the inductance resonates with its distributed capacity forming a high-impedance anti-resonant circuit. At this frequency the amplification is a maximum. Below this frequency the inductance is not great enough to build up the maximum load impedance; at higher frequencies the shunting distributed capacity together with other capacities as explained below reduces the plate load impedance and reduces the amplification.

The impedance amplifier saves B batteries since the voltage drop is much less than in a resistance-coupled amplifier. The latter, however, will have a flat characteristic over a much wider range of frequencies. In addition the choke costs much more than a resistance; for these reasons the impedance-coupled amplifier is seldom used. In tetrodes and pentodes the plate current is more or less independent of plate voltage and therefore much greater voltage amplification can be obtained by using moderately low plate voltages compared with that obtainable from triodes.

Not only do the tubes and wiring capacities, which are represented in Fig. 155, play havoc with high frequencies, but the

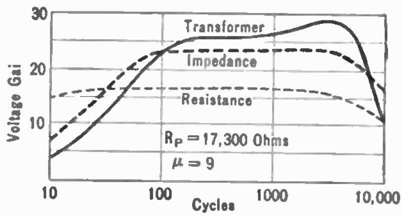


FIG. 158. Comparison of three types of audio amplifiers showing high amplification of transformer coupling; wide range of resistance amplification. (Terman.)

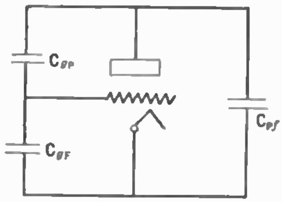


FIG. 159. Tube capacities.

effect of the grid-plate capacity of the second tube is multiplied by the μ of the tube—a very interesting and unfortunate fact.

The capacities which cause trouble at high frequencies are:

1. Grid-filament capacity, C_{gf}.
2. Plate-filament capacity, C_{pf}.
3. Grid-plate capacity, C_{gp}.
4. Stray capacities in wiring, etc.

The capacity C_g across the input to the tube is equal to

$$C_g = C_{gf} + C_{gp}(\mu_o + 1)$$

where μ_o is the effective amplification in the circuit, and the other factors are as itemized above and shown in Fig. 159.

These values for the UX-240, a tube adapted for resistance-coupled amplifiers, are $C_{pf} = 1.5$ $\mu\mu$f, $C_{gf} = 3$ to 4 $\mu\mu$f, and $C_{gp} = 8.8$ $\mu\mu$f. In practice C_g may vary from 20 to as high as 300 $\mu\mu$f depending upon the intrinsic values of its components and the amplification of the system. That is, if the $C_{gf} = 3.0$ $\mu\mu$f, and $C_{gp} = 8.0$ $\mu\mu$f and the effective amplification of the system is 20, C_g becomes 3 plus 8×20 or 163 $\mu\mu$f—which is an appreciable capacity and not at all what one would expect. The effective capacity across the input to the tube is a function of the μ of the tube; thus the greater the amplification factor the more trouble one gets into because of this capacity-multiplying effect. Low-mu tubes are not so troubled, but their amplification is low; and so the amplifier designer and experimenter must compromise between a good frequency characteristic and a high gain. If the gain is good the high frequencies are discriminated against, and if the characteristic is very good the over-all gain is likely to be low.

Problem 12-11. The μ of a tube is 8, its grid-filament capacity is 6 $\mu\mu$f, its plate-grid capacity is 8.0 $\mu\mu$f. The effective amplification of the circuit is 7, and stray capacities across the filament and grid circuit amount to 2 $\mu\mu$f. What is the effective shunting capacity C_g?

203. Frequency characteristic of amplifiers. So far we have discussed only isolated points in the frequency response, either high, medium, or low frequencies. What happens at other points? In the resistance-coupled circuit the reactance of the coupling condenser reduces the amplification at lower frequencies as indicated before; in the impedance amplifier the reactance of the choke limits the response. If the response at any frequency is calculated, it will be less at lower frequencies and will rise to the maximum possible amplification, which will in general be higher in the impedance-coupled stage than in the resistance stage.

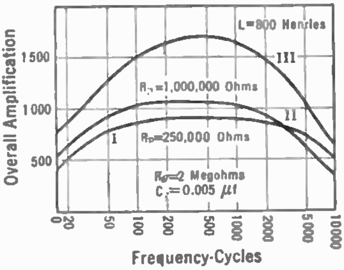


FIG. 160. Frequency characteristic of resistance- and inductance-coupled amplifiers.

At the higher frequencies in both amplifiers the shunting capacities of tube and wiring control the characteristic. Therefore the stray capacities must be kept low. The capacity between tube elements is effective in reducing the amplification, particularly the capacity existing between grid and plate of the second tube. This value is multiplied by the (effective gain in the circuit plus 1). Therefore the higher the gain the greater becomes the difficulty of keeping the response up at the high frequencies. The higher the coupling resistor the greater in effect become these capacities.

Example 2-11. Suppose a 1-megohm resistor is in the plate circuit of a tube and that 10 volts are developed across it. If 100,000 ohms are shunted across it, the effective impedance becomes 0.91×10^5, and if the current is the same the voltage developed has been reduced to 0.91 volt. Now, suppose 10 volts are developed across 100,000 ohms and that another 100,000-ohm resistor is shunted across it. What is the resultant reduction in voltage? Clearly it is 50 per cent—a much smaller percentage reduction.

Problem 13-11. A tube with an amplification factor of 30 and a plate resistance of 150,000 ohms is used with a half-megohm coupling resistance. Suppose that in construction a path of soldering flux is placed across the terminals of this resistor accidentally so that the half-megohm is effectively shunted by 100,000 ohms. What is the resultant amplification? What is the amplification without the shunting resistance? What is the percentage loss due to the flux?

204. Tuned-inductance amplifier. In both the resistance-load and the inductance-load amplifier the maximum amplification is attained when the impedance in the plate circuit is a maximum. If, then, we desire to receive only one frequency, say 1000 cycles, we can get greater amplification by tuning the inductance with a shunt condenser so that we have an anti-resonant circuit in the plate circuit of the tube, as shown in Fig. 161. If an inductance of 0.1 henry is tuned with a 0.254-μf condenser the resonant frequency will be about 1000 cycles. If the coil has a resistance of 100 ohms the impedance of the anti-resonant circuit will be roughly 3950 ohms whereas the reactance of the coil alone will be only 628 ohms. Tuning the coil therefore increases the load impedance in the plate circuit by about 6.3 times.

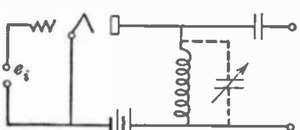


FIG. 161. Tuned inductance output.

The voltage gain will be given by the formula:

$$G = \mu \frac{R_o}{R_o + R_p}$$

which shows that the maximum possible amplification is the μ of the tube, and, as we have already seen, increasing the load impedance, R_o, to the point where it is three times the tube internal resistance results in a voltage amplification of $\mu \times 0.75$.

Problem 14-11. An inductance of 170 μh has a resistance of 6.0 ohms at 500 kc, 10 ohms at 1000 kc, and 18 ohms at 1500 kc. Assuming a fixed capacity—due to distributed capacity of winding, connections, etc.—across the coil of 60 $\mu\mu$f, calculate the condenser capacity that will tune the coil over the broadcast-frequency band. Calculate the reactance of the coil at the three frequencies above and the voltage gain to be expected when used with a tube whose plate resistance is 12,000 ohms and a μ of 8. Then calculate the impedance in the plate circuit if the inductance is tuned at each of the three frequencies and the voltage gain to be expected when connected as in Fig. 161. Plot the voltage amplification of this single stage against frequency. Explain why the curve is not flat.

The untuned inductance or "impedance" amplifier can be used where it is desired to transmit a fairly wide band of frequencies; tuning it makes it possible to get greater amplification over a narrow band of frequencies.

205. The transformer-coupled amplifier. The output a-c voltage across the resistance or inductance—tuned or not—can never be higher than the input grid voltage multiplied by the μ of the tube, and can attain that value only when the resistance or impedance is high compared with the plate resistance. Suppose, however, we use a transformer, as in Fig. 162. The voltage across the secondary will be increased by the turns ratio of the windings and so the voltage developed in the plate circuit of the tube may not only be passed on to a following tube multiplied by the μ of this tube but also multiplied by the turns ratio as well.

If the secondary circuit takes no current or power the greatest voltage will appear across the secondary when a very high turns ratio is used, but this is not true when power is taken—and some always is.

The maximum power in the secondary circuit will be obtained when the turns ratio N is given by the expression

$$N^2 = \frac{R_s}{R_p}$$

where R_s and R_p are the resistances between which the transformer works. When such a turns ratio is used the voltage across the secondary is given by

$$e_s \text{ (max)} = \frac{\mu_1 \, e_{g_1} N}{2} \qquad [3]$$

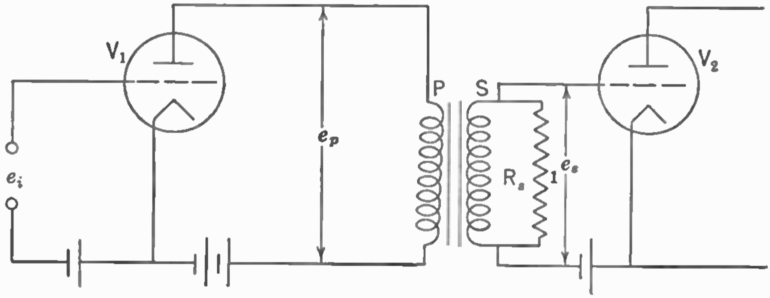


FIG. 162. Transformer-coupled amplifier.

All this assumes that a perfect transformer is used, that is, one which has no d-c resistance, no magnetic leakage, and infinite primary and secondary reactances. If the resistance of the load across the secondary is 1 megohm, and the plate resistance of the tube is 10,000 ohms, the proper turns ratio,

$$N = \sqrt{\frac{1{,}000{,}000}{10{,}000}} = 10$$

and the voltage gain from (3) is

$$\frac{e_s}{e_{g_1}} = \mu_1 \times 5 = 40 \text{ if } \mu_1 = 8$$

The foregoing mathematics discloses several interesting points. In the first place it is possible to get much greater voltage amplification by means of a transformer than is possible with the same tube and either resistance or inductance output. In the second place, for every ratio of resistance across the secondary and primary of the transformer there is a certain turns ratio which will produce the maximum voltage step-up. This means that once the resistances on either side of the transformer are determined, the turns ratio for maximum voltage gain is fixed. This, in turn, means that a transformer can be used as an impedance adjusting device, that is, a coupling device between two circuits of different impedance, one of which acts as a source of voltage and the other is the recipient of a voltage, amplified or not.

Whenever the impedances of the two sides of the transformer are not that indicated by the expression above, there is a loss in secondary power, a transmission loss, engineers say. Whenever two circuits are to be coupled together with the least loss in voltage or power the proper turns ratio transformer must be used, that is, $N^2 = Z_s/Z_p$, where Z_p and Z_s are the impedances between which the transformer works.

Problem 15-11. A tube whose plate resistance is 12,000 ohms works into a resistance, R_o, of 600,000 ohms. What is the proper turns ratio, and what is the voltage gain if $\mu = 8$? If $e_{g_1} = 1$ volt what voltage will appear across R_o?

Problem 16-11. One tube whose plate resistance is 25,000 ohms is connected to another whose grid circuit has a resistance of 400,000 ohms. What is the turns ratio of the transformer for maximum voltage amplification?

Problem 17-11. An "output" transformer is to be used to connect a loud speaker to a tube. The impedance of the loud speaker at the desired frequency is 4000 ohms, the tube has a resistance of 2000 ohms. What is the proper value of N?

Problem 18-11. A telephone line has an impedance of 600 ohms. The a-c voltages in the plate circuit of a 6000-ohm tube are to be transferred to this line. What must be done to effect such a transfer with least power loss?

206. Transformer with no secondary load. If the secondary of the transformer works into a true no-load impedance, that is, an open circuit, or $R_g =$ infinity, the voltage appearing across the secondary will be μe_g multiplied by the turns ratio of the transformer and not, as given in (3) $\mu e_g \times N/2$. The voltage gain is equal to

$$G = \mu \frac{2\pi f L_1 N}{\sqrt{R_p^2 + (2\pi f L_1)^2}} = \frac{N\mu}{\sqrt{1 + \left(\frac{R_p}{X_L}\right)^2}}$$

where L_1 = inductance of the primary, etc.

Example 3–11. Transformers of a few years ago had very little primary inductance. Assume an inductance of 2 henries, $f = 800$ cycles, $\mu = 8$, and $R_p = 10{,}000$ ohms, $N = 4$. Calculate the voltage amplification. Then assume $f = 80$ cycles and calculate G.

$$G = 8 \frac{2 \times 3.14 \times 800 \times 2 \times 4}{\sqrt{10^8 + (2 \times 3.14 \times 800 \times 2)^2}} = 22.7$$

If f = 80 cycles

$$G = 8 \frac{2 \times 3.14 \times 80 \times 2 \times 4}{\sqrt{10^8 + (2 \times 3.14 \times 80 \times 2)^2}} = 3.2$$

Problem 19–11. What is the maximum shunting capacity in Problem 11–11 if the gain at 10,000 cycles is down not more than 10 per cent from the value at, say, 1000 cycles?

207. The advantage of the transformer. The transformer has the great advantage that it can contribute toward the voltage amplification, and can contribute toward the maximum power output when the load resistance or impedance differs from the tube resistance. In addition, high plate supply voltages are not necessary.

A transformer can be constructed so that it has little loss in itself. This loss is due to the d-c resistance of the windings, the fact that perfect coupling between primary and secondary is not attained, and because of iron losses, that is, currents set up in the iron core represent a loss in power which must be supplied from the source. This power therefore does not get out of the transformer and cannot appear in the output.

If a good transformer is used, its transmission loss is small. Its effect, then, upon the circuit is of two sorts: first, it may contribute toward the voltage gain by having a voltage step-up in it;

second, it may be used to "match" the load resistance to the tube resistance. Let us suppose the tube resistance is 10,000 ohms, and that the secondary load resistance is 100,000 ohms. A resistance of this value interposed in the plate circuit of a tube will not have the maximum power developed in it. But if we use the proper transformer such that N^2 equals 10, this 100,000 ohms will look, to the tube, like a resistance of $100{,}000 \times 0.1$ or 10,000 ohms—the condition for maximum voltage and maximum power.

The transformer can always be forgotten if we substitute for it and its secondary load, Z_p, this load divided by N^2. Looked at from the secondary we may replace the transformer by $N^2 \times Z_p$. These statements are true provided that a step-up in voltage occurs in going from primary to secondary. If a step-down occurs, these expressions must be reversed.

Example 4–11. A transformer with a turns ratio of 3 connects a 10,000-ohm tube with a load which has a frequency characteristic such that at 100 cycles the load has one-tenth of the impedance it has at 1000 cycles. The load impedance at 100 cycles is 90,000 ohms. The μ of the tube is 8. What are the voltage amplification and the power output at 100 and 1000 cycles?

The transformer may be dispensed with in the calculation if we transfer the secondary load directly into the plate circuit of the tube by multiplying it by $1/N^2$, that is, 1/9.

Thus at 100 cycles the impedance in the plate circuit is

$$90{,}000 \times \tfrac{1}{9} = 10{,}000 \text{ ohms}$$

and the voltage amplification is

$$\frac{\mu \times R_o}{R_o + R_p} = \frac{8 \times 10{,}000}{20{,}000} = 4$$

and the power

$$P_o = \frac{\mu^2 e_g^2 R_o}{(R_o + R_p)^2}$$
$$= e_g^2 \times 1600 \times 10^{-6} \text{ watts}$$

At 1000 cycles

$$R_o = 900{,}000 \times \tfrac{1}{9} = 100{,}000 \text{ ohms}$$

and

$$G = \frac{8 \times 100{,}000}{110{,}000} = 7.3 \quad \text{and} \quad P_o = e_g^2 \times 533 \times 10^{-6} \text{ watts}$$

Problem 20–11. Assuming no loss in the transformer, what is the power transmitted to a 6000-ohm load from a 2000-ohm tube when they are coupled by a transformer whose load winding has 2.24 times as many turns as the primary? Assume $\mu = 3$, $e_g = 10$ volts rms. Use formula 5 in Section 183. What would be the value of N for maximum power in the load? What would be the power then? What value of N would deliver maximum undistorted power output into the load? What is this value of power?

208. Transformer-coupled amplifiers. The single transformer has already been discussed. It was stated in Section 205 that the maximum ratio for a transformer working between a 10,000-ohm tube and the input of another tube which might have an impedance of 1 megohm was 10 to 1. Unfortunately, this is only theoretically true, just as the calculations on resistance coupling without regard to certain factors produce erroneous results. A transformer to give a good low-frequency response when worked out of a detector tube—which normally has a rather high plate resistance—must have a primary inductance of about 100 henries. Now a 9 to 1 transformer would have a secondary inductance of $9 \times 9 \times 100$ or 8100 henries, and unfortunately such a transformer cannot be wound without its secondary having considerable capacity between layers of wire and between individual turns. This secondary distributed capacity shunts out the high frequencies just as the stray capacities in a resistance- or inductance-coupled amplifier lose the high audio tones.

It has not been found possible to build a transformer which will yield a flat frequency characteristic when worked out of a high-impedance tube, and when using ordinary iron for the transformer core, with a turns ratio of much greater than 3 to 1. Using higher permeability iron, a somewhat greater turns ratio can be secured because less wire need be used to get a given value of inductance but there are very few transformers on the open market with a turns ratio of more than 4 to 1 that give a flat characteristic over a wide frequency band.

This statement does not preclude the possibility of using a higher ratio and overcoming the loss of either low or high tones —or both—in some other part of the circuit, and in fact many amplifiers have been so designed.

Figure 163 is a characteristic of a single transformer obtained by putting known voltages across the primary and measuring the secondary output voltage, but without secondary load.

The hump at 5000 cycles is due to the leakage inductance between primary and secondary resonating with the secondary dis-

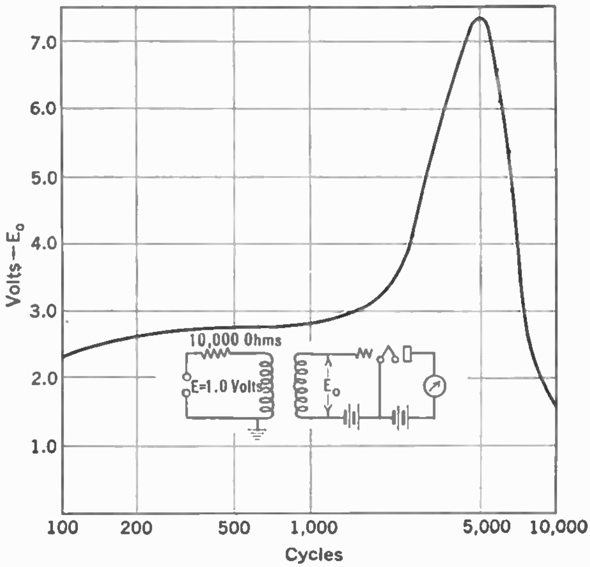


FIG. 163. Characteristic of single audio transformer. The high peak at 5000 cycles would be reduced in practice by placing a resistance load across the secondary.

tributed capacity. Beyond this point the whole transformer looks like a capacity to the tube and hence the effective resistance into which the tube works becomes steadily less as the frequency increases.

Well-designed transformers of low turns ratio, using special iron cores of high permeability, can be made to have a flat characteristic over a very wide band width—from 30 to 15,000 cycles.

209. Measurements on transformer-coupled amplifiers. The curve in Fig. 163 on a single transformer may be no indication at all of what a two-stage amplifier may do, because a certain amount of "regeneration" takes place in the average amplifier unless considerable pains are taken to prevent such difficulties. This regeneration distorts the curve, and makes laboratory measurements difficult to check.

210. Calculation of over-all voltage amplification. Let us consider the amplifier in Fig. 164. The over-all amplification is the

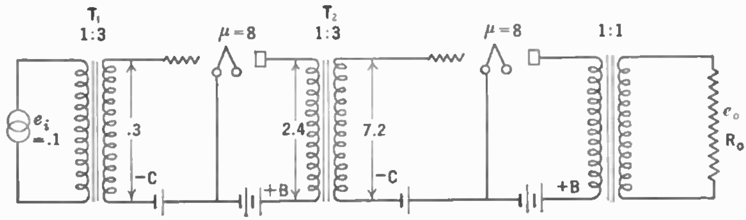


FIG. 164. How a voltage e_i is amplified in a transformer-coupled amplifier.

ratio between the voltage, e_o, across the output load and that across the input, e_i.

$$G = \frac{e_o}{e_i} = \frac{3 \times 8 \times 3 \times 8}{E_i} \times \frac{R_o}{R_o + R_p}$$

$$= \frac{576\ R_o}{E_i\ (R_o + R_p)}$$

where R_p = plate resistance of last tube.

It is actually not possible to realize all this amplification because it is never possible to realize the full μ of the tubes. The voltage gain measured and calculated will usually check very closely.

Now suppose we apply an input voltage of, say, 0.1 volt across the primary of the first transformer. Across the secondary this will become 3 × 0.1 or 0.3 volt and so the value of the C bias for this first tube which is fed out of the secondary of T_1 need not be greater than 1 volt since that will take care of severe overload, and if the tube is a triode type a plate voltage of 45 will be sufficient. Somewhat better amplification and fidelity will result by using 90 volts on the plate and 4.5 volts bias on the grid, since the plate resistance will be somewhat less under these conditions. If the impedance of the following transformer as looked at from the tube is high compared with the R_p of this first tube—as it will be at frequencies of the order of 1000 cycles if the transformer is any good—nearly all the μ of this tube will be realized. Across the primary of the second transformer, T_2, then will appear a voltage of 0.3×8 or 2.4 volts and across the secondary a voltage of 7.2 volts which will require C bias of 9 volts and about 135 volts on the plate. This voltage will be multiplied eight times in this tube and will appear across the output load as 38.4 volts, provided the load is twice the resistance of the last tube. This voltage across a 10,000-ohm load will produce 147 mw of power.

211. "Equalizing." It is possible by means of correcting circuits to get almost any kind of frequency response curve desired. For example, if a certain amplifier is deficient at low frequencies, one stage may be made resonant to these frequencies and so pull up the characteristic. If the amplifier tends to sing at some frequency, a loss may be put in at this frequency, and the over-all curve will be flatter than without the equalizer. In the telephone system the use of equalizing networks is very important and has come to be almost an exact science. These consist of resistances, inductances, and condensers. Equalizing usually results in an over-all loss in amplification, that is, some loss is incurred which must be made up by additional stages. In other words, one gains a better characteristic at the expense of amplification. In some amplifiers a better low-frequency response is secured by tuning the primary of the transformer by a capacity to a low frequency.

212. The power amplifier. The final tube in an audio amplifier which is feeding audio frequencies into a loud speaker must be essentially a power amplifier. Its task is to deliver undistorted power to the loud speaker, and not to develop any great amount of voltage amplification. The task of the previous amplifier stages is to build up the small output voltages of the detector so that the large voltages necessary to excite the grid of the power tube may be obtained. The a-c power in the plate circuits of tubes previous to the power stage is small; what is required is that each previous stage shall give a maximum of voltage amplification without distortion, and the fact that maximum power may not be developed in these plate circuits is not important. These tubes work into very high impedances in which it is not possible to generate much power although it is possible to build up considerable voltages across them.

The alternating plate current of the last tube, then, must be rather large and this means that the grid a-c voltages must be large, which in turn means that the E_g–I_p curve of this tube must have a long and straight part. The 45 tube, for example, which can deliver about 1600 mw without much distortion must have an rms grid voltage applied to it of about 35 volts; there must be a portion of the E_g–I_p curve which is straight over at least twice this number of volts. Thus if the grid is biased 50 volts, the characteristic must be straight from minus 97.5 to minus 2.5 volts. The next preceding tube has much smaller voltages to handle and so its characteristic need not be straight over such a long part.

The final tube, then, is to deliver power. Its grid must be supplied with sufficient voltage so that the plate current variations, acting through the load, produce this desired power. The final tube (or tubes) may be a fairly low-mu triode or a high-mu pentode. The triode will produce the same amount of power as a pentode but will require more grid excitation. It will produce a cleaner output, i.e., less distortion. Single tubes are rarely used in either high-class radio receivers or public-address system final stages. It is better practice to use two tubes in push-pull.

Since the triode requires greater input voltages, the gain of the system ahead of the final tube must be greater than if a pentode were used. Therefore there is more chance for hum to enter the amplifier.

The pentode, however, is a high-mu tube which will deliver considerable power output. Class B amplifiers, as described below, utilize high-mu tubes. In fact, the tube is so designed that the plate current with no grid bias and no signal is very low and therefore no bias is needed. This permits the total voltage output of the rectifier-filter system to be applied to the plate of the tube. For example, the 46 has a no-signal plate current of 4 ma on 300 volts and delivers 16 watts (two tubes) in a Class B circuit.

Types of Tube	Power Output Watts	Plate Volts
45	1.6	250
50	4.6	450
47	2.5	250
2A3	3.5	250

213. The push-pull amplifier. High-quality receivers, public-address systems or other places where considerable sound output

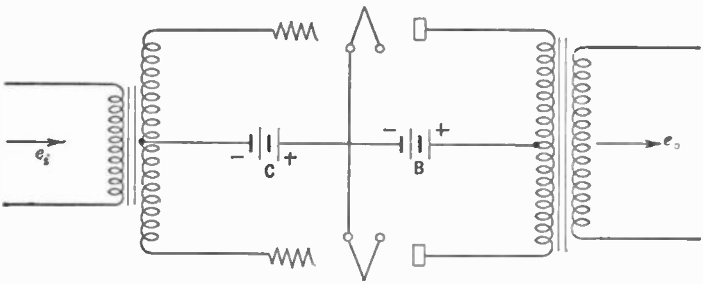


Fig. 165. Push-pull amplifier.

is desired with maximum tone fidelity utilize two power-amplifier tubes connected in a push-pull circuit shown in Fig. 165. The advantages of this circuit are several, as outlined below.

Distortion due to second harmonics is reduced to a low figure compared to a single tube; the power output is more than twice that obtainable with a single tube, and because of the elimination of troublesome second harmonics the input voltage can be raised somewhat with corresponding greater output; there is no direct current in the output transformer which can therefore have less iron; there are no hum voltages in the output and therefore less filtering of the plate supply is necessary; there are no currents corresponding to the frequency of the signal in the center tap which supplies plate voltage, and therefore these signal currents cannot get into the plate supply system to create regeneration.

Tubes may also be operated in parallel. Twice the power output is then delivered on the same signal excitation. To deliver equivalent power the push-pull amplifier must be supplied with twice this input voltage. Distortion will be comparable in the parallel case to that encountered in the use of a single tube.

Push-pull operation is not limited to any type of tube. Either low-mu triodes of the 45 or the 2A3 type, or pentodes like the 47 may be operated in this manner. Frequently a combination of the push-pull and parallel operation of tubes is utilized. In this case two tubes in parallel are on each side of the amplifier, making four tubes in all. The two parallel tubes give twice the output of a single tube and the push-pull setup of these two sets of parallel tubes multiplies the output by another factor of two or more. Therefore at least four times the power output is secured. The same result could be attained by substituting a single tube of double the rating for the parallel tubes, but such single tubes usually require high plate voltages, are large in size, and increase the expense of the power supply considerably.

In broadcast stations where great power is required it has come to be standard practice to use tubes in parallel. Thus if 25 kw of power is desired, a bank of 10-kw tubes in parallel will be used rather than a single tube. Then if any one tube goes bad the others carry on with only slight lowering of the total output power.

The push-pull amplifier circuit is shown in Fig. 165. It consists of a center-tapped input transformer, two tubes of identical characteristics, and a transformer, or a choke, with a center tap. When a voltage is induced into the secondary winding of the input transformer, one grid becomes less negative a certain amount and the other grid becomes more negative the same amount.

If the C bias which is attached to the center of the input winding is 35 volts and if across the entire secondary winding appears a peak a-c voltage of 20, one tube has its negative grid voltage increased by 10 volts, or to 45 volts, and the other decreased by 10 volts, or to minus 25 volts. Therefore one plate current increases and the other decreases. These variations in alternating plate current flow through the output winding and may be transferred to the load. These plate circuit current variations are out of phase by 180 degrees, one increasing, the other decreasing a like amount. One tube "pushes" current through the output, the other "pulls" current through it. Suppose both tubes pushed at the same time. What would happen? If they both pushed the same amount and at the same time no current would flow through the output winding because the two currents would neutralize each other.

If, then, we can cause the second harmonic currents to be in phase, that is, to push or pull at the same instant, and the same amount, they will not get into the load, and distortion due to these extra currents will not appear in our loud speaker.

214. Push-pull characteristics. Distortion is caused in an amplifier because the characteristic curve is not a straight line, but has a curve in it near the bottom. This curve is such that even harmonic currents, not only the second but all even-numbered harmonics, will either push or pull simultaneously. Whereas the fundamental and odd harmonics decrease in one tube and increase in the other as the grid is excited and so cause an effective voltage to appear across the output transformer windings, the even harmonics decrease and increase together and effectively balance each other out across the transformer. They do not appear in the load.

All this hinges on the supposition that the two tubes are alike, that is, they have identical characteristics. If they do not have identical characteristics, some even harmonics will appear in the output.

Because the input voltage across such an amplifier is divided into two parts this amplifier requires twice the input voltage to give the same output power—unless the turns ratio of the input transformer is doubled, which is difficult to carry out in practice. Because of the push-pull arrangement, however, considerable overloading can be tolerated before the third harmonics which are not canceled out become objectionable. And there is another advantage—the output transformer or choke need not have such a large core because of the fact that the direct currents in the two halves are flowing in opposite directions, and, since the two windings are closely coupled, the resultant magnetization of the core is very low. Since the two windings are connected, "series-aiding" so far as alternating currents are concerned, the total inductance is increased. Not only less iron is necessary but also less copper. The proper match between the tubes (twice the impedance of a single tube) and the loud speaker can be obtained by the use of such a transformer.

The output resistance of such an amplifier is double that of the single tube; therefore when worked into a low impedance load an output transformer must be used to see that maximum undistorted power is fed to the load. In other words, the plate load must be matched to the plate resistance of the amplifier by means of an appropriate output transformer.

215. Coupling the amplifier to its load. The output device for the push-pull amplifier may have at least two forms. Either it is a straight transformer with two windings of the proper turns ratio, or it is a center-tapped choke. The output transformer is almost invariably used. Its turn ratio may be arranged to match properly the tubes to the load. With the choke there is no matching function; the tubes "look into" the load directly unless the choke has taps enabling "impedance matching." With a choke, at first thought one would judge that the terminals of the loud speaker would be at high voltages from each other because they are attached to the plates of the tube, but this is not true. It is true, however, that they are at high potential with respect to earth and so one may get a severe shock if the voltage is high and if one of the terminals of the speaker is touched by anyone who is in contact with ground, but the two ends of this choke are at the same d-c voltage and so no d-c voltage exists across the speaker. This situation, of course, prevents any current from flowing through the speaker. If one desires protection against the high d-c voltage from one speaker terminal to ground, he may isolate the loud speaker from the plates of the tubes by means of a condenser, but even here there are large a-c voltages developed, particularly when a percussion instrument in the orchestra to which one is listening is hit a sharp blow.

The push-pull amplifier, then, is a device for eliminating the even harmonic distortion which occurs when tubes are worked too far down on the curved part of their characteristic. Since the distortion is inherently less, the tubes can be worked harder, having greater input voltages impressed on them, and having

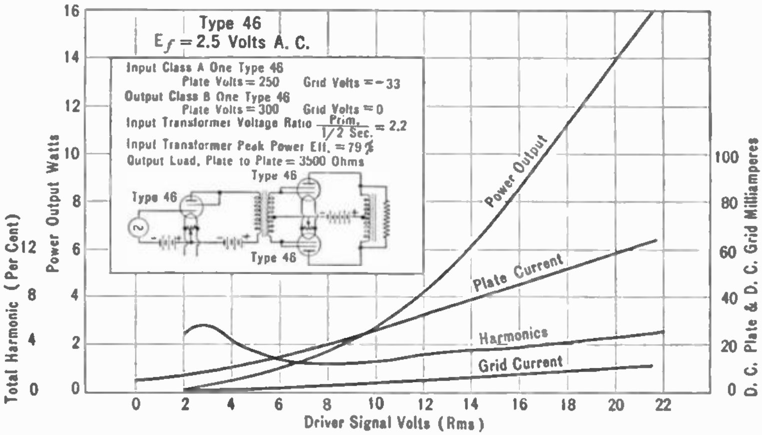


FIG. 166. Characteristics of Class B amplification.

somewhat lower output resistance loads to work into. Therefore the lowering of efficiency caused by the division of input voltage by the two halves of the input transformer is somewhat ameliorated and the over-all efficiency may not be different from a single tube.

216. Class B amplification. Suppose, for example, we increase the steady C bias to the two push-pull tubes so that the plate current is near zero. Now there will be no plate current flow until the input a-c signal overcomes this d-c bias. For this reason there will be an appreciable fraction of the input a-c cycle in which no plate current flows.

It is also possible to drive the grids of these tubes positive so that they actually consume power. This power must be supplied by the circuit from which the two tubes are driven. This preliminary stage is called a "driver" and must be essentially distortion-free. Ordinarily this driver stage is push-pull.

Such an amplifier is known as Class B. Very high efficiency from small tubes with medium plate voltage can be secured. The two tubes must be well matched, and frequently are in the same envelope.

Two tubes must be used; they are connected just as any other push-pull amplifier. No C bias is used, the tubes being specially built with a high mu so that with no bias the plate current is small. When the excitation is applied little or no current flows in the plate circuits except on the half-cycles which make the grid positive.

Where the ordinary push-pull circuit, connected and biased for Class A operation, draws plate current in both halves at all times, one tube taking more current when the other takes less from the plate supply source, Class B tubes draw current in spurts. When one tube grid is going negative the other is going positive. The latter tube draws current; the other tube does not.

The amount of current each tube draws depends upon the exciting grid voltage. The power output of such a pair of tubes may be very high; the distortion may be made quite low by careful design. Since the current taken from the plate supply system varies with the exciting voltage applied to the tube grids, the voltage regulation of this supply must be very good, that is, the terminal voltage of the filter must not drop appreciably when a sudden large current is drawn from it. For this reason the rectifier usually employed is a mercury-vapor tube which has a very low and constant voltage drop across it regardless of the current taken from it. This voltage drop amounts to about 15 to 20 volts.

Since the grids of the two tubes are driven positive, they will draw current. This flow of current represents power and this power must be supplied by the previous tube. The previous tube is usually called a "driver" and is connected to the Class B tubes through a step-down input transformer. Distortion present in the driver stage will go through the power stage to appear in the output. Therefore this stage must be carefully designed.

The 46 is a tube especially designed for this service. With 300 volts on the plates, zero bias, load resistance of 5200 ohms and with an average power input (grid to grid) of 950 mw—nearly 1 watt—the two tubes will deliver 16 watts.

In 1933 the functions of several tubes were combined into one envelope. Thus the two tubes of a Class B stage were put into a single bulb, for example, the 79, which has a 6.3 volt heater and will produce 5.5 watts on 180 volts.

Another interesting combination of tubes especially designed for a-f amplification is the 2B6 in which a single heater supplies two cathodes. There are two grids and two plates. The grid of the second section is connected within the tube to the cathode of the first tube which is above ground potential by the bias of the second tube. The plate of the first tube is connected to B plus, the second plate feeds the output into a transformer. The second grid draws power which is supplied from the first section. With a signal input to the second tube of 25 volts rms, a power output of 4 watts is obtained.

217. General conditions for voltage and power amplification. In general, voltage amplification must always take place between a source of voltage in a low impedance circuit and a receiver of a voltage which is higher in impedance. The turns ratio of a transformer for the greatest voltage amplification is given by N equals $\sqrt{Z_s/Z_p}$, where Z_s is the impedance into which the secondary looks and Z_p is the impedance of the transmitter. If these two impedances are equal, the transformer must have a one-to-one ratio. There will be no step-up in voltage, no direct currents in the output.

Where voltage amplification is the goal the greatest amplification will be attained when working from a very low-impedance device into a very high-impedance device, for example, a tube with a low plate resistance working into a tube with a very high grid-filament resistance. This means that the grid of the following tube must never be permitted to go positive, for then the input resistance of this circuit becomes quite low and the amplification falls and amplitude distortion results.

218. Networks. It is often desired to limit a voltage which may be applied to an amplifier, and to limit it in such a way that all frequencies are reduced alike, i.e., the limiting device must have no frequency characteristic. For example, suppose that an amplifier is to be bridged across a line carrying a broadcast program. It is desirable to have the level of this signal on the line as high as convenient so that the ratio of signal to noise may be high, but the level may be too high to impress upon the amplifier.

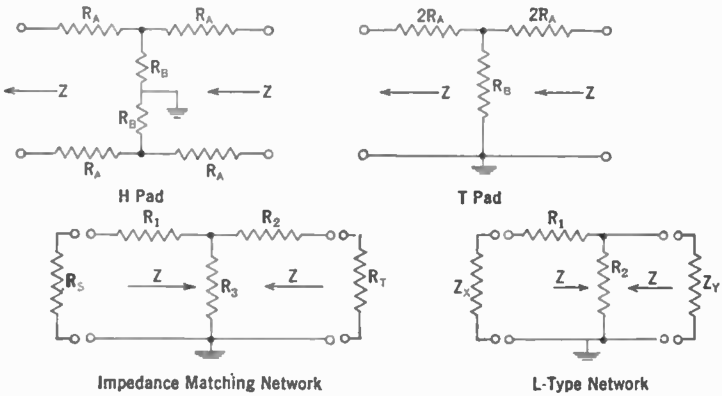


FIG. 167. Types of networks known as "pads."

In such cases it is customary to make use of a network of series and parallel resistances known as a "pad." Figure 167 shows several such pads. In practice they may be variable as to loss or they may be fixed units of so much loss. Thus, if it is desired to control the output of an amplifier or microphone, without controlling the frequency characteristic or without changing the impedance relations in the circuit, a variable pad is used. Pads are often used when it is desired to isolate an amplifier from impedance changes on a line, for example, by providing a more or less constant load impedance for the amplifier to work into.

In many circuits it is desirable to have both sides of the system balanced with respect to ground. Thus the balanced H pad has its series resistances equal to each other, and the shunt resistance grounded at the center point. The T pad can be used where minor unbalances with respect to ground are not important. In other cases a network is desired which will insert a given loss between devices which do not have the same impedance, or conversely, to use a network to adjust the two devices so that the impedance unbalance will not be so marked. Here the network takes the place of a transformer and will have a greater loss than a transformer but might have a better frequency characteristic.

219. Design of pads. The formulas below are used in designing fixed pads of the T or H type. One must start with the value of the impedance into which the pad works, and the value of the loss desired. This loss can be expressed in several ways, but it is simplest to use the decibel system described in the next chapter.

$$R_A = \frac{Z(K-1)}{2(K+1)}, \quad R_B = \frac{2ZK}{K^2-1}, \quad K = \text{antilog}\,\frac{\text{db}}{20}$$

Example 1–11. Design a T pad to work between 600-ohm lines and having a loss of 10 db.

Solution. Solve first for $K = \text{antilog db}/20$

$$= \text{antilog } 10/20 = \text{antilog } 0.5$$

What is needed here is the number whose logarithm is 0.5. Looking this up in a log table, this number is found to be 3.17. Therefore $K = 3.17$.

$$R_A = \frac{600(3.17-1)}{2(3.17+1)} = \frac{600 \times 2.17}{4.17 \times 2} = 156 \text{ ohms}$$

$$2R_A = 312 \text{ ohms}$$

$$R_B = \frac{2 \times 600 \times 3.17}{3.17^2 - 1} = 424 \text{ ohms}$$

To check, solve first for the power produced in one 600-ohm resistance when a voltage E is in series with the other 600-ohm resistance. In other words, a generator E is in series with two 600-ohm resistances. What is the power in one of these resistances? Then solve for the power produced in one 600-ohm resistance when the T pad is between the two resistances. Divide the larger value by the smaller value. The result is the advantage of the simpler circuit. The advantage may be expressed as 10 log

P_1/P_2 where P_1 is greater than P_2. If one gains 10 db by *not* using the T pad, he will *lose* 10 db by using it.

220. Filters. There are many places in the telephone system where it is desirable to cut off the response of an amplifier or the transmission of a line at a certain upper or lower frequency. Often it is desirable to pass a given band of frequencies, or to refuse passage to (attenuate) a certain band of frequencies. A tuned circuit is a very simple circuit of the type that will pass or attenuate a band of frequencies, and a series of tuned circuits may be thought of as a band-pass or band-rejection filter.

These **filters,** as they are called, are made up of inductances and capacities and are of the recurrent type, i.e., they are made up of several identical sections of fairly simple or perhaps very complex unit circuits. Thus a two-section filter has a sharper cut-off and greater attenuation than a single section and is made up of two single sections connected in series. Telephone engineers have worked out extremely complicated and useful filters or networks of these general types, and the study and use of them have become very complicated.

CHAPTER XII

THE DESIGN OF AUDIO AMPLIFIERS

The audio amplifier is at least half of the modern radio receiver. In addition to being necessary to the reception and reproduction of radio signals, the audio amplifier may be used with phonographs, talking films, public-address systems, etc. The design of audio-amplifying equipment forms a large part of the work of any radio engineer. This chapter gives some of the theoretical and practical work that must be understood before one can intelligently design an amplifier.

221. The decibel. When one compares the voltage amplification or the power output of any system in which the ear is likely to play a part—as in an audio amplifier—it is convenient to express the greater amount of amplification or power which one amplifier gives over another by means of a unit that bears some relation to the sensitivity of the ear. For example, one amplifier may turn into a loud speaker a power output of 800 mw and another an output of 1000 mw. How much difference would this make to the ear? Offhand it seems that a considerably greater volume would result, but this is not true. Such a ratio of one power to another as 1000 to 800 is scarcely discernible to the ear.

We can state that an amplifier has a voltage gain of 50 and that under some other condition it has a gain of 60 and imagine that the latter is easily noted by the average ear. But is it?

Several attempts have been made to express gain in units more nearly like the units in which the ear hears, logarithmic, for example. Such a convenient unit of loss or gain is the **decibel,** abbreviated as **db.** The bel was universally adopted in 1928—it is ten decibels—and is named in honor of Dr. Alexander Graham

Bell, the inventor of the telephone. The difference in two powers differing by 1 db is just discernible to the ear.

The db is a logarithmic unit—that is, each time the amount of power of a device is doubled—or multiplied by 2—we add 3 db. When the power is increased tenfold—multiplied by 10—we add 10 db. Here, then, is the second advantage in the db. We can add them, instead of multiplying them. For example, let us suppose the voltage amplification of an amplifier is 25 and that it is to be connected after another similar amplifier. What is the voltage gain? Evidently, if the second amplifies what the first gives it, the over-all gain will be 25^2 or 625. Here we must multiply 25 by 25, which is awkward, but if we knew that one amplifier had a voltage gain corresponding to 25 db and was to be used after another of similar characteristics, we would state that the over-all gain was 25 plus 25 or 50 db. The db is defined as "ten times the common logarithm of the ratio of two powers" or

$$N_{db} = 10 \log_{10} (P_1/P_2) \qquad [1]$$

in which N is the number of db by which the two powers P_1 and P_2 differ. The table below gives some easily remembered values of db and their corresponding power or voltage and current ratios:

N_{db}	Approximate Power Ratio	Approximate Voltage or Current Ratio
3	2 0	1.41
4	2.5	1 59
6	4	2.0
7	5	2 24
9	8	2 82
10	10	3 16
20	100	10 0
23	200	14 1
30	1000	31.6

Let us consider an amplifier with an output power of 100 mw. How much must we increase its power output before the ear can just detect the difference? Suppose we double the output. The ratio is then 200/100 or 2 and the db corresponding to this power ratio is 3. The ear can detect one db difference and using a table of db or a slide rule we find that 1 db corresponds to a power ratio of 1.25 roughly. Thus the power output to which 100 mw must be increased before the ear can detect the difference is such that $P = P_2/100 = 1.25$ or 125 mw. Adding another db brings the level up to 160 mw and another unit brings it to 200 mw, as indicated above.

In this case it would have been foolish to go to great efforts to effect an output of 115 compared to an output of 100, because the ear could not tell the difference. In fact the ear can only with some difficulty tell the difference between the amplifiers differing by 3 db—double the power—unless single tones are used and then only in a quiet room.

222. Voltage and current ratios. Strictly speaking the db should be used only when expressing the ratios of powers. Let us suppose two amplifiers are feeding current into equal resistances. The currents are different. How can we express in db the advantage of the one as a current amplifier? We need only find out the ratio of the powers as before, and multiply the logarithm of this ratio by 10. Thus,

$$P_1 = I_1^2 R$$

$$P_2 = I_2^2 R$$

$$\text{db} = 10 \log P_1/P_2 = 10 \log \frac{I_1^2 R}{I_2^2 R}$$

$$= 10 \log \frac{I_1^2}{I_2^2}$$

$$= 20 \log \frac{I_1}{I_2} \qquad [2]$$

If the resistances are not equal (2) becomes

$$\text{db} = 20 \log \frac{I_1 \sqrt{R_1}}{I_2 \sqrt{R_2}} = 20 \log \frac{E_1/\sqrt{R_1}}{E_2/\sqrt{R_2}} = 20 \log \frac{E_1 \sqrt{R_2}}{E_2 \sqrt{R_1}} \qquad [3]$$

The factor 20 arises from the fact that when one squares a number the logarithm is doubled. For power ratios, the db is 10 times the logarithm, for current or voltage ratios the db is 20 times the logarithm of the ratio.

Voltage or current ratios can be translated into db only when the impedances into which the current flows, or across which the voltage exists, are taken into account. If these impedances are equal for both currents or both voltages, they cancel out, one being in the numerator and one being in the denominator, but, in general, they do not cancel out and must be considered.

The db is always an expression for a ratio. We cannot speak of an amplifier that has an output of so many db, but if we assign some arbitrary level—say 10 mw—and compare all amplifiers to this amount of power we can say that one has 20 db or 100 db greater output, or less output, or is "up" or "down" 20 or 100 db. All these db are expressions for the ratio between these powers and the "zero level" power of 10 mw.

Example 1–12. An amplifier has 1 volt applied to its input resistance of 10,000 ohms. Across its output resistance of 4000 ohms appears a voltage of 40. What is the power gain in db? The voltage gain? Would it be worth while to increase the output voltage from 40 to 50 volts?

Solution.

Power input $P_i = \dfrac{E_i^2}{R_i} = \dfrac{1}{10{,}000} = 10^{-4}$ watts

Power output $P_o = \dfrac{E_o^2}{R_o} = \dfrac{40^2}{4000} = \dfrac{1600}{4000} = 0.4$ watt

$$\frac{P_o}{P_i} = \frac{0.4}{10^{-4}} = 4 \times 10^3 = 4000$$

Power gain $= 10 \log 4000 = 36$ db (because the log of 4 is 0.6 and the log of 1000 is 3 and the log of 4000 is 3.6)

Voltage gain $= 36 \text{ db} = 20 \log \dfrac{E_o\sqrt{R_i}}{E_i\sqrt{R_o}}$

Hence

$$\log \frac{E_o\sqrt{R_i}}{E_i\sqrt{R_o}} = 1.8$$

$$\frac{E_o\sqrt{R_i}}{E_i\sqrt{R_o}} = \text{antilog } 1.8$$

Voltage gain $= 63$

If E_o becomes 50 volts,

$$P_o = \frac{50^2}{R_o} = \frac{2500}{4000} = 0.625$$

The gain due to this increased output over P_o (above) is

$$10 \log \frac{0.625}{0.400} = 10 \log 1.56$$

$$= 2.0 \text{ db (approx.)}$$

And so the gain due to increasing the output from 40 to 50 volts—or from 400 to 625 mw—will be audible to the ear, but the difference is not worth a great deal of effort to attain.

The solution of the above example is characteristic of the solutions of all such problems. Given the power ratio it is only necessary to look up the logarithm of this ratio to get the db gain. The student must not forget that all numbers between 100 and 1000 have as the first digit of their logarithms the number 2. Hence all power ratios between 100 and 1000 lie between 20 and 30 db. Multiplying any power by 10 represents a gain of 10 db. Thus of two amplifiers having outputs of 50 and 500 watts, the latter is said to be 10 db better than the former. A loss of 10 db means that the power in any circuit has been divided by 10. If it is decreased or increased by 100 times the loss or gain in db is 20 db.

Example 2-12. A certain amplifier has a characteristic such that at 100 cycles its amplification in voltage is 8, at 1000 cycles it is 80, and at 6000 cycles, where the amplifier tends to "sing," the voltage amplification is 200. Are these differences appreciable to the ear?

Let us take the amplification at 1000 cycles as a zero level and find out how much above or below this level the other frequencies are. At 100 cycles the voltage ratio is 80/8 or 10. At 6000 cycles the voltage ratio is 200/80 or 2.5. At 100 cycles there is a loss, at 6000 cycles there is a gain. Thus,

$$\text{Loss at 100 cycles} = 20 \log \frac{80}{8} = 20 \log 10 = 20 \text{ db}$$

$$\text{Gain at 6000 cycles} = 20 \log \frac{200}{80} = 20 \log 2.5 = 8 \text{ db}$$

Such a characteristic indicates a poor amplifier. The low notes would be totally lost and high ones would overload the last tube.

Example 3–12. In a certain circuit there is a loss of 25 db. What power ratio corresponds to this loss?

Power ratios of 10 = 10 db, 100 = 20 db, and 1000 = 30 db. Therefore the power ratio of 25 db lies somewhere between 100 and 1000. The figure 2 of 25 db tells us that the loss is somewhere between 100 and 1000 times. The figure 5 of 25 db is 10 times the logarithm of 3.1 and so 25 db corresponds to a power ratio of 310.

The solution of such a problem is as follows:

$$25 \text{ db} = 10 \log_{10} \frac{P_1}{P_2}$$

$$2.5 = \log \frac{P_1}{P_2} \quad \text{(dividing both sides by 10)}$$

$$\frac{P_1}{P_2} = \text{antilog } 2.5$$

$$= \text{antilog } 2.0 \text{ times antilog } 0.5$$

$$= 100 \times 3.1 = 310$$

If the loss were a voltage loss of 25 db the solution would be:

$$25 \text{ db} = 20 \log \frac{E_1}{E_2}$$

$$1.25 = \log \frac{E}{E_2} \quad \text{(dividing both sides by 20)}$$

$$\frac{E_1}{E_2} = \text{antilog } 1.25 = \text{antilog } 1.0 \text{ times antilog } 0.25$$

$$= 10 \times 1.78 = 17.8$$

223. The use of the db. The decibel may be used to express any ratio of power, voltage, current, mechanical loss or gain, etc. Thus we may say that a symphony orchestra has a range of 60 db in power, that is, when it is playing very loud, fortissimo, it is 60 db louder than when playing very softly, pianissimo. This corresponds to a power range of one million to one. In the wire circuits which carry the microphone currents from the symphony hall to the broadcast station, the weakest of the desired signals must be 40 db above the noise in the line. The very weak passages of the orchestra are built up by local amplifiers until the currents are greater than the noise currents. The limit to the louder passages is the overloading of the amplifiers either at the hall or in the broadcasting station or by causing "cross talk" from one telephone circuit to another. And so the stronger passages are cut down.

Whenever a circuit suffers a loss in power or voltage or current, we may express that loss in db. The frequency characteristic of an amplifier, or a loud speaker, or of a telephone line may be expressed in db by plotting a curve in which zero level is the amplification or power output at some arbitrarily chosen frequency. Thus if we choose 1000 cycles as a reference frequency, all other frequencies are either up, down, or flat with respect to the level at 1000 cycles.

Problem 1-12. What in db corresponds to a voltage ratio of 100? Power ratio of 100? What voltage ratio corresponds to 100 db? What power ratio?

Problem 2-12. A current of 0.006 amp flows through a resistance of 1000 ohms. A switch reduces this current to 1.0 ma. How much is the current reduced in db?

Problem 3-12. An amplifier has a normal output of 1 watt. A switch is provided so that its output can be reduced in 5-db steps. What is the output in watts when it is reduced by 5, 10, 20, and 25 db?

Problem 4-12. An amplifier has its power output reduced by 25 per cent. Is such a reduction in power audible to the ear?

Problem 5-12. A radio receiver has a voltage gain in its radio-frequency amplifier of 50 db. Express this in voltage gain, and in power amplification provided that the same impedance closes the input and output of the amplifier.

Problem 6-12. A radio receiver is so adjusted that a station 20 kc off the frequency at which the receiver is tuned is reduced by 40 db in voltage below the station that is being listened to. What is the ratio in voltage between the desired and undesired station?

Problem 7–12. A broadcasting station increases its power from 500 to 5000 watts. What is this in db? What is the increase if the power is increased to 50,000 watts?

Problem 8–12. If an audio amplifier has two stages and each stage has a gain of 25 db, what can the gain of the receiver be reduced to when listening to the 50,000-watt station compared to the 500-watt station provided they are equidistant? In other words, a given station increases its power from 500 to 50,000 watts. How much audio gain in db is this worth to the listener?

Problem 9–12. The noise on a certain telephone line is 40 db down from the broadcasting signals. What is their power ratio? If the telephone currents are of the order of milliamperes, what are the noise currents?

Problem 10–12. Phonograph records with single frequencies have been made for use as frequency standards. A certain record is labeled as being "—2.0 db" compared to a certain arbitrary level. What is the voltage ratio of the record compared to the arbitrary zero level?

Problem 11–12. The maximum power output from a 45 type of tube is 1600 mw. The 2A3 has an output of 3500 mw. How much greater in db is the 2A3 power output?

Problem 12–12. A loud speaker is 5 per cent efficient and requires 1.5 watts to give sufficient volume output. If it is made 50 per cent efficient how much can the power input be reduced to give the same output?

Problem 13–12. A tube has a plate resistance of 5000 ohms. Calculate the power into a load which varies from 1000 to 20,000 ohms and convert the ratio between the power at maximum to the power at other values of load resistance in db. How great can the difference between the load and the tube resistance be before the ear will note the difference?

Problem 14–12. The sensitivity of a condenser microphone used in broadcast studios is said to be -60 db where 0 db $=$ 1 volt per dyne of force exerted by an air wave impinging on each square centimeter of the diaphragm. The carbon button microphone has a sensitivity of -40 db. How much more sensitive is the latter over the condenser transmitter, expressed in db? How many stages of transformer-coupled audio amplification using 2 to 1 transformers and tubes with a μ of 8 will be required to bring the output of the condenser transmitter up to the level of the carbon button microphone? A commercial telephone transmitter—such as is used in ordinary telephones—is tuned to the average speech frequency and therefore amplifies what corresponds to its input about 1000 times. Express in db its sensitivity compared to the other two microphones.

Problem 15–12. A radio receiver is so adjusted that its output is 8 db above an arbitrary level. The maximum power the receiver can put out is 10 db above this level. If the output power is proportional to the square of the power of a broadcasting station which is producing the output of

8 db, by how much will the output tube of the receiver have to be increased in db if the transmitter doubles its power?

Problem 16–12. A radio receiver is tuned to a certain distant station which gives at the receiver input a voltage of 500 μv. A near-by station on a different frequency produces a voltage of 50,000 μv at the same time. How much loss in db must be put into the receiver at the frequency of the undesired station to reduce the signals to the same level? How much additional loss must be put into the receiver to reduce the unwanted station to 60 db below the desired signal? The curves in Fig. 168 will be in-

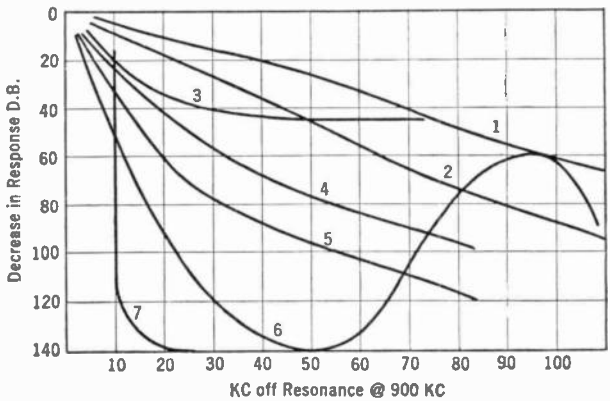


FIG. 168. Selectivity of several circuit combinations.

1. Single circuit non-regenerative.
2. Coupled circuit non-regenerative.
3. Single circuit regenerative.
4. Tuned radio frequency.
5. Tuned radio frequency.
6. Double detection (superheterodyne).
7. Ideal characteristic.

teresting in connection with this problem. They were published by Lloyd Espenschied in the *Bell System Technical Journal*, January, 1927. They show the relative selectivity of several types of receiver. The "double detection" receiver is a superheterodyne.

Problem 17–12. It is desired to make a gain control which will affect the output of a receiver in steps too small to be noted by the ear. An average person will readily note a change of volume of 3 db in the middle of the audio-frequency band, but changes of 10 db at the extreme upper and lower frequencies are not noticed. Suppose the loud speaker has an impedance of 4000 ohms, and that the gain control is to be placed across it What shunting resistance will be necessary in the gain control so that the changes in volume will occur in steps too small to be noticed? The gain control has a maximum value of 20 db.

Problem 18–12. The ratio of peak power in the voice (accented syllable) to average may be 200 to 1. Thus if the average power is 10 μw, the peaks may be as high as 2000 μw. Express the range in power of the human voice in db.

224. Three general types of amplifiers. Amplifiers have been divided into three general types according to which part of the grid-plate characteristic is used and according to the magnitude of the applied signal voltage. Class A amplifiers are operated so that plate current flows at all times; the grid is not usually driven positive; the plate current represents exactly the input signal. It has low efficiency and low output.

Class B amplifiers have the grid biased almost to plate current cut-off; plate current flows to any extent only when the grid is on the positive half-cycle of input voltage, and during this half-cycle the plate current in an ideal amplifier will represent exactly the input grid voltage. This amplifier has medium output and efficiency. Class B amplifiers are used in push-pull only.

Class C amplifiers are operated so biased that no plate current flows when the grid is not excited, and as a matter of fact it flows only during a portion of the half-cycle when the grid is driven positive. This type of vacuum-tube amplifier has high efficiency and high power output. The distortion inherent in this type of amplification precludes its use for speech or musical amplification. It is useful at radio frequencies where harmonics generated will be filtered out of the antenna, for example, by tuned circuits resonant only to the fundamental.

Amplifiers are often spoken of as voltage, current, or power amplifiers. These are more general terms and are used to indicate that one or the other of these three fundamental electrical quantities is amplified particularly. Voltage amplification is the ratio of the output voltage to the input voltage; likewise current and power amplification are ratios of the output to the input.

Radio-frequency amplifiers for use in receivers are invariably voltage amplifiers; in transmitters they may be power amplifiers or they may produce very little, or no, amplification, merely acting as an isolating circuit or a "buffer" stage to separate two circuits.

225. Rules for the amplifier designer. In general, the rules the amplifier designer must follow are these:

1. He must so design the amplifier that no stage can overload even on the strongest signals that are to be received. This implies that each tube has its proper grid bias and plate voltage.
2. In the plate circuit of each tube must be a sufficient impedance that at low audio frequencies the characteristic is straight and not curved. This implies that the dynamic E_g–I_p curve for a circuit may be one thing for 1000 cycles and another for 100 cycles—which is correct when apparatus is used that has reactance. At 1000 cycles the tube works into one impedance—at 100 cycles into a much lower one.
3. He will get a better characteristic—although less gain—from triodes if he uses low impedance, low-mu tubes. This will require more tubes, of course, to get a predetermined amount of amplification.
4. He will get more amplification—with a satisfactory characteristic with high-mu, high-impedance pentodes.
5. The more tubes in the amplifier, the greater will be the noise in the output due to "tube noise." Where the amplification must be carried to a high degree, special tubes with low internal noise must be used, for example, in the microphone amplifier. The signal must always be louder than the noise and, if it is not, no amount of amplification will do any good.
6. The more tubes and the higher the over-all gain of the amplifier the greater will be troubles from instability and from unwanted pickup from nearby a-c magnetic fields.

The maximum voltage amplification that can be secured from a transformer-coupled stage is μ times the turns ratio of the transformer. If the impedance into which the tube works—the *reactance* of the primary if the secondary is open-circuited—is twice the plate resistance of the tube, 89 per cent of the μ of the tube will be realized. If the impedance of the transformer at the lowest frequency it is desired to amplify is two times R_p, the amplification at this frequency will be 89 per cent of the maximum possible, and nearly 100 per cent of the maximum possible will be attained at all frequencies. Then the range in amplification will be from 89 per cent to 100 per cent at all useful audio frequencies. The difference between these values of amplification will not be audible to the ear.

226. Comparisons between amplifiers. The only fair test between two amplifiers is made by means of a switch which alternately throws one setup and then the other to the source of test signal being used. A test on one amplifier at one time and a test on another at some different time is no test at all. The music may be different, the mood of the listener may be different, and there are too many other variables to give any faith in such a test. A simple four-pole double-throw switch will throw the amplifiers to the input and to the loud speaker almost without delay.

The engineer must remember that the ear can scarcely detect volume differences in which the power ratio is 2 to 1 and that, at the two extremes of the audio-frequency range, differences in power of 10 to 1 are none too easily noted. It has become standard practice in public-address systems and in amplifiers for broadcast station pickups to use very high-quality components amplifying a wide band of frequencies, even if radio receivers go no higher than 4000 to 5000 cycles.

227. Volume control. The point in a radio receiver where the volume is controlled has varied from time to time. In the early sets the volume was controlled by changing the audio amplifier gain, or by shunting the loud speaker. Then it shifted to the radio-frequency part of the circuit. With the advent of automatic volume-control circuits the volume control (manual) was shifted back to the audio amplifier. It became standard practice to take more or less of the detector output by means of a potentiometer, for example, in Fig. 169, where the detector feeds a following audio amplifier through a resistance-capacitance network.

If the amplifier is to be used with a phonograph pickup, or practically any other source of tone to be amplified and controlled as to volume, the potentiometer method may be used. Since the grid-cathode circuit bridged across the potentiometer is virtually an open circuit, so far as taking power is concerned, the load put upon the source of tone is not far from the load taken by the resistance of the potentiometer.

The virtue of controlling volume by affecting the amount of voltage to be amplified rather than by changing the gain of the amplifier lies in the fact that the best operating conditions for the tubes can be chosen, i.e., load resistance, bias voltage, and

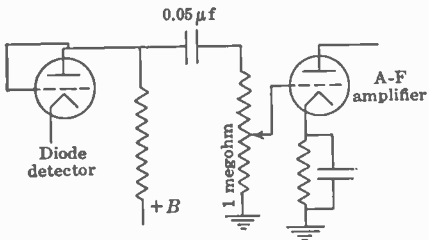


FIG. 169. Gain or volume control using a potentiometer.

plate voltage. Changing the volume does not change these conditions.

Likewise the detector input voltage (rf or if) can be chosen for maximum sensitivity or least distortion, and by means of the avc system this voltage will be fed to the detector regardless of the setting of the manual volume control.

228. Proper C bias for power tubes. The proper value of C bias for an amplifier tube is determined partly by the input voltages to be encountered and partly by the amount of d-c power the plate can dissipate safely. This power is the product of the plate voltage and the plate current, and the latter is controlled to some extent by the C bias.

Problem 19–12. A power tube's plate current is as follows,

E_p	E_c	I_p, ma
450	0	100
	20	55
	30	35
	40	18

and the maximum safe power that can be dissipated at the plate is 10 watts. What is the minimum value of grid bias (E_c)?

229. Compensating amplifiers at low frequencies. Very often the loss in low frequencies in parts of the circuit may have to be

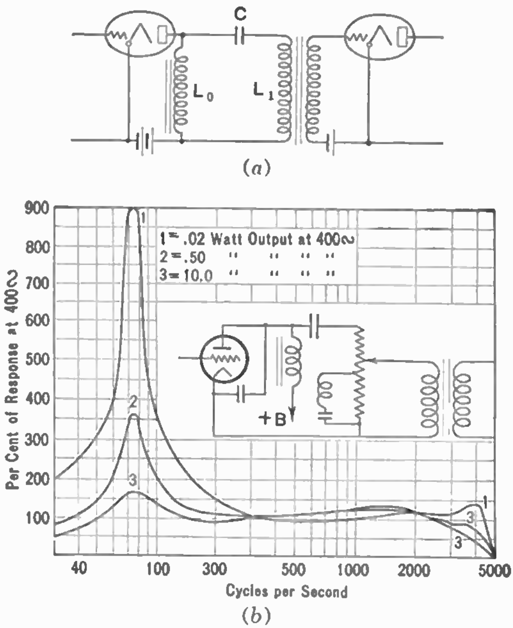


Fig. 170. (*a*) Simple means of boosting low-frequency response. (*b*) Circuit and response of acoustically compensated volume control.

made up in the audio amplifier. For example, if the baffle in which the speaker is placed is too small to radiate properly the low tones, the amplifier may be "tilted" so that these frequencies are over-emphasized. Coupled with the loss in the baffle the over-all response may be fairly flat.

One of the simplest methods of pulling up the low frequencies is that shown in Fig. 170*a*. Here the primary of the coupling transformer is resonated by the series capacity. The coupling inductance which carries the plate current must have a reactance at any frequency which is high compared with the reactance of the transformer inductance and the series capacity.

230. Bass-boosting network. Since audio transformers have practically passed out of the radio-receiver designer's list of components because of the high gain now available from tubes using cheaper resistance coupling, the method of increasing bass response shown in Fig. 170*a* is not found in manufactured receivers. Instead, a simple network is shunted across the volume-control system in such a manner that at ordinary volume levels the amplifier characteristic may be comparatively flat. At low levels, however, where the ear tells the listener that the bass is very weak, the bass-boosting system automatically pulls up the bass. This is shown in Fig. 170*b* where a tuned circuit is shunted across part of the volume-control potentiometer.

When the volume is turned down, both low and high frequencies are given a boost, but the low ones are increased relatively much more. This is known as the acoustically compensated volume control.

231. Compensation for high-frequency loss. Just as a tuned circuit may be used to pull up the response at a low frequency, so may high frequencies be increased if desired. For example, in television amplifiers, very wide bands of frequencies should be amplified. Owing to the various capacitances in tubes, sockets, wiring, etc., the high end of the frequency response curve of television amplifiers tends to droop. If a small inductance can be added to the circuit in such a way that it resonates with these small capacitances at some high frequency, the characteristic will tend to rise and the loss in high frequencies may be completely, or at least partially, overcome.

232. Power levels. Engineers frequently use the decibel system in expressing the output level of a signal, mentally comparing it with some fixed and understood level.

In Fig. 171 is indicated the amount the broadcast system compresses the power range encountered in music. A symphony orchestra covering a range in power from minus 40 to plus 20, or 60 db, must be compressed into a range of 27 db when it is broadcast. Here the zero level is the power output of the orchestra when playing at what a musician knows as forte. In the broadcast system zero level is standardized as 1 mw into a standard line impedance of 600 ohms.

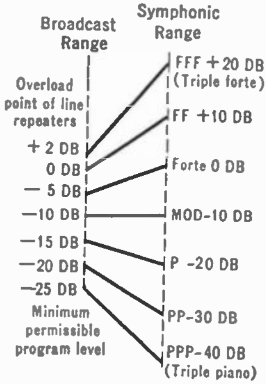


Fig. 171. Compression of dynamic range in broadcasting system.

Radio engineers have debated whether to rate the sensitivity of receivers in the microvolt or the decibel system. Thus to state that a receiver is a 10-μv set indicates that it requires this input to produce a given output, probably 50 mw. A receiver which requires 100 μv would be a 100-μv set.

In the decibel system the sensitivity of the set would be rated in decibels below 1 volt. Thus a receiver which required 1 volt to produce a given output would have a rating of zero; one which required only 0.5 volt would have a rating of 6; one requiring only 1 μv would have a rating of 120. Zero level would then be 1 volt, or one million μv. Thus a high sensitivity set would have a high rating number or value.

233. Regeneration in audio amplifiers. The troubles from regeneration in audio- and radio-frequency amplifiers were largely overlooked in the early days of broadcast receiver history. Al-

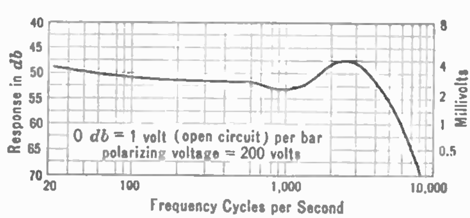


Fig. 172. Studio characteristics of microphone.

ternating currents in an amplifier must be returned directly to the cathode of the tube they are generated in, and never permitted to roam around through the wiring, through the power supply, through the grid-bias resistor, etc. Otherwise, regeneration cannot help being sometimes helpful, sometimes harmful.

Regeneration occurs when any impedance is common to two amplifier circuits. Currents from one circuit set up a voltage across this impedance. If this voltage is impressed upon a previous amplifier circuit, regeneration takes place. Coupling may take place across a resistance, a condenser, a coil, or across any complex combination of these three components of impedance.

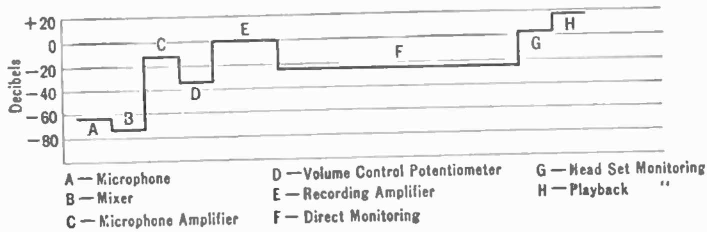


Fig. 173. Another example of the use of power levels. A level diagram of a recording studio.

To avoid unwanted coupling between stages, it is necessary that currents carrying audio frequencies go directly to the points desired and not through some roundabout way. Thus in the plate circuit of a tube there may be a-f currents as well as direct current. The a-f currents must flow through the load and then directly back to the cathode of the tube, not through the power supply and then to the cathode.

This is accomplished (see page 313) by proper use of series and shunt by-paths which make it easy for currents to go where they are wanted and difficult to go where they are not desired. This is most important in amplifiers in which there is considerable voltage amplification.

234. Filtering in audio amplifiers. A filter in an audio amplifier, as indicated in the last section, is designed to keep out of a certain circuit alternating currents of a certain frequency or frequencies. Let us see the grid circuit of the first tube in Fig. 175. Plate current flowing through the resistance R_2 causes a voltage drop. This drop is utilized as the grid bias for the tube. If al-

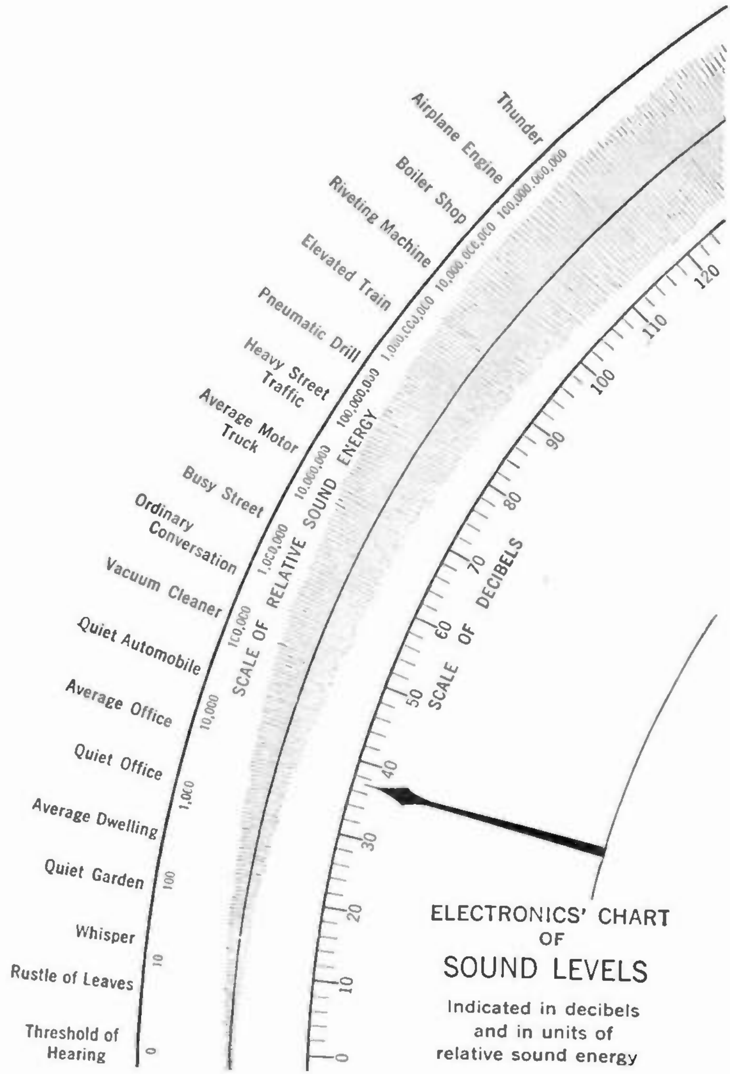


FIG. 174. Zero level for sounds has been taken as one ten-billionth of a microwatt of sound energy per square centimeter.

ternating currents flow through the resistance, they, too, cause a voltage drop, and since this resistance is now part of the grid circuit the voltages are impressed on the grid. Since the plate and grid a-c voltages are out of phase, these unwanted voltages getting into the grid circuit from the plate circuit cause a reduction in the amplification.

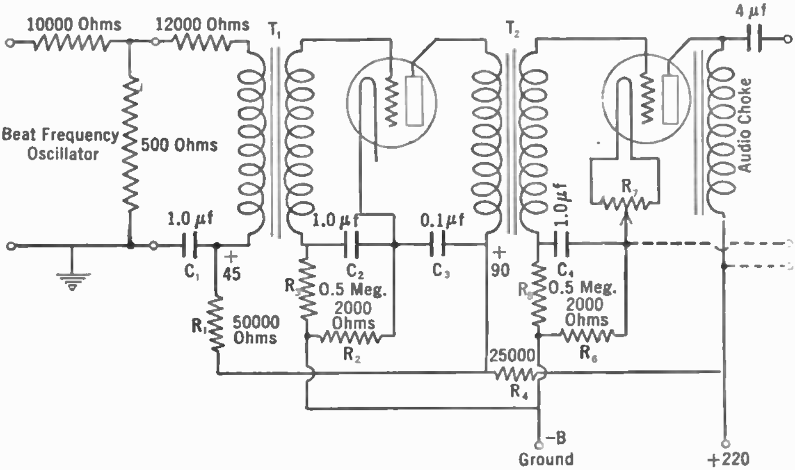


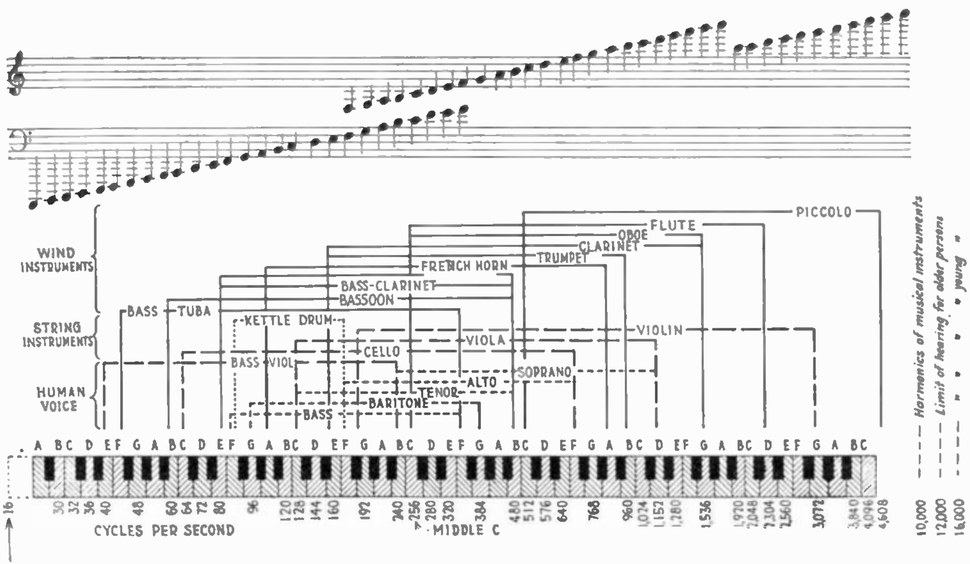
FIG. 175. A high quality, well-filtered audio amplifier.

If the inductance in the plate circuit is 100 henries and the frequency is 100 cycles, the current through the 2000-ohm resistance R_2 will be such that for every volt across the inductance there will be 0.032 volt across the resistor. This voltage is impressed on the grid of the tube and if multiplied by 8 will reappear in the plate circuit as though coming into the system from the outside via the transformer. Thus a 25 per cent reduction in output will occur. This is a loss of 2.0 db in voltage.

Now this loss may be reduced by by-passing the resistor so that the impedance offered to 100-cycle currents is smaller and so the voltage there will be smaller. A 1-μf condenser C_2 has a reactance of 1600 ohms at 100 cycles and when placed across this resistor will reduce the voltage there by a ratio of 2000 to 1250.

Electronics' Chart of

Sound Frequency Characteristics



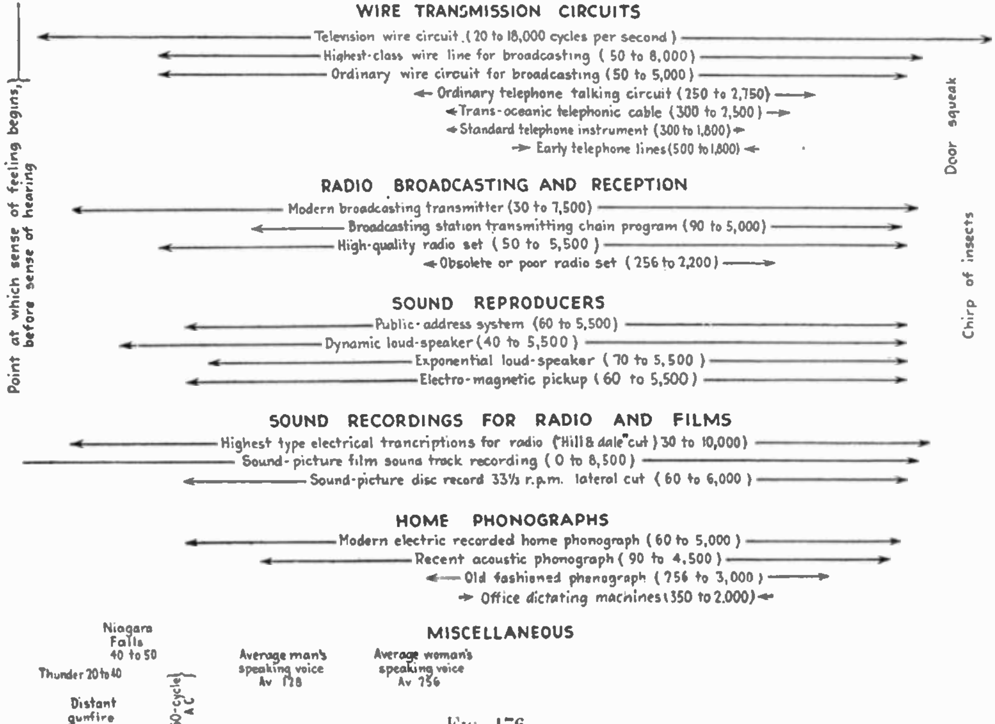

WIRE TRANSMISSION CIRCUITS
Television wire circuit (20 to 18,000 cycles per second)
Highest-class wire line for broadcasting (50 to 8,000)
Ordinary wire circuit for broadcasting (50 to 5,000)
Ordinary telephone talking circuit (250 to 2,750)
Trans-oceanic telephonic cable (300 to 2,500)
Standard telephone instrument (300 to 1,800)
Early telephone lines (500 to 1,800)
RADIO BROADCASTING AND RECEPTION
Modern broadcasting transmitter (30 to 7,500)
Broadcasting station transmitting chain program (90 to 5,000)
High-quality radio set (50 to 5,500)
Obsolete or poor radio set (256 to 2,200)
SOUND REPRODUCERS
Public-address system (60 to 5,500)
Dynamic loud-speaker (40 to 5,500)
Exponential loud-speaker (70 to 5,500)
Electro-magnetic pickup (60 to 5,500)
SOUND RECORDINGS FOR RADIO AND FILMS
Highest type electrical trancriptions for radio ("Hill & dale" cut) 30 to 10,000
Sound-picture film sound track recording (0 to 8,500)
Sound-picture disc record 33⅓ r.p.m. lateral cut (60 to 6,000)
HOME PHONOGRAPHS
Modern electric recorded home phonograph (60 to 5,000)
Recent acoustic phonograph (90 to 4,500)
Old fashioned phonograph (256 to 3,000)
Office dictating machines (350 to 2,000)
MISCELLANEOUS
Niagara Falls 40 to 50
Thunder 20 to 40
Distant gunfire
60-cycle AC
Average man's speaking voice Av 128
Average woman's speaking voice Av 256
Point at which sense of feeling begins, before sense of hearing
Door squeak
Chirp of insects

FIG. 176.

Much greater isolation of the grid circuit will take place, however, if a high resistance R_3 is placed in series with the grid and a by-pass condenser C_2 is placed as shown in Fig. 175. Still greater isolation and freedom from unwanted coupling will occur if the plate circuit is filtered too, either through a resistance R_4 or through a low-resistance, high-reactance choke and, of course, a condenser C_3. Such filtering prevents alternating current from flowing through the C-bias resistor. Grid circuit filtering reduces the effect of such alternating currents as do get into C-bias resistors. Present practice is to use very large by-pass condensers across the bias resistor in a-f amplifiers, for example, 10 to 50 $\mu\mu$f.

In all such circuits, and indeed in radio-frequency amplifiers, too, the alternating currents in the plate circuit should be returned directly to the cathode of the tube in question. They should not be permitted to go back through any part of the power supply or even through the leads to it. The condenser should be a part of the amplifier, and the choke or resistor may be a part of the power supply, although it is preferable to have it in the amplifier itself. Then the amplifier is forever independent of its source of plate voltage.

The purpose of the series impedance in such filter circuits is to impose a high series loss on any a-c voltages or currents that may try to get into the grid or out of the plate circuit. The purpose of the condenser is to provide a low-loss shunt path for these same voltages or currents to get to the cathode. Any alternating current that gets through the resistance or choke must be very greatly attenuated and on arriving at the grid end of such a series impedance it finds an easy path to the cathode which is at ground potential, and therefore does not affect the plate or grid as the case may be. In plate filtering, alternating currents find an easy path to the cathode through the condenser and a high-impedance path to the power supply.

Such a filter is helpful in keeping any hum at 60 or 120 cycles from getting into the amplifier from the power supply.

235. Individual transformer characteristic. An audio-frequency transformer may be looked at as a simple series circuit which may go resonant at some one or more audio frequencies. Such a transformer is never perfect; it has some primary and secondary resistance which consumes power and puts losses into the system, and there is always some magnetic leakage (Section 64) even though this may be reduced to a very great extent by using high-permeability cores, etc. The secondary resistance and leakage inductance may be transferred to the primary circuit, theoretically, and for purposes of analysis, by simply multiplying them by $1/N^2$ where N is the turns ratio of the transformer.

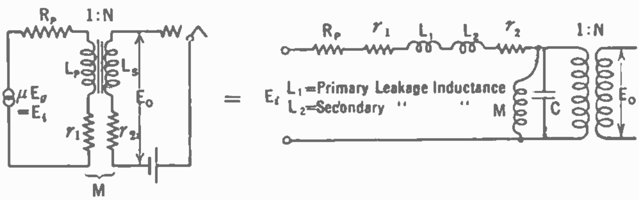


FIG. 177. Equivalent circuit of transformer.

The transformer then looks like Fig. 177 in which are the series resistances R_p, r_2 and r_1, and leakage inductances L_1 and L_2 and the shunt mutual inductance M—which should be very high—shunted by the capacity C of the tube and the windings, and followed by a perfect transformer which only serves to give the proper turns ratio N. If the mutual inductance—coupling between primary and secondary—is very high, it may be neglected in the following analysis of why a transformer characteristic goes up at high frequencies.

If the series inductances, caused by magnetic leakage, and the capacity C form a series resonant circuit, a voltage input E_i of this resonant frequency will build up a high output voltage E_o. This resonant peak varies from 4000 to 9000 cycles in transformers usually used in audio amplifiers. The greater the distributed capacity plus tube capacity across the secondary of the transformer, the lower in frequency is this peak. If the series resistances, due to primary and secondary resistance and other losses, is low enough the Q (Section 128) may be high enough for the circuit to oscillate at this resonant frequency, or to sing.

as amplifier engineers say. Since the plate resistance of the tube is part of the series resistance, any decrease in R_p through use of a low-resistance tube will increase the tendency to peak or to sing at the high resonant frequency. Such a rise at the high-frequency end of the audio band may be seen in Fig. 163.

So much for the high audio frequencies. What happens at low frequencies? At low frequencies the series leakage inductance is not of importance because of the low impedance to low frequencies. The ratio between the tube plate resistance and the mutual reactance of the transformer, which is large, determines how much of the low-frequency voltage generated in the plate circuit of the tube is usefully applied to the transformer. If the plate resistance is high, or the mutual reactance is low—a poor transformer—the low frequencies will be largely lost in the tube and will not be impressed upon the amplifier. If the capacity across the transformer resonates with this mutual inductance another peak may occur in the response characteristic of the tube and transformer. This peak will be at a low frequency, and in some cases may occur as low as several hundred cycles. After this resonance occurs, there is a tendency for the response to fall off, and in some poorly designed transformers a rapid rise in amplification at say 500 cycles is followed by an equally rapid drop beyond 1000 or 2000 cycles. This tendency to drop off at high frequencies is usually overcome by the tendency to rise because of series resonance between the capacity and the leakage inductance. Making the plate resistance of the tube very high drops out all the low frequencies.

Some tricks can be played with individual transformer circuits to change the response. For example, a resistance in the secondary circuit, either next to the grid or next to the filament (a bias resistor, for example) will drop off the high-frequency response. If next to the filament, as is customary for grid-bias requirements, the current through the capacity of the secondary of the transformer flows through the resistance and sets up an out-of-phase voltage there which may cut down the high-frequency response considerably.

236. Degenerative feedback circuits. The advent of the 6L6 type of beam power tube introduced to public-address and radio-receiver amplifiers a principle which had been worked out by Black and others at the Bell Telephone Laboratories for use at somewhat higher frequencies. This is known as the feedback amplifier. It can be used where more voltage gain is available than is necessary and where distortion is to be reduced to very low values.

The system consists in feeding back to the input of an amplifier a certain portion of the output. Now offhand this sounds like getting into trouble, but when carefully engineered it is capable of producing amplifiers with very flat characteristics and of very low distortion.

The feedback must be in the correct phase. In this case it is in such a direction as to lower the amplification: it is a reversed feedback, or a degeneration system. Since the amplification is thereby reduced, an excess of amplification to start with is necessary. There are various methods of securing this feedback voltage from the output and of introducing it into the input.

The frequency characteristic of such amplifiers may be improved by using feedback, amplitude distortion is reduced by the feedback, and the stability of the amplifier is increased by the use of feedback. Another characteristic is the fact that when the amount of voltage fed back is large, the effective amplification of the system depends only upon the percentage of the output that is fed back and therefore is practically independent of the actual gain of the amplifier.

Since the feedback can be produced through resistance or other elements which are permanent in characteristic, the amplification with large feedback is practically independent of tube characteristics and electrode voltages.

Feedback reduces amplitude distortion, cross talk, and noise originating in the amplifier. Since all of these factors are effective at the higher audio frequencies, the use of degeneration may be thought of as one way in which to make usable, amplifiers employing wider audio-frequency ranges.

Simple circuits using feedback are shown in Fig. 178 (from *Electronics*, January, 1937) and the effect of using feedback in an amplifier made by Professor Terman is shown in Fig. 179.

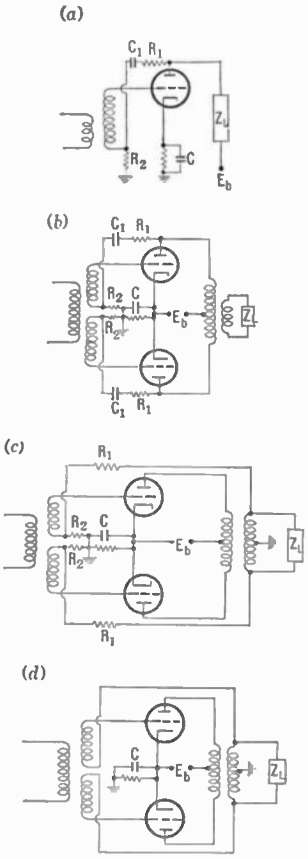


FIG. 178. Negative feedback or degenerative circuits.

237. Direct-coupled amplifiers. It is possible to make a resistance-coupled amplifier respond to and amplify very low a-c frequencies by increasing the size of the coupling condenser. But there is a limit. It may take so long to charge the large coupling capacity that difficulties are encountered. For example, no matter how large the coupling condenser, direct current (zero frequency) will not go through it, and often it is desirable to amplify direct currents.

If the coupling condenser is eliminated, the grid of the second tube will be at a high positive potential because it is directly connected to the plate of the previous tube—unless the cathodes of the two tubes are at different potentials with respect to ground. If, for example, the second cathode can be isolated from the first so that the grid of the second tube is negative with respect to its own cathode, even though it may be positive with respect to the first cathode, then the circuit will amplify direct currents and voltages.

With filament types of tubes this necessitates two filament batteries insulated from each other, one of which is considerably above ground potential. With heater-type tubes, however, the two cathodes may be appreciably different in potential even

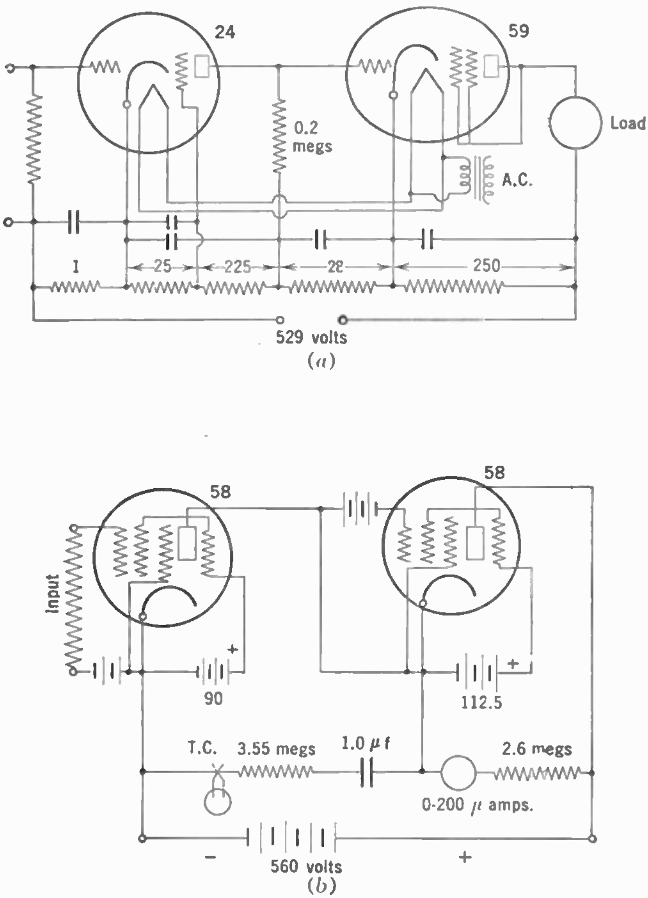


FIG. 180. (a) Simple direct-coupled amplifier. (b) High-gain amplifier for use on direct or alternating voltages.

though the two filaments which heat the cathodes may be operated from the same battery or transformer. In this case one cathode is higher in potential than the heater, therefore adequate insulation must exist between heater and cathode.

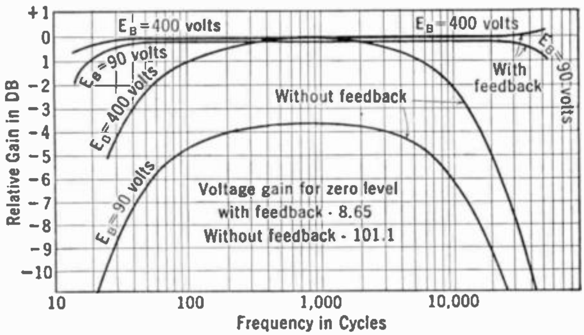


FIG. 179. Frequency response in feedback amplifiers.

In Fig. 180*a* is a simple circuit representing a "direct-coupled" amplifier. Note that both heaters are run from the same transformer but that the cathodes are at different potentials; that the grid of the second tube is connected directly to the plate of the first tube, but that adequate bias exists between grid and cathode of the second tube.

A typical amplifier with a voltage gain of 56 db (613) is shown in Fig. 180*b*. It uses type 58 tubes. It will amplify alternating voltages too, and is flat from 30 cycles to about 1000 and then drops slightly until at 10,000 cycles it is down 3 db.

CHAPTER XIII

RADIO-FREQUENCY AMPLIFIERS

238. Basic qualities of a radio receiver. There are three basic qualities which must be weighed not only by the designer of a radio receiver but by the purchaser and ultimate user as well. These are the **sensitivity,** the **selectivity,** and the tone **fidelity** of the receiver. The sensitivity of a receiver is an indication of the over-all amplification from antenna-ground binding posts to loud speaker. A receiver that is very sensitive requires but a small input voltage to deliver considerable output power. The selectivity of a receiver is an indication of its ability to discriminate between wanted and unwanted signals. An infinitely selective receiver would be one that would respond only to a given station and not at all to another no matter how powerful this undesired signal was, nor how close in frequency it was to the desired signal. That there is no such receiver goes without saying. The fidelity of a receiver tells how well it reproduces what takes place in the broadcasting studio. A receiver that delivers a high-fidelity signal is one which has a flat audio-frequency response curve over a wide frequency band, is free from noise, and free from distortion.

A receiver that is perfectly selective, infinitely sensitive, and delivers a perfectly faithful signal is impossible to obtain. A receiver which is selective and sensitive enough for practical purposes, and the frequency curve of which is so good that the ear would not detect its infidelity is not difficult to design, to build, or to operate.

It is an unfortunate fact, however, that the human ear is so easily deceived. Every engineer of any experience has had trained musicians congratulate him on the "perfect" tone quality of some assembly of apparatus whose frequency characteristic was anything but good and whose content of harmonics was anything but low. All broadcast and phonograph music suffers considerable distortion at the start of its journey by being greatly compressed in volume range—the reason being the inability of lines, transmitters, and receivers to handle the volume range.

239. Field strength. The voltage that is set up across a receiving antenna is called the **field strength** of the transmitter at that particular point on the earth's surface. It is of the order of microvolts or millivolts, and because a higher antenna will pick up a greater signal, that is, the voltage across it will be greater, it is the practice to rate field strength as so many microvolts or millivolts per meter. Thus an antenna that has an effective height of one meter and has 4 μv across it is situated in a field strength of 4 μv per meter. The effective height of the antenna is somewhat less than its actual physical height above ground, and in most receiver measurements is assumed as 4 meters (13 ft). An antenna that has an effective height of 4 meters and a voltage of 10 μv across it is immersed in an electric field due to some transmitting station whose strength is 2.5 μv per meter.

The greater the field strength at a given point the more volume one can get out of a receiver with a fixed amount of amplification. Similarly the greater the field strength the less receiver amplification is necessary to give out a certain amount of power.

240. Desirable signal strengths. Experience has indicated that signal strengths of three general classifications are necessary to provide good service to listeners. In city business areas 10 to 25 mv per meter are required to override high interfering electrical noise and the shadows cast by large buildings; in the residential areas of large cities, field strengths of 2 to 5 mv per meter are required; and in rural areas where man-made noise is low, fields as low as 0.1 to 0.5 mv per meter will provide satisfactory service. It must be remembered that the absolute value of the signal is seldom the important quantity; it is how much louder the signal is compared with the noise; and that in a locality where noise is low (as in the country) the signals need not be so strong.

The signal strength at a remote receiving point is proportional to the square root of the power at the transmitter; and depends also upon the frequency of transmission, the heights of the receiving and transmitting antennas, the kind of soil or terrain between transmitter and receiver and, of course, the signal strength varies inversely as the square of the distance because of the spreading in all directions of the energy from the transmitting antenna. At a point far from the transmitter a much greater area must be permeated by the same energy as at a point near the transmitter, and therefore a given area, such as that covered by a receiving antenna, picks up less total energy at the distant point.

The purpose of the transmitting station is to provide a good lusty signal that will override static and other disturbances; the purpose of the radio-frequency amplifier is to provide the listener with good loud signals from the field strengths which the stations produce.

241. Advantage of high power at transmitting station. Whatever voltage exists across the antenna, whether noise or desired signal, is amplified by the radio-frequency amplifier; there is therefore a distinct advantage, so far as the receiver is concerned, in using large amounts of power at the transmitting station. The greater the ratio of signal to noise the better will reception be. No matter how great the voltage gain of a radio-frequency amplifier, it cannot bring a weak signal out of the noise and give satisfactory reception. The signal must always be about 40 db above the noise level in order to provide an entertainment free from a noisy background that is apparent on weak musical passages. Whenever the noise increases, as on a warm summer day, and the transmitter station power remains constant, reception suffers, and it suffers more the farther the receiver is removed from the station. The noise about a given receiver is more or less constant under a given set of conditions, whereas the field strength due to a transmitter decreases as one gets farther and farther from the transmitter.

If a receiver is situated in a quiet locality, where the noise level made up of stray voltages from street cars, elevators, are lamps, power leakages from high-tension wires to trees, sputtering flatirons, X-ray machines, etc., is weak, the greater the amount of the over-all amplification, the greater the distance away a transmitter of a given power can be and still provide an adequate loud speaker signal; and, of course, with this amount of amplification the weaker a station can be at a given distance to provide this loud speaker output. The purpose of the radio-frequency amplifier is the same as of a telescope; it is to decrease the effective distance between the transmitter and the receiver. Unlike the telescope, it cannot be aimed at a particular station but must pick up all the r-f voltages not only between it and the desired station but in other directions as well. If the power of the transmitter is increased by 10 db (ten times the power), unwanted signals are thus automatically reduced 10 db compared to the desired signal.

242. The task of the radio-frequency amplifier. The r-f amplifier employed in a broadcast-frequency receiver may differ decidedly from that used in a receiver serving other purposes or tuned to other frequencies. For example, it is possible to make a much more efficient amplifier if it is to work at one frequency instead of at any one of many. A broadcast receiver, for example, must be capable of amplifying at any frequency between 500 and 1600 kc. It must be easily changed from one frequency to another, and its amplification at all frequencies within this band should be uniform. If it selects and amplifies too, its task is much more difficult to perform, as we shall see.

The energy thrust upon the ether from a given broadcasting station is a complex bit of wave motion. If the microphone is idle, what comes from the antenna may be considered as a very narrow band at, say, 600 kc, called the **carrier wave**. If a tone, say 1000 cycles (1 kc), is put into the microphone, the antenna current has in it frequencies not only of 600 kc but also 599 and 601 as well, and when music is broadcast the frequencies in the antenna may be varying between zero and 5000 cycles above and below the carrier from instant to instant. These frequencies on either side of the carrier are called the **side bands**. The characteristics of the transmitter must be such that each of these audio frequencies is given equal power compared with the others. The resonance curve of the antenna system of the transmitter, then, must not be sharp but must be rather flat or dull as shown in Fig. 181. It must have a rather flat top from 5 kc below to 5 kc above its carrier frequency.

If audio frequencies up to 5000 cycles are transmitted, each station requires a channel 10 kc wide for its transmission, and if there are 1000 kc available there are 100 channels or places for 100 simultaneous transmissions.

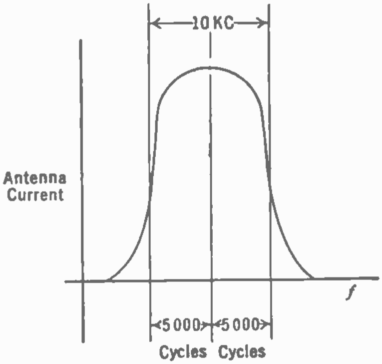


FIG. 181. A flat-topped, steep-sided response curve is the ideal. This curve approaches it.

At the listening station, the receiver must be able to pick out any one of these stations, and to receive it without being bothered by others on other channels. This means that a receiver with a good degree of selectivity is one which will receive, transmit, and amplify signals on the band from 595 to 605 kc but not recognize a signal in the adjacent channels, that is, on the channel extending from 585 to 595 kc and the channel extending from 605 to 615 kc. In other words, to cope with conditions in the broadcasting band a receiver should have "ten-kilocycle selectivity."

243. The ideal response curve of a receiver. To carry out this double purpose of the r-f amplifier the response curve should be a square-topped steep-side curve as in Fig. 181, like the transmitter curve. This is very difficult if not impossible to attain. In some sets, the response curve is either so broad that stations on the adjacent band, or even two or three channels away, will be audible during weaker passages of the desired signals, or so selective that the high audio tones are lost, owing to what is called "side-band cutting."

A receiver which has such a sharp curve that the higher audio tones are discriminated against cannot possibly deliver a high-quality loud speaker output even though a flat audio amplifier is used. A receiver that has a flat-top curve usually has too gently sloping sides so it is subject to interference from unwanted signals.

In a given local community, high-powered stations are allocated frequencies which are not too close to each other, say 50 kc apart. Therefore there may be no two local stations separated from each other by only 10 kc. But suppose that a strong station is located only 30 kc away from a local station and is geographically so situated that it delivers a strong signal at the receiving point. Then the receiver will have interference trouble even if it has "10-kc selectivity" unless the "skirts" (bottoms) of the response curve cut off sharp at the bottom. If they extend out from the desired band width they may include the signals of the distant station and permit interference of a strong local station by another strong station located quite far away.

244. Types of radio-frequency receiving systems. All radio receivers for use on broadcast frequencies amplify and select at the same time. They use tuned circuits, and so the receivers are called tuned radio-frequency sets, or simply "trf." Because of the steepness of a resonance curve, the over-all response of several circuits to frequencies off resonance is diminished, and is a logarithmic function, that is, if two amplifiers deliver ten times as much voltage at resonance as they do at some other frequency the total discrimination in favor of a desired signal is 100 times in a two-stage amplifier, or 10^N if there are N stages.

Another type of receiver, the superheterodyne or double detector, changes the frequency of the incoming signal to a lower frequency and then amplifies at this frequency.

Systems have been devised and operated whereby the selectivity and sensitivity were not secured in the same circuits. Thus in one receiver all the amplification was secured in an untuned amplifier.

Problem 1–13. The response curve of a single tuned circuit in a radio-frequency amplifier is given in Fig. 182. Remember that the amplification of two stages is the square of one stage, and calculate and plot the result of using two such stages. Then calculate and plot the response curve in per-

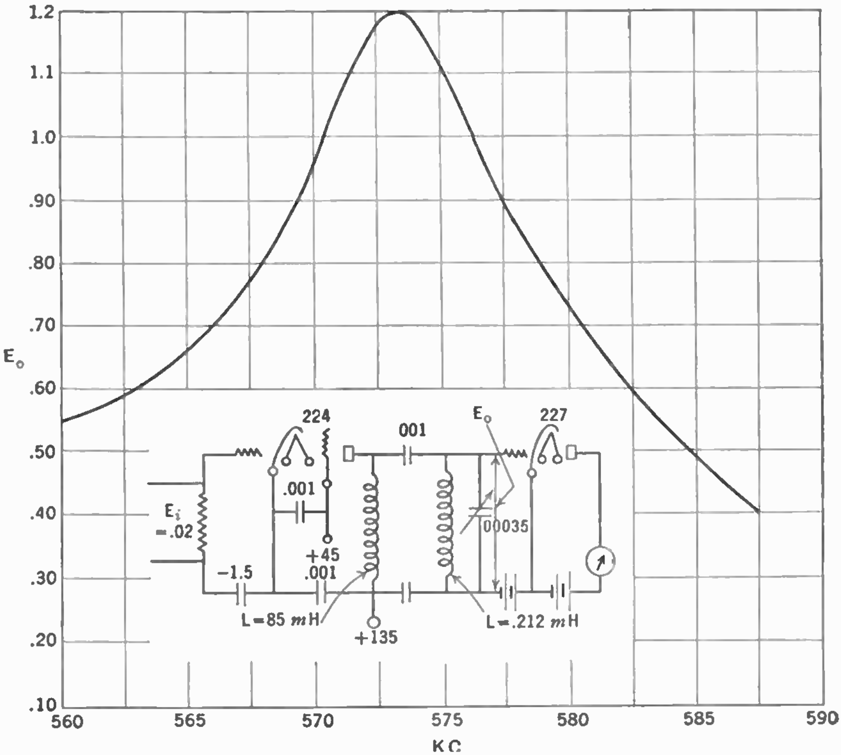


Fig. 182. Response curve and diagram of connections of single screen-grid stage.

centages, using the response at resonance as 100 per cent. Finally, plot this curve in db using the response at resonance as 0 db; and remembering that a station 10 kc off resonance must be about minus 40 db in voltage if it is not to be too loud during weak passages of the resonance signal, determine if two stages of such amplification and selection are sufficient. If not, would another stage be sufficient? How many db does a single stage "put down" a signal 20 kc off resonance? How many db down is it after passing through two stages? How many after going through three stages?

Problem 2–13. Suppose a station increases its power from 500 watts to 5000 watts and thereby increases its "service range" (radius) from 10 miles to 30 miles. Suppose the density of population in the area covered by the station's signals is 140 people per square mile. Calculate how many more people can now hear the station and the saving to the community if each listener would have to pay $1.00 each to increase the r-f gain of his receiver to get the station properly if it had not increased its power. If it costs the station $35,000 to make this change in power, has it been economical from the standpoint of the community?

245. Radio-frequency amplifiers in general. In amplifiers which are to operate at frequencies far above the audio tones with which Chapters XI and XII dealt, we have, in addition to the problems encountered there, several new ones. The difficulty in maintaining amplification with ordinary tubes and circuits at high audio frequencies was mentioned, and the reason—the stray capacities and those due to the tube input circuit—was discussed. These stray capacities in a radio-frequency circuit become much more important, not only for their shunting effect—which is severe at frequencies of the order of one million cycles—but also because of other interesting phenomena which will be discussed at this point.

246. Effect of tube input capacity. In general a voltage amplifier must be one which works from a low-impedance into a high-impedance load. The problem in all tube amplifying circuits in which high-voltage amplification—at the expense of low power amplification if necessary—is desired, is to get a high impedance for the tube to work into. Suppose this load impedance is a resistor shunted by the succeeding tube grid-filament path. The effect of the input capacity of this tube upon the load impedance was discussed in Section 202. If the frequency at which the amplifier is to work is multiplied by 100, the shunting effect of the condenser becomes 100 times as great.

Problem 3–13. A tube with a plate resistance of 12,000 ohms and a μ of 8 has a resistor in its plate circuit of 50,000 ohms. The following tube is a 40 with an effective μ of 20 and a grid-filament capacity of 4.0 $\mu\mu$f, a plate-grid capacity of 8.8 $\mu\mu$f, and a plate-filament capacity of 1.5 $\mu\mu$f.

Other capacities across its output circuit bring up the total plate-filament capacity to 6.0 $\mu\mu$f. What will be the impedance in the plate circuit of the first tube and what will be the voltage gain at 10, 100, 1000 kc?

Now it is generally assumed that if an amplifier tube has a sufficiently high grid bias that no grid current flows, the input impedance of the tube is infinitely high and acts as a pure capacity which is given by the expression,

$$C_o = C_{gf} + C_{gp}(G + 1)$$

where G = the effective amplification,

C_{gp} = the plate-grid capacity,

C_{gf} = the grid-filament capacity.

If this were true at radio frequencies, as is usually true at audio frequencies, we could find a way to get around the shunting effect of the input capacity, but at high frequencies this is not precisely true. The fact that the input impedance is not a pure capacity becomes important. There is resistance as well as capacity in this input circuit, and this resistance may vary from a high positive resistance which absorbs power from the previous tube's output circuit, to a negative resistance which delivers power to the previous circuit.

247. Tuned radio-frequency amplifiers. The serious shunting effects of the input capacity of the circuit into which a tube works and which make it difficult to build resistance-coupled amplifiers to work at frequencies of the order of 1000 kc can be avoided by the simple expedient of using this capacity to tune an inductance, or, stated in another way, by balancing out the capacity reactance by means of an inductance. For example, in Fig. 183 the effect of the capacity C_o is to so reduce the impedance in the plate circuit that no amplification can result. If, however, we place an inductance across this condenser of such a value that at the desired frequency the coil and condenser form an anti-resonant circuit of very high impedance, the load into which the tube works will be not much less than R_o and high enough to permit some amplification. Since fairly low-resistance coils are easily obtainable, and since the effective resistance of such a tuned circuit is $L^2\omega^2/r$ or L/C_or, a value that may be considerably beyond that of the resistor, we may as well do away with the resistor and use merely the coil and condenser. For purposes of selectivity we may place a variable condenser across L and so tune the coil over the entire broadcasting—or other—band.

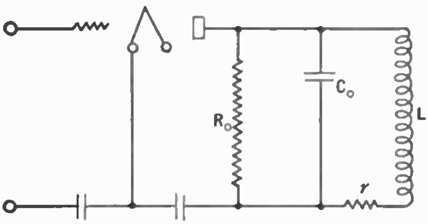


FIG. 183. Balancing out capacity reactance by means of shunt inductance (L).

Problem 4–13. Suppose an inductanc of 200 μh is in the plate circuit of the tube in Problem 3. Its resistance is negligible in comparison to its reactance. Calculate the impedance in the circuit at 1000 kc and at 1010 kc and hence the voltage gain. Then assume that the coil has a resistance (r) of 10 ohms, and when tuned by means of a condenser to 1000 kc calculate the impedance in the circuit at 1000 kc and at 1010 kc. Calculate the voltage gain of tube and load, and the relative advantage of the tuned circuit in selectivity over the untuned inductance.

The advantages of such a circuit are: first, the effect of the capacity C_o is eliminated; second, the effective resistance in the plate circuit of the tube may be made as high as we desire by making the inductance large and its resistance low (effective resistance values of 100,000 ohms are not difficult to attain); and third, where a resistance amplifier would be absolutely non-selective, this tuned amplifier can be made very selective.

248. Effect of negative input resistance. Now, such a tuned radio-frequency amplifier works out very nicely theoretically, and practically comes quite close to the final solution, except for one thing. This is the changing input resistance of the tube.

The input impedance of a tube is not a pure capacity. It is a capacity and a resistance. The value of this resistance may be high and positive if the load in the plate circuit of this tube is negative in sign—a capacity reactance, or negative if the load

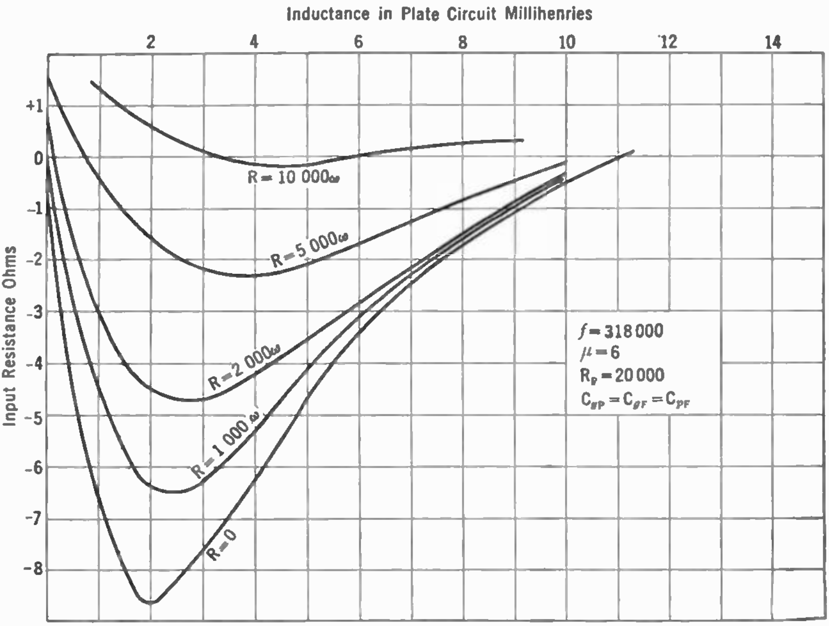


FIG. 184. Dependence of input resistance upon inductive load. This is known as the "Miller effect."

is inductive and of sufficient value. For example, the curves in Fig. 184 (taken from *Bureau of Standards Circular* 351, "Effect of Load on Input Impedance of Tubes," by J. M. Miller) show the input resistance of a typical tube at various values of inductance and resistance in the plate circuit. In other words, the minute we put an inductance in the plate circuit of a radio-frequency amplifier, we have done something to the grid circuit of that tube. If (*a*) the inductance is high enough, we have decreased the input resistance of the tube to a very low value; if (*b*) the inductance is increased still more, the input resistance becomes negative.

Up to the point when the input resistance becomes negative, it takes power from the circuit to which it is attached, because any r-f currents flowing through this resistance must suffer an I^2R loss, but the minute the resistance becomes negative, power is fed into the circuit to which the tube is attached. Now, feeding power into that circuit has the same effect as decreasing the resistance of that circuit by some other means, and when sufficient power is fed into the circuit so that all its resistance has been reduced to zero, radio-frequency currents flow, although the input is removed from its original driving source, and the circuit is said to oscillate. Direct-current power from the batteries is used up in producing and maintaining radio-frequency power in the coils and condensers. The circuit is useless as an amplifier.

We come then to this impasse, that, to get any amplification out of a tube at radio frequencies, we must put an inductance in its plate circuit and tune that inductance with a condenser. Putting the inductance in the plate circuit reduces the input resistance of the tube, and when the inductance is tuned to resonance, the circuit is in a highly critical condition. Any increase in inductance, or decrease in capacity—which amounts to the same thing—is likely to make the whole system oscillate. Any inductance in the plate circuit reduces the resistance in the grid circuit and results in a reduction in the effective resistance losses in the circuit out of which it works. So any resonant circuit that may be present—an antenna for instance—becomes very sharply tuned, and the higher audio frequencies are completely lost. The circuit is said to be regenerating. Regeneration is merely a minor case of oscillation.

For the moment let us forget this trouble from regeneration and oscillation with the remark that it is caused by the inter-electrode capacity of the tube, and is of sufficient magnitude to have prevented efficient r-f amplifiers from becoming generally used for a long time after the need for such equipment was felt. Let us look into the tuned radio-frequency amplifier, just as though we never heard of oscillation or regeneration, and see what engineering we can bring to bear on the problem of getting the most amplification and the best fidelity with the apparatus at hand.

249. Engineering the tuned radio-frequency amplifier. The inductance and capacity required for resonance at any point in the broadcast frequency band (550 to 1600 kc) may be calculated easily. These values are more or less fixed by the sizes of condensers generally available. Let us suppose their values are such that with the resistance of the coil taken into consideration they produce an effective resistance at resonance L/Cr (an anti-resonant circuit) of 100,000 ohms. In the plate circuit of a 12,000-ohm tube this load should give considerable amplification except for the fact that bridging a resistance of 12,000 ohms across such a coil-condenser combination would have the same result as adding considerable resistance in series with the coil, and therefore the effective resistance into which the tube works will decrease at an alarming rate.

For example, if the effective resistance of a coil-condenser combination is 100,000 ohms and is shunted by a 12,000-ohm tube, the equivalent impedance is now reduced to 10,700 ohms which represents the same change produced in the selectivity of the anti-resonant circuit as if its resistance had been increased by something over nine times. Of course, this would give a very poor degree of selectivity, and the voltage amplification would not be so high as desired.

If, however, we use a transformer with a step-up ratio from the plate of one tube to the next grid circuit, the plate resistance is stepped up by the turns ratio squared and is then placed upon the tuned circuit. If, for example, the turns ratio between secondary and primary is 4, the effective resistance placed across the tuned circuit would be $12{,}000 \times 4^2 = 193{,}000$ and so the effective series resistance of this tuned circuit would be increased only by a ratio of 10 to 6.1. The transformer may then be looked at as a kind of selectivity adjuster, since one can adjust the selectivity by its use.

Let us look at the problem in another way. A transformer with tuned secondary will give maximum power in the secondary load and maximum voltage across the secondary when the resistance across secondary and primary are related by the proper turns ratio. If, then, the load across the secondary is the effective resistance of the secondary when tuned to resonance, and the resistance across the primary is the plate resistance R_p of the preceding tube, the proper turns ratio can be found by the usual means, namely,

$$\frac{Z_s}{Z_p} = N^2 = \frac{L^2\omega^2}{rR_p} = \frac{L}{C\,r\,R_p}$$

whence

$$N = \frac{L\omega}{\sqrt{rR_p}}$$

and when this turns ratio is used the voltage gain of tube and transformer is

$$G = \frac{\mu}{2} \times \frac{L\omega}{\sqrt{rR_p}}$$

This expression involving the turns ratio is not the number of turns on the secondary divided by the number of turns on the primary because in an air-core transformer of this type it is not possible to obtain 100 per cent coupling, but for the moment let us not bother about this problem. We shall return to it later. The actual turns ratio is somewhat greater than N, and can be determined by experiment.

250. Gain due the tube and gain due the coil. There are two parts to the above expression for the voltage gain of tube and transformer. Part is due the tube and part is due the transformer, that is, we may divide up this expression into two parts:

$$G = \frac{1}{2}\frac{\mu}{\sqrt{R_p}} \times \frac{L\omega}{\sqrt{r}}$$

in which the first part shows that the gain is proportional to one-half the μ of the tube divided by the square root of its plate resistance and the second part shows that the gain is proportional to the inductive reactance of the coil divided by the square root of its high-frequency resistance. From such an expression we may learn several things.

In the first place G is the maximum possible voltage gain that can be obtained from a given tube working into a given resistance and this is obtained only when the turns ratio N of the

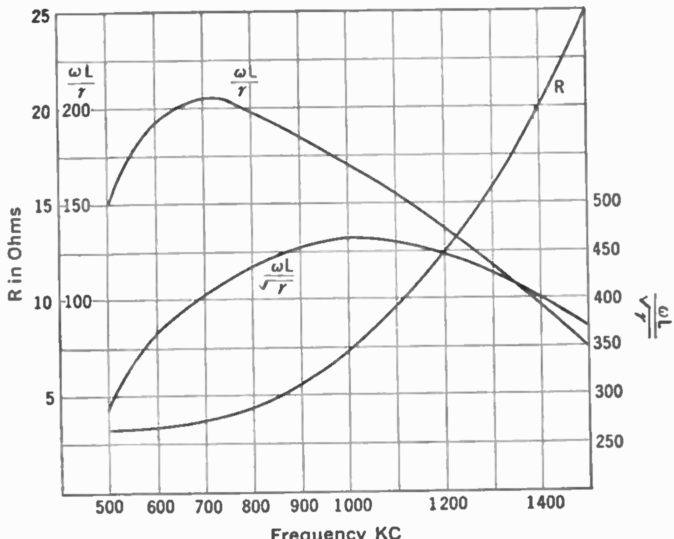


FIG. 185. How resistance and figure of merit "Q" $\left(\frac{\omega L}{r}\right)$ of a coil vary with frequency.

transformer is properly adjusted. For a certain tube, the expression $\mu/\sqrt{R_p}$ is a constant and is related to the mutual conductance so that once we have determined its value we can multiply it into the corresponding values for the voltage gain due the transformer and we then have the maximum voltage gain. The figure of merit for the transformer $(L\omega/\sqrt{r})$ is not constant over the broadcast-frequency band as the curve in Fig. 185 shows, and from it we learn at once that the over-all gain, G, of tube and transformer will not be equal at all frequencies. It is a characteristic of tuned radio-frequency receivers to have less selectivity at the higher frequencies because the coil resistance increases faster than the frequency increases. Thus the Q is less at high frequencies.

We are now in a position to perform a very interesting experiment, one that requires neither laboratory nor apparatus. We need only a pencil, some paper, a slide rule, some values of the factors that enter into the expression for the maximum voltage amplification, G.

Experiment 1–13. A coil has an inductance of 168 μh, and a high-frequency resistance, r, of 4 ohms at 700 kc, 6 ohms at 1100 kc, and 9 ohms at 1500 kc. Plot this resistance against frequency. Calculate the figure of merit $(L\omega/\sqrt{r})$ for the coil and plot against frequency. Assume it to be used out of a tube whose plate resistance is 12,000 ohms and whose mu is 8. Calculate the proper turns ratio for maximum voltage amplification at the above frequencies and what the amplification is, that is, calculate and plot $N = L\omega/\sqrt{R_p r}$ and $G = \frac{1}{2}\mu \times N$ against frequency, assuming that the proper turns ratio is used at each frequency.

Then calculate N and the voltage amplification at 1000 kc of such a coil and a tube with a plate resistance of 16,000 ohms and μ of 6.6, and then when a tube is used which has a plate resistance of 150,000 ohms and a μ of 30.

Problem 5–13. The effective resistance of a coil-condenser combination is 100,000 ohms when the resistance of the coil is 10 ohms, that is, $L/C\,r =$ 100,000 ohms, where r is the series resistance. Calculate what the equivalent resistance of such a circuit is when shunted by 10,000 ohms. (Two resistances in parallel have a resistance equivalent to their product divided by their sum.) Then assuming that this value is the effective resistance of another tuned circuit having the same L and C but a different series resistance, calculate what the value of r is.

Problem 6–13. A tube of 5000 ohms is to be used as an r-f amplifier and to be worked into a tuned circuit whose effective resistance is 120,000 ohms. What is the proper turns ratio for maximum voltage amplification and what is the amplification? If we remember that a resistance across a primary of a transformer is equivalent to another resistance across the secondary stepped up by the square of the turns ratio of this transformer, what is the equivalent resistance that is placed across the tuned circuit by this transformer? What happens to the effective resistance $L/C\,r$ of this circuit?

Problem 7–13. A voltage gain of 10 is desired. The plate resistance of the tube is 12,000 ohms, its μ is 15, the inductance of the coil is 186 μh, and the capacity is 0.0001 μf. What is the maximum resistance the coil can have?

251. Effect of coupling. The foregoing argument on maximum possible amplification of tube and its accompanying transformer has been based on the assumption that the coupling between primary and secondary was adjusted to the proper value at each frequency. Actually, such is seldom or never true, and even if it were it is doubtful if receiver designers would so choose the coupling that maximum amplification would result, owing to the decrease in selectivity of the circuits under these conditions.

In general the voltage amplification of a tube and transformer when the secondary is tuned may be expressed as

$$G = \mu \frac{\omega^2 M L_2}{R_p R_s + \omega^2 M^2}$$

which involves not only the resistance of the apparatus (R_p and R_s) on the two sides of the transformer but also the coupling M in the transformer itself. If we go into the laboratory and measure the voltage across the secondary with a constant input voltage to the tube but with various degrees of coupling we shall find that the amplification increases with increases in mutual inductance but only up to a certain value. Then it falls off. We shall also find that a continuously variable mutual, increasing at lower frequencies, would result in uniform amplification. Mechanical systems for effecting this change of coupling as the set is tuned have been worked out but have not come into general use. Figure 186 is from Morecroft's *Principles of Radio Communication*.

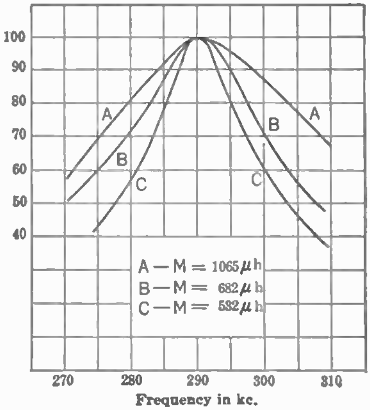


FIG. 186. Relation between coupling and selectivity in transformer-coupled r-f amplifier.

252. Effect on secondary resistance of close coupling. The increase in resistance—and consequent decrease of selectivity—of the secondary circuit may be calculated from the expression

$$r = \frac{M^2\omega^2}{R_p}$$

which states that the resistance introduced across the secondary by the transformer is equal to the square of the mutual reactance divided by the resistance in the primary, in this case the plate resistance of the tube. This resistance introduced across the secondary rises with the frequency and the mutual inductance squared and is inversely proportional to the plate resistance of the tube out of which the transformer works. This means simply that the greater the resistance of this tube, the less will the selectivity be decreased with a given turns ratio, and the reason for such an inverse function is simply that a larger resistance shunted across the tuned circuit will introduce less resistance in series with that circuit than will a smaller resistance across the circuit. No matter what the plate resistance, if M is adjusted for maximum possible voltage amplification the selectivity of the secondary circuit will be cut in half, because this selectivity is a function of the series resistance of the secondary which is doubled when the turns ratio is such that G is a maximum. Now the coupling between primary and secondary is controlled not only by the physical proximity of the two windings, but also upon the number of turns in the primary, if the secondary turns are held constant. Therefore, decreasing the primary turns will increase the selectivity and decrease the amount of voltage amplification. Mathematical analysis of the problem will show that if the turns in the primary required for optimum voltage transfer are decreased to zero, the selectivity will be increased only by a factor of two. This only means that when the number of turns in the primary is zero, none of the plate resistance of the tube is transferred to the secondary circuit, and, of course, then the selectivity of the secondary is its selectivity when standing alone. No voltage is transferred under this condition, and so such selectivity for a single stage is never attained.

There is another variable factor in this transformer: this is the ratio of L to C. We have already discussed the voltage gain and selectivity as controlled by the secondary resistance and the turns ratio and the plate resistance of the previous tube. Calling upon either experimental proof or mathematical analysis, we can show that the greater the inductance of the secondary, other factors being maintained, the greater will be the selectivity of the system, and that when the secondary is adjusted to give the maximum amplification, given by

$$R_pR_s = \omega^2L^2$$

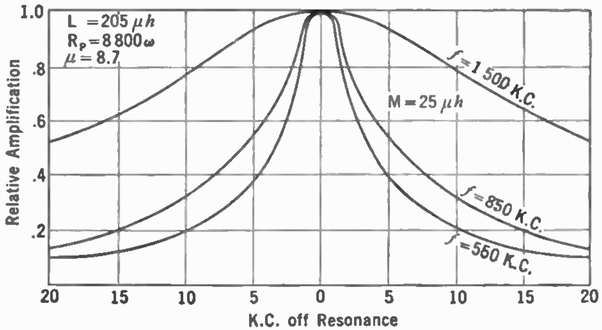


FIG. 187. Curve showing how selectivity of tuned r-f circuit depends upon frequency.

(where $\omega = 2\pi \times$ resonant frequency) the selectivity will depend only upon the ratio of L to R_s (secondary resistance) and that if the circuit is adjusted for the greatest amplification for a desired signal it will also give the smallest amplification to an unwanted signal (K. W. Jarvis, *Proceedings Institute of Radio Engineers*, May, 1927). Other curves showing the influence of coupling, etc., on selectivity and amplification are shown in Figs. 187 and 188.

253. Selectivity. So far we have treated the selectivity problem in a qualitative way only. We have not said anything about how much selectivity we needed or desired, or how much we could get. We stated that increasing the coupling between the primary and secondary circuits (decreasing N) of our tuned transformer increased the resistance in the secondary circuit and thereby decreased the selectivity of that circuit, and that at the coupling for maximum voltage gain the selectivity was halved What does this mean? How much selectivity is needed to prevent cross talk between stations 10 kc apart? How much selectivity can be secured? What are the coil characteristics to provide such selectivity? How much selectivity can be tolerated before side band cutting becomes audible to the ear? These are questions that assail every receiving set engineer.

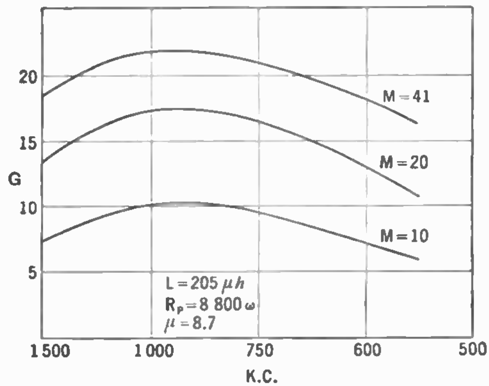


Fig. 188. Relation between mutual inductance and gain in an r-f amplifier.

In Chapter VII we discussed the simple series resonant circuit, and stated that the steepness of its response curve at resonance depended upon the resistance in that circuit. The greater the resistance, the less steep the curve, and the less difference in voltage or current between the resonant frequency and frequencies off resonance by, say, 10 kc. In fact, the width of the resonance curve is a direct measure of the resistance in the circuit. Consider such resonance curves as that in Fig. 187. If f_1 and f_2 are two frequencies on either side of the resonant frequency, f_r, such that the current or voltage at these frequencies is 0.707 of the value of voltage or current at resonance, then the following formula is true:

$$\frac{L\omega}{r} = \frac{f_r}{f_2 - f_1}$$

Here again we run into an expression involving the inductive reactance and the ohmic resistance of the coil. It states that knowing the value of $L\omega/r$ of the coil, we can tell at once how wide the resonance band is going to be at a point where the current, or voltage, is 0.707 of its maximum value. (This amounts to a 3-db loss in voltage in a single circuit.) How is this useful in our present problem?

The tuned transformer used in trf sets, or in any system in which the secondary of a transformer is tuned, may be considered as a simple series circuit provided we choose the constants of that series circuit correctly. The resistance of that circuit will be its series resistance, r, usually consisting of the high-frequency resistance of the coil alone, plus the resistance "reflected" into that circuit by the transformer. This resistance considered as shunted across the tuned secondary is the plate resistance of the tube stepped up by the square of the effective turns ratio of the transformer.

Now any resistance shunted across the tuned circuit is equivalent to a smaller resistance in series with the circuit, and such a resistance is the controlling factor in determining the width of the resonance curve. And since selectivity is but a term describing the width of this resonance curve, we have in our hands all the necessary facts regarding the voltage amplification and the selectivity of such circuits.

For example, at the coupling between the primary and secondary for maximum voltage amplification the effective turns ratio is given by

$$N^2 = \frac{Z_s}{Z_p} = \frac{L^2\omega^2}{rR_p}$$

which means that the secondary of the coil will be shunted by a resistance equal to the plate resistance of the previous tube multiplied by the turns ratio squared, and this numerically will be equal to the effective resistance of the tuned secondary, $L^2\omega^2/r$. Now the secondary effective resistance, being shunted by another resistance equal to it numerically, becomes half its former value (two equal resistances in parallel have a resultant resistance of one-half of one of them). Such a decrease in effective resistance can also be produced in one other way—by increasing the resistance of the coil to twice its normal value. And what effect has doubling the coil resistance upon selectivity? Clearly it halves it, because selectivity may be thought of as proportional to $L\omega/r$ and doubling r halves this factor.

The following example may fix the whole problem in one's mind.

Example 1–13. Consider a coil whose inductance is 200 μh, and whose resistance r at 1000 kc is 10 ohms. This coil is to be tuned and fitted with a primary to work out of a tube whose plate resistance is 12,000 ohms and whose μ is 8. What is the proper turns ratio for maximum voltage amplification? What is the voltage amplification? What is the width of the frequency band with and without the tube connected across the primary?

Effective resistance of coil condenser alone

$$= \frac{L^2\omega^2}{r} = \frac{(200 \times 10^{-6})^2\,(10^6 \times 6.28)^2}{10}$$

$$= 158{,}000 \text{ ohms}$$

Width of frequency band when $I = 0.707$ maximum value

$$= f_2 - f_1 = \frac{f_r r}{L\omega} = \frac{r}{2\pi L}$$

$$= \frac{10^6 \times 10}{200 \times 10^{-6} \times 6.28 \times 10^6}$$

$$= 8000 \text{ cycles}$$

Turns ratio for maximum voltage amplification

$$= \sqrt{\frac{Z_s}{Z_p}} = \sqrt{\frac{158{,}000}{12{,}000}} = 3.6$$

Voltage gain

$$G = \frac{\mu L\omega}{2\sqrt{r\,R_p}} = \frac{8 \times 200 \times 10^{-6} \times 6.28 \times 10^6}{2\sqrt{12{,}000}\,\sqrt{10}}$$

$$= 14.5 \text{ times}$$

Resistance reflected from primary to secondary

$$= Z_p \times N^2$$

$$= 12{,}000 \times 13 = 158{,}000$$

New effective resistance of secondary circuit

$$= \frac{158{,}000 \times 158{,}000}{158{,}000 + 158{,}000} = 79{,}000 \text{ ohms} = \frac{L^2\omega^2}{R_1}$$

New effective series resistance in secondary

$$= R_1 = \frac{L^2\omega^2}{79{,}000} = \frac{158{,}000 \times 10}{79{,}000} = 20$$

Width of frequency band where $I = 0.707$ maximum value

$$= f_2 - f_1 = \frac{f_r R_1}{L\omega} = \frac{10^6 \times 20}{200 \times 10^{-6} \times 6.28 \times 10^6}$$

$$= 16{,}000 \text{ cycles}$$

This indicates that a voltage gain of 14.5 would be obtained with such a coil-condenser combination and tube at a frequency of 1000 kc and that at a frequency 8000 cycles either above or below resonance, the current in the secondary circuit, or the voltage across it, would be 0.707 of its value at exact resonance. This voltage ratio corresponds to a loss of 3 db, which is not very great. The selectivity of the transformer and tube, then, is not very great, certainly not great enough to provide much discrimination between a station on 1000 kc and another at 1010 kc.

254. Overcoupled amplifiers. It has been mentioned that the effect of coupling upon selectivity might be utilized if a system were provided so that as the receiver is tuned to the lower frequencies, the coupling between the coils could be increased automatically. In an intermediate frequency amplifier, where a single frequency (say 456 kc) is to be handled, this variable coupling may be utilized.

In a superheterodyne with minimum coupling between primary and secondary of the i-f transformers the selectivity is very great. Now if the coils are pushed closer together the selectivity decreases, which means that a wider and wider band of frequencies is amplified. Such a receiver would have variable selectivity and it can be arranged that this change in coupling be accomplished mechanically or by the use of electric circuits and tubes. It is possible to have the band passed only a few thousand cycles wide, say 2500 cycles, at the most selective position and as wide as 10,000 cycles when the coupling is increased.

Now it will be shown in the next chapter that overcoupling two coils tuned to the same frequency results in a curve which has two peaks separated by a dip. Thus the frequency characteristic of such a transformer, when its coils were closely coupled, would not be ideal because the center of the response band would get much less amplification than the outer limits.

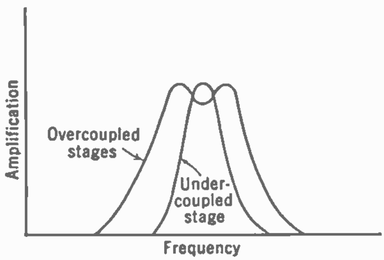


FIG. 189. Response of variable and fixed (undercoupled) coupling stages in an i-f amplifier.

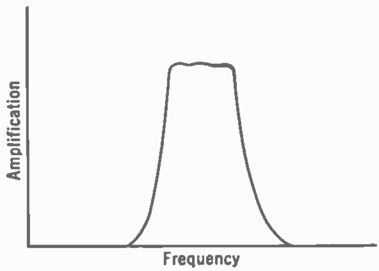


FIG. 190. Over-all response produced by amplifier of Fig. 189.

What would happen, then, is that the higher audio frequencies would get a lot of amplification and those near the carrier frequency (i.e., the low audio notes) might be decreased materially. Engineers have worked out a clever way of getting around this difficulty and of producing a response curve that has steep sides and an almost flat top.

Suppose the receiver has three i-f transformers, the final one feeding into the diode detector. Now let us connect the first two transformers mechanically so that the coupling can be increased or decreased. The third one, however, is undercoupled so that it is fairly sharp. When the coupling of the first transformer is increased so that a dip occurs in the curve, the third transformer still has a sharp response exactly on the carrier frequency and on the lower audio frequencies.

If the over-all response of such an amplifier is measured it will be found that the overcoupled transformers produce amplification at the higher audio frequencies filling in the portion of the range not covered by the third transformer. Furthermore, the final transformer, having good response at low frequencies, fills up the gap in the characteristic produced by overcoupling the earlier transformers. This is shown in Fig. 189.

255. Regeneration and oscillation in r-f amplifiers. All the discussion up to this point assumes that the tubes and transformers operated in a stable manner, repeating in amplified form into the plate circuit what appears in the grid circuit and not repeating back to the grid circuit any of this amplified voltage. Practically, such conditions do not hold. Unless precautions are taken, the circuit oscillates long before the proper inductance has been added to the plate circuit to provide a reasonable amount of amplification.

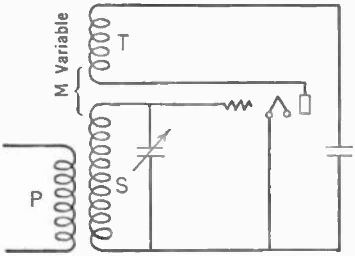


FIG. 191. A simple regenerative circuit.

There are two reasons for this unwanted oscillation. One lies in the unintentional couplings provided between output and input circuit, for instance through mutual inductance between the coils, through capacities which connect the two circuits, and through other couplings. The other source of coupling is also unintentional but, unlike those mentioned above, cannot be eliminated. This second coupling is that existing within the tube, and is due to the capacity between the plate and the grid.

Let us look at Fig. 191 and assume that there is an amplification in voltage of 10 in the tube, that is, whatever voltage, e_i, is placed across the input appears as 10 times this value in the output. The voltage is applied to the input through the mutual inductance between the primary, P, and secondary, S, of the transformer. Whatever alternating current flows in the plate circuit must also go through the coil, T, commonly called a "tickler." If this coil is coupled to S in the proper manner, it will induce a voltage in the input coil S in such a direction that it will be in phase with the voltage induced there from P. Suppose the voltage due to P is 1.0 volt and that the voltage on S due to T is 0.5 volt. We now have not 1 volt on the grid of the tube but 1.5 volts. This is what is known as regeneration; part of the output voltage is fed back to the input and *in phase*. When the feedback voltage is of the correct magnitude and phase, we may remove the input voltage due the primary, P, and alternating currents will still flow because whatever came from P originally has been amplified in the tube and fed back to the grid where it is amplified again, and again returns to the input. In other words, the tube oscillates; it supplies enough energy from the B battery to wipe out all the power losses in the circuit.

Let us look at the phenomenon of regeneration in another way. Suppose the input circuit to the tube is tuned. The current in the tuned circuit is controlled by the resistance in that circuit—provided a constant voltage is impressed from P. If, now, we decrease the resistance in the circuit the current increases, and the voltage across the circuit (and hence on the grid) increases.

Now suppose the voltage across the input is increased by means of the tickler coil, T. This produces exactly the same result as if the resistance in the tuned circuit were decreased. We may express what has happened by stating that feedback, if in proper phase and magnitude, may introduce a *negative* resistance into the tuned circuit. This negative resistance added to the already existent positive resistance decreases the total resistance there. When the tube feeds back sufficient negative resistance so that the entire resistance losses in this circuit are wiped out, the system maintains itself in a state of continuous oscillation requiring no additional a-c energy from without, and capable of supplying considerable a-c power to some external circuit coupled to it.

Such a feedback of voltage from the plate to the grid circuit may take place through desired coupling—as by the tickler feedback—or through unwanted coupling, as mentioned above. The grid-plate capacity is the most prolific source of trouble from regeneration, because the voltage fed back from this small inter-element capacity may be of the proper phase and magnitude to cause not only regeneration but also oscillation.

It is an important fact that the input impedance of a vacuum tube is not a pure capacity, but that it may be a capacity plus a resistance which may be either positive or negative depending upon the load in the plate circuit. If the load is a positive reactance, an inductance, the input resistance of the tube may be negative, and so the voltage fed back there from the plate circuit through the grid-plate capacity will be in phase with the voltage already appearing there. Regeneration takes place. If the resistance of the input circuit is sufficiently negative the circuit may oscillate.

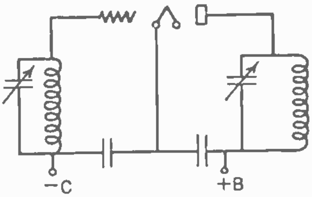


FIG. 192. Tuned plate-tuned grid circuit.

If the load in the plate circuit is a negative reactance, a capacity, the input resistance of the tube will be positive, and will shunt the input circuit. If this circuit is a coil-condenser combination tuned to resonance with some incoming voltage, the positive resistance of the grid-filament circuit of the tube will be placed across this tuned circuit and, of course, will decrease its selectivity.

The input impedance of a tube, then, depends upon the plate load. Any change occurring in the plate circuit is repeated back to the input grid circuit through unwanted couplings, usually through the grid-plate capacity, and may cause either regeneration due to an inductance load or degeneration due to a capacity load, which produces a positive input resistance.

If the load in the plate circuit is resistive or capacitive the tube and circuit cannot regenerate or oscillate. Signals may even be weaker.

256. Bridge systems. There is a large class of circuits in which unwanted feedback is fought in an elegant way—a way that seems more scientific to many engineers, although it may be not a great deal more effective than the simple use of resistance to damp out the oscillations. These circuits are the "bridge circuits" of Hazeltine, Rice, Hull, Ballantine, Hartley, Horle, and several others.

The Rice circuit is the simplest to understand. It appears in Fig. 193. It involves tapping the input coil in the exact center,

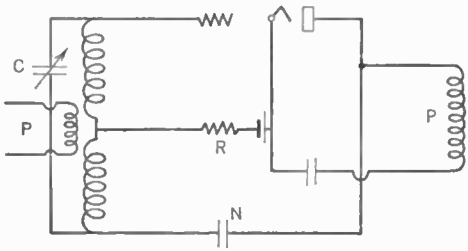


FIG. 193. Rice neutralized circuit.

and connecting a "neutralizing" condenser from the plate of the tube to the bottom of this coil. If the input coil is tapped at the exact center, and if the neutralizing condenser has the same ca-

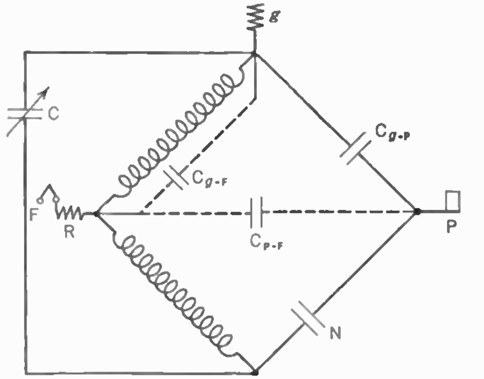


FIG. 194. Equivalent bridge circuit of Fig. 193.

pacity as the grid-plate capacity, for every voltage fed back through the latter capacity, of the proper phase to cause regeneration—due to the inductive load in the plate circuit—there will be an equal and opposite voltage fed back through the neutralizing condenser. The equivalent bridge circuit is shown in Fig. 194. If the coupling between the two halves of the input circuit is perfect and if the grid-filament capacity and the filament-plate capacity (in dotted lines) are equal, the bridge will be balanced at all frequencies. Actually these conditions do not exist and so there may be some regeneration, or even degeneration in a given circuit.

Other neutralizing circuits have found more or less wide use. Some simple and some complex circuits are still in use in transmitters.

The Rice circuit has the advantage that the circuit is complete in itself and no wires need to go to any other circuit for neutralizing voltages. The plate circuit load may be placed at some distance from the amplifier tube itself. It has the disadvantage that half the input voltage is not usefully used, that is, it is not applied to the grid-filament path of the tube. It also has the disadvantage that both sides of the tuning condenser are above ground potential, one side being connected to the grid and the other to the neutralizing condenser. Some trouble with "hand capacity" will be experienced in using this circuit unless precautions are taken to use a non-metallic shaft on the condenser.

The Rice circuit is troubled with parasitic oscillations, that is, oscillations at some other frequency than those determined by the capacity and the inductance of the tuned circuit. For example, in a Rice neutralized amplifier operating on broadcast frequencies, oscillations frequently take place on a wavelength of about 75 meters, corresponding to the inductance of half the input coil and the capacity across it due to the grid-filament capacity of the tube, wiring, etc. The other half of the input coil may be thought of as a tickler.

A high loss put into this oscillating circuit, as R in Fig. 193, will stop all such oscillations. A loss of this kind may be a high resistance, 500 ohms will do, a choke coil, or an anti-resonant circuit tuned to the offending frequency.

Practically no receiver circuits are neutralized nowadays, because the necessity has been removed with the wide usage of screen-grid tubes. In transmitters, however, it is standard practice to neutralize certain push-pull amplifiers where it is not desirable to use screen-grid tubes. Even when screen-grid tubes are used, however, great care must be taken to prevent feedback.

257. Filtering r-f circuits. Oscillation is the most serious difficulty which amplifier designers run into. It is caused by coupling part of the plate voltage back to the input of the tube. When occurring through wiring, or faulty layout of apparatus, or from one coil to another, it is unpardonable, because it shows

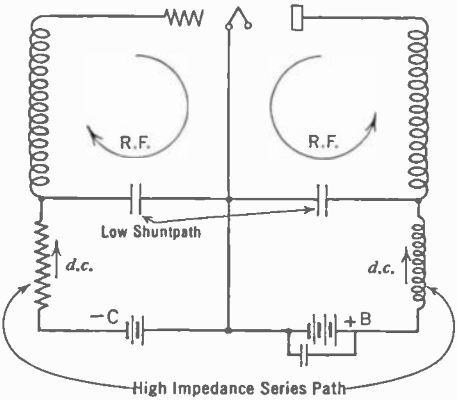


FIG. 195. Proper use of filtering to keep r-f currents where they belong.

evidence of poor design. Let us consider the circuit in Fig. 195. The r-f currents should return to the cathode directly from the grid and plate circuits and should go nowhere else. If they do they are sure to become mixed with similar r-f currents from other stages of the amplifier, and thereby cause unwanted coupling. This is analogous to the audio-frequency amplifier problem of keeping alternating currents where they belong and out of external circuits.

Filtering of all grid and plate leads will keep the alternating currents in their proper places in the circuit and will keep them from becoming sources of unwanted coupling with other parts of the amplifier. Such a filter may consist of a 50,000-ohm resistor in series with the plate battery leads and a fairly large condenser in shunt as shown in Fig. 195. A capacity of 100 $\mu\mu$f at 1500 kc has a reactance of 10^3 ohms and is much to be preferred to a large paper condenser of perhaps 1.0 μf capacity which may have considerable inductance in it. Some condensers made of large sheets of paper rolled up together have such an inductance that they present a very high anti-resonant reactance at the higher radio frequencies. For this reason a small condenser of 0.01 or 0.001 μf capacity will provide good by-passing if the series impedance is fairly high.

A ground wire carrying r-f currents and near a grid wire also carrying r-f currents may provide sufficient coupling between circuits to cause trouble from regeneration. No alternating currents should be permitted to flow through the filament circuits, or the metallic shields, if such are used. Shields should be grounded at only one place, to avoid circulating currents in them.

Magnetic coupling from a plate to a grid coil is a prolific source of unwanted coupling. One method of avoiding this difficulty is to use coils in metallic containers which are grounded. Any magnetic field from the coils which would ordinarily become mixed up with similar fields from other circuits (and thereby induce unwanted voltages in them) induces voltages in the grounded shield instead. It must be remembered that the induced voltage is capable of setting up an r-f current in this shielding and that the I^2R loss in power in the shields must be supplied from the power in the coils themselves. This results in an equivalent increase in the resistance of the coils inside the shield and a decrease in their inductance. This, of course, decreases the coil's $L^2\omega^2/r$ factor with consequent decrease in both amplification and selectivity. When coils are to be shielded they usually have small diameters and small fields. This construction minimizes the increase in resistance and decrease in inductance.

Modern practice is to filter every circuit with series resistance and shunt capacities to ground. Thus the r-f currents are returned directly to the cathode of the tube whence they come. None are permitted to get into the plate voltage supply; screens of multi-grid tubes are carefully grounded and filtered. So extensive is the filtering in modern complex circuits that ten or more resistors and an equivalent number of capacitors serve no other purpose than to keep r-f currents where they belong.

258. Use of screen-grid tube as r-f amplifiers. The screen-grid tube removed the necessity for neutralizing the grid-plate capacity; but it did not remove the necessity for carefully shielding "hot" leads, for shielding the coils, and for taking many precautions to prevent feedback. One manufacturer found his receiver unstable. One coil was nearly completely shielded but the end near the metal chassis was open. A hole had been cut in this chassis so that the remaining metal plate resembled a large closed loop of wire. This metal loop picked up r-f currents from the partially shielded coil, transferred them to an adjacent grid lead, and caused regeneration. It was necessary to cut a slot in the chassis to break up the closed loop of metal; and several hours of frantic hunting for the trouble were required to discover this simple cause of feedback.

For a time certain manufacturers coated the tube envelopes with conducting material as a sort of shield; then all tubes carrying radio or audio currents were covered with metallic shields; and finally the metal tube provides a self-shielded tube.

All modern receivers display the set makers' desire to shield completely the various circuits from any stray fields. Coils, tubes, tuning condenser, wiring are protected.

259. Gain with screen-grid tube. The screen-grid tube has almost completely displaced the triode as an amplifier at high frequencies, not only because it is easier to control on account of the greatly decreased grid-plate capacity (about 0.007 compared to 3 $\mu\mu$f), but also because of greater stage gain, due to its higher internal resistance and to its higher amplification factor. Greater selectivity may be obtained per stage than with triodes.

Using the formulas given in Section 250 for the gain of tube and coil it may be calculated that with a secondary inductance and resistance such that a load impedance of 100,000 ohms is obtained, a gain of 200 is possible with a 58 tube having a resistance of 0.8 megohm, a mutual conductance of 1600, and an amplification factor of 1280. In practice the gain is not permitted to go so high at broadcast frequencies largely because it would tend toward making the set unstable. Gains of 30 to 60 per stage at broadcast frequencies and more may be obtained. For example, with a particular interstage coil wound with Litz wire so that the capacity is low (bank wound) a gain of 62.5 at 1500 kc and 42.5 at 550 kc was obtained. The coil tuned from 1700 kc to 550 kc.

One of the difficulties of getting high gain out of screen-grid tubes at broadcast frequencies is the necessity of having a high mutual inductance between primary and secondary of the interstage transformer. This arises from the fact that the formula on page 339 giving the relation between mutual inductance and gain shows that for maximum gain the coupling between coils increases as the plate resistance of the tube increases. Thus in a typical calculation the mutual inductance between coils amounted to 325 μh whereas the secondary standing alone had an inductance of 180 μh. This implies a very large primary with appreciable distributed capacity.

Interstage coils have been made and widely used with high-inductance primary coils. In other receivers both primary and secondary are tuned increasing the impedance into which the screen-grid tube works. In a typical receiver the primary and secondary of the interstage i-f transformers and the primary of the r-f interstage transformer had inductances of 5.5 mh; the antenna coil was 0.9 mh.

Modern practice is to use small coils, well shielded, usually of Litz, universally or bank wound and of as high Q as can be obtained. Considerable loss to the higher audio frequencies occurs in stages using such coils with high-resistance tubes; but this loss cuts out tube noise, static, and other undesirable noise which the public seems not to like. The Q values are of the order of 100 at intermediate frequencies.

260. Selectivity with screen-grid tubes. With low-resistance tubes, triodes for example, the maximum amplification per stage is obtained when the load the tube works into equals the tube load. Under these conditions the Q of the circuit is one-half the Q of the coil-condenser combination. This is because the effective resistance of this anti-resonant circuit, numerically equal to the product of the reactances divided by the coil resistance, is shunted by a resistance (the internal tube resistance) equal to itself. Therefore the effective resistance has been reduced by a factor of 2, which is the same result as if the coil resistance had been doubled.

With screen-grid tubes the tube resistance is so high that it is difficult to make a tuned circuit with an effective resistance equal to the tube resistance. In other words, whatever the effective resistance of the tuned circuit, it is shunted by a resistance much larger than itself; therefore the Q of the circuit is reduced by much less than a factor of 2. Therefore the selectivity of the stage is much better than if a low-resistance tube were used.

Thus the use of screen-grid tubes has increased not only the gain per stage but also the selectivity per stage. The actual value of the selectivity may be ascertained as follows.

Suppose the tube resistance to be bridged directly across the tuned circuit. Across this circuit is impressed the input grid voltage multiplied by the mutual conductance of the tube. Thus the voltage at resonance divided by the voltage at any other frequency, which will give us an idea of the selectivity, will be expressed as

$$\frac{e_g g_m Z_o}{e_g g_m Z} = \frac{e_o}{e}$$

The resonant impedance, if the coil has low resistance, is

$$Z_o = \frac{L^2\omega^2}{r}$$

where r equals the resistance of the coil.

Now if the plate resistance of the tube is connected across this tuned circuit, the impedance of the tuned circuit, at resonance, will be decreased because of the shunting effect of the tube resistance, r_p. How much will the impedance be decreased? It will be decreased the same amount as if some fictitious additional series resistance had been introduced into the coil. We have seen in Section 252 that the effect of such a shunt rsistance may be calculated by the equation $R = M^2\omega^2/r_p$ where M is the mutual inductance existing between two windings, across one of which is the shunt resistance whose effect on the resistance of the second circuit is desired.

In this case we have only the single coil, no mutual inductance between two circuits. What represents M in our setup? Section 62 shows that M of a single coil is equal to the inductance of the coil, L. Hence we may substitute L for M in the above equation to determine the shunting effect of placing the plate resistance of a tube across a tuned circuit composed of a coil having low resistance across which is a condenser.

The effective resistance of the coil has been increased by the amount given by $L^2\omega^2/r_p$. The tuned circuit resistance is now equal to $r + (L^2\omega^2/r_p)$.

where $r =$ coil resistance,

$r_p =$ tube resistance.

Therefore, the new impedance of the tuned circuit at resonance is equal to

$$Z = \frac{Z_o}{\sqrt{1 + \dfrac{\left[1 - \left(\dfrac{\omega_0}{\omega}\right)^2\right]^2}{\alpha^2}}}$$

where $\alpha = \dfrac{r}{\omega L} + \dfrac{\omega L}{r_p}$, $\omega = 2\pi \times$ off-resonant frequency, and $\omega_0 = 2\pi \times$ resonant frequency.

Thus at 1000 kc the following table gives the attenuation for signals off resonance.

Cycles Off Resonance	Attenuation (db)
1,000	....
2,000	0.3
3,000	0.65
4,000	1.07
5,000	1.6
10,000	4.4

Carrying out the same calculations for an intermediate frequency of 175 kc the attenuation at 10 kc off resonance is 13.4 db. Thus is demonstrated as one of the virtues of the superheterodyne system—the increased selectivity per stage possible at the lower frequency. This is because 10 kc off resonance at 175 kc is much further from the resonance peak than it is at 1000 kc. To secure the same selectivity at broadcast as at intermediate frequencies, more stages must be used. Thus the superheterodyne system, in which the incoming signal is lowered in frequency, is a more economical system than the tuned r-f system in which all the gain and selectivity are obtained at the incoming frequency.

261. Class B and C radio-frequency amplifiers. In radio transmitters it is naturally desirable to get the maximum power output with the least expenditure of power input. Class A amplifiers, although essentially distortionless, have very low output and low efficiency. Class B or C amplifiers, therefore, are employed in transmitters.

The only difference between Class B and C amplifiers lies in the grid bias employed; Class B being biased so that the plate current is almost zero if the a-c grid excitation is removed and Class C amplifiers being biased considerably beyond cut-off so that the plate current is zero without grid excitation. Both types deliver much more power at higher efficiency than Class A amplifiers. In both Class B and C circuits, the grid may be driven positive, and in Class C amplifiers the grid may be driven so far positive that plate current saturation occurs on positive grid voltage swings. Both circuits produce considerable distortion in the form of harmonics, which, however, are filtered out of the output. These are harmonics of the carrier frequency and the circuit can be so adjusted that any modulations of the carrier are amplified practically free of distortion.

In Fig. 196 is the characteristic of a Class B amplifier. Note that the grid bias is at the point where no plate current flows, and that when sine waves of voltage are put on the grid, half-sine waves of current flow in the plate circuit, resembling a half-wave rectifier. The load resistance into which the tube works is so adjusted that a linear region of the tube characteristic is utilized. The theoretical efficiency of the plate circuit is about 78 per cent, that is, the output in watts divided by the total plate power fed into the tube equals 0.78.

In Fig. 196 note how the plate current waves follow the modulations in the grid voltage wave and that the curve joining the peak values of plate current (known as the envelope) has the

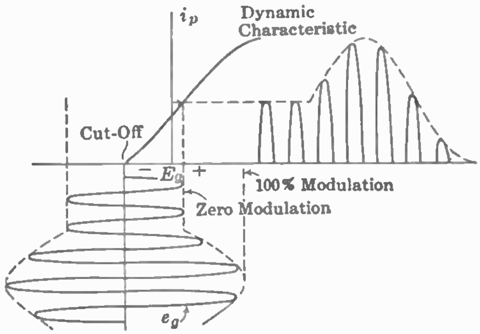


FIG. 196. Characteristic of amplifier biased to cut-off. Note how the dotted lines, known as the "envelope," of plate current follow the envelope of grid voltage.

same form as the curve joining the peak values of the grid voltage wave.

262. Class B characteristics. When the load into which the tube works is adjusted so that the tube characteristic (E_g–I_p) is essentially linear, the maximum amplitude of the plate current at the fundamental frequency of the grid excitation is

$$I_p = \frac{\mu E_g}{2R_p + R_b}$$

where R_b is the effective resistance, at resonance, of the load circuit as shown in Fig. 197. This resistance is obtained by the familiar expression for the effective resistance of an anti-resonant circuit at resonance

$$\frac{L^2\omega^2}{R_0} = \frac{L}{C\,R_0}$$

where R_0 is the series resistance of the coil and condenser.

The direct plate current under these conditions is

$$I_b = 0.637\ i_p$$

and the plate efficiency is $E_0\ I_p/2E_b\ I_b$ and since E_0 is approximately equal to E_b at the former's maximum value the efficiency works out to be approximately 78.54 per cent. In practice the maximum efficiency at 100 per cent modulation is about 65 per cent and the efficiency at no grid excitation is about 33 per cent. In the above discussion E_0 is the peak a-c voltage developed across the

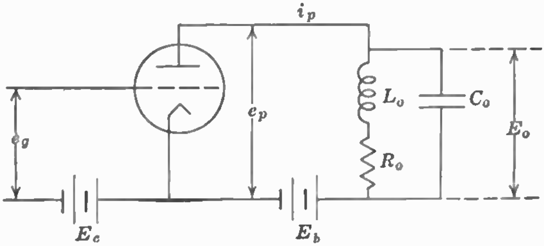


FIG. 197. Elementary r-f amplifier circuit which may be operated as Class B or C. It has a tuned circuit, known as a "tank" load.

tuned circuit in the load, E_b is the battery voltage, and I_b is the direct plate current.

The effective value of the alternating current in the tank circuit will be

$$I_L = \frac{E_0}{\sqrt{2(R_0^2 + \omega^2 L_0^2)}}$$

and when the Q of the tuned circuit is high the currents in the coil and the condenser branches are very nearly equal to each other and to

$$I_L = I_C = E_0\ \omega C_0 = \frac{E_0}{\omega L_0}$$

263. Class C amplifiers. In this type of amplifier the grid is biased so that no current flows in the plate circuit unless there is some excitation on the grid. Such amplifiers are usually operated in keyed transmitters but may also be employed when the modulation is voice or music. If the grid is excited enough, plate current saturation occurs as shown in Fig. 198. Plate efficiencies as high as 90 per cent may be attained with Class C amplifiers.

264. Elimination of distortion. Both Class B and C amplifiers produce severe harmonic distortion. They operate with a tuned circuit as the plate circuit load, however, and since these circuits are made up of shunt inductance and capacity, the second and higher harmonic plate currents find low impedances to flow through, and therefore only low voltages at these frequencies appear across the load.

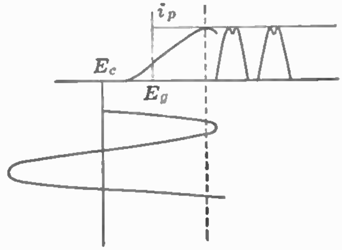


FIG. 198. Characteristics of Class C amplifier. A tuned circuit in the output will filter out higher harmonics generated by saturation of plate current at peak modulation.

Problem 8-13. Assume a Q for the tuned circuit of 25 at the fundamental frequency, and that the voltage at this frequency is proportional to the effective resistance of this anti-resonant circuit ($L^2\omega^2/r$), and that at the second harmonic the voltage across the circuit is proportional to the reactance of the tuning condenser only. What is the ratio between the voltages at fundamental and second harmonic frequencies? *Ans.* 50.

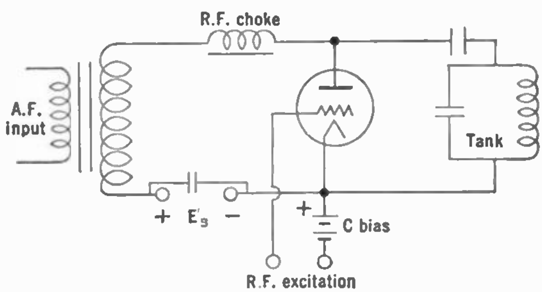


FIG. 199. Class C modulated amplifier circuit.

265. Modulated amplifiers. In all voice-modulated transmitters, some means must be found for modulating the r-f power at the desired audio frequencies. One method makes use of the

Class C amplifier as shown in Fig. 199. Here is an amplifier excited at the carrier frequency of the transmitter. In series with the plate voltage supply is a transformer across the primary of which appears a-f voltages from the microphone system. The plate voltage to the tube, therefore, is made up of three parts: the d-c part from the plate battery, an a-c part from the a-f amplifier and an a-c part from the grid excitation. The audio frequency may vary in frequency and in amplitude from instant to instant; the radio frequency is constant and is derived from a constant-frequency oscillator.

The current flowing in the oscillatory or tank circuit may be made to rise and fall in amplitude with the a-f voltage. A linear relation must exist between plate voltage and tank circuit current for good operation. The plate efficiency is about 60 per cent; triodes or tetrodes may be used. The latter do not need to be neutralized.

In such a modulated amplifier, the output peak power will be four times the unmodulated carrier power and the continuous power output with complete modulation is 1.5 times the power at zero modulation. The increase in power must be furnished by the input from the a-f system. Therefore at full modulation, the a-f system must be capable of supplying a considerable amount of power. Modulation will be treated in a later chapter.

266. Ultra-high-frequency amplifiers. The history of the short waves, those below 200 meters, will undoubtedly be repeated on the very short waves, below 10 meters.

In 1932–1933 when the tubes with dome-shaped top were developed, new possibilities for waves of the order of 5 meters were opened up. Prior to this time much difficulty was experienced in making stable oscillators at waves of 5 meters or somewhat above, and amplification at such wavelengths was impossible. The dome-shaped tubes, however, with smaller elements and better shielding made possible efficient operation at 5 meters.

In 1933, other very interesting developments took place. B. J. Thompson described before the Institute of Radio Engineers work he had carried on for months leading toward the ultimate manufacture of tubes especially designed for ultra-short-wave work. His premise is interesting: if you reduce the physical dimensions of the tubes their inter-electrode capacity will go down but the tube constants will remain the same. Thus a tube, say a triode of mutual conductance of 1000 and an amplification factor of 10, might have a grid-plate capacity of 3.3 $\mu\mu$f. If all dimensions were reduced by a factor of 10, the electrical characteristics would not change but the capacity between plate and grid would be reduced by a factor of 10.

With such tubes, which are scarcely larger than a thimble, amplification at wavelengths less than 1 meter is possible. Oscillators operate without trouble at 1 meter, and a superheterodyne was made which would give a gain of 4 per stage at this wavelength, prior to the frequency changing.

These oscillators use conventional circuits, i.e., Hartley or Colpitts. Other types of oscillators have been developed which will generate frequencies much higher than well-known triode oscillator circuits. In conventional circuits, generation is due to feedback of energy from the output to the input. In the other circuits to be described the phenomena of generation is produced in another way.

For example, in a circuit called, after its discoverers, the Barkhausen-Kurz arrangement, the grid of a triode is maintained positive with respect to the cathode and the plate is negative. Now one would not suppose that any current would flow in the anode circuit under these conditions, but it is a fact that if the voltages are correct and if the dimensions of the tube are correct, oscillatory currents will flow in an external tuned circuit connected to the plate and grid.

Suppose an electron leaves the cathode and is attracted toward the grid because of its positive potential. If the grid is fairly open, the electron may overshoot and not hit the grid and give up its charge. Now the electron goes on and comes within the negative field of the plate. Here it is repelled and turns about, going back toward the grid and cathode. When it gets within the positive field of the grid it is again attracted and again overshoots its mark, going through the open mesh toward the anode on the other side. This cycle may become continuous. Tubes for this purpose are usually made with concentric cylindrical elements.

The frequency of oscillations is mostly independent of the inductance and capacity of the circuit elements and is controlled by the voltages and the tube dimensions. Oscillations corresponding to wavelengths of a fraction of a meter have been detected from such an arrangement. The power that may be obtained from these oscillators is small because the tubes are small and not much power may be dissipated at the plate.

There are other types of oscillators in which the time of flight of the electrons within the tube is the factor determining the frequency, and still others in which other phenomena come into play. Present trends, however, are to use conventional tubes of small size, although they may be water-cooled, when it is desired to generate power at wavelengths of 1 meter and shorter.

As higher and higher frequencies are to be generated and amplified, dimensions of circuit elements must be reduced until finally the interelectrode tube capacities and lead inductances themselves become comparable to the external circuit elements. Another problem is the fact that electrons require finite time to travel from cathode to plate and at the higher frequencies not enough time may be available before the alternating voltage the tube is amplifying has reversed its direction, tending to impel the electrons away from the plate. Still another problem is that of skin effect at high frequencies, forcing currents to travel on the surface rather than through the core of a conductor. These matters are discussed later a bit more in detail.

Just as developments worked out during the World War I gave rise to broadcasting as we know it today and led to a tremendous change in the art of communication by wire and by radio, so developments during 1940 and later years, instigated by military requirements, will call for a vast readjustment of the communication system. High-power energy at extremely short waves will be possible; no one knows what we will find ourselves able to do with these new means.

CHAPTER XIV

DETECTION

Suppose we have received a signal and have amplified it in a radio-frequency amplifier. It is still inaudible. How may it be detected, or demodulated so that it can be put into an audio amplifier and then a loud speaker?

Up to the present time we have considered the applications of the vacuum tube which call for its operation on a straight part of its characteristic where little distortion takes place. We have considered the tube only as an amplifier. We shall discuss now the uses for the curved part of the characteristic.

Tubes act as amplifiers either with or without distortion and as detectors and modulators in which distortion is the essential feature. The latter uses of the tube require a curved characteristic. The output no longer is an exact replica of the input.

267. Distorting tubes. In Section 190 we were able to calculate the amount of distortion (second harmonics) that resulted when the tube was worked on a curved part of its characteristic, and found that in the distortion process a certain amount of direct current was generated. In other words a pure sine wave voltage put on the grid-filament input of a tube resulted in an output current or voltage composed of not only the frequency that was put on the input but also some additional frequencies and some additional direct current as well.

If we desire to get direct current from an a-c voltage, the tube acts as a rectifier. If we desire to get a-f voltages from a modulated r-f voltage, the tube acts as a detector. If we desire to mix two frequencies, say a low audible frequency with a high or radio frequency, we put them both into a modulator. All these uses require a non-linear characteristic. Detectors and modulators have three essential elements just as amplifier tubes have.

Tubes designed for rectifiers need have only two elements, plate and cathode.

268. Modulation. Consider the circuit in Fig. 200. If the r-f generator is turned on and the audio-frequency generator is shorted, high-frequency currents will flow in the antenna. Their amplitude will depend upon the amplifying ability of the tube and the amplitude of the applied grid voltage at this frequency. If the grid voltage is of constant maximum amplitude and fre-

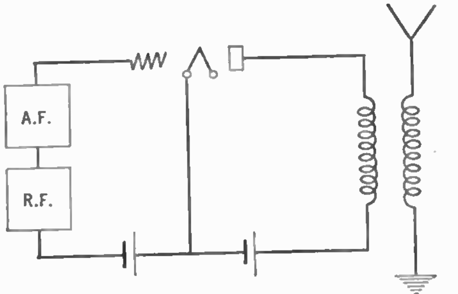


FIG. 200. A simple modulator.

quency, the plate current variations and hence the antenna current variations will be of constant frequency and constant maximum amplitude. Now let us turn on the low-frequency generator. The amplitude of the antenna current will vary and if the proper relations between the plate current and the grid voltage are satisfied the amplitude of the high-frequency antenna current will vary at the frequency of the low-frequency generator.

An idea of how the antenna currents look before and after modulation may be seen in Fig. 201. The high frequency is called the **modulated** or **carrier frequency,** and the low frequency is called the modulating or **side-band** frequency.

Let us call the maximum amplitude of the antenna current B, and its frequency f_c. Then the current at any instant will be $i = B \sin 2\pi f_c t$ in which the t expresses the amount of time that has elapsed since the beginning of the cycle. Now instead of a constant maximum amplitude B let us vary this amplitude above and below B at some rate, say in the form of a sine wave. The maximum amplitude is no longer constant, but is equal to $B + A \sin 2\pi f_m t$ in which f_m stands for modulating frequency just as f_c indicates carrier frequency. The current at any instant is, now, a function of two factors, and may be expressed as $i = (B + A \sin 2\pi f_m t) \sin 2\pi f_c t$.

This process whereby a high frequency is varied in amplitude by a lower frequency is called **modulation.** The system outlined above is called **grid circuit modulation.**

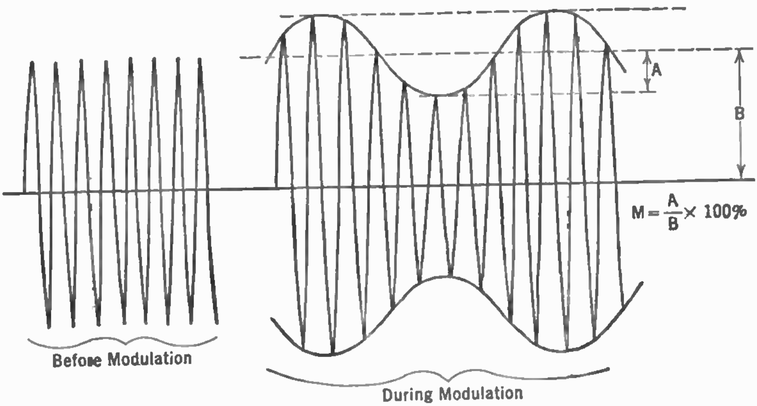


FIG. 201. Unmodulated and modulated wave.

The tube in such a process is called a modulator. Once the high-frequency wave is modulated, it acts as a carrier for the low frequency and wherever it goes it takes the modulating frequency with it.

The depth to which the high frequency is modulated depends upon the relative maximum amplitudes of the two frequencies. If they are equal, the wave is said to be completely modulated, and the **"percentage modulation"** is 100.

269. Percentage modulation. If the two peak voltages are not the same, the high-frequency wave will not be completely modulated, and the modulation will be less than 100 per cent. In broadcast transmission the modulation rarely exceeds 90 per cent. The greater the modulation percentage the farther will the signals from a given station be heard.

In Fig. 201 is the carrier before and after modulation. The percentage modulation is defined as the ratio between A, the peak current of the modulating frequency, and B, the peak current of the non-modulated carrier. A glance at Fig. 201 will give a good idea of what is meant by the expression. When 100 per cent modulation is effected, the values of A and B are equal.

$$\text{Percentage modulation} = M = \frac{A}{B} \times 100 \text{ per cent}$$

270. Demodulation. If such a modulated wave is turned into a "demodulator," the modulating frequencies can be got back. A demodulator, or detector, acts as though it were made up of two filters, of which one will not pass the high or carrier frequency and the other will not pass the low or modulating frequency. In the demodulator the two frequencies are separated.

A modulator, then, is a device for combining two frequencies. A demodulator, or detector, is a device by means of which we get back from the radio-frequency carrier the modulation or intelligence-carrying frequencies.

271. A simple detector. Let us consider a device which has a voltage-current characteristic like that in Fig. 202. This shows that no current will flow through the device until the voltage across it reaches the limiting value of 4 volts. Then current begins to flow and reaches 6 ma when the voltage is 8 volts. Over the region in which it conducts, the characteristic is linear. Suppose we place a direct voltage upon it, say from a battery, which has a value of 8 volts. Now, in addition, let us place an alternating voltage so that the voltage increases and decreases from 8 volts. The current will increase and decrease from its value of 6 corresponding to the steady voltage of 8. Since the characteristic is linear, the current waves will have the same form as the voltage waves.

If, however, we place 4 volts on the device from a battery and add the alternating voltage at this point, current will be zero at some instants and will be positive and measurable at other instants. The alternating voltage wave appears in the output as half-waves of current. Clearly the device has distorted the voltage wave, cutting half of it off so that only half-waves appear as current in the output. If, therefore, the normal steady current is 0 ma when no a-c voltage is applied, this current will become

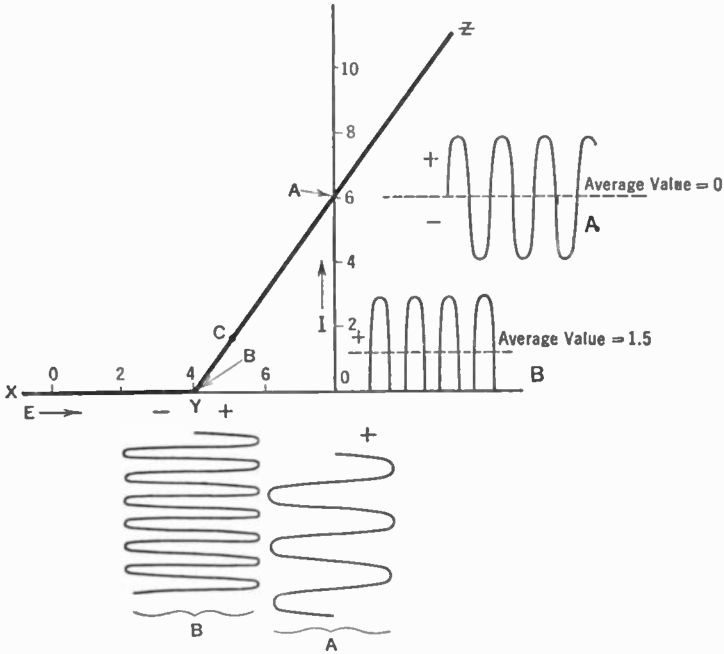


Fig. 202. Rectification takes place when the operation is at Y but not at A. Thus the plate current in A is similar to the input voltage, although at B the output differs from the input.

some positive measurable value when the alternating current is applied because, although a meter cannot follow these spurts of current, it will take up some average value between the peak of the spurt and the zero value.

In such a detector there is an increase in current when a-c voltages are applied. Now if the a-c voltage is modulated as in Fig. 203, the average value of detector current goes up and down in accordance with these modulations. This varying average value is the useful part of detection since it has the same form as the original modulating voltage and in a distortionless system is exactly proportional to this voltage. This varying value occurs at an audible frequency.

272. The plate circuit detector. One form of vacuum-tube detector is the plate circuit or C bias detector, that is, a rectifier which operates upon a curved part of the E_g–I_p characteristic

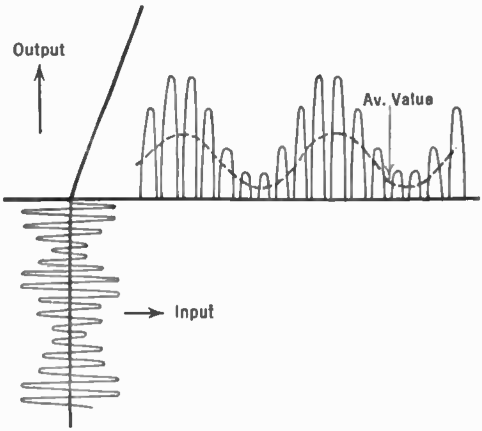


FIG. 203. Rectification taking place about a non-linear part of a characteristic.

curve of a tube. It is not a perfect rectifier, but as greater and greater voltages are placed upon it the positive halves of the current waves are much greater than the negative waves, and so the average value of plate current due to rectification increases a corresponding amount.

In this process, there are three points to note. First, the very rapid radio-frequency variations in input voltage modulated at an audio rate. Each audio cycle is made up of thousands of radio-frequency cycles—only a few of them are shown in the diagrams, for simplicity. When this r-f voltage is placed upon a curved part of the plate current curve, the difference between the positive and negative current waves takes the form of the audio variations. Because these positive and negative portions differ in amplitude, the average between them is not zero and therefore the plate circuit contains a current of the frequency of the audio signals. In this process there is an increase in average direct plate current when the input wave is modulated. The plate current meter cannot follow the change in audio plate current and does not indicate whether or not the carrier is being modulated.

273. Detection of modulated wave. Suppose, for example, we connect antenna and ground to the grid and filament input of a tube. A near-by station is putting into the ether an unmodulated wave. As soon as we tune to this station's frequency a voltage is developed across the input circuit to the tube; this a-c voltage fluctuates the grid voltage, and a change takes place in the average value of the plate current. If the station is powerful enough, and if it is modulated with a key, that is, if its antenna current is started and stopped in accordance to some code, we can use a sensitive relay in the plate circuit of our detector and either read the signals directly from the relay, or operate a telegraph sounder with it, or light a lamp, or fire a gun. If the transmitted frequency is 1000 kc it may be necessary to tune the input of the tube to this frequency. A pair of telephones in the plate circuit of the detector, in place of the relay, will indicate by means of clicks when the transmitter started and stopped the antenna current but would not give off any sound in the middle of dots and dashes. If, however, we operated a buzzer with the relay we could read the signals by the audible sound of the buzzer.

We can get around the difficulty of needing a receiving buzzer by having a buzzer or "chopper" at the transmitting station to modulate the 1000-kc voltage. Now when the key is pressed, the modulated 1000-kc wave is sent into the ether. If the modulator tone, say 1000 cycles, has a maximum amplitude equal to the maximum value of the 1000-kc voltage, the antenna current will be doubled 1000 times a second when these two voltages will be in phase. At 1000 other instants the two voltages will be out of phase and the antenna current will be reduced to zero. Across the receiving tube is a 1000-kc voltage broken up into 1000-cycle sections—modulated as we say.

Now if we place a pair of telephones in the plate circuit of the detector tube, it will offer a certain amount of impedance to these 1000-cycle sections of 1000-kc currents. A voltage will be built up across the telephones, and our ears will tell us that 1000-cycle signals are being received. The direct plate current meter will still indicate an increase in average plate current when the trans-

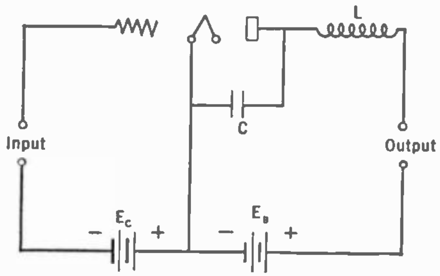


Fig. 204. To keep r-f currents from the output, a low-impedance path (C) and a high series impedance (L) are used.

mitter key is pressed, but of course its needle cannot follow the 1000-cycle variations. Neither will a relay indicate that the 1000-kc input is modulated, because it is too sluggish to follow the variations, but it will indicate the average of each section and will close when the key is pressed. The telephones, however, will respond to frequencies as high as 10,000 cycles per second.

If, now, we use a microphone at the transmitter instead of a buzzer and talk into it, the voltage variations impressed on the 1000-kc voltage may be very complex, perhaps something like Fig. 203, for example. Telephones in the output of the detector will respond to these modulated sections of 1000 kc. Hence the telephones will give off a note or sound corresponding to what was put into the microphone. If, in the process of detection, other audio frequencies are generated, distortion results, because the audio components heard in the telephones are no longer exact replicas of what was put into the microphone.

The process of detection by means of the bend in the plate current curve is essentially one of distortion, in which the r-f wave is distorted and out of which we get the audio wave by placing some a-f impedance in the plate circuit of the detector. Usually the plate circuit has a low impedance to the r-f plate currents, that is, an easy path around any plate load is provided by a by-pass condenser such as *C* in Fig. 204, and sometimes an additional precaution is taken to prevent any r-f voltages from being built up across the audio impedance in the plate circuit. For example, in Fig. 204 a choke, *L*, is used.

274. Conditions for best detection. There are several variable factors in such a detector circuit as shown in Fig. 204. One is the grid bias, E_c, and the other is the plate voltage. Some combination of these two voltages will create the greatest amount of a-f voltage across a given impedance when a given r-f voltage is put on the grid.

In such a detector the greater the r-f voltage the greater the change in average plate current and the greater the audio signal in the output load. With a given r-f voltage the audio signal will be proportional to the amount of modulation at the transmitter, that is, as the power at the transmitter is varied by the voltage coming from the microphone, the audio notes at the receiver should vary in exact proportion.

275. Diode detection. Although rectification, and therefore detection, will occur at any non-linear portion of an E–I curve, as in the grid circuit of a tube (E_g–I_g characteristic) or in the plate circuit of an over-biased tube (E_g–I_p characteristic) and although these methods have been used and have their advantages, nowadays a tube operating as a diode is ordinarily utilized as a detector.

The diode may be made especially for the purpose of detection, like the 6H6, or any triode or more complicated tube may be made into a diode by connecting two or more elements together. Thus a triode can operate as a diode by connecting grid and plate together or plate and cathode together and operating the tube between these two elements and the third element. In all diode circuits there is a resistance load shunted by a condenser.

The diode is used for several reasons. First, its internal resistance during the time it conducts is low, and therefore a high-load resistance will tend to make the *E–I* characteristic linear and so produce little distortion. In the second place the diode permits the use of simple automatic-volume-control circuits which are now part of all home radio receivers.

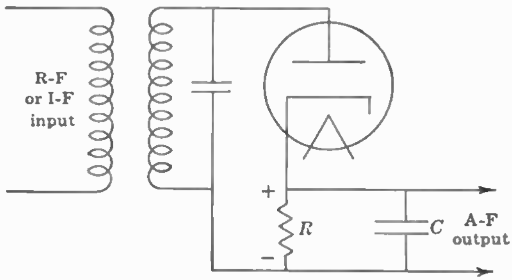


FIG. 205. Simple diode detector. Rectified voltages appear across *R*.

The diode has disadvantages compared to grid detection or plate detection. The diode draws current from the input circuit and therefore puts a definite load upon it, drawing power from it. This decreases the selectivity of the input circuit. Grid circuit detectors are very sensitive since the demodulated voltages are amplified in the plate circuit of the tube used, but they, too, place a load upon the input. Plate circuit detectors amplify the input signal before demodulation takes place, have a very high input resistance and, therefore, do not affect the selectivity of the input circuit. The diode, however, is preferred today and will be described first.

The simplest circuit is shown in Fig. 205. The load *R* is ordinarily about 0.5 to 1.0 megohm in resistance; *C* is about 150 $\mu\mu$f at broadcast frequencies and higher than this value at intermediate frequencies. Except at low input voltages, *R* is large compared with the internal resistance of the tube, and most of the voltage produced in the rectification process appears across *R* for this reason. The actual value of the rectified voltage is almost equal to the peak value of the a-c voltage across the tuned circuit. Values of C are chosen so that this condenser offers little reactance to the r-f voltage but has high reactance to the modulating voltages.

If one applies unmodulated alternating voltages across the tuned circuit in Fig. 205 and reads the rectified direct current

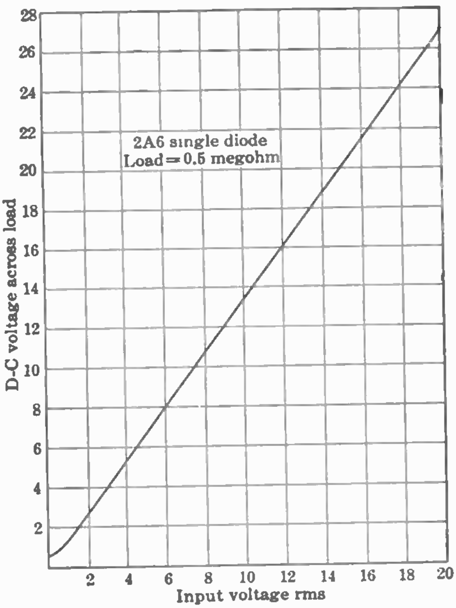


Fig. 206. Input-output characteristics of a diode detector.

through R, a curve like that in Fig. 206 will be obtained. This shows, for example, that 10 volts on the input produce a direct voltage across the load resistor, R, of approximately 13.5 volts. Now if this input voltage is completely modulated, at some instants it will be zero and therefore no (or very little) rectified voltage will be produced, and at some other instants the input will be 20 volts and approximately 27 rectified volts will appear. In other words, the voltage across R varies between 27 volts and zero and has an average value of approximately one-half of 27 or 13.5 volts. An a-c voltmeter across R would measure a voltage having a peak value of 13.5 volts.

Since the load resistance of the diode is high, 0.5 megohm or more, it must be coupled to the next tube (a-f amplifier) by a resistance-capacity coupling circuit. It would be most difficult to couple by transformer a high impedance of this nature to the following tube. Just as in a resistance-coupled amplifier, the diode load is shunted by the grid resistor of the following stage, which has in series with it a condenser to isolate the d-c voltage of the diode circuit from the grid of the following tube. To keep the shunting effect low, the grid resistance of the following tube must be high compared with the load resistance of the diode. This increases the difficulty of keeping down the effect of stray capacity, since the higher the grid resistor, the more important become these stray capacities in removing the higher audio frequencies.

Thus the design of a diode detector is not unmixed joy, and a vast amount of work and study has gone into this simple detector.

276. Plate circuit detector. When we studied audio amplifiers we learned that it is necessary to bias them correctly with respect to the input alternating voltage. Otherwise distortion results. In a plate circuit detector, the amplifier tube is deliberately over-biased so that distortion to the r-f input wave results. Out of this process, however, may appear the a-f modulations practically without distortion. The r-f input, of course, is greatly distorted.

Since the plate circuit detector and the vacuum-tube voltmeter have much in common, we will discuss the former by studying the characteristics and adjustments of the latter. In the plate circuit detector, the input resistance is very high; r-f voltages are placed upon the grid and are amplified in the tube before they are rectified. The plate circuit detector is more sensitive than the diode for this reason, that is, a given amount of input r-f voltage, modulated to a certain degree, will produce more a-f output voltage than the diode. Since the input resistance of the tube is high, because it is so highly biased that no grid current flows, it has no shunting effect upon the previous tuned circuit. Therefore not so much amplification nor selectivity needs to precede the plate circuit detector as is necessary when using a diode.

277. The vacuum-tube voltmeter. The principle of the vacuum-tube voltmeter is simple. The operating point of the tube is chosen by adjusting the grid bias and the plate voltage, so that it is on a point of considerable curvature. When an a-c voltage is put on the grid, rectification takes place in the plate circuit, and the d-c part of the rectification product is read on a d-c instrument. If the voltmeter is properly biased, its input resistance is very high and it takes so little power from the device whose voltage is being measured that it may be considered as having no effect upon the circuit.

The choice of grid bias depends upon the input voltages to be measured. Let us suppose we are to measure a peak voltage of 5 volts. Clearly the grid bias cannot be less than this because of the decreased input resistance when the grid draws current and the effect of such a meter upon the circuit under measurement. The grid bias would be some value over 5 volts, 6, for example. The next step is to fix the plate voltage. This is determined by the range in input volts to be measured, and the kind of instrument used to read the direct current. For greatest accuracy E_p should be such that the greatest deflection of the current meter will be obtained by the given input voltage. In general a voltage range of about 5 to 1 is all that can be read with an ordinary voltmeter, that is, from about 0.5 volt to 3.0 volts. The problem then is to choose a plate voltage that will enable the desired range to cover completely the scale of the meter being used.

For measurements of average voltages, say up to 10 or 15 volts and as low as 0.5 or 1.0 volt, a microammeter reading 200 μa and costing about $35 is a good instrument. A small laboratory model of milliammeter reading 1.0 or 1.5 ma can be used although the accuracy of measurement will not be so great as with a more sensitive instrument.

What is desired is the greatest change in plate current with a given a-c voltage. In Fig. 207 are some curves taken with a 3-volt, 60-ma tube, showing the plate current at various values of a-c grid voltage and at various values of plate voltages. The change in plate current (ΔI_p), that is, the value *with* a-c input voltage minus the value *without* input, is plotted and shows the

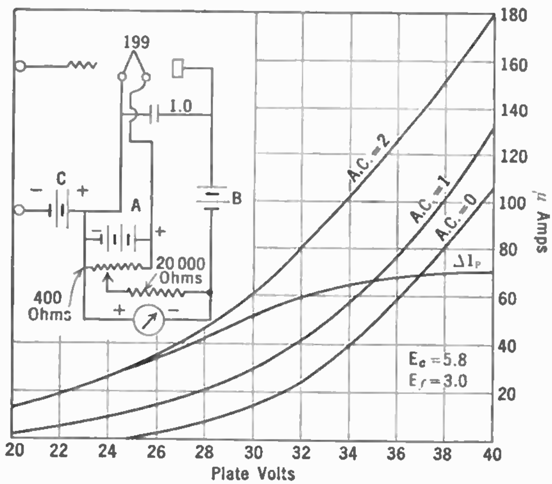


FIG. 207. Calibration and circuit of vacuum-tube voltmeter.

futility of using plate voltages greater than 35 volts when sensitivity is the criterion.

Because the tube takes some plate current even when there is no a-c grid voltage, part of the scale of the d-c meter is taken up with this steady reading. This reading can be balanced out by means of the zero adjuster on the meter, or by using another current through the meter in such a direction that the original plate current is "bucked out." The whole meter scale is available then for plate current changes occurring under input grid voltage excitation. Such a balancing out voltage may come from an additional battery and adjustable resistance, as in Fig. 208, or from the voltage drop across the tube filament as in Fig. 207.

Experiment 1–14. Use of the vacuum-tube voltmeter. There are two types of vacuum-tube voltmeter: the C-bias type and the grid leak and condenser type. The latter is more sensitive but draws current from the device whose voltage is being measured. Both types should be experimented with. They are the most versatile and useful of all radio instruments.

Connect up a C-bias voltmeter using a 0 to 5 milliammeter in the plate circuit, about 45 volts on the plate, and add sufficient C bias to decrease the plate current to nearly zero. Then use a more sensitive plate current meter, and a bucking battery to reduce the deflection to zero. Calibrate

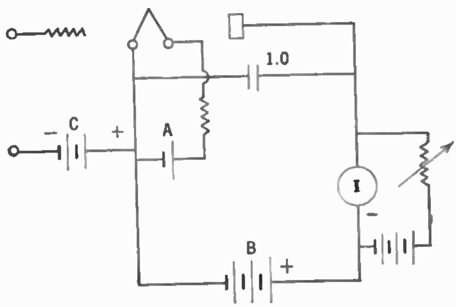


FIG. 208. Method of balancing out the steady plate current from the indicating meter.

the meter by putting known currents through known resistances at 60 cycles or at any radio frequency. With 45 volts on the plate and about 9 to 13 volts C bias with average tubes, voltages as low as 1.0 will give a good deflection and peak voltages up to about 7.0 can be read on a meter reading about 1.0 ma.

Fairly accurate calibration may be performed by using the voltages available from a filament current transformer, that is, 1.5, 2.5, and 5.0, and, of course, combinations of these voltages depending upon how the windings are connected.

Connect the voltmeter across the tuned circuit of an r-f stage, or across a coil-condenser combination that can be coupled to an oscillator. Tune the condenser and note how the voltage across the coil increases through resonance. Insert some resistance into the tuned circuit and repeat. Note how much broader the resonance curve is and how the minimum voltage has decreased.

Connect the voltmeter across the resistor of a resistance-coupled amplifier tube—inserting a large capacity between the plate terminal of the amplifier tube and the grid of the voltmeter so that the d-c voltage across the resistor will not bias the grid of the voltmeter. Apply a known voltage to the input of the amplifier and measure the output voltage. Then change the plate resistor and again measure the output voltage. Plot a curve showing amplification against plate load resistance.

Place the voltmeter across the secondary of an audio transformer and apply a known voltage in series with a resistance of about 15,000 ohms and the primary. Measure the turns ratio of the transformer at 60 cycles or some other frequency by measuring the secondary voltage.

These are but a few of the many experiments that can be performed with the vacuum-tube voltmeter. It can be used to measure field strength of distant transmitters, resistance of coils, amplification of amplifiers, resonance curves, frequency characteristics of amplifiers, etc.

278. Direct plate current as a function of a-c grid voltage. The vacuum-tube voltmeter is really a C-bias or plate circuit detector, and the change in plate current is a function of the a-c voltage on the grid. It is only necessary to calibrate the detector, using any source of alternating current and any standard a-c voltmeter as a standardizing voltage, or a known current can be passed through a known resistance and the voltage drop used for calibration.

The detector in one's radio is also a vacuum-tube voltmeter although it is not so calibrated. If a sensitive meter, say reading up to 0.5 ma, is placed in the detector plate circuit of a radio receiver, changes in the reading will be noted when a strong signal is tuned in. If greatest sensitivity is desired, the steady no-signal current may be balanced out and then a sensitive micro-ammeter may be used. The changes in this meter reading may serve as a measurement of fading, signal strength, etc. No change will occur unless the r-f voltage on the input to the tube changes. Modulation will not cause any change unless the transmitter is over-modulated.

279. Plate circuit detector characteristics. How much a-f voltage one gets from a plate circuit detector when it has certain r-f voltages placed upon the input and the effect of modulation on these input voltages may be determined experimentally as follows. We may fix upon some grid-bias voltage, e.g., for a 27 tube about 18 volts with a plate voltage of 180. Then we can put on the input to this tube, operating as an over-biased amplifier, or detector, various alternating voltages which need not be at radio frequencies. These input voltages cause some change in plate current which may be read with a fairly good milliammeter. All that is needed then to determine experimentally the

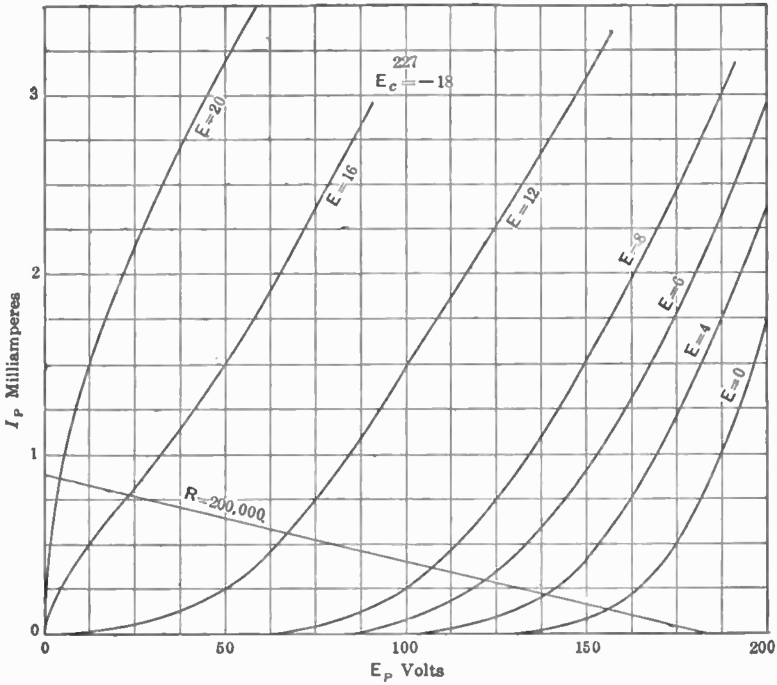


FIG. 209. Plate current curves as controlled by plate voltage and input carrier voltage E applied to grid.

detection characteristic of a C-bias detector is a source of known alternating voltages and a good milliammeter.

Such a series of curves is shown in Fig. 209. For example, with 100 volts on the plate, an input alternating voltage of 12 produces a plate current of 1.5 ma. Across such a family of curves a load line (see Section 188) can be drawn for any load resistance, in this case 200,000 ohms. This is about the highest resistance load that can be used because of various capacities which will shunt it and reduce its impedance at the higher audio frequencies.

The rectified output voltage of the detector, e.g., the a-f voltage applied across the 200,000-ohm resistor and hence to the input of the a-f amplifier, can be obtained from such a curve. For example with an input of 12 volts ($E = 12$) the rectified voltage may be found by noting the intersections of the load line with the $E = 0$ line and with the $E = 12$ line. Thus the rectified voltage is the difference between $E_p = 156$ (intersection with $E = 0$) and 66 (intersection with $E = 12$) or 90 volts. Taking several of such voltages a curve like that in Fig. 210 can be plotted.

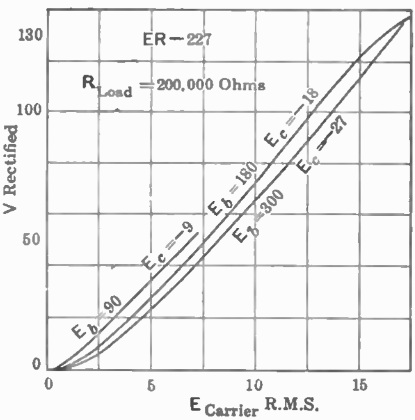


Fig. 210. Plate rectification "power" detector characteristic.

Now this curve gives not only the rectified voltage due to various values of *carrier* voltage but also by knowing how strongly this carrier is modulated, the actual a-f voltages applied across the load resistance may be ascertained. For example, if the plate voltage is 300 and $E_c = 27$ volts, suppose a carrier voltage of 12 is modulated 33 per cent. The carrier voltage will then vary between $12 - (12 \times 33$ per cent$)$ and $12 + (12 \times 33$ per cent$)$ or between 8 and 16 volts. These values of carrier voltage represent rectified voltages of 47 and 124 and because the carrier swings as far up as it goes down from its unmodulated value of 12, the audio voltage produced by these variations is $(124 - 47)/2$ or 38.5 volts.

280. Detection in a radio-frequency amplifier. Because the r-f stages of a receiver are biased, it often happens that some detection takes place in one or more of them, probably in the first. What happens is something like the following: the first tube is so biased, and may have such a low-load impedance in its plate circuit at the frequency under consideration that the operating point is on a part of considerable curvature. Now a strong signal comes in, a large a-c voltage is impressed on the r-f grid, and detection is the inevitable result. A pair of receiving telephones in the plate circuit of this tube would have an a-f voltage across them, due to the rectified voltage, and would give an audible response.

For example, suppose the receiver is tuned to a frequency of 600 kc. This means that the load impedance in the plate circuit of the r-f amplifiers will be high at 600 kc but low to all other frequencies. The tube will have a curved characteristic to any signal of frequency other than this. A powerful local station on some other frequency puts a strong signal on the grid of the r-f tube, and the rectified voltages modulate the r-f voltage of the 600-kc wave so that what gets into the second r-f stage is a 600-kc signal modulated with what is going on at the studio of the other station. The modulation of the distant 600-kc station may be inaudible. A wave trap tuned to the offending local station is a good remedy for such trouble. Use of super control tubes is another remedy.

281. Grid leak and condenser detector. In the plate circuit detector, we may look upon the signal as having first been amplified by the tube and then as going through the detection process when it reaches the plate circuit. There is little amplification in such a tube at radio frequencies because of the low plate circuit resistance at radio frequencies. The grid leak and condenser detector shown in Fig. 211 is more sensitive and more complex in theory but has limited power-handling ability. In this case we may think of the r-f signal as going through the demodulation or detection process in the grid circuit of the tube and then having the resulting audio tones amplified in the plate circuit just as in an ordinary amplifier. Because of this amplification, this type of detector is more sensitive than the C-bias type.

Such a tube detects on its grid current curve, and so the grid voltage must be such that the operating point is on a curved part of the E_g–I_g curve, and because it amplifies on its plate current curve the plate voltage must be fixed so that the operating point for the modulating voltage is on a straight part of the plate current curve.

The grid current plotted against grid voltage of a typical tube is given in Fig. 212. It will be noted that even though the grid is negative a certain amount of grid current flows. This is because of the few electrons which leave the filament with sufficient velocity to get to the plate even through the negative retarding

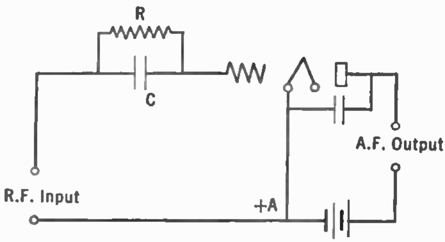


FIG. 211. Grid leak-grid condenser detector.

force of the grid. This direct grid current must flow through the grid leak, usually of the order of from 1 to 10 megohms. The voltage drop across this resistance is such that the grid end is negative with respect to the filament even though the "grid return" is connected to the positive end of the filament battery. The value of the grid leak fixes the point on the grid current curve at which the input signals operate. In Fig. 212 the operating point is about 0.3 volt negative.

282. Effect of grid leak and condenser values. Changes in grid leak value produce no other change in the detector action than is produced by changing the operating point. This is the entire purpose of the grid leak. The purpose of the grid condenser is to by-pass the high resistance so far as r-f currents are concerned so that the greatest possible r-f voltage may be built up across the grid-filament input of the tube. If the condenser is too small, there will be an appreciable r-f voltage loss in it, and the tube will not get all possible of the input signal. If the grid condenser is too large, the a-f voltages built up across the grid leak will be by-passed. A good value to use is 0.00025 μf and a value of 0.0001 may be used satisfactorily. Smaller condensers than this produce some loss in r-f voltage, and result in decreased sensitivity.

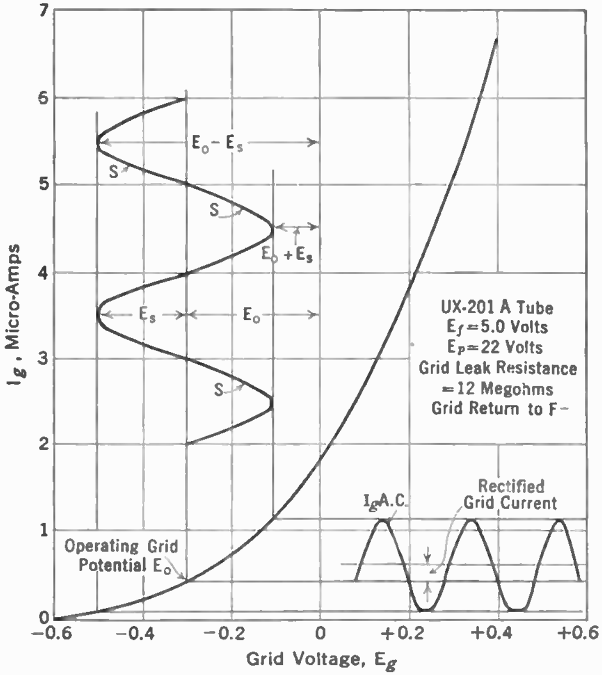


FIG. 212. Rectification on the grid voltage-grid current curve.

When an input signal is applied to the tube the grid voltage changes in accordance with the incoming signal just as it does for an amplifier or a plate current detector. These changes in grid voltage produce a change in grid current in accordance with movements up and down on the curve of Fig. 212. Because of the curvature the grid current increases more when the grid is positive than it decreases during the negative half-cycles of input voltage. The result is a net change in grid current, in this case an increase which produces an increased voltage drop across the grid leak and a greater negative voltage in the grid. This increase in bias causes a *decrease* in plate current. It will be remembered that an input signal caused an *increase* in plate current in the plate circuit detector. These audio grid current changes produce corresponding plate current changes whence they are passed on to the audio amplifier.

In practice, then, modulated r-f voltages are put on the input to a detector; within this detector the modulations are separated from the carrier that brought them to the receiver; and finally these modulations in the form of audio frequencies are applied to a plate circuit load—usually the input to an a-f amplifier.

283. Automatic volume control. A notable advance in radio receiver design took place when avc circuits were developed and placed in active use. By the use of automatic volume control the effects of swinging in and out of voltage at the antenna terminals are overcome to a great extent. Furthermore, when tuning the receiver, blasts of loud signals are prevented when tuning from a weak station for which the volume control might be turned up high, to a powerful station for which the volume control must be turned down.

As the name implies, automatic-volume-control circuits control the gain automatically. This is accomplished by varying the amplification of the r-f and i-f circuits inversely as the strength of the incoming signal. When this signal is high, the gain is low and when the incoming signal is weak the gain of the receiver is high. The circuits attempt to maintain a constant voltage at the detector terminals and are able to do this over a very wide range of incoming signals.

Although a separate tube may be employed to produce the voltages necessary for avc control, it is common practice to utilize the d-c voltages developed in the diode detector. Thus in Fig. 205 the lower end of the diode load resistor has a negative potential with respect to the cathode of the diode tube. This negative potential may be utilized as avc by impressing it upon the grids of r-f and i-f tubes as bias. The stronger the signal impressed upon the input of the receiver, the stronger will be the signal impressed upon the detector input (in the absence of avc).

The stronger this signal, the more direct current is developed in the diode by the process of rectification, and this current flowing through the diode load resistor produces a voltage drop along this resistor. A greater voltage is developed when a greater current flows through the resistor and this greater voltage applied to the previous tubes as bias will reduce the gain of these tubes.

What actually occurs is that the transconductance of the amplifier tubes is controlled by varying the bias on the grids of

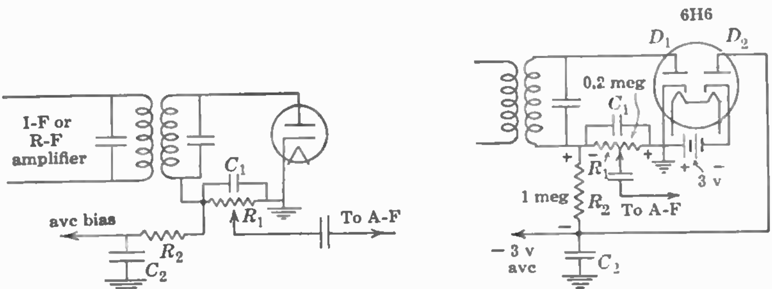


FIG. 213. Typical avc circuits. In the second a permanent bias of −3 volts is applied to i-f tubes as a "delayed" avc voltage.

the tubes, and this bias is caused to vary automatically with the strength of the signals applied to the receiver but in an inverse sense, that is, the stronger the signal the more negative bias that is applied.

In Fig. 213 are two avc circuits. Note that a filter made up of series resistance (R_2) and shunt capacity (C_2) is placed in the avc lead as it is taken from the diode. This is necessary because the voltage across the diode load varies with the modulation of the incoming signals. If this voltage were applied directly to the grids of the amplifier tubes, the bias of these tubes would go up and down with the modulation, and again in the inverse sense, so that all that came out of the detector would be a variation of tones all of the same strength. There could be no variations of audio volume.

In practice, then, the voltage from the diode charges the condenser C_1 through the resistance R_1. This condenser can discharge at only a slow rate and therefore the voltage applied to the amplifier grids as bias cannot follow the modulations of the incoming signals although it may follow the variations in the signals due to fading or tuning from one station to another. The design of this filter is important. The values of R_1 and C_1 must be chosen so that the time taken by the condenser to discharge (its **time constant**) is such that the lowest modulation frequencies will not cause any variation in the grid bias of the amplifier tubes, but the discharge time must not be so large that a delay occurs when the system is recovering from a crash of static. A time constant of $\frac{1}{10}$ to $\frac{1}{5}$ second is usually employed.

There are many variations of this simple avc circuit. Sometimes the avc voltages are amplified before they are applied; sometimes more avc is applied to one tube than to another; sometimes no avc is applied until the incoming signal reaches a certain value. This is known as "delayed" avc since the action is delayed until signals of a certain strength are attained. Sometimes the avc tube is connected to a point in the circuit at which the selectivity is less than that at the detector terminals. In this system, noise encountered when the receiver is tuned off resonance is reduced. Sometimes a parallel chain of amplifier tubes is used to produce the avc voltages.

284. Delayed avc. One of the circuits in Fig. 213 represents a system for delayed avc. The tube is a 6H6 which has two diodes in it. Diode D_1 acts as detector and avc tube. R_1 and C_1 are the load of this diode. R_2 and C_2 are the filter for the avc. A 3-volt potential exists between the two diodes and a direct current flows through R_1, R_2, and D_2. The avc tap, therefore, is approximately —3 volts potential with respect to ground. This is a permanent negative bias of —3 volts which is applied to the grids of the previous amplifier tubes. So long as not more than 3 volts is developed by the diode across R_1, this bias remains at —3 volts. When, however, stronger signals are placed upon the input to the diode the plate of diode D_2 becomes more negative than the cathode of D_2 and so current ceases to flow in this circuit. The avc lead, therefore, takes the voltage that is produced by the drop across R_1. This negative voltage is applied as bias to the amplifier tubes, in accordance with the signal strengths applied to them.

Thus the amplification of the receiver is at a maximum for weak signals, but varies inversely as the strength of strong signals.

285. Manual volume control. The avc system supplies constant voltage to the detector over a very wide range of incoming signals. Variations in loud speaker volume, therefore, must be controlled by a manual adjustment. This is accomplished by taking more or less of the audio output of the detector and applying it to the a-f amplifier.

Where no avc is available, volume control may be effected in several ways. One is to decrease the gain of the r-f or i-f amplifiers manually by adjusting the bias. Since more bias adjustment is required for the amplifiers near the detector than those near the antenna, some means is usually provided for proportioning the volume control potential inversely with the signal applied to each tube.

Sometimes the bias on the oscillator tube is adjusted at the same time the amplifiers are controlled, either manually or by avc circuits.

CHAPTER XV

RECEIVING SYSTEMS

There are two general types of receiving circuits in use: (1) the tuned r-f receiver, and (2) the superheterodyne. There are other systems such as the simple regenerative circuit of many types, and the super-regenerator in which the circuit is allowed to build up almost to the oscillation point and is then quenched. The simple regenerative set has almost passed out of existence; the super-regenerator has not come into wide use.

286. The tuned radio-frequency set. This type of circuit was once most popular. It suffered from various faults: poor selectivity at high radio frequencies, and excessive selectivity and low gain at the lower frequencies. Until neutralized circuits were developed the t-r-f set was unstable and had low sensitivity. Then the screen-grid tube simplified and improved the t-r-f circuits.

For a time this circuit was not so popular as the super; then the desire for very small inexpensive sets coupled with the development of better tubes and new circuit features brought the t-r-f set back into popularity.

287. The superheterodyne. The double detector or superheterodyne circuit operates on a very interesting principle. The stage gain possible, with stability, at broadcast or higher frequencies is not sufficient to make a really sensitive receiver unless several stages are employed. For a number of reasons much greater amplification can be obtained at lower signal frequencies. If, then, we can change an incoming frequency of, say, 1000 kc to 100 or even 50 kc, we can get as much amplification in two stages as are obtained from four stages at the original frequency. This means simplification in apparatus, and because of the lower frequencies the problems of stability and shielding are also simplified. An additional advantage lies in the constant band width passed by the amplifier, regardless of the frequency of the incoming signal. How is such a frequency change performed?

288. The phenomenon of beats. Suppose two loud speakers are attached to two oscillators, one generating a 1000-cycle tone and the other an 1800-cycle tone. When these two tones enter the ear, the listener hears not only the two individual tones but also an 800-cycle tone. If one of the two original tones is modulated at another frequency, say 50 cycles at a given per cent, this

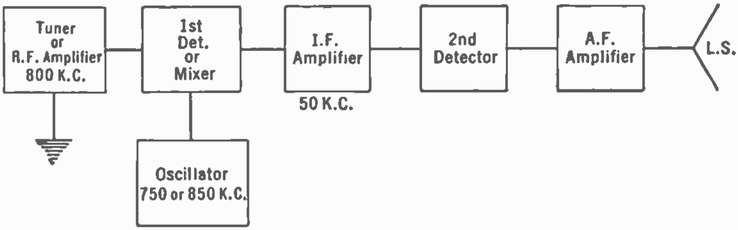


FIG. 214. Symbolic diagram of superheterodyne.

800-cycle tone will be so modulated. By turning this modulated 800-cycle tone into a demodulator, the 50-cycle modulations can be got back.

The two frequencies above are said to **beat** with each other and the difference frequency is called the **beat note.** If the two oscillators are adjusted so that they are at **zero beat** they have the same frequency and no beat note will be heard. In addition to the two beating frequencies and the difference of the two (the difference or beat frequency) there is a third frequency generated. This is the sum of the two beating frequencies. It is called the **sum** frequency. Thus in the above case the ear will hear 1800-, 1000-, 800-, and 2800-cycle tones.

Now suppose we are receiving a 1000-kc signal and want to turn it into a 100-kc signal. All we need is a local oscillator which turns out either 1100-kc or 900-kc signals. We turn these two signals into a mixing tube where the difference or beat frequency is generated, put its output through a filter which cuts off everything but the 100-kc signal (which is now modulated at the same modulations as the incoming 1000-kc signal), and amplify it in an **intermediate-frequency** amplifier. After sufficient amplification has been attained, the 100-kc signal is put through a demodulator and the original microphone modulations secured. These frequencies can be put through an a-f amplifier of conventional design and the output finally put into a loud speaker. The system is shown in Fig. 214.

289. Superheterodyne design. Some superheterodynes use a stage or two of r-f amplification ahead of the frequency changing system; others do not. Some have sufficient amplification so that the input voltages are taken from a small loop; others require an antenna of conventional form and size. Some have one, two, or three stages of intermediate amplification. In some the function of oscillation and frequency mixing goes on in the same tube; in others these functions are separate. Some systems amplify the sum of the two beating frequencies; most of them utilize the difference frequency. Some have high and some low intermediate frequencies. Most use diode detection. Some use air core and some iron core intermediate transformers. And so on. In one receiver of this type the beat frequency was secured from mixing a locally generated second harmonic of the incoming frequency with the signal frequency.

In all double detector receivers, the signals must first be received and usually tuned—whether amplified or not—at the frequency of the incoming signals. Then the mixing with the local oscillator goes on, either in a separate tube—the first detector—or in the oscillator tube, and then the unwanted products consisting of the beating frequencies, etc., are filtered out. There need be no more than two dials, one tuning the input circuit to the incoming signal, the other tuning the oscillator within the required intermediate frequency of the incoming signals. This produces the beat frequency which is passed through the intermediate amplifier.

Modern design has eliminated one of the dials, so that both the tuning process and the adjusting of the oscillator to produce the required difference frequency are controlled by the same dial.

290. Modern superheterodyne practice. This circuit has changed greatly since the days when it first came into popularity. Supers have been made with very few tubes, for example, a frequency changer operating through an interstage transformer directly into the second detector and thence to a pentode output. The antenna circuit gain added to the voltage step-up in the i-f transformer, plus regeneration in both detectors, provides the only amplification. Supers have been built of many tubes, composed of elaborate preselector circuits with or without gain, several i-f stages, diode detection with avc on the frequency changer as well as the r-f and i-f tubes, intercarrier noise suppression and finally audio amplifiers of various sorts.

It is generally believed that a certain amount of selection at radio frequencies must take place before the frequency is changed. This lowers the noise compared with the signal by narrowing the band of frequencies that are admitted to the receiver. This preselection may take the form of tuned circuits without tubes and, therefore, with little or no voltage gain. Then comes the first detector, and parallel to it, or perhaps in the same tube, is the oscillator. This is followed by two interstage transformers with a tube between, sometimes two tubes and another transformer and then the demodulation process and a-f amplifier.

Considerable use has been made of antenna coils in which the primary has a high inductance tending to resonate the system to a frequency below the lowest radio frequency to be received. This brings up the sensitivity of the receiver at the lower end of the tuning range and flattens out the reception characteristic.

Radio-frequency coils are usually made of Litz wire to sharpen these preselecting circuits. The intermediate stages are sometimes of Litz, but in general more than sufficient selectivity is obtainable at intermediate frequencies with solid wire coils. Oscillator circuits have been worked out which give uniform output over the tunable range. The i-f coils are often tuned both on the primary and secondary sides in an effort to broaden the top of the response and not cut high frequencies too much.

291. Superheterodyne troubles. Early receivers suffered from many faults. Getting a given station at more than two points on the tuning dial was one of these faults.

Suppose that the beat or intermediate frequency is 50 kc and that a station on 600 kc is to be received. Now the oscillator can be set at either 600 plus or 600 minus 50 kc to produce the required beat frequency which will carry with it the modulation into the i-f amplifier. Therefore, the operator can tune in the desired station at two points on his oscillator dial.

This trouble is avoided by tuning the input to the set at the same time that the oscillator is tuned.

It is general practice to make the oscillator generate frequencies higher than the incoming frequency. Thus if the intermediate frequency is 50 kc the range will be from 550 plus 50 kc to 1600 plus 50 kc and the oscillator will tune from 600 kc to 1650 kc at the same time that the input circuits are tuned from 550 to 1600 kc. This covers the broadcast band.

As a typical example suppose that an 800-kc station is to be received. The input will be tuned to this frequency; the oscillator to 850 kc. But if the input is tuned to 700 kc and the oscillator to 750 kc the required difference of 50 kc will exist between the 800-kc station and the local oscillator. Therefore, unless the input circuits are sharply tuned so that the station will produce little voltage when the set is tuned 100 kc away from the station, trouble will exist with repeat points.

Furthermore, consider the set tuned to 800 kc and oscillator to 850 kc. Now suppose a local station to be operating on 900 kc. Between this undesired station and the oscillator will be a 50-kc difference, and unless there is sufficient selectivity in the input both stations will be heard. This is called "image-frequency" trouble.

There is still another cause for difficulty. If the oscillator generates harmonics, they may heterodyne a higher frequency incoming signal for the following reason. Suppose the oscillator is set at 600 kc but generates a strong second harmonic, 1200 kc. This harmonic will provide the proper 50-kc beat note with either a 1150- or a 1250-kc station at the same time the fundamental heterodynes a 550 or 650 station. Such harmonics can be reduced by making the oscillations feeble, by reducing the plate voltage or by placing a large resistance in the plate circuit to make its characteristic straight, or by giving the grid the proper bias.

Let us suppose, however, that the beat frequency is 600 kc. The oscillator frequency range must be from 550 plus 600, or 1150 kc, to 1600 plus 600 or 2200 kc, and there will be no repeat points due to heterodyning two incoming signals to give the required 600-kc beat frequency.

The use of an r-f amplifier ahead of the frequency changer will provide considerable discrimination against unwanted stations. It must be tuned to the required station at the same time the oscillator is tuned so that it gives the required beat frequency. Increased selectivity in the r-f amplifier will provide selectivity not only against image frequencies, but also against stations differing from the desired station by the intermediate frequency, and will add something to the "adjacent channel" selectivity which is largely secured from the i-f amplifier.

Thus it has become standard practice to use one or more stages of tuned radio frequency ahead of the frequency changer in high-class supers. There are still other sources of interference, for example harmonics of the oscillator heterodyning undesired stations or harmonics generated in the second detector.

292. Choice of intermediate frequency. When preceded by some preselection, the chance of image-frequency trouble decreases as the intermediate frequency increases. At the same time the chance of trouble from stations separated from the desired station by the intermediate frequency is decreased. For these reasons it is desirable to have a high intermediate frequency.

With a low intermediate frequency the chances of harmonic troubles due to energy from the second detector getting back to the input of the set are lessened because only the higher and weaker harmonics would fall in the broadcast band. At the same time, lower frequencies are amplified better in the i-f amplifier.

And, finally, more selectivity against adjacent channels can be obtained if the intermediate frequency is low.

All manner of beat frequencies are used, going from 175 kc to several hundred kilocycles, depending upon the manufacturer, the type of set, the input frequencies to be received, etc. It has become almost standard practice to use intermediate frequencies in the vicinity of 456 kc for home radio receivers.

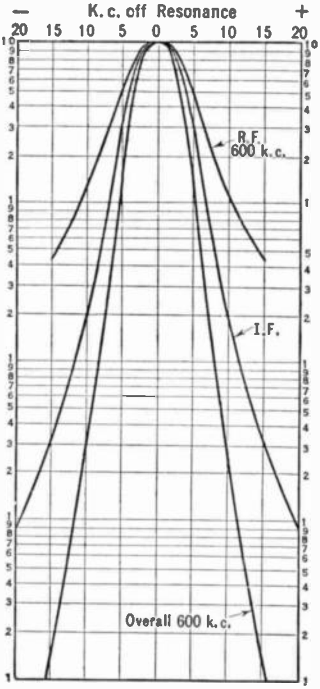


FIG. 215. Response of modern superheterodyne. Note that the paper on which this is plotted is logarithmic, that is, each vertical series of ten lines represents values ten times greater than the series immediately below it. Thus, the over-all 600-kc line indicates that there is ten thousand times the response at resonance than there is 15 kc off resonance.

Problem 1–15. A broadcast receiver is to cover the band from 1600 to 550 kc. If the oscillator is tuned higher than the input circuit so that a beat frequency of 456 kc is produced, what must be the frequency band of the oscillator? Suppose that identical inductances are used in the tuned circuits and that the maximum capacity of the input circuit tuning condenser is 250 $\mu\mu$f. What will be the approximate maximum value of the oscillator tuning condenser?

Problem 2–15. The intermediate frequency is 456 kc in an all-wave receiver. What frequency band must the oscillator cover if one of the short-wave bands tunes from 4.5 to 12 Mc?

Problem 3–15. Using an intermediate frequency of 600 kc find from Fig. 215 how much loss in voltage would be sustained at the output of the i-f amplifier if the oscillator drifted in frequency so that the input to the i-f amplifier were 595 kc, and if there were no avc in the receiver.

293. Selectivity of superheterodynes. The curves in Fig. 215 show the degree of selectivity obtained in the r-f and the i-f systems of a good super. It will be noted that the selectivity gained in the i-f amplifier is greater than that secured at the incoming frequency, because 10 kc is a small part of the incoming frequency; but it differs by quite an amount from the intermediate frequency. The image-frequency ratio of high-class sets is about 20,000 to 1. This is the voltage required to produce the same output as the desired signal but differing from it by twice the intermediate frequency.

294. Frequency changers. Any tuned r-f receiver can be converted into a superheterodyne by the addition of an oscillator and a mixing tube. In such a system the r-f amplifier is used as the i-f amplifier, and is set to give maximum amplification at some fixed frequency within the broadcasting band. Then the oscillator beats with the incoming signals so that this frequency is generated and the signals are finally detected in normal manner.

295. Frequency conversion. The great virtues of the superheterodyne are several. Simplicity of tuning (since the r-f amplifier tuning system can be very simple) is one of these advantages. The i-f amplifier, tuned to a single frequency, and not tuned over the whole broadcast band, is another advantage. Most of the amplification can be attained in the i-f amplifier, since it can be made much more stable than an amplifier that must be tuned over a wide band. Since the frequency of the i-f circuits is somewhat lower than that of the r-f circuits, the superheterodyne can produce somewhat greater selectivity.

The process demands a change in frequency from the input which may be at any conceivable frequency within the r-f spectrum, to a fixed single frequency which is passed by the i-f amplifier. This change in frequency is called **frequency conversion,** and there are several methods by which it is accomplished.

Before special tubes were available for frequency conversion, a triode or more complex tube was used for a *mixer* tube. In this tube two frequencies were impressed on the grid, one frequency corresponding to that of the desired incoming signal and the other frequency was that generated by the local oscillator. These two signals were introduced into the mixer tube in various ways, as by inductances or capacities, and, as a matter of fact, could be introduced in any of the methods by which one frequency is modulated by another.

In the mixer tube, the two frequencies beat together, producing the sum and the difference frequencies whose values are determined by adding or subtracting the individual component frequencies. The output of the mixer was tuned, usually, to the difference frequency and this was the intermediate frequency. It bore the audio modulations of the incoming signal.

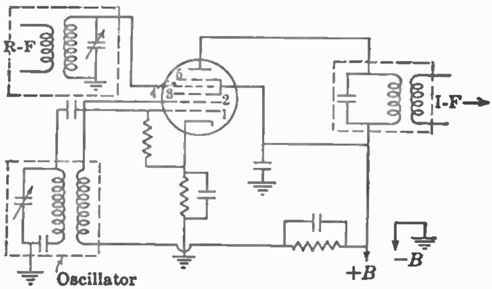


Fig. 216. Pentagrid converter circuit for frequency changing.

In a more elegant method, the two frequencies were coupled by means of an electron stream. In the pentagrid-converter tubes (like the 6A8) there are five grids, a cathode and an anode. With these seven electrodes, all the functions of oscillation and frequency mixing take place. A typical circuit is shown in Fig. 216. Grids 1 and 2 and the cathode form a triode oscillator with external connections to inductances, etc. Grid 2 acts as the anode of this oscillator. Because of the open mesh of this anode, electrons shoot on through it to the remainder of the tube. This anode plus the cathode of the tube can be looked upon as a "virtual" cathode, supplying an electron stream for the remainder of the tube. This stream varies at oscillator frequency.

Grid 3 is a positive screen like that in any screen-grid tube. Grid 4 is connected to the signal input and its voltage varies at the frequency of this input signal. As the electron stream flows past grid 4 (which is already modulated at oscillator frequency) it gets its second modulation from grid 4. The final grid is a continuation of grid 3 or the screen grid and is followed by the anode which collects the doubly modulated electron stream. The screen grid hurries on the electrons by its positive potential and at the same time acts as a screen to prevent unwanted electrons from getting to grid 4.

A good example of the tube designers' ingenuity is evidenced by a modification of this type of tube. In the 6A8 tube and circuit, good frequency conversion takes place up to moderately high frequencies, but as the frequency rises, the performance decreases because of two principal reasons. In the first place, the output of the oscillator falls off at the higher frequencies, and in the second place, there are certain unavoidable couplings between the oscillator and the signal frequency sections. These couplings increase as the frequency increases.

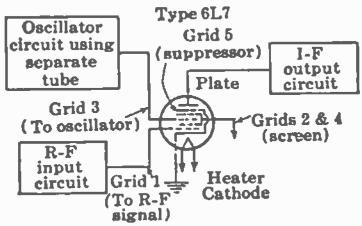


FIG. 217. Mixer tube and circuit useful at high frequencies.

In tubes like the 1R5 and the 6SA7 these faults are overcome. Here the grid 1 is the oscillator grid. The second grid is connected inside the tube to grid 4 and acts as anode for the oscillator, but at the same time as shield or screen to protect the signal grid (3). Grid 5 acts as suppressor. In these tubes the space charge around the cathode is unaffected by electrons from the signal grid or by the electrostatic field of this grid. Thus r-f voltage on the signal grid has little or no effect upon the cathode current, and, therefore, changes in avc bias have little effect upon the oscillator transconductance or the capacitance of the grid 1. The effect is an increased freedom from troubles due to oscillator detuning by variations in avc voltage.

In the 6K8 still another tube structure is employed in which the oscillator grid is connected to grid 1 of a hexode mixer arrangement of electrodes. The functioning of the tube is not critical with respect to changes in oscillator plate voltage or signal grid bias. It is used in all-wave receivers where it is important to reduce frequency shift at the higher signal frequencies.

Another mixer tube is especially good at high frequencies. This is the 6L7 and requires a separate oscillator tube. The 6L7 has two control grids, 1 and 3. The first is a remote cut-off type and the second a sharp cut-off. Incoming signal voltages are applied to grid 1 and oscillator voltages to grid 3. Grids 2 and 4 are connected and act as shield for 3 and at the same time accelerate the electrons. The final grid 5 is a suppressor. The 6L7 is known as a pentagrid-mixer tube.

The translation gain of circuits using the pentagrid converter, like the 1A6 is of the order of 40. This is a term describing the gain in converting radio frequency into intermediate frequency. Thus a microvolt of radio frequency energy put into the frequency changer becomes 40 μv of intermediate frequency in the output.

296. "Short-wave" receivers. The majority of the traffic carried on in the higher frequency bands, from 1500 to 15,000 kc, is in code and it is not necessary to transmit a very wide range of frequencies to convey good signals.

Older short-wave receivers for code reception consist of an "autodyne" detector, that is, a tube which is generating oscillations and at the same time acting as a detector. The signal generated by the tube differs in frequency from the incoming signal by about 1000 cycles. The plate circuit has a low impedance to both the locally generated and the incoming frequency but a high impedance to the 1000-cycle note which is amplified by an ordinary audio amplifier and then passed into a pair of headphones. Frequently, one or more screen-grid tubes are used between the detector and the antenna, to provide somewhat greater amplification, to prevent interaction between antenna and detector, and to prevent oscillations in the detector circuit from getting into the antenna and being radiated from it.

Of course, it is possible to make the beat frequency between the detector oscillation and the incoming signal some intermediate frequency and to pass it into an i-f amplifier. Many of the short-wave "adapters" consist of such apparatus. The i-f amplifier can be the usual r-f amplifier from a broadcast receiver. To receive short-wave signals on a super designed for broadcast frequencies, it is only necessary to have a second input circuit, or taps on the broadcast input circuit, to make it tune to shorter wavelengths.

297. Short-wave receiver circuits. Although the detector which oscillates while it detects may be fed directly from the

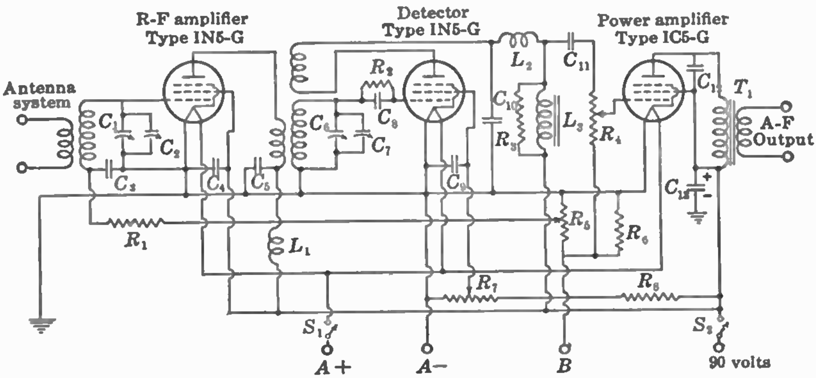


FIG. 218. Typical short-wave receiver using one stage of r-f amplification and a regenerative detector.

antenna circuit, it is better practice to use a stage of amplification between it and the antenna. Such a circuit may be seen in Fig. 218. The amplifier is conventional. Note that the transformer between the output of this tube and the input to the second or detector tube has an extra winding on it and that this winding is connected to the plate circuit of the detector. This winding, known as a "tickler" is to feed back from the output a small amount of voltage into the input where it is amplified again and in phase with the input from the r-f amplifier to reappear in the output as a stronger signal.

This is controlled regeneration and the purpose is to get stronger signals. If enough feedback is employed the detector tube begins to oscillate, that is, to generate signals all by itself which may be added to the input signals. If the frequency at which the detector is oscillating is slightly different from the frequency of the incoming signals, the headphones will cause this beat note to be audible to the listener. Thus the tube is performing the same function as the combined oscillator-mixer tube in a superheterodyne but for a different purpose. The beat frequency is audible, say 1000 cycles, instead of having a much higher frequency such as is employed in superheterodynes.

There are numerous ways in which this useful trick of adding regeneration may be employed. They all, however, must permit some of the output of the tube to be fed back into the input of the tube. In this case the amount of regeneration is controlled by varying the voltage on the screen grid. Other methods involve varying the coupling between the input coil and the tickler, or varying the amount of feedback voltage in the tickler by a resistance adjustment.

Modern communications receivers, tuning over the very wide spectrum covered by the "short waves," are as complex as modern all-wave broadcast receivers. They contain separate beat-frequency oscillator tubes which may be used or turned off at the wish of the operator, they may contain quartz crystal filters which are exceedingly sharp and so limit the band width accepted by the receiver that interference is reduced, they employ avc, high-gain amplifiers, etc.

298. All-wave receivers. Most modern home radio receivers will tune to frequencies outside the standard broadcast band, and many of them will cover the entire frequency spectrum from 60 megacycles to 1600 kc (5 meters up). These are called "all-wave" receivers although many of them skip certain regions of the spectrum and concentrate on the bands in which broadcasting takes place.

The all-wave receiver started modestly. A few manufacturers discovered that the public liked to listen to police reports which took place in the frequency band adjacent to the highest broadcast frequency. It was a simple matter to extend the tuning range of the receiver so that the police band could be heard comfortably. This required only minor modifications in the receivers, but the next step, that of really extending the receiver range to cover the higher and higher frequencies, was not too successful until some real engineering effort was expended upon the problem.

From powerful stations in Europe and South America it is now possible to receive good steady signals in the United States and Canada. Antennas erected in clear areas, away from sources of man-made noise, will bring in these programs better than antennas contending with noise, as in the city. The most important wave bands are situated near 49, 31, 25, and 19 meters, but other broadcast stations can be picked up on other frequencies and most interesting programs (and much propaganda) can be found in the ether by one who learns how to operate an all-wave receiver.

All-wave receivers introduced new problems in engineering. It is not possible to tune a given coil over a band much wider than three to one in frequency range. Therefore it became necessary to use more than one set of coils for each r-f and oscillator stage. Many arrangements were perfected for switching the tubes to these various sets of coils which were connected in series, at times, and at other times and in different sets, in parallel. The beautiful switches, with low losses and short leads, developed by component parts manufacturers, were one of the important factors making all-wave receivers possible.

Such receivers have been a gradual development. If a manufacturer had requested his engineering department to build a receiver covering the band from 60 megacycles to 550 kc the first year the idea took hold, he would have requested the near impossible. The set would probably have had little amplification at the higher frequencies and still less selectivity. It would probably have oscillated or been unstable.

Choice of intermediate frequency is now related to the all-wave problem, because a low intermediate frequency will not provide selectivity at the higher incoming frequencies even if it were satisfactory at the broadcast wavelengths. The antenna to be used on an all-wave set enters into the problem, especially because the signal coming from a station 3000 miles away is weak compared with the signals nowadays expected from broadcast stations. Furthermore, the power of these short-wave broadcast stations may be low compared with the broadcast band stations.

Thus the manufacturers encouraged users to install antennas especially engineered to be receptive to the short waves and at the same time discriminative against local forms of man-made interference. In general, these antennas are made resonant or partially resonant to the desired short-wave bands and by complicated switching systems they are changed in their resonance

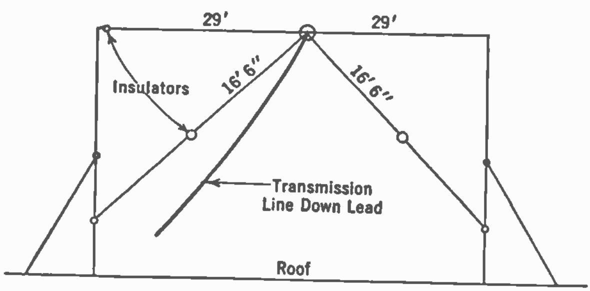


FIG. 219. Special form of antenna for reception on the short-wave broadcast bands.

characteristics as the listener adjusts his receiver to cover the several bands. This switching now takes place at the same time the various sets of coils are chosen.

It has been found that much of the noise that enters into radio receivers from the outside does so by virtue of the ground lead. Noise is brought near this down lead by electric light wires which enter the house after being exposed to all sorts of interferences. Thus if the ground lead can be kept clean of noise, the signal-to-noise ratio will be better. One way to do this is to have a very short ground lead. Suppose the antenna in the back yard consists of a vertical mast insulated from ground. Now secure good ground connection at this point and bring both ground and antenna leads to the set, after going through a matching transformer, through an underground conduit.

299. Long-wave receivers. Although a simple long-wave receiver may use an autodyne detector a better scheme is to use a separate oscillator and to beat the output from it with the incoming signal. In an autodyne the detector-oscillator is actually detuned from the frequency of the desired station. For this reason there is a loss in signal strength. The separate oscillator makes it possible to tune the detector to the exact frequency of the desired signal.

When listening to long-wave stations for the first time on such simple receivers, one is struck by the fact that many stations are heard at the same time. The reason is as follows: These stations operate on the frequency band from 10,000 to 20,000 meters or from 15 to 30 kc. When a receiver is tuned to a 20-kc station, it is detuned only 1000 cycles—an audible amount—from a 21-kc station, only 2000 cycles from a 22-kc station, and so on. If the operator tunes to the 10,000-meter—30 kc—station he is only detuned by 15 kc, an audible amount, from the station allotted the channel at the extreme other end of the band.

TABLE 1

Number of Turns	Inductance at 800 Cycles in Millihenries	Natural Wavelength in Meters	Distributed Capacity in $\mu\mu f$	Wavelength Range in Meters	
				0.0005-μf condenser	0.001-μf condenser
25	0.039	65	30	120 to 245	120 to 355
35	0.0717	92	33	160 to 335	160 to 480
50	0.149	128	31	220 to 485	220 to 690
75	0.325	172	26	340 to 715	340 to 1,020
100	0.555	218	24	430 to 930	430 to 1,330
150	1.30	282	17	680 to 1,410	680 to 2,060
200	2.31	358	16	900 to 1,880	900 to 2,700
249	3.67	442	15	1,100 to 2,370	1,000 to 3,410
300	5.35	535	17	1,400 to 2,870	1,400 to 4,120
400	9.62	656	13	1,800 to 3,830	1,800 to 5,500
500	15.5	836	13	2,300 to 4,870	2,300 to 2,000
600	21.6	1045	14	2,800 to 5,700	2,800 tc 8,200
750	34.2	1300	14	3,500 to 7,200	3,500 to 10,400
1000	61	1700	13	4,700 to 9,600	4,700 to 13,800
1250	102.5	2010	11	6,000 to 12,500	6,000 to 18,000
1500	155	2710	13	7,500 to 15,400	7,500 to 22,100

In commercial receiving stations the signals are tuned and filtered so that a very narrow band is passed, about 200 cycles. In this manner stations can be separated. All the long-wave stations in the world are in this limited band, and, of course, any station can be heard in any other part of the world.

The coils frequently used in receiving high-power long-wave stations are commonly known as "honeycomb" coils and are highly concentrated multilayer inductances. A table showing the wavelengths to be received with certain sizes of coils is given on page 405.

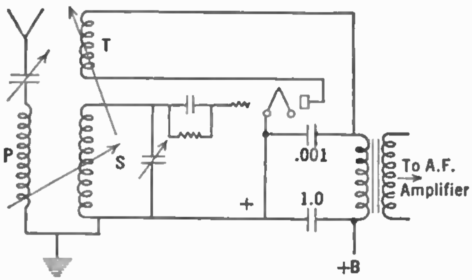


FIG 220. The beat note in a code receiver may be obtained in the "autodyne" manner, in which the detector is detuned from the incoming signal.

Experiment 1-15. Connect three honeycomb coils as shown in Fig. 220 making *S* a 1500-turn coil, *P* about 1000-turn, and *T* about 750-turn. The tuning condenser can be either 500 or 1000 $\mu\mu$f, preferably the latter. Connect an antenna as long as possible to the 750-turn coil and listen in the plate circuit. It may be necessary to reverse the connections to the coil *T* in order to make the tube oscillate. It should be possible to hear many long-wave stations transmitting traffic to foreign countries. The phenomenon of zero beat is beautifully illustrated by such an experiment.

Although the long-wave stations are important in transmitting part of the world's transoceanic telegraph traffic, the short-wave stations have taken over the big burden of handling the many thousands of words per day that go across the oceans.

300. Detuning loss in autodynes. Some loss in signal strength is experienced in autodynes because the detector is actually detuned from the incoming signal. At high frequencies where such a system is frequently used, the detuning is not serious. Thus at 30 meters, 10,000 kc, a deviation of 1000 cycles is only 0.01 per cent. At the longer waves, however, detuning only 1000 cycles to get an audible beat note represents an appreciable loss. Thus at 20,000 meters, 15 kc, a detuning of 1000 cycles represents a detuning of over 6 per cent. The use of a separate oscillator, as in Fig. 221, will prevent this loss.

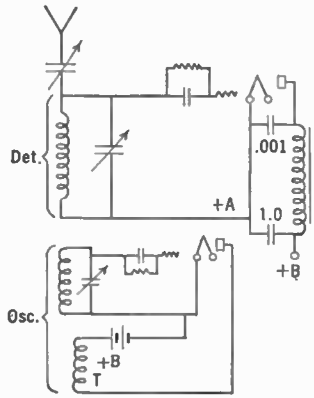


FIG. 221. Use of separate oscillator in a code receiver enables detector to be in tune with desired signals.

Problem 4-15. The following voltages were measured across a 600-turn honeycomb coil when it was tuned to 40 kc and the input frequency was changed. How much loss in signal strength would be incurred if the coil and condenser were used in an autodyne detector and detuned from 40 kc so that a 1000-cycle beat note was secured? Plot the curve of voltage against frequency and note the loss from it.

TABLE II

Frequency	Voltage	Frequency	Voltage
38.0 kc	0.4	40.0 kc	2.5
38.5	0.65	40.5	1.75
39.0	1.05	41.0	0.95
39.5	1.75	41.5	0.55

301. Poor quality on long waves. It is much more difficult to transmit or receive high-quality music or speech on the longer waves. Suppose the transmitter is tuned to 10,000 meters, 30 kc. The band transmitted must be 10 kc wide or 30 per cent. At broadcast frequencies, however, the band passed is only 10,000 cycles in a mean frequency of 1000 kc or 1.0 per cent. This means that very broad circuits must be used at intermediate or low radio frequencies, which in turn means poorly selective circuits.

302. Band-pass amplifiers. The ideal response characteristic of a receiver would be a flat top with very steep sides. The flat top should be approximately 10,000 cycles wide, or more, and the

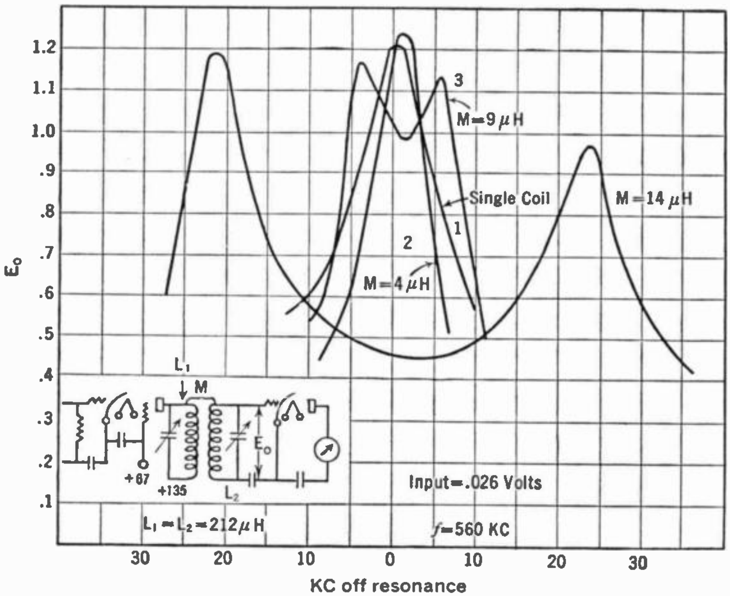


FIG. 222. Experimental determination of effect of close coupling in band-pass filter at high frequencies.

sharper the sides the more selective would be the receiver without cutting off the higher modulation frequencies. An amplifier with such a characteristic may be said to be a "band-pass" amplifier, meaning that it passes and amplifies a band of frequencies and rejects all falling either above or below that band. Numerous attempts have been made to accomplish this effect.

By the use of coupled circuits it is possible to approach the ideal. Thus in Fig. 222 if both coils are individually tuned to the same frequency, and then coupled together, the resultant response characteristics may be a single narrow-topped curve, like that of a single tuned circuit, or a flat-topped curve, or a curve of two more or less widely separated peaks with a hollow between, depending upon the degree to which the circuits are coupled.

In Fig. 222 is given the result of coupling two such circuits together with various degrees of coupling. It will be seen that too close coupling gives the widely separated peaks, proper coupling gives a comparatively flat-topped characteristic, and too loose coupling gives a sharply tuned circuit, cutting side bands as badly as a single circuit. In a multi-stage circuit, one might use

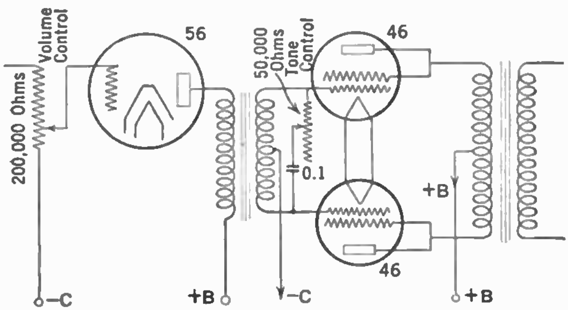


FIG. 223. Tone control across input to power amplifier.

a combination of two coupled circuits, one like 3 and the other like 1 or 2 in Fig. 222. The over-all effect would be better than one alone.

Superheterodynes now use such a band-pass circuit in the i-f amplifier. Here the frequency is fixed, and one adjustment will do for all signals put into it. When the band-pass arrangement is used at broadcast frequencies, the width of band passed may differ at each frequency to be received. If the coupling is by inductance the band will be broad at the high frequencies; if the coupling is capacitive, the curve will be broad at low frequencies. Some combination may be arranged so that a more or less uniform band is passed at all broadcast frequencies.

303. Tone control. Manual control of the tone emitted by the loud speaker is incorporated in many receivers. This consists, usually, in a resistance in series with a capacity and the combination shunted across some part of the audio amplifier. The capacity shunts out the higher audio tones; the resistance, which is the variable feature, increases or decreases this shunting effect. In other words, the usual tone control is nothing but a device to eliminate high notes.

304. Automatic tone control. When static is bad, as when receiving a weak station, cutting out the higher audio notes is advantageous. Often a program that is hopelessly lost in noise can be received with a certain amount of pleasure if the tone control is advanced to the point where little beyond 2000 cycles is received.

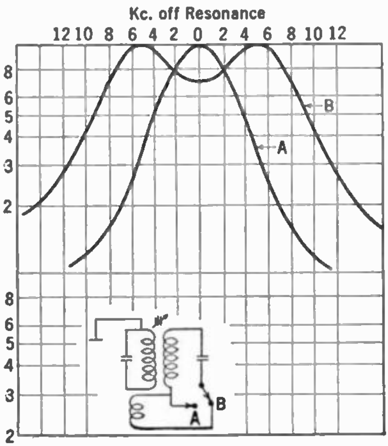


FIG. 224. Selectivity curve for two-position i-f transformer.

Circuits have been devised which give some measure of automatic tone control. Thus when the receiver r-f gain is low, as it would be if receiving a strong station, or local, the tone-control function is not in operation. Then as weaker and weaker stations are tuned in, this tone-control function, which is connected with the avc system, cuts off more and more of the high frequencies. In certain circuits this function is inherent; in others, an additional tube acting as a variable resistance or reactance is employed.

To date (1942) such circuits have not come into general use. Automatic selectivity control (asc) circuits which make the set less selective when receiving strong signals and more selective on weak signals will probably be incorporated in receivers ultimately. The circuit in Fig. 224 is one method of overcoupling an interstage transformer for the purpose of broadening the tuning so that higher audio frequencies can be heard. A simple switch connects or removes the additional coupling inductance.

305. Measurements on radio receivers. It is now possible to make very comprehensive and thoroughly quantitative tests on radio receivers, either as a whole or upon the component parts. Such tests consist in measuring what comes out of a receiver when known voltages at known frequencies modulated at known percentages are placed on the antenna-ground binding posts of the receiver.

The voltage on the antenna-ground posts is secured in several ways. Some laboratories use an artificial or "dummy" antenna consisting of concentrated capacity and inductance and resistance of such values that they simulate the antenna-ground system ordinarily used. Values used in some laboratories are: inductance 200 μh, capacity 200 $\mu\mu$f, and resistance 25 ohms. Other laboratories use a coupling coil into which the desired voltage is induced, and others take the voltage drop across a known resistance which is in series with the artificial antenna. If comparative measurements and not absolute are required, the output from the receiver when it is attached to an antenna of the usual type can be employed. Of two receivers the one which gives more output from a given station on a given antenna has the greater over-all amplification. A crystal rectifier and meter will measure output.

The load into which the output of the receiver is measured is usually a non-inductive resistance and the voltage required to deliver 0.5 watts has been used as a measure of the sensitivity of the receiver. Sometimes a loud speaker is placed across the receiver output and the current into it and voltage across it are measured with given input voltages and at various frequencies. These volt-amperes plotted against input frequency or against input modulating frequency give an indication of the over-all voltage amplification as well as the over-all fidelity characteristics of the receiver. A calibrated microphone may be used to pick up the output of the receiver so that a curve of acoustic output versus volts input or versus frequency can be plotted.

For receiver measurements some means must be provided for furnishing known amounts of r-f voltages. Since the modern radio receiver has a very high voltage and power amplification, these voltages must be very small when it is desired to measure the over-all characteristic or performance. It is desirable to have a known voltage at least as low as 1 μv, and anyone who has worked intimately with r-f voltages—at one million cycles, for example—knows how difficult it is to know when one has an emf of this order or a current of one-millionth of an ampere. The laboratory worker must know how much current or voltage he

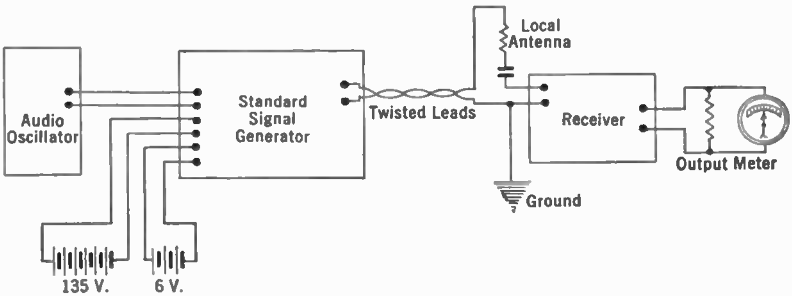


FIG. 225. Circuit diagram and method of using signal generator.

has, and he must be certain that his meter shows all the current or voltage, no more and no less.

The "signal generator" is the device used by laboratory workers to supply known voltages, say from 1 to 20,000 μv, at known frequencies, say from 500 to 1600 kc, for test purposes. It consists in a shielded oscillator with means for utilizing all or a known part of its output voltage.

306. Receiver performance. Graphical data taken on sixty-four superheterodynes are summarized in Fig. 226. The curves give the characteristic of the least, the most selective, and the average selectivity. These curves do not indicate such selective sets as were obtainable before the midget became so popular. Voltage gain in i-f amplifiers in these years was of the order of 15,000 to 30,000 for three transformers and two tubes and 5000 for one tube with two transformers.

Screen-grid tubes have made possible receivers with fewer tubes, greater sensitivity, greater selectivity, and better fidelity. The total amplification in a high-class set is tremendous. Only at rare intervals and in few localities is it possible to utilize any appreciable proportion of this amplification.

The rapid development of small sets in 1933 resulted in some decrease in average selectivity and somewhat better transmissal of high audio frequencies.

307. Noise suppressor systems. In an avc receiver the sensitivity is at maximum when no signal is being received, for example, between carrier signals. Therefore, any static or other radio noise will be amplified to the limit of the circuit and be passed to the loud speaker. Circuits have been developed which shut off this noise. They operate in various ways. For example, a tube may be so connected that its plate current will be high in absence of signal. This plate current can be used to supply bias voltage to the a-f systems. Absence of signal thus will over-bias the audio amplifier preventing any sound coming from it.

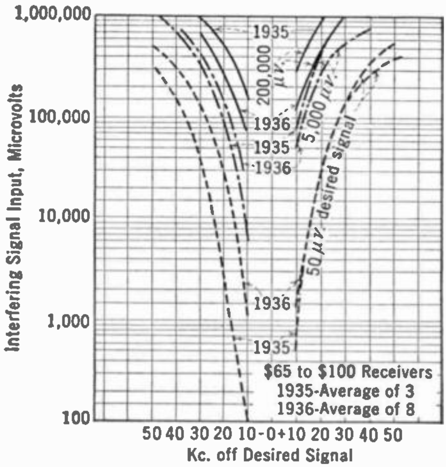


FIG. 226. Selectivity curves of 1935 and 1936 superheterodynes.

308. Automatic frequency control. Another automatic feature which has been incorporated into modern receivers is that of maintaining the oscillator frequency accurately at the desired value. The frequency at which an oscillator functions is dependent upon several variables: one of them, the voltage on the plate;

another, the capacity of the input (grid to cathode). If, after a receiver is tuned to the desired station, these values should change, because of temperature or line voltage variations, or any other cause, the oscillator would not be tuned to the frequency which would provide the required intermediate frequency.

Furthermore, in a highly selective superheterodyne with several tuned stages, the difficulty of accurately tuning it is very

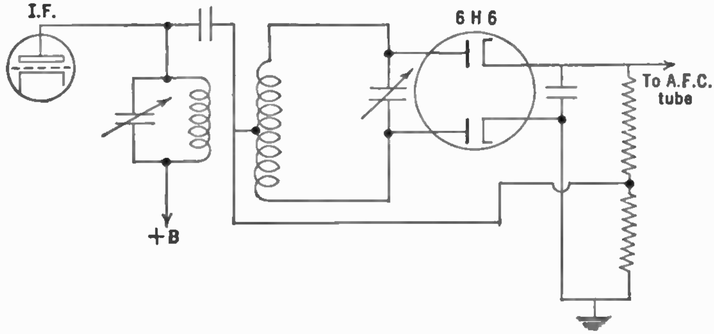


FIG. 227. Discriminator circuit for afc. This circuit is also used in converting f-m signals to a-m signals.

real. When tuned off resonance with the desired signal, bad quality results.

309. How afc works. A fundamental circuit for an afc system is shown in Fig. 227. Here is an i-f transformer, primary and secondary tuned to the same frequency, secondary connected to two diodes. Positive or negative voltages are obtained from the diodes, depending upon whether the receiver is tuned above or below resonance. These voltages of opposite sign are connected to a control tube as a bias and have the ability to change the capacity of a condenser up or down from some mean value through this control tube.

This variable capacity is shunted across the tuned circuit of the oscillator in the frequency-changing system of the superheterodyne. Thus when the oscillator tends to drift in frequency, the afc network begins to function and forces the oscillator to generate the correct frequency.

Furthermore, when the listener has tuned his receiver to the vicinity of resonance with the incoming signal, the afc system takes hold and forces the oscillator to generate the correct frequency to be amplified by the i-f amplifier.

This was a splendid development and worked successfully. It required more tubes and more apparatus, however, and receiver manufacturers shied away from adopting the system as standard. The virtues of receivers which do not go out of tune were made evident, however, and soon components manufacturers began to improve their condensers and coils so that shifting of frequency with time or temperature variations was greatly reduced.

310. Shielding. In any high-gain amplifier it is necessary to prevent any source of high energy from being coupled in any way to a point of low energy. For example, if the plate lead of a tube near the detector feeds voltage by coupling of any sort to the grid lead of a previous tube, regeneration and instability will result.

Proper filtering by series resistance and shunt capacity of all plate, grid, and screen voltages will aid in keeping r-f or i-f currents where they belong. All inductances must be shielded; often grid wires are run in shielded wire.

Now placing a coil in a metal box seems like a simple trick to keep the lines of force from that coil from becoming mixed with lines of force from another coil. But the size of the metal box, its material, the size of the coil, whether or not the metal box is grounded, and to what, and whether it carries current or not—all these things enter into the problem of shielding.

The subtraction of energy from the tuned circuit by the shield has the same effect as though the resistance of the tuned circuit were increased. In other words, if currents are induced in the shield, the effective resistance of the coil is increased, its selectivity factor goes down, the voltage gain due the coil and condenser is decreased. It is also true that the inductance of the coil decreases too, so that the value of effective resistance, $L^2\omega^2/r$, or Q, is greatly decreased. The nearer the coil is to the shield, and the greater the resistance of the shield, the greater is the power loss in it.

The shield should never carry current. It should be heavy and should be made from the best conductor possible, and all joints in it should be carefully soldered. It should be connected at only one point to a heavy conductor leading to the common ground of the set. Holes in it for leading-in or leading-out wires should be small.

From the electrical standpoint, copper is better than brass or aluminum, but it is handicapped from the standpoint of weight and cost per pound.

Each stage must be separated from the others and separately shielded. Even the individual sections of the gang-tuning condenser are often shielded from each other by means of baffle plates mounted on the condensers. Some coils are separated from other coils by being placed beneath a steel chassis whereas the others are mounted on top of the chassis. Metal-clad tubes aid shielding materially.

311. Push-button receivers. Three types of the push-button tuning system have been applied to receivers, one or the other of which is now found on most of the automobile sets and on many home receivers as well. The advantages are, of course, simplicity, quietness, and speed of tuning from one station to another.

In one system, individually tuned circuits are provided for each push button. These circuits are tuned to the desired stations by variations in capacity or inductance. This tuning may be effected by a service man or the owner by simple screwdriver adjustments. The push buttons are mechanically connected to switches which select the required tuned circuits. The number of stations that can be tuned in is limited and depends upon the number of push buttons provided.

In a second system, the gang-tuning condenser may be rotated throughout its range by means of the conventional dial. In addition, cams are attached to the condenser shaft so that when a push button is depressed the shaft is rotated to the proper position to get the desired station. The position on the shaft of these cams may be changed easily.

In a third system an electric motor is utilized to turn the condenser shaft. This method is more expensive and more likely to get out of order but it permits remote control and has the advantage that any desired channel may be selected.

None of these systems would work well without the development of stable components or without automatic frequency control. The trend is toward the use of components, i.e., condensers and inductances, which do not vary in their electrical characteristics with time or temperature or humidity.

312. Tuning indicators. Highly selective receivers must be correctly tuned. Otherwise severe distortion results. Early examples of receivers of this type utilized d-c milliammeters with various kinds of indicating needles to advise the operator when the receiver was tuned to the exact center of the pass band. The current for operating these indicators was obtained from the avc system, the greatest amount of avc voltage being obtained when the receiver was tuned to the center of the i-f band.

Introduction of the electron-ray tubes simplified the tuning indication problem. These tubes indicate visually the condition of correct tuning by means of a fluorescent target which is bombarded with electrons and which glows when so bombarded. There are several types but each depends upon the same fundamental principle. Between the cathode (source of electrons) and the fluorescent target is a ray-control electrode. Variations in voltage on this electrode control the flow of electrons to the target and therefore control the amount of the target that glows.

In one tube, such as the 6N5, there is a triode in addition to the ray tube. The triode acts as a d-c amplifier. The grid of this tube is supplied with voltage from the avc system. In Fig. 228 the flow of plate current, under control of the voltages supplied to the grid of the triode through the resistor R, fixes the voltage of the control electrode of the indicator tube. When the voltage of this electrode decreases, less of the target is illuminated. When more plate current flows from the triode through R the voltage drop in R increases and there is less voltage on the control electrode of the indicator tube. The shadow on the target increases. When the triode grid is more negative, less plate current flows, more voltage is across the electron-ray tube and the target becomes brighter.

In another tube of this general type there is no triode amplifier but there are two control electrodes, one on either side of the cathode, and both are brought out to base terminals. Thus,

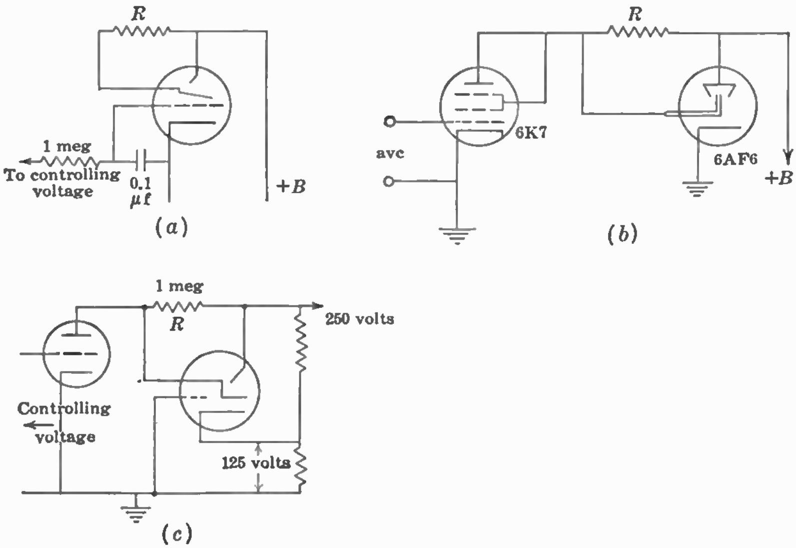


Fig. 228. Electron-ray tuning indicator tube circuits. In (b) and (c) separate d-c amplifiers are used whereas in (a) the triode amplifier is in the same envelope with the indicator element.

two symmetrically opposed patterns or two unlike patterns may be obtained depending upon how the ray-control electrodes are connected. This tube requires an external d-c amplifier.

Still other tubes have sharp cut-off or remote cut-off ray-control electrodes.

In operation, the electron-ray tubes get their controlling voltage from the avc system. Since the maximum of negative voltage is produced in the avc circuit when the receiver is tuned to resonance with the desired station, a maximum of negative voltage is supplied the control grid of the triode acting as d-c amplifier for the indicator tube. Under these conditions the least plate current will flow through the resistor R, the greatest voltage will appear across the ray tube, and there will be the smallest shadow angle on the target.

Electron-ray indicator tubes are found in many measuring instruments, taking the place of indicators of the milliammeter type. The sensitivity of the indication may be increased by using a separate d-c amplifier to control the action of the ray-control electrode as shown in Fig. 228.

313. Frequency modulation. In the standard broadcast band, stations are placed on channels 10 kc apart. If two stations are transmitting on channels so close, and if the receiver will receive a band of frequencies more than 5000 cycles wide, the receiver will at times pick up the modulation of the second station although it is tuned to the first. The highest audio-modulation frequency which a receiver may be permitted to receive is distinctly limited then by the amount of interference the listener will tolerate. If he listens to a strong local station and there are no strong signals from other stations on adjacent channels, or channels within the pass-band of his receiver, he can open up the frequency response of the receiver and take all he can get from the local transmitter. However, so long as stations are placed 10 kc apart, there is an automatic limit to the higher audio tones the listener can comfortably receive.

One answer to this problem, which limits the fidelity of tone reception, is to go to the short waves where there is more room and where stations need not be placed so close in the frequency spectrum. There is a further advantage in the short waves. There is less natural static there. Reception, therefore, is naturally freer from static. Man-made noise, however, is more prevalent on the short waves. To overcome this increase in noise and to widen the tone response somewhat, it is standard practice for television transmitters to boost the higher end of the audio spectrum on their sound channels, and to reduce the response to these frequencies in the receivers a corresponding amount. The result is that the listener hears the high audio tones with less interference from unwanted noise.

Frequency modulation is one more advance in the fight against static and for the cause of high fidelity.

Since f-m broadcasting takes place in the high-frequency bands (40 megacycles and up) there is less static, there is more room, transmitters can be modulated with frequencies (15,000 cycles) which could not be tolerated in the crowded quarters of the standard broadcast band, and, furthermore, frequency modulation has other advantages which will be discussed later. Frequency modulation, therefore, offers the listener high-fidelity reception, essentially noise-free.

The technical background for this new service will be described in a later chapter.

314. Loud speakers. The loud speaker is the final link in the broadcasting system, and because of its position with respect to the listener it is frequently blamed for much of the bad reproduction that really originates somewhere else.

The task of the loud speaker is to translate into sound energy the electrical energy in the power tube. It must do this as effectively and faithfully as possible. It is useless to design and operate a high-class amplifier with a poor loud speaker. The wide range of tones coming from the amplifier is lost in the loud speaker and does not get to the listener. Likewise, it is absurd to install a perfect loud speaker in the hope that the fidelity of reproduction from an antiquated or poorly engineered receiver will be bettered. The full benefit of a wide-range loud speaker cannot be attained until the complete chain of apparatus is perfect—amplifier, power tubes, plate voltage supply, loud speaker, etc.

315. Elements of the loud speaker. Every speaker has three essential elements. First, a **motor** converts electrical into mechanical energy which is imparted to a **diaphragm.** The diaphragm, the second element, vibrates and sets air in motion to form sound waves. Third, a **horn** couples the diaphragm to the impedance of the air load. Thus the horn is a sort of transformer or transmission line to couple the impedance of the diaphragm to the load which is the air which is to be set in motion. Some loud speakers have no horn, proper, but the diaphragm is extended in size and accomplishes the needed coupling by itself.

Each of these elements may take one of several forms, and one assembly may be considerably more efficient than another, that is, more of the electrical energy may be converted into acoustic energy in one type of speaker than in another. Some speakers will handle quite a lot of electrical energy with relative freedom from distortion. Other types are limited in the volume they can handle. Some types will reproduce a wide range of frequencies, and others have narrow bands in which they will convert electrical energy into acoustical energy.

The engineering of loud speakers is quite as complex as the engineering of an audio system or the designing of a radio receiver. The terms and quantities used are different, but there are certain analogies between the electrical and mechanical-acoustical systems. Each involves coupling a generator to a load at as great efficiency as possible over as wide a frequency band as possible.

316. The horn speaker. This type of speaker is highly efficient, perhaps 30 to 50 per cent. A source of sound of small volume but high intensity is coupled to a large volume of air. Here the intensity of vibration is low. The horn must permit the air vibrations (the sound wave emitted by the source) to expand in such a manner that it will leave the horn without reflections back into the horn. The small end of the horn is called its **throat,** the large end its **mouth.** The rate and manner in which the horn changes its shape are known as the **taper.** The relative dimensions of the mouth and throat determine the load on the diaphragm which produces the sound at the throat end.

The impedance seen by the diaphragm, looking into the horn, should equal the impedance of the diaphragm for best transfer of power. The lowest frequency that can be radiated into space by the horn is controlled by the mouth of the horn. The area of the mouth should be the area of a circle having a diameter one-fourth wavelength at the lowest desired frequency.

The taper usually follows an exponential law. This means that the cross-sectional area increases at a rate which is proportional to the area. The taper controls the efficiency of sound transmission along the length of the horn. High frequencies are transmitted quite well but at the lower frequencies the propagation falls off. Until 1941, the exponential horn was most used because it gave the best transmission at low frequencies of any taper utilized up to that date. In 1941, however, a new horn design (known as the Hypex) was worked out mathematically and put into production. It performs at the low frequencies appreciably better than the horns using exponential tapers.

If the impedance seen by the diaphragm (source of sound) is not high enough, an "air" transformer is used. This is a chamber in which air pressure may be built up. Its dimensions are critical; its volume should be small and its radius should not be greater than one-fourth wavelength at the highest frequency to be reproduced.

317. Diaphragm speakers. The horn is large, and is, therefore, unfitted for use in home radio receivers. For this service the cone speaker has been developed to a high state of efficiency. To transmit from a localized source of sound to an acoustic load spread over a large area, the cone diaphragm must be light (to avoid loading up the motor with a resistance load) and at the same time it must be rigid so that it does not break up into all sorts of vibrations when driven by the motor. The highest frequency that will be transmitted satisfactorily will depend upon the size and weight of the cone, a small cone transmitting high frequencies better than a large one. On the other hand, to couple energy at low frequencies to the air load, the cone must be large, in order to move a large mass of air. And so the loud speaker designer is in a dilemma. If a wide range of frequencies is to be reproduced, he compromises by using two speakers, one large to reproduce the low frequencies, and one small, often called a "tweeter," to reproduce the high frequencies. These may be on the same axis, or may even be part of the same diaphragm, or they may be distinct speakers, physically displaced from each other.

Cone speakers can be made which will "sound loud" although there is really little acoustic energy being radiated. They distort badly, but the listener is happy if the sound seems loud. Speakers can be made which will sound as though they reproduced low frequencies, although the cone is small. Again the distortion is high, the low frequencies are really synthetic and a comparison with a good low-frequency speaker will instantly show the difference. Speakers can be made which will disguise the distortion coming out of a cheap amplifier—in fact the speaker engineers have done much to save the situation in the radio industry where cheap components, low prices, high-pressure selling have fostered on the public many shoddy pieces of equipment. But they "sounded good" and did not cost much, and the public was happy.

318. Loud speaker motors. Any device which will move when a modulated electric current flows in it will make a loud speaker. Its movements are imparted to the air which in turn affects our ear drums and our auditory nerves in a sensation we call sound. The object is to effect as large a movement of air as possible with the least possible electrical input, and to effect this efficient transfer of electrical energy into sound energy over as wide a band of audio tones as possible.

The horn type of speaker may use a thin steel or iron diaphragm as the moving element, or a non-magnetic diaphragm actuated by a mechanical coupling system as in Fig. 229. The electric currents are sent through the winding of a nearby electromagnet which has a certain amount of permanent magnetism in it. When the electric currents change the latter's magnetism, the diaphragm or the armature is moved accordingly. These movements are imparted to the air.

If the horn is large enough the resonance effect of the diaphragm may be partially eliminated. Otherwise when the frequency at which this diaphragm mechanically resonates comes through the speaker windings, a very loud output will be given out showing that the loud speaker element is more efficient at this particular frequency. The horn acts as a load upon the diaphragm much as a resistance across the secondary of a transformer acts as a load on a generator connected to the primary which supplies the power. The power in this case is sound power radiated from the horn. Up to the present time exponential horns give the best response characteristic in that they are freest from resonances and reproduce the low frequencies best.

If the horn is replaced by a cone, as shown in Fig. 230, much better frequency response results because the cone has a larger area and can give appreciable sound output at low frequencies. With a given diaphragm area, halving the frequency requires four times the relative motion of the diaphragm to produce the

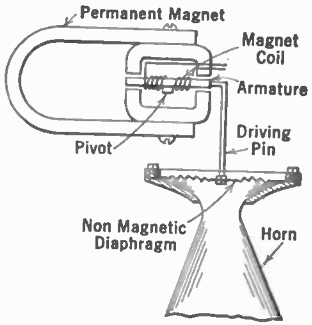


FIG. 229. Horn-type speaker mechanism.

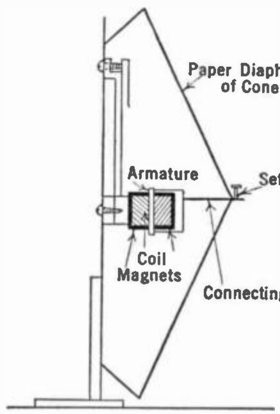


FIG. 230. Cone-type speaker.

same sound power, whereas increasing the size of the cone so that much greater areas of air are displaced with a given amount of diaphragm (cone) motion, enables lower frequencies to be reproduced.

Such speakers have an impedance that increases with frequency, since it is about 1000 ohms at 100 cycles and runs as high as 40,000 ohms at 5000 cycles. This means that the tube works into a constantly varying impedance as the frequency varies, and that most efficient transfer of energy, or transfer with least distortion, can occur at only a small range of frequencies. Since the impedance is low at low frequencies, more distortion due to curvature of the tube characteristic takes place at this end of the audio band. It is a fact that such speakers have a very limited motion so that it is impossible to transmit very large low-frequency responses to them, and so the distortion due to curvature is not so pronounced as theory would indicate. For average home use, a good cone speaker about 2 ft in diameter will satisfy the vast majority of listeners.

319. The moving coil speaker. The construction of the moving coil or dynamic type of speaker is shown in Fig. 231. A strong permanent magnet or an electromagnet energized by a direct current, either from a storage battery, or from part of the plate current supply system, or from the 110-volt a-c line by means of a rectifier furnishes a steady field. The voice-frequency currents coming from the final power tubes in the amplifier are passed through a few turns around a small movable coil to which is attached the diaphragm or cone. When alternating currents flow through the coil, it tends to move at right angles to the lines of force across the air gap. These motions of the coil are imparted to the cone and thence to the air.

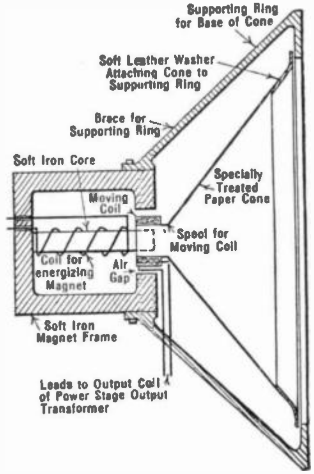


FIG. 231. Modern "dynamic" or moving coil loud speaker.

The impedance of this movable coil is very low, of the order of 5 to 10 ohms, and is almost constant at audio frequencies. This means that the tube looks into its own impedance through a step-down transformer. For this reason a much flatter response curve is possible. Because the coil can move through a considerable distance without danger of any mechanical noises—such as caused by the diaphragm rattling against the poles of a unit of the type of Fig. 229—much better low-frequency response is possible. Considerable sound energy can be got from such a speaker. The resonant frequency of the moving part is usually lower than the lowest audio tone to be reproduced.

320. Baffles for dynamic speakers. It is necessary to install such a speaker in the center of a rather large and heavy "baffle" if the low notes are to be properly reproduced. Otherwise the wave set up from the back of the cone can interfere with the wave set up by the front, with the result that little or no sound gets to the listener. The baffle increases the air path between front and back and should be great enough so that the shortest mechanical path between front and back edges is at least one-quarter wavelength for the lowest note to be received. Since the

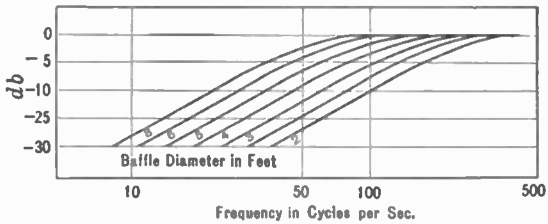


FIG. 232. Effect of using large or small baffles on dynamic speakers.

wavelength of sound, like that of radio waves, is equal to the velocity it travels divided by the frequency, it is not difficult to prove that a baffle at least 32 in. square is necessary for notes as low as 100 cycles, and 110 in. for notes as low as 30 cycles. When the unit is mounted in a box, peculiar resonances are set up which spoil the good qualities of the moving coil speaker. These resonances are sometimes smoothed out by the use of resonating chambers or diaphragms which absorb energy at the offending frequency.

321. Improvement in loud speakers. Several methods have been developed for increasing the bass response of loud speakers (for it is at the low frequencies that it is difficult to get good coupling between motor and load) and for eliminating troublesome resonances. One method of reducing resonance in the cabinet was to use cones (not driven by motors) in the front of the cabinet. These cones were of such dimensions that they were resonant to the frequencies at which the cabinet "boomed."

These resonant cones absorbed energy and acted as dissipators of this unwanted resonance energy.

To eliminate the loss of low frequencies because the wave from the back of the diaphragm, at low frequencies, could cancel some of the energy radiated from the front of the diaphragm, several schemes have been applied. One makes use of a total enclosure like a box closed on all sides. Ordinarily if such a cabinet is used, the system will boom at some frequencies and at low frequencies may be quite inefficient. If, however, vents or holes are

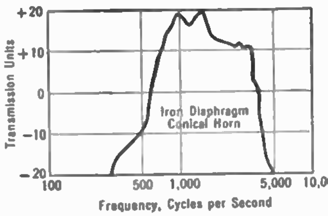


Fig. 233. Limited response of horn speaker.

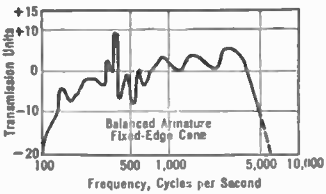


Fig. 234. Response characteristic of good cone.

placed in the front of the enclosed cabinet and if these holes have the correct placement with respect to the speaker diaphragm and are of the correct size, an appreciable increase in low-frequency response will be discovered, and at the same time there will be much less distortion at low frequencies.

This is known as the "bass reflex" principle which makes it possible to improve the low frequencies as much as 10 db compared with a total enclosure without the vent. The distortion may be reduced to as little as one-third. The vent acts like a second loud speaker which furnishes acoustic power only at frequencies near the cut-off frequency of the speaker. Other frequencies are absorbed within the cabinet by lining it with material which is highly absorptive at the intermediate and higher audio frequencies. The speaker diaphragm looks into a high anti-resonant impedance at the low frequencies, and for this reason the mechanical movement of the diaphragm is small. At high excursions of the diaphragm, distortion is created. The vent supplies most of the low-frequency energy, and since there is nothing in it to move (no mechanical parts) there is no non-linear flux or non-linear edge stiffness of the paper cone. No distortion is created.

Another method of improving low-frequency response is to connect a transmission line (acoustic) to the diaphragm in such a manner that it brings the back-side radiation of the diaphragm

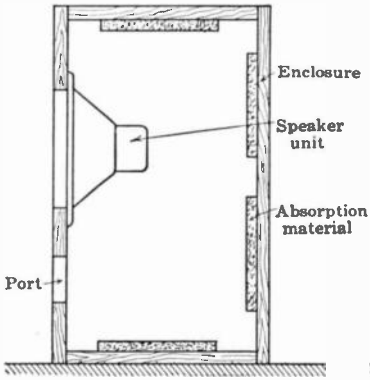


FIG. 235. Bass reflex housing for improving low-frequency response of dynamic speaker.

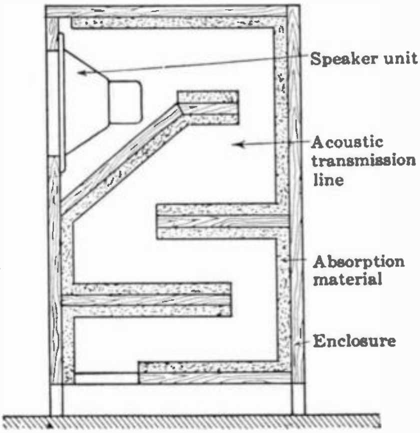
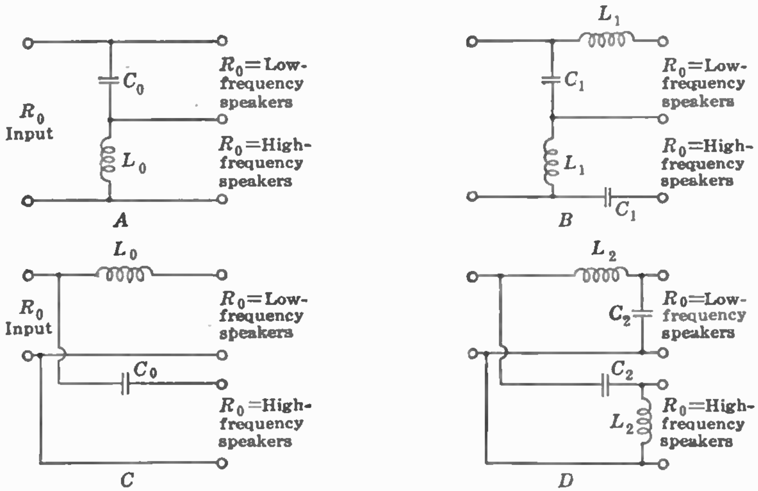


FIG. 236. Construction of the labyrinth speaker enclosure.

in phase with the front-side radiation and thereby improves the response. The acoustic transmission line is called a "labyrinth" and is shown in Fig. 236. Distortion at the low frequencies is reduced compared with a cone speaker without the labyrinth.

Other methods involve a series of resonant pipes placed in the cabinet, and, of course, the two-speaker system is widely used when a wide range of frequencies must be reproduced. In this system a small speaker called a "tweeter" is used for the high frequencies and a large speaker called a "woofer" for the lows. By means of a "dividing network" the low frequencies are kept out of the small speaker, and the high frequencies are kept out of the large speaker. Thus each is required to handle only that power which will produce useful acoustic output. Each speaker can be engineered with its own restricted range in mind, rather than expecting a single speaker to cover the whole audio range equally well.

322. Loud speaker measurements. One method of measuring the performance of a loud speaker is to hang a calibrated micro-



$$L_0 = \frac{R_0}{2\pi f_a} \qquad L_1 = \frac{L_0}{\sqrt{2}} \qquad L_2 = \sqrt{2}\, L_0$$

$$C_0 = \frac{1}{2\pi f_a R_0} \qquad C_1 = \sqrt{2}\, C_0 \qquad C_2 = \frac{C_0}{\sqrt{2}}$$

f_a= Cross-over frequency of network
Inductances in henries
Capacitances in farads

FIG. 237. Dividing networks to keep low frequencies out of high-frequency speaker and vice versa.

phone in front of the speaker which is actuated by various tones of known amplitudes from an oscillator. The output of the microphone is amplified and measured, and thus a curve of output versus frequency may be obtained. Another method is to rotate a microphone through a rather large arc in front of a loud speaker. This tends to average the effects due to resonances in the room in which measurements are made.

CHAPTER XVI

RECTIFIERS AND POWER SUPPLY APPARATUS

Among the many useful functions of the vacuum tube is that of rectification. Tubes which act as rectifiers transform alternating currents into direct currents and thereby are useful as sources of unidirectional current either for charging batteries or for supplying plate voltages to a receiver or other device. Such tubes generally have only two elements, the source of electrons and the plate or receiver of electrons. Tubes of this general type have been developed for high-voltage, low-current work, as for supplying transmitters with plate voltage, or for low-voltage, high-current work for battery charging. Rectifier tubes may be high vacuum and may handle several hundred thousand volts, or they may be gaseous to handle several thousand amperes, and for special purposes they may have grids in them, then being known as controlled rectifiers (grid-glow tubes and thyratrons).

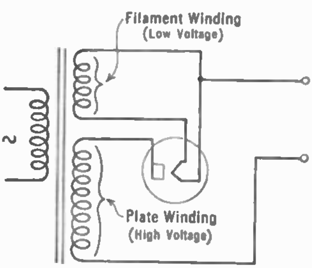


FIG. 238. Simple rectifier circuit for producing direct currents from alternating.

323. The fundamental rectifier circuit. When such a two-element tube filament is heated to a proper temperature electrons will flow to the plate provided it is at a higher positive potential than the filament. If an a-c voltage is connected between the filament and the plate (Fig. 238) an electron current will flow to the plate when the latter is positive and not when it is negative. In other words, current flows on the halves of the cycle when the plate is positive; on the other half of the cycle there may be very little or no conduction. The a-c voltage may be introduced into the plate-filament path by means of a transformer, which also supplies the heating current for the filaments.

A d-c meter in the plate circuit would read a current which would have a value somewhere between the maximum current that flowed during each positive half-cycle, and zero. The meter needle would not follow the rapid spurts of current and so would assume some average value. If we consider as the input the a-c voltage, and the d-c meter as the output circuit, it is clear that distortion is taking place, because there is no direct current in the input and there is a readable amount of direct current appearing in the output. In other words the output is not a perfect replica of the input. This is of no importance, however, in rectification.

Such a rectifier may be arranged to transform alternating current to pulsating direct current either at low, medium, or very high voltages. Whenever one wants a source of direct voltage or current and an a-c voltage only is available, a vacuum tube operating as a rectifier may be employed.

Rectification takes place only in this one direction. It is not a reversible process. If we want alternating current from direct current we must use a motor-generator, a converter, or a vacuum tube which can be made to oscillate and thereby convert a certain amount of d-c power from batteries into a-c power.

The amount of direct current that would be read by a meter in the plate circuit of such a tube would depend upon the voltage, the form of the wave being rectified, the shape of the tube characteristic, the amount of current that flows when the plate is negative with respect to the filament, and upon other factors. If one could listen to the output of such a tube, as one may by putting a loud speaker in series with it, he would hear a buzzing or throbbing sound.

The a-c voltage input wave is as in *A*, Fig. 239, which shows the output without a rectifier. The pulses of direct current in the plate circuit of a single wave rectifier are as in *B*. This is not a direct current in the ordinary sense of the expression. It is a current which varies in amplitude over the half-cycle of the a-c voltage which makes the plate positive. The current throughout this half-cycle flows in the same direction, however, and so may be considered as a pulsating direct current. These pulsations may be smoothed out by filters and as a result nearly

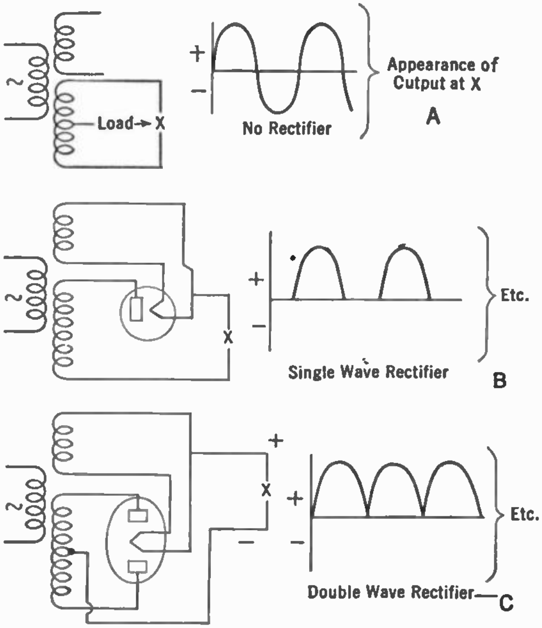


FIG. 239. At A, voltage at X has the same wave form as the line voltage. At B, one half of the wave has been eliminated by the rectifier. At C, the effect of using a full-wave rectifier is seen.

pure unidirectional constant-amplitude direct current may be obtained.

324. Kinds of rectifiers. A rectifier, then, is a device which transforms alternating current into a pulsating current which can be smoothed out into pure direct current if desired. Rectification may take place (*a*) in a device which passes more current in one direction than it does in another, or (*b*) in a device which does not pass any current at all in one direction, or (*c*) in a device which passes current when the voltage is increased beyond a certain limiting value, but no current below that value or in the opposite direction.

If the plate of a rectifier tube is kept cool, so that it cannot act as a source of electrons, the tube will pass no current when the plate is negative with respect to the filament and the two-element tube rectifier then is a member of class (*b*) above. If, however, a large amount of rectified current is permitted to flow through

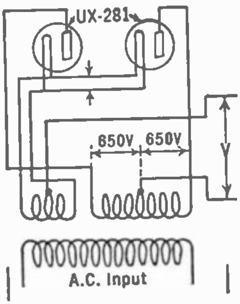


FIG. 240. Connections of a full-wave rectifier.

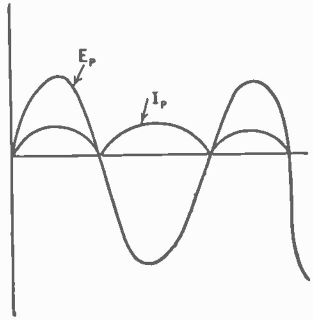


FIG. 241. Current from a double- or full-wave rectifier has a form approximated by I_p.

a fairly high-resistance tube the plate may become hot, and so act as a source of electrons on the half-cycle when the plate is negative with respect to the filament, and some "back" current will flow. The tube then falls into class (*a*). Such a condition in a modern plate voltage supply system is not likely to occur and will be evidenced by a high degree of hum in the output of the receiver.

Certain crystals such as galena, silicon, or silicon carbide (trade name "Carborundum") are rectifiers, passing more current in one direction than they do in another and fall into class (*a*). Some tubes do not use a filament, but have in them a gas, neon or helium, for example, which ionizes when the voltage reaches a certain value and conducts current in a definite direction. They are members of class (*c*).

The more perfect the rectification the greater will be the d-c output from a given a-c input. If the rectifier is perfect and if the input is a sine wave, a d-c meter in a resistance load will read 0.901 times the a-c input current. If 1 amp alternating current flows in, 0.901 amp direct current flows out.

325. Typical filament rectifiers. Tubes used primarily for rectifiers have only two elements, the plate and the filament. They

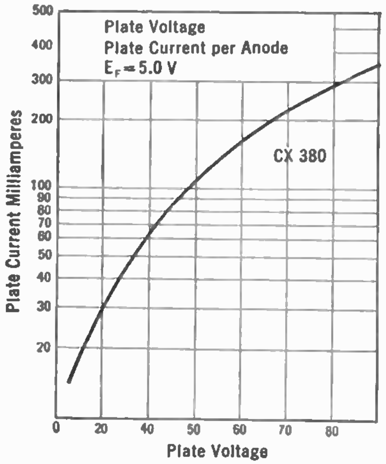


FIG. 242. Characteristic of double-wave rectifier tube.

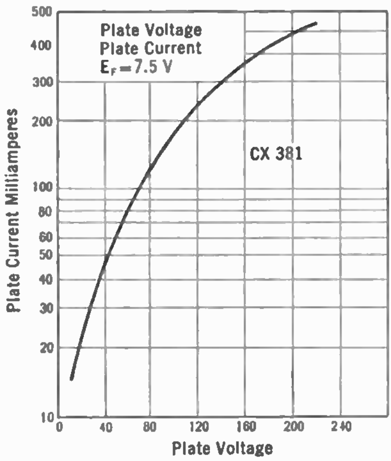


FIG. 243. Single-wave rectifier tube characteristic.

are of two kinds, the single or half-wave rectifier, and the double or full-wave rectifier. The single-wave rectifier has a single filament and a single plate and rectification takes place in it according to the process described above. If desired two such tubes may be arranged, as in Fig. 240, so that each half of the a-c cycle is rectified, and so the output current would look like Fig. 241.

A single-tube rectifier which operates on only half the a-c cycle is called a half-wave or single-wave rectifier. The two-tube rectifier is called a full- or double-wave rectifier. It is possible to combine both the single-wave rectifier tubes into one envelope by using two filaments in series and two plates. Full-wave rectification then takes place with the use of only one tube. The 80 is such a tube. It has two filaments and two plates and is connected as in Fig. 239.

Characteristic curves of single- and full-wave rectifiers are shown in Figs. 242 and 243.

326. Requirements for rectifier tubes. The filament of a rectifier tube must be rugged and capable of supplying many more electrons than are ever needed for the proper operation of the output circuit. Thus if a tube is to supply 125 ma steadily, it is possible that in some circuits the instantaneous current through the tube may be as high as 300 ma and the tube must be able to supply this current without saturating. If the tube saturates, the pulse of current when the plate is positive will be difficult to filter, and the rectifier and circuit would suffer from other faults.

The resistance of the tube should be low so that no great amount of voltage is lost in it, and so that the "regulation" of the rectifier and filter may be good. A low-resistance tube of course wastes less power, and so less heat must be dissipated. The insulation between filament and plate must be such that breakdown cannot occur either because of direct puncture of some part of the tube or due to heating by leakage currents.

327. Single-wave rectifier. A typical single-wave rectifier circuit is shown in Fig. 244. If we consider this figure when the plate end of the secondary or high-voltage winding of the transformer is positive, the other end of the secondary winding is negative with respect to the plate end and a large voltage exists across it—perhaps 400 or 500 volts. This makes the end of the load attached to this end of the transformer negative; and as we proceed in this direction, through the load and back to the filament of the tube, the circuit becomes more and more positive. The filament of a rectifier, then, is the positive end of the circuit so far as the load is concerned. The plate end is the negative or grounded end so far as the load is concerned, and a voltmeter across the load must be connected with this polarity in mind.

When the polarity reverses, on the other half-cycle, the plate end of the transformer becomes negative and the filament end positive. No current flows through the load or tube then, because the plate cannot attract electrons to it from the filament. The device is a half-wave rectifier only. It rectifies half the time. When current flows, the voltage drop across the tube is only the *IR* drop there—not the full transformer voltage.

Now suppose we connect another transformer secondary and another tube as in Fig. 245. When the plate terminal of S_1 attached to the plate of tube 1 is positive, current flows through

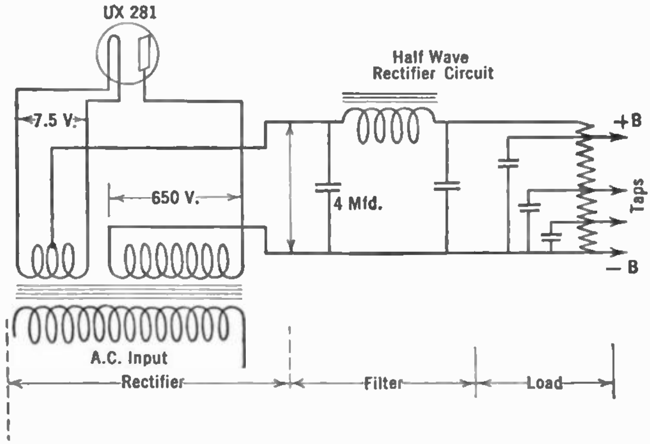


Fig. 244. Circuit of single-wave rectifier, filter, and load.

that tube and returns to the center of the transformer. Nothing happens in tube 2 because the plate of this tube is negative. When the direction of the a-c voltage reverses, the plate of tube 2 becomes positive and current flows through this tube returning through the center of the secondary winding as before. Current flows in a given direction through the load resistance regardless of which tube is passing current.

328. Gaseous rectifiers. Whenever a large amount of current with a low voltage drop in the rectifier is desired, gaseous rectifiers are used. The gas is usually mercury but in small tubes may be other gases such as neon or argon. The gas plays a very important role as will be seen below. There are several types of gaseous rectifiers; one of the earliest, the Raytheon tube, had no filament. Other types are the Tungar or Rectigon tube for battery charging, and the mercury-vapor rectifier such as the 82, 83, or 866.

The purpose of the gas in heated cathode types is to neutralize the space charge which in a high-vacuum tube prevents a large flow of electrons from cathode to plate.

Now suppose that there is a gas in the tube. An electron leaves the filament and goes toward the plate. On its way it

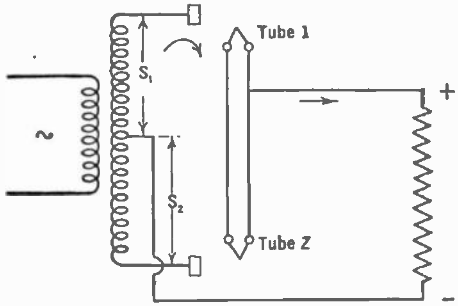


Fig. 245. Direction of flow of current in full-wave rectifier.

may collide with a gas atom with sufficient velocity to "ionize" it. In this process the gas atom loses an electron. The remaining part of the atom is charged positively and is now known as a positive **ion.** The second electron may join the first and go on toward the plate. The positive ions will attract the electrons in the space charge, each ion neutralizing the effect of one electron. Therefore, as soon as ionization begins, the space charge is neutralized, additional electrons are produced by the ionizing process, and more current can get through to the plate.

The high-vacuum tube is a high-resistance tube. It gets very hot if much current is taken from it because of the resistance in the space charge. A gaseous rectifier is a low-resistance tube and a thousand times as much current, or more, can be taken from it as from a high-vacuum tube without getting too hot. Furthermore, the voltage drop in the gaseous rectifier is low and constant regardless of the current taken. This voltage drop corresponds to the voltage necessary to ionize the gas, which depends upon the kind of gas and the temperature of the tube.

A rectifier made with a high-vacuum tube has a bad regulation curve, that is, its terminal voltage falls off rapidly when higher and higher currents are taken from it. Therefore, the voltage output is a function of the current output. In the gaseous rectifier the internal drop is constant, the only resistance in such a supply system being in the filter chokes which can be made as low as one desires by using large wire. Its output curve then is flat when voltage versus current is plotted.

Another type of rectifier of very great virtues in the control of large amounts of power is the three-element gaseous rectifier known in the trade as a **thyratron.** In this tube the current can be prevented from starting, even though the anode is positive, by placing a certain negative bias on a third element or grid. Thus the tube can start conducting as soon as the anode is positive, or it can start at any point in the cycle by adjusting the relation between grid and plate voltages. For each positive anode voltage there is some grid voltage which will permit the tube to conduct.

Once the anode current starts to flow the grid loses control and the tube acts like an ordinary gas rectifier until the end of the positive half-cycle when the grid will again get control. The most important features of the gaseous rectifiers are good regulation and low internal drop.

The output is somewhat harder to filter than the output of a high-vacuum rectifier; there is a tendency for r-f oscillations to occur. Therefore small chokes are connected in the rectifier plate lead when the tubes are used in sensitive radio receivers.

Several rectifier tubes may be connected in parallel for greater output. Thus if a heavy load is to be supplied by a rectifier, it may be more economical to connect several small tubes in parallel than to use a higher powered tube. If two full-wave tubes are connected in parallel, the plates of each tube may be connected so that each tube acts as half-wave rectifier. Although no greater voltage can be placed across the tubes, and although each tube should not supply more than it can when acting as a single tube, the current output is effectively doubled.

When mercury-vapor tubes are connected in parallel, it is wise to equalize the load taken by the several tubes. This is done by connecting resistances (of the order of 50 to 100 ohms) in the plate leads of the tubes. Equalizing resistors may be necessary when high-vacuum rectifiers are operated in parallel.

It is common practice in broadcast transmitters to operate several rectifiers in parallel. Then if one of them goes out of service there is still some power available for the transmitter.

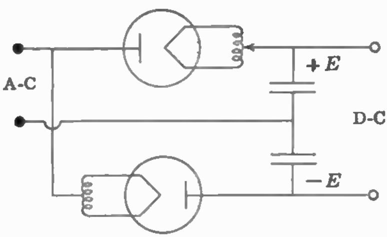


Fig. 246. Use of two half-wave rectifiers in a voltage-doubler circuit. D-C voltage will be twice the peak a-c voltage.

329. Voltage-doubler circuits. Ingenious circuits are available which will deliver a maximum d-c voltage equal to twice the peak voltage of the a-c line from which the circuit derives its energy. It requires two rectifiers and the circuit connects the outputs of the two in series. This type of rectifier is most useful in places where it is impossible or undesirable to use a power transformer since, for example, a useful output voltage of 240 may be obtained at a load of 40 ma from a 117-volt a-c line.

The elementary circuit using two single-wave rectifiers is shown in Fig. 246. For the moment consider only the upper half. When the plate is positive, current flows through the tube and charges the condenser in its output. Now consider the lower section. When the plate is positive, current flows through the tube and charges the lower condenser. Since the two tubes are connected opposite to each other across the line, the two condensers are charged in the same direction, so that the positive terminal of one connects to the negative terminal of the other. If no current is taken from them, as by a load, they will charge to the full voltage of the a-c input line. When load is taken, the terminal voltage drops somewhat.

In practice, a special tube such as the 25Z5 or 25Z6 is used. This has two separate diodes within one envelope. The heater

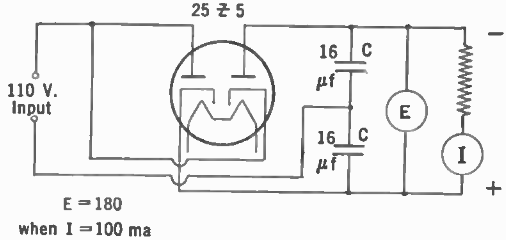


FIG. 247. Use of a rectifier with two plates and two cathodes to double the input voltage.

requires 25 volts and is connected in series with the heaters of the other tubes in the receiver and across the line. A typical circuit is shown in Fig. 247.

This circuit has one disadvantage. It cannot be grounded nor can the d-c output be connected to one side of the a-c line. This

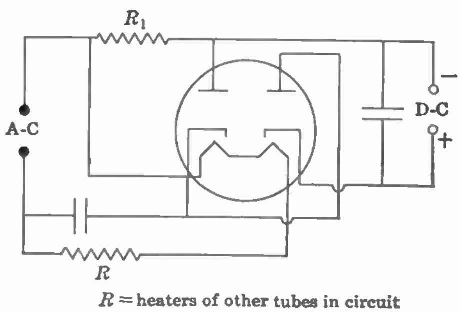


FIG. 248. Voltage doubler in which one terminal is at line or ground potential.

may cause hum because of the high voltage between heaters and cathodes. A circuit which overcomes this difficulty is shown in Fig. 248. One side of the output is connected to the line. It is called a half-wave doubler because rectified current flows to the load only on alternate half-cycles of the input voltage. One of the diodes charges a condenser which discharges in series with the line and through the other diode on the next half cycle. The regulation is not as good as the circuit in Fig. 247.

Voltage-doubler tubes have other interesting applications. Since the cathodes and anodes are separate, they really constitute two complete rectifiers. Thus one half of the tube might be used to supply plate voltage and the other half to supply grid-bias voltage; or one side might supply plate voltage and the other half supply energy for a dynamic loud speaker field coil.

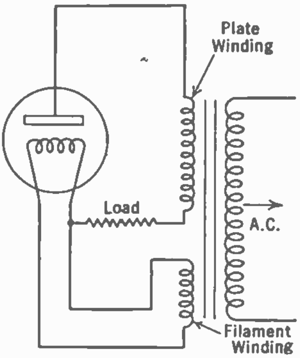


FIG. 249. Tungar rectifier circuit.

330. Battery-charger rectifiers. The Tungar rectifier introduced in 1916 is a low-voltage, high-current, gaseous tube. It is designed to rectify alternating current into a form suitable for charging batteries, and was used to supply current for the filament circuits of early models of a-c-operated radio receivers. Its starting or breakdown voltage is about 15 volts and useful life about 2000 hours. The gas is usually argon. A similar tube is known as the Rectigon.

A diagram of the connections of a typical Tungar rectifier is shown in Fig. 249. It consists of a transformer to reduce the input a-c voltage from 115 to from 30 to 75 volts; the tube itself, which is a simple two-element gaseous tube, consisting of a plate and a filament.

The theory underlying the battery-charger tube does not differ essentially from that already described for the filament and gaseous types of tubes. The filament supplies the electrons which bombard the inert gas and thereby produce more electrons and enable a heavy current of 2, or even 5 amp in larger tubes, to be carried across the space between plate and filament.

Gaseous tubes with which radio amateurs are familiar are of a high-voltage, low-current type such as the 866. These are used for transmitters, and large ones will supply power to the amount of many kilowatts at 10,000 or higher voltages. Such tubes have replaced high-vacuum tubes for transmitter purposes. The low-voltage drop has been simulated, however, in high-vacuum tubes for certain purposes by using very small spacing between cathode and plate. Gaseous tubes create r-f disturbances and must be carefully filtered.

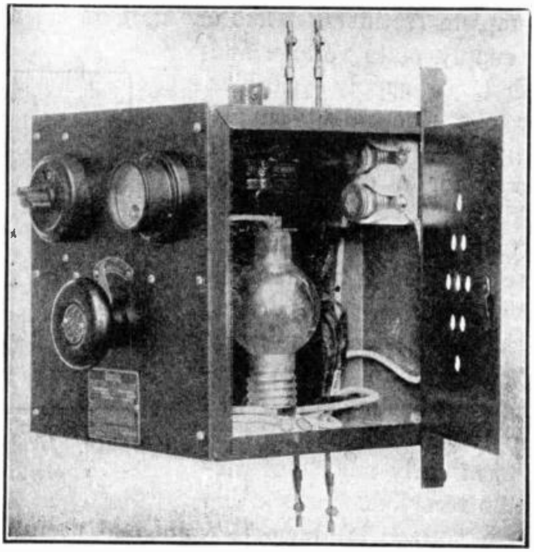


FIG. 250. A typical Tungar rectifier.

331. The copper oxide rectifier. The copper oxide rectifier is outstanding among rectifiers by virtue of its simplicity and reliability. The rectifier consists of a sheet of copper on one side of which has been formed a coat of cuprous oxide (Cu_2O). Properly made, this combination has relatively low resistance in the direction oxide-to-copper, with very high resistance in the reverse direction.

The units are generally made in the form of washers, of 1½-inch-outside diameter. These washers are then assembled in any desired series and parallel arrangement on mounting bolts. Soft metal washers are placed between the oxide layer and the adjacent metal surface for the purpose of improving the contact with the oxide. The surface of the oxide is graphitized for the same reason.

This rectifier operates electronically and not electrolytically. Rectification commences instantly on the application of voltage, with no forming or transient condition interposed. Current is carried not at points but uniformly over the available area. Furthermore, the rectifying elements can be paralleled to any extent. Operation in series presents no difficulties, as the disks divide the voltage with approximate uniformity.

The outstanding feature of the rectifier is its long life. Units on continuous duty life test, with battery load, show a reduction of a little over 20 per cent in charging current in 3½ years' operation. This is remarkable performance for a rectifier, since it operates entirely without attention or maintenance.

There are no limitations to the application of the copper oxide rectifier. It may be used either half wave or full wave. The bridge connection is commonly used since it simplifies the transformer design and furthermore permits units to be operated direct from the a-c line without intervening transformer if so desired. The quality of the d-c wave obtained is excellent so that filtering is readily accomplished. Battery charging, battery elimination, magnet operation, loud speaker excitation, etc., in fact almost any d-c application can be successfully handled by the copper oxide rectifier. They are often used in measuring instruments. Thus a d-c movement can utilize the rectified current produced by a copper oxide disk when alternating current is applied. The disk is kept as small as possible so that it will have low electrostatic capacity. Somewhat similar rectifiers are made of selenium or of copper sulfide.

332. Filter circuits for tube rectifiers of the filament type. The output of the rectifier circuit is not an even flow of current. Its output must be smoothed out or filtered.

A good plate voltage supply device, then, consists first of a transformer which raises the a-c voltage to the value required by the receiver plus the losses in voltage in rectifier, filter, and voltage divider. Second, the rectifier which performs the task already described. In the third place comes the filter whose task it is to smooth out the pulsations of current in the plate circuit of the rectifier so that the final product will be direct current of constant amplitude and a minimum amount of alternating current in it, and of a voltage high enough to supply the voltage and current required by the receiver and amplifier as well as the losses in the device itself.

A conventional filter circuit consists of series inductances, which smooth out the ripples of current and keep the current flowing at the a-c voltage reversals, and shunt condensers which act as reservoirs of voltage as described in Section 73. A two-section filter, that is, two chokes and their accompanying condensers, is usually employed. The amount of filtering necessary depends entirely upon the amount of residual hum that is tolerable after the filtering has taken place. A very quiet power supply device is required in those receivers which have a rather high a-f voltage amplification and which amplify frequencies as low as 120 to 60 cycles.

There is always a certain amount of a-c voltage left after the filtering has taken place. This voltage is a matter of millivolts compared to several hundred volts of direct current, but even these small a-c voltages may become objectionable when a loud speaker that is efficient at low frequencies is used. This voltage is a combination of the fundamental frequency, 60 cycles, and its harmonics. In double-wave power supply devices the second harmonic or 120 cycles is particularly strong.

A good loud speaker which reproduces notes as low as 120 cycles will hum badly when used with a power amplifier which gets its voltages from a poorly filtered supply. Even with a very good filter, some a-c voltages are likely to be picked up by the cores of audio transformers if they are near power transformers carrying alternating currents. The ultimate extent to which hum may be reduced may be the amount that transformers can be shielded from stray fields, and not the extent to which a rectifier's output may be filtered. The freedom from such troubles of resistance-coupled amplifiers is one of their favorable characteristics.

333. Regulation. Across the output of the filter is a resistor which acts as a potentiometer to reduce the full voltage to the values desired. If the full voltage is 180 volts, a tap at the proper place will give 90 volts and another will give 45 or any other desired voltage. Now it is apparent that the voltage across this resistance depends upon the current through it, and if there were no other resistances in the circuit Ohm's law would tell us at once what the voltage across the resistance would be. Unfortunately the transformer, the rectifier tube, and the filter chokes all have resistance, so that the greater the current taken from the whole device the lower is the voltage across its output. From batteries one gets 90 volts for his tubes whether he runs one or a dozen of them; the drain from the batteries is all that changes. With a voltage supply device, however, the voltage at the amplifier tap would be less than 90 if the current taken from it exceeds a certain amount. This is true simply because batteries have so much lower internal resistance than conventional rectifier-filter systems.

Curves showing the output voltage at various output current drains give what is known as the **regulation** of the device, that is, the manner in which its voltage drops with increase in current taken from it. The history of plate supply systems can be traced in a record of the regulation of such units, the older they are the worse their regulation curves, or the higher their internal resistance. The steep regulation curve and low output of an early "B eliminator" may be seen in Fig. 251.

334. A typical rectifier-filter system. Several curves showing the relation between the current and voltage in a modern rectifier-filter are shown in Fig. 252.

The losses in voltage are those due to the *IR* drop in the resistance of the tube and the transformer. In Fig. 252 the voltage across the output resistance of the filter would be less than these voltages by the drop in the filter resistance. If the filter chokes

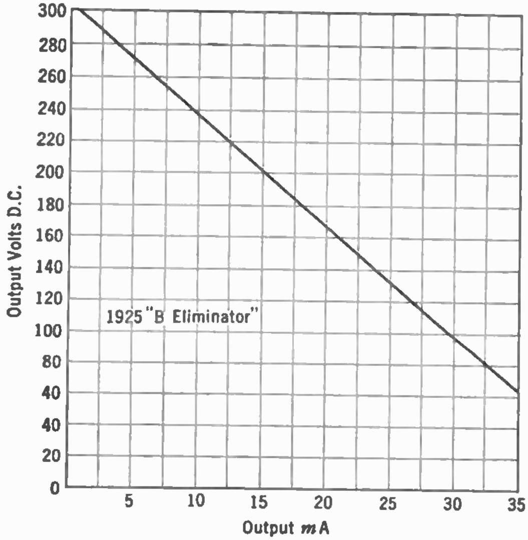


Fig. 251. Regulation curve of early B eliminator. Note the great voltage drop.

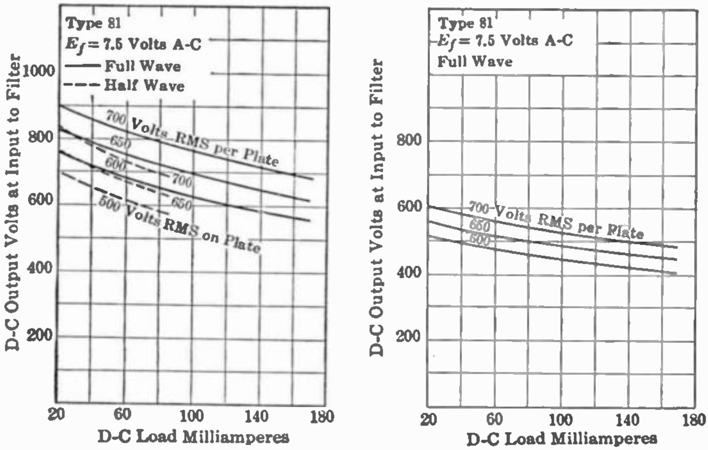


Fig. 252. Comparison of condenser-input (*left*) and choke-input (*right*) filter systems. Voltage drops due to resistance of filter chokes are not considered and must be added to these regulation curves if complete regulation data are desired.

have a d-c resistance of 1000 ohms there would be an additional drop of 1 volt per milliampere of current from it.

A transformer which supplies 220 volts to each plate of an 80 tube will deliver a voltage of 220 across the input to the filter and if the latter has a resistance of 1000 ohms about 150 volts will appear across the output at a current drain of 65 ma.

The variations in transformer voltage, current through the tube, and steady load current are shown in the oscillographs in

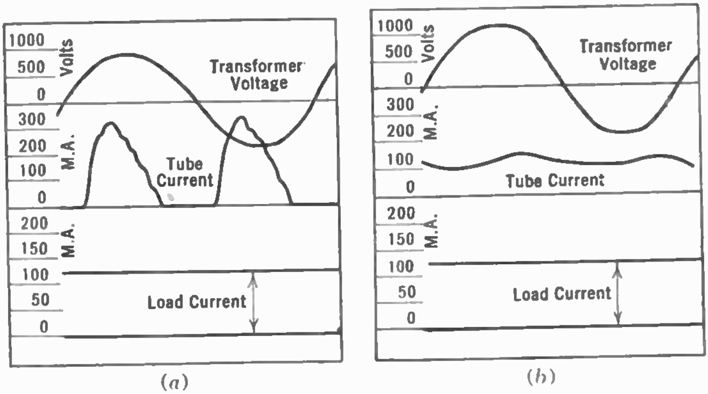


FIG. 253. (*a*) High instantaneous current required from rectifier with capacitive input. (*b*) Reduced tube current in an inductance input filter.

Fig. 253. The fact that abnormally high instantaneous values of currents must be passed by the tube is clearly shown in the tube current wave. No current flows until the transformer voltage reaches a certain minimum value and current ceases to flow as the voltage across the transformer secondary decreases. The peak current rises as high as 310 ma, and on the assumption that the resistance of the tube remains constant, the power lost in it increases as the square of the current, showing that this high current puts a severe burden on the tube. As a matter of fact the internal resistance of the tube is almost constant, decreasing somewhat at higher current loads.

If the first filter condenser is removed and placed across the output, as shown in Fig. 254, not only does the peak current passed by the tube decrease, thereby decreasing the power lost in it, but the regulation is also improved. The disadvantage of such a connection is slightly greater hum output and the fact that the output voltage is decreased by about 20 per cent. This loss in voltage may be made up by increasing the secondary voltage of the transformer, and even then the power losses in the tube will be less. The peak current passed through the tube in the second case is about 140 ma when a steady current of

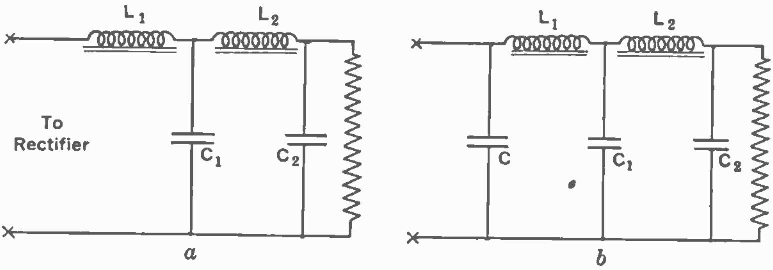


FIG. 254. Two types of filter: (*a*) inductance input; (*b*) capacity input.

125 ma is required, thereby reducing the power losses in the tube by about 35 per cent.

The connection which omits the first filter condenser increases the life of the tube, permits the use of a tube whose emission has fallen below the point at which the tube would be useless in a capacity input filter, gives better regulation at current drains over 20 ma, reduces the filament emission required, and reduces the heating of the tube.

Using chokes of 11.5 and 13.5 henries for L_1 and L_2 and 4 μf and 8 μf condensers as C_1 and C_2, a hum output of 44 mv was reported as typical. Although the amount of hum that can be tolerated is a matter of opinion, the following figures may be useful. With a sensitive dynamic speaker in a 3-ft baffle, a 120-cycle voltage of 540 mv across the primary of the transformer feeding the speaker was too loud for comfort. A desirable maximum was 150 mv. At 60 cycles these values were 5.2 and 1.3 volts. These values depend upon the loud speaker.

Small receivers with inadequate baffle and using small speakers can be fed from very poorly filtered sources of supply.

335. Automotive receiver power supply. In 1933 a very rapid development of new methods of supplying high voltage from low-voltage direct current took place. Neglecting the motor generator or other types of rotating machinery whose use is obvious, the general method of attack was to interrupt the battery voltage

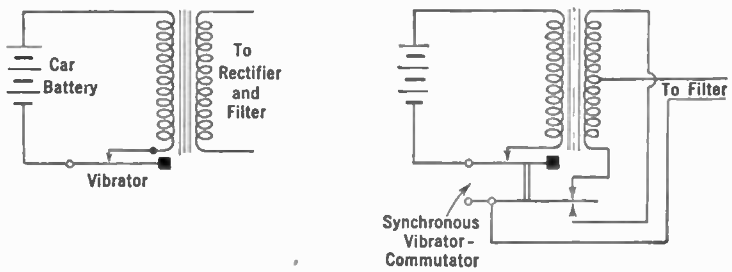


FIG. 255. Simple vibrator to produce alternating current from direct current and combined interrupter and rectifier.

(6 volts) producing pulses which were fed into a step-up transformer and then rectified and filtered.

In most devices the vibrator rectifies as well as interrupts by operating in synchronism with it a commutator which feeds the output of the transformer in one direction only to the filter.

336. The voltage divider. The maximum voltage available is usually applied to the plates of the tubes. Sometimes the power tubes require higher voltages than the other tubes, but in general radio receivers are designed to use tubes which take 250 volts on the plates. The screens require lower voltages. Grid-bias voltages must be negative.

The screen and lower positive voltages are usually supplied from the maximum voltage by means of a voltage-dropping resistor properly filtered. The bias resistors may appear in the cathodes of the individual tubes or in the negative lead to the power supply system. Sometimes a resistor known as a voltage divider may be put across the entire output of the filter and various taps brought out with the proper voltages. Thus the entire plate current of all the tubes flows through some part of this resistor. In other cases the voltage divider is a part of the bias system. The following description, although of older practice, illustrates the purpose of the voltage divider.

Let us consider the preliminary diagram in Fig. 256. Disregarding for the moment the resistance across the B voltage terminals, it may be seen that the plate of the tube gets its positive potential by being connected to the positive end of the plate supply unit. The negative end of the unit is connected to the center of the filament through a resistance R. The plate current of the tube must flow through this resistance to return to the filament of the tube. Therefore, there is a voltage drop across R. The grounded end of the plate voltage supply is the most negative point in the circuit. As one proceeds toward the filament and then toward the plate one proceeds steadily toward a more positive point in the circuit. The filament end of the grid-bias resistor R marked (+) is at a higher or more positive potential than is the grid end. The grid end, then, is negative and the voltage drop across this resistor, due to the plate current flowing through it, may be used as the grid bias for the tube. The voltage actually between the center of the filament and the plate is the total voltage across the plate supply unit minus the grid-bias voltage; or as shown in Fig. 256, the plate supply unit must have a terminal voltage of 220 in order to place a voltage of 40 between grid and filament and a voltage of 180 between plate and filament.

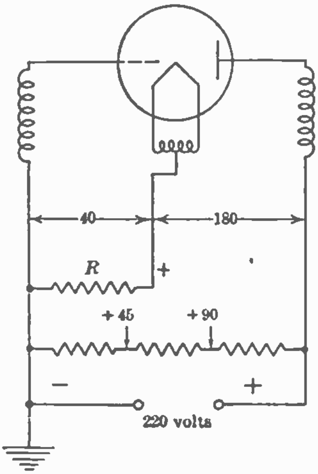


FIG. 256. Elementary diagram of voltage divider, a resistor with taps placed across the plate voltage supply system.

To get other voltages, all lower than the maximum positive voltage delivered by the plate supply system, it is now only necessary to place a resistance across the plate voltage supply system so that various voltages appear along it, each voltage being less than the voltage across the two ends. It is only necessary to fix the values of the taps so that the voltages desired are attained.

If another grid bias is needed another resistor can be connected to the negative end of the plate voltage supply and the filament of the tube requiring the bias. The plate current of that tube flowing through the new resistor to return to the filament will cause a voltage drop across the resistance the negative end of which is toward the grid of the tube in question.

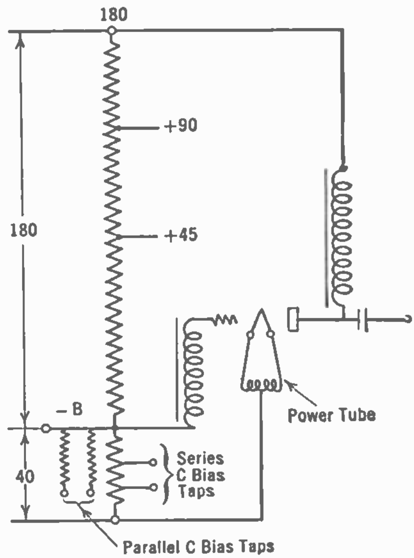


FIG. 257. Both series and shunt grid-bias resistances are illustrated.

There is another method whereby the bias for the power tube is tapped and lower voltages are obtained for other tubes. Such a method is liable to lead to unwanted couplings between tubes. For example, in an r-f amplifier such a method of obtaining bias may lead to regeneration or even oscillation because the plate current of some tubes flows through the grid bias of other tubes.

Both these grid bias connections are shown in Fig. 257. One set is in series, the other is a parallel set. The importance of by-passing all such resistors has been mentioned in Section 236. A better method is to make the voltage divider part of the amplifier, as in Section 236. It is only necessary then to supply one B plus voltage to the amplifier.

It is good practice in receiver design to supply all plates at, say, 250 volts and to drop this voltage for screens, etc., with individual resistances and to use capacities to cathode to act as filters.

337. Engineering the voltage divider. The lower the resistance of the voltage divider, the better will be the regulation of the entire device, but the greater the load the tube must bear. In general, a voltage divider is engineered as follows. In Fig. 258, suppose the current flowing through the resistance R_1 is 20

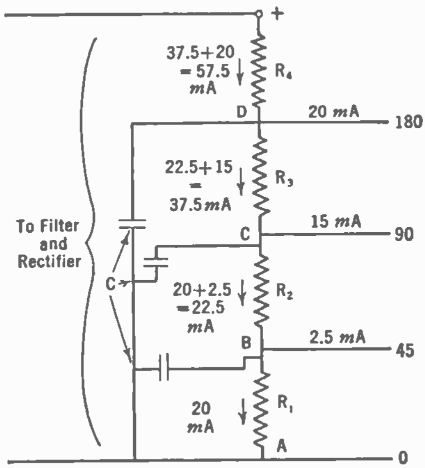


FIG. 258. Designing the voltage divider.

ma. This is known as the "bleed" or "waste" current. It flows whether or not there are any tubes in the receiver that is supplied with voltage from the device. At the point B, a voltage of 45 is desired. The value of resistance is, according to Ohm's law, $E \div I$ and so is $45 \div 0.02$ or $R_1 = 2250$ ohms. Since this tap supplies only a single plate circuit the current will be about 2.5 ma, and is added to the 20 ma taken by the lowest resistance. Thus through R_2 flows 22.5 ma and since 90 volts is desired at point C the resistance R_2 will be $45 \div 22.5$ or 2000 ohms. If the tubes which require 90 volts take a total of 15 ma, the final resistance will be $180 - 90 \div 37.5$ or $90 \div 37.5$ or 2400 ohms. The entire resistance will be 6650 ohms, with taps at 2400, 2000, and 2250 ohms. The greatest amount of power must be dissipated by the 2400-ohm resistor and so if the entire resistance up to R_4 is wound with wire large enough and on a frame that can dissipate the heat corresponding to 4 watts, there will be no trouble. Voltage dividers are available which consist of a single winding of resistance wire on a heat-resisting form. There are several sliders so that the correct voltages can be obtained easily.

In systems using loud speakers whose field coil is energized by the plate current of all or several tubes flowing through an electromagnet, the voltage drop along this field coil may be used as grid bias. All that is required is to place the coil in the negative high-voltage line and, by connecting to the negative end of this *IR* drop, the bias is secured. Such a coil should be heavily bypassed since the negative high-voltage line may carry a-f currents.

Problem 1–16. The maximum voltage needed with the voltage divider of Fig. 258 is 180 volts, but the output of the filter is 200 volts under load. What is the value of resistance R_4 to reduce this voltage to 180 and what must be its power dissipation in watts?

Problem 2–16. Using a tube with a filament voltage of 7.5 volts and operated from direct current the proper C bias is 50 volts. The plate current then is 25 ma. What is the voltage that must appear across the C-bias resistor when the tube is operated from alternating current and when this resistor is connected to a center of a resistanceless transformer winding?

Problem 3–16. What power in watts is dissipated in each of the resistances in Fig. 258 under the conditions of Problem 1–16?

Problem 4–16. The resistance of the filter is 300 ohms. What must be the output of the rectifier if the output of the filter is 250 volts and if 40 ma flow through the voltage divider resistance R_4?

338. Voltage regulation. In districts where the line voltages vary considerably from hour to hour or from day to day, trouble is had with the poor regulation. When the line voltage is high, the filament or heater voltages on the tubes will be high and their life will be short. When the line voltage goes down the voltages on the tubes go down and the receivers do not work properly. Several methods have been worked out to alleviate this difficulty.

One method involves the use of a current regulator or ballast lamp which passes 1.7 amp (876) at any voltage between 40 and 60. The lamp is connected in series with the primary of the power transformer. If the line voltage averages 115 volts, the load is so adjusted that 65 volts appear across the primary of the transformer and 50 volts across the tube. Then when the line voltage varies the voltage drop across the tube varies and the voltage across the primary remains at 65 volts. The chief

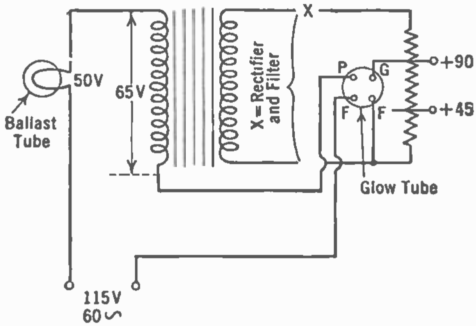


Fig. 259. Ballast tube to maintain constant a-c voltage input to power transformer and glow tube on d-c side to maintain voltage constant in spite of current variations.

difficulty with this tube is its slow action. It requires several minutes for a steady condition to be reached. Other line ballast lamps have been used in the more expensive sets. In the cheap sets the user must take his chances with bad line conditions. In general, tubes have been so engineered that increases of filament voltage do not cause the short life experienced with the old battery types of tubes.

A high-voltage regulator (874) was used to some extent in receiving circuits. This is a gaseous tube of two elements. No current flows until a certain critical voltage across the tube is reached. Then the voltage drop across the tube is maintained regardless of the current taken through it. The glow tube (874) maintains 90 volts across it for current values of 10 to 50 ma.

One method of connecting the glow tube is shown in Fig. 259. It will be noted that the plate and one filament prong of the four-prong socket are connected in series with the line and the transformer primary. Since there are only two elements in the tube, these prongs are shorted within the base. Therefore the circuit in which such a tube is used will not operate until the tube is placed in its socket. The tube thereby acts as a switch preventing operation without the voltage regulator in position to carry out its function.

One of the most prevalent causes for tube failure in service is the varying line voltage conditions under which they must operate. In many towns the voltage at the light socket may vary as much as from 95 to 125 volts with corresponding percentage changes in the tube cathode voltage. In spite of the rough usage they get, home radio receiving tubes, on the average, last well over 1000 hours of actual operating time.

339. Controlled rectifiers. A most important addition to the vacuum-tube family has been made in the thyratron, which is a

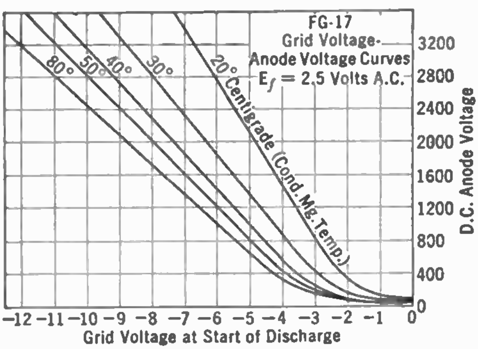


FIG. 260. Characteristics of mercury-vapor thyratron. Note that the temperature of the tube affects the starting voltage.

gaseous rectifier with a control grid. The characteristics of such a tube present many interesting points. For example, if the grid is made negative by the proper amount no current whatever will flow to the plate even though it is positive with respect to the cathode. At any given plate voltage, however, there is a value of grid voltage which will permit current to flow—and when this occurs all the current the tube can possibly create will flow, unless it is restricted in some way.

In other words, all the current flows, or none of it. There is another interesting characteristic. Once the current begins to flow, the grid has lost control over it and negative voltages on it make no difference—the current still flows. The only way to stop the flow of electrons from cathode to plate is to remove the positive voltage from the plate.

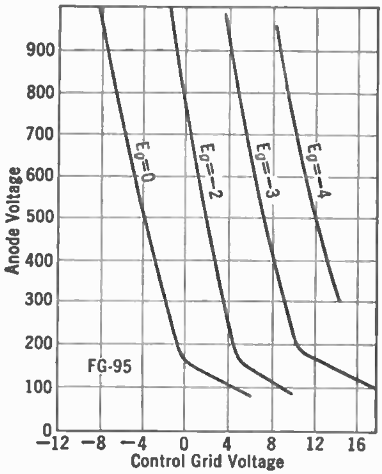


Fig. 261. Characteristics of shield-grid thyratron. Note that various starting voltages are possible, depending upon voltage of shield grid.

Thus the tube acts like a relay and can be used to key a radio transmitter or for any other purpose where the proper voltages and sequence of voltages may be applied.

Now suppose we place a-c voltages on the plate and a fixed bias on the tube. Whenever the plate has reached the point in the positive half-cycle such that its positive voltage is high enough to overcome the inhibiting effect of the grid, current will flow. Then, at the end of the cycle, the plate becomes negative with respect to the cathode and current flow stops. By adjusting the bias on the grid the point in the cycle at which current starts may be controlled—but it will flow throughout the rest of that half-cycle.

Now if alternating voltage is placed on the grid as well as the plate and if the phase between grid and plate is adjusted, any amount of average current may be taken from the tube, from zero to the maximum cathode emission permissible. Thus the thyratron is a gaseous rectifier, with low internal voltage drop which can supply many amperes of current under the control of the user by means of the variable phase between voltages on grid and anode.

The thyratron is becoming of considerable importance in non-communication applications, as in the control of power. In broadcast stations and elsewhere in the radio system the useful characteristics of the tube are becoming recognized and are being put to work.

340. Relay tube. The OA4G is a gaseous triode useful for relay services. In an envelope filled with an inert gas or vapor at low pressure are a cathode, an anode, and a grid. The cathode is cold, that is, there is no heated filament or heater to supply electrons. The grid is a starter electrode, to initiate and control the gaseous discharge. A relatively small voltage on the starter electrode starts the discharge between starter electrode and cathode. This discharge ionizes the inert gas and enables a discharge between cathode and anode to take place. This is the discharge which performs the work required of the tube, such as closing a relay.

The first use to which this tube was put was remote operation of a radio receiver. A very small amount of energy is required to start the initiating discharge. This energy was transmitted over the power lines to the tube which was located within the radio receiver itself. The remote-control energy was generated at radio frequencies and the power lines were utilized as the carrier of this controlling energy.

The tube may also be used as an oscillator of non-sine waves or as a voltage regulator.

In the remote-control function, the starter electrode is maintained at a voltage just below that required for breakdown. In Fig. 262 this voltage is supplied from the power lines by R_1 and R_2. A tuned circuit with a high Q made up of L and C has a considerable voltage across it when a carrier of the proper frequency is impressed on the line at the distant point. This voltage increases the potential between cathode and starter electrode, and this starts the discharge which flows between cathode and anode and closes the relay. The tube ceases to pass current when the carrier is removed, since the tube is supplied with alternating current.

An interesting application of remote-control circuits is the "alert" receiver by A. F. Van Dyck and his associates at the RCA License Laboratories. By means of this device home radio receivers could be turned on automatically by the operators at a distant broadcast station. The alert receiver merely acted as a

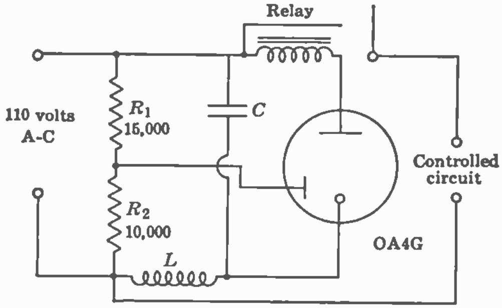


FIG. 262. Use of gas tube in a remote-control circuit.

switch which, operated by a signal from the transmitter, closed the a-c circuit into the broadcast receiver. This was accomplished in the following manner. At the broadcast station, certain low frequencies were used to modulate the transmitter. These frequencies were lower than could be made audible by the average loud speaker, perhaps 20 cycles or somewhere in this region. At the remote listening station, a circuit—electrical or mechanical—was resonant to this low frequency. The resonant voltage operated the OA4G and thus the home receiver was turned on.

The applications of such a system for police or fire alarms or for summoning the people in times of national or local distress are obvious.

CHAPTER XVII

OSCILLATORS, TRANSMITTERS, ETC.

Because a tube acts as an amplifier, it can be made to generate alternating currents of constant amplitude and at frequencies covering the entire range from one or two cycles per second to well over 300 million cycles (one meter). Because the energy in the plate circuit of the tube is greater than exists in the input or grid circuit, some of this energy can be fed back by several ways into the input circuit and there amplified again. Starting with an initial oscillation in the grid or plate circuit, provided the coupling between input and output circuits is of the proper phase and magnitude, this oscillation can be repeated and amplified, until finally the tube maintains stable oscillations without the necessity of exciting the grid from any outside circuit.

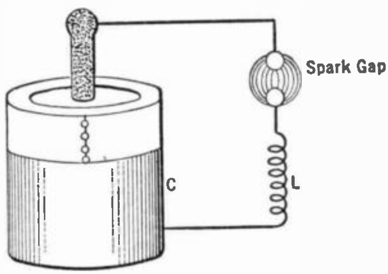


FIG. 263. Leyden jar, an early form of condenser.

Before endeavoring to learn how a tube oscillates, etc., we should get an idea of what the term oscillation means.

341. Oscillating circuits. One of the most famous experiments in all radio history is that of charging a condenser and letting it discharge through a resistance and an inductance. If the resistance takes the form of a gap (Fig. 263) in the circuit across which a spark jumps, a photograph of this spark made on a rotating-mirror oscillograph shows that during the instant of discharge the spark jumps back and forth across the gap several times, first in one direction and then in another. In other words, the current in the condenser surges back and forth across the gap instead of making one spark and thereby thoroughly discharging the condenser.

Now such a circuit will produce an oscillatory spark in the manner just explained if the resistance, inductance, and capacity have correct values. When such an oscillatory spark takes place,

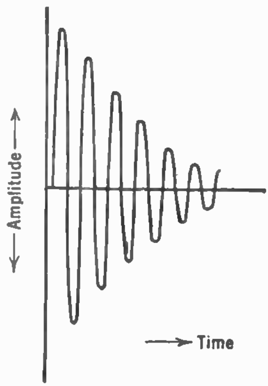


FIG. 264. Highly damped series of waves.

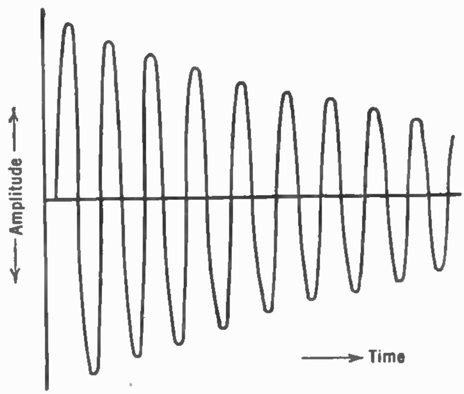


FIG. 265. Slightly damped (low-resistance circuit) waves.

electric waves are set up in the ether. These waves have a frequency determined by the well-known expression:

$$f = \frac{1}{2\pi \sqrt{LC}}$$

If the resistance is too great, the spark will not set up such waves. The circuit is then non-oscillatory. If the resistance is decreased to a very low value, the number of oscillations that take place before the spark finally dies out becomes very great.

Thus in Fig. 264 the circuit has a high resistance; only a few oscillations take place and these at a rapid reduction in amplitude, each from the other. In Fig. 265 the resistance is very low and many oscillations take place, the amplitude falling off slowly. A circuit with much resistance is called **highly damped** because the waves decrease in amplitude—are damped out by the resistance—at a rapid rate. An **undamped** or **continuous** wave is generated by a theoretical circuit with no resistance, or one in which there is a device which supplies the power dissipated in the various resistances. With a given circuit, if the resistance can be reduced to zero through some means—adding a negative resistance, for example—the damping factor due to the resistance is wiped out and the circuit generates continuous-amplitude or undamped waves.

342. The amplifier as an oscillator. Consider the box in Fig. 266, which is an amplifier. Any voltage put into it reappears in the output magnified by the amplification factor of the device. Suppose that the input is composed of a coil and condenser, and that part of the output voltage can be coupled to the input coil. At the start suppose this coupling coil T, commonly called a tickler, is short-circuited, or removed from the input coil. Now if the condenser C is charged and then allowed to discharge suddenly by closing the key, K, oscillations will be set up which will die out at a rate depending upon the resistance of the coil and condenser.

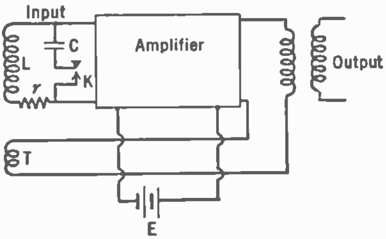


Fig. 266. Essentials of an oscillator—an amplifier with feedback from output to input.

In the output circuit of the device will reappear an amplified version of these oscillations. They too will die out. The energy in them comes from some local battery, E, and the oscillations in the input circuit only serve to release some of this local energy. Now couple the tickler coil to the input in such a manner that the voltage induced into the input coil by ordinary transformer action is in phase with the oscillatory voltage. Then when the switch is closed, a voltage appears across the input, is amplified in the device, and in amplified form is impressed back on the input. This will cause an increase in the oscillatory voltage, and so the effect will be an ever-increasing series of oscillations, as in Fig. 267.

Ordinary oscillations are started in a tube circuit by thumping the tube, or by turning on the plate battery, or by any sudden change in the electrical or mechanical constants of the circuit.

Oscillations in some circuits require appreciable time to build up to their final value. For example, a loud speaker which feeds back mechanically into the elements of an amplifier may finally result in a steady howl. These elements may be those of a tube, or the plates of the tuning condenser (especially in short-wave sets). A tone from the loud speaker sets in motion the plates, let us say, thus changing the tuning. This change takes place at an audio rate depending upon the natural mechanical frequency of the element in question. This audio tone is amplified by the following tubes and finally comes from the loud speaker. The vibrations from the loud speaker strike the plates and set them into even greater vibrations and finally the whole system howls, or oscillates at an audio rate. Microphonic tubes, particularly those with very small filaments, are prone to "bongs" which may be amplified and lead to steady howls which take a second or two to build up to final intensity.

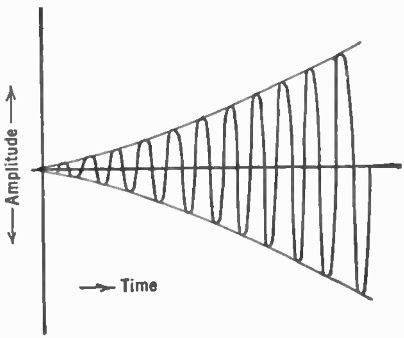


Fig. 267. Building up of oscillations in resistanceless circuit.

Oscillations depend upon the coupling between output and input, upon the fact that the device, usually a tube, can amplify, and the fact that a combination of inductance and capacity exists of such values that the oscillations have the desired frequency. It is more difficult to start and to maintain oscillations in a high-resistance circuit.

343. Maximum oscillatory plate current. The oscillating tube may be thought of as an amplifier in which the exciting or input voltage which is amplified comes from the tube itself; in other words, it is a self-excited amplifier. An alternating current flows in its plate circuit just as in any ordinary amplifier. What is the maximum value of this current?

Consider the tube working at the point A in Fig. 268. When oscillations start, the alternating plate current increases from a

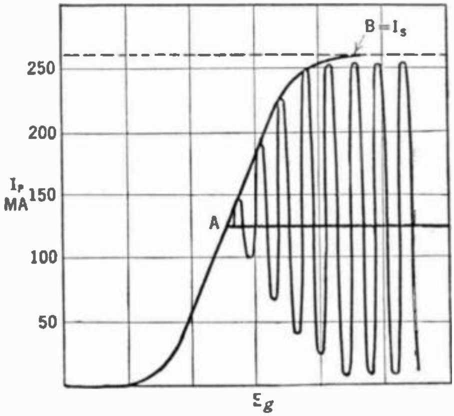


FIG. 268. Manner in which oscillations beginning in tube circuit build up until entire characteristic of tube is utilized.

small value during the first few oscillations until it goes from zero to double the d-c value at A if a sine wave is being generated, or until the plate current curve flattens out. Then an increase in excitation does not result in an increased alternating plate current. The limit has been reached for the alternating plate current.

If the current at B is the saturation current, I_s, of the tube, the peak value of the alternating plate current will be

$$i_p = \frac{I_s}{2} \qquad [1]$$

and because the alternating plate current is equal to the a-c grid voltage multiplied by the mutual conductance of the circuit, or $i_p = g_m e_g$,

$$e_g = \frac{I_s}{2g_m} \quad [2]$$

which is also equal to the voltage induced in the grid coil by an alternating current flowing through the plate coil of Fig. 269.

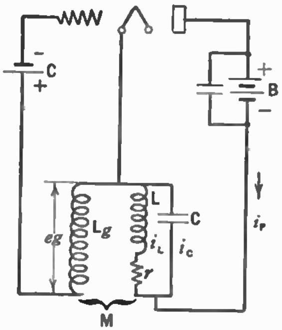


FIG. 269. Tuned plate crcuit (grid tickler) oscillator.

This voltage is the current in the oscillatory circuit multiplied by the mutual reactance, or

$$e_g = i_L M\omega \quad [3]$$

from which we can calculate the current through this coil,

$$i_L = \frac{e_g}{M\omega} = \frac{I_s}{2g_m M\omega} \quad [4]$$

$$= \frac{I_s}{2\sqrt{2}g_m M\omega} \quad \text{(rms)} \quad [4a]$$

Example 1–17. Suppose the saturation current of a power tube is 100 ma (a low figure) and the other constants in Fig. 269 are $L = 500\ \mu\text{h}$, $r = 10$ ohms, $R_p = 7150$ ohms, $g_m = 0.76 \times 10^{-3}$, $M = 160\ \mu\text{h}$, $f = 100$ kc. What is the peak and rms oscillatory current, that is, the current through the inductance, L, and what is the grid voltage due to this current?

Solution:

$$i_L = \frac{I_s}{2g_m M\omega}$$

$$= \frac{100 \times 10^{-3}}{2 \times 6.28 \times 100{,}000 \times 0.76 \times 10^{-3} \times 160 \times 10^{-6}}$$

$$= 0.655 \text{ amp} = 0.465 \text{ rms}$$

$$e_g = i_L M\omega$$
$$= 0.655 \times 160 \times 10^{-6} \times 6.28 \times 10^5$$
$$= 66 \text{ volts}$$

Problem 1–17. The voltage across the condenser in the tuned circuit of the above example is equal to the current through it (which differs but little from i_L) times the reactance of the condenser at the resonant frequency. Calculate the voltage across the condenser. The power used up in heating the resistance of the coil is $(i_L)^2 \times r$. Calculate this power (use the rms value of i_L). Let this be called the useful power supplied by the tube. The power from the plate battery is the product of the plate voltage and the plate current $= I_p \times E_p$. If the steady plate current is 50 ma and the efficiency of the system is 50 per cent, calculate the plate voltage necessary.

Modern tubes have such high values of saturation current that they are never operated at the point at which the direct plate current is half the saturation value. Instead, they are so biased that the average value is such that the power dissipated on the plate is within the limits of safe heating. Then if sine waves are generated, the maximum value of the alternating plate current is twice the value read on the d-c meter. This value should be used in problems and examples instead of the saturation value. For example, a UX–210 has a saturation current of an ampere or more, but such a tube could never be operated so that the direct plate current would be of the order of 500 ma. Instead it is usually less than 100 ma.

344. Conditions for oscillation. There are numerous oscillatory circuits. All depend upon some means of coupling some of the output energy back into the input in the proper phase. In the circuit in Fig. 269, the plate circuit has a tuned circuit in it. The inductance of this circuit is coupled to an inductance in the grid circuit. Proper phase is secured by coupling these two coils together in the correct way (reversing one coil will stop oscillations), and proper amount of feedback voltage is controlled by varying the coupling between the plate and grid coils. If the coils are separated, oscillations will not occur. As coupling is increased, at some point oscillations will suddenly occur and will continue so long as this coupling is maintained at or near the same value. It may be increased or it may be decreased somewhat without stoppage of oscillations but too great a change will cause interruption of oscillations.

The minimum value of coupling between the coils is equal to

$$M = \frac{L}{\mu} + \frac{CrR_p}{\mu} = \frac{L}{\mu} + \frac{Cr}{g_m}$$

Now all the factors in this equation are positive with the exception of M which may be either positive or negative depending upon how L is coupled to the grid coil. When it is connected so that oscillations occur, M is negative, and so the resistance r in the oscillatory circuit is decreased. If the coupling coil is reversed, the total resistance in the oscillatory circuit is increased, and sustained oscillations cannot be built up. By making L, C, and M have the proper value, we can either add resistance to the oscillatory circuit—and then no oscillations are possible—decrease the total resistance to zero, or make it negative.

A useful approximation is that the oscillatory current, i_L, is equal to i_p multiplied by the Q of the circuit.

The better the tube, that is, the greater its transconductance g_m, the looser can be the coupling and still maintain oscillations; with a given tube whose mutual conductance is fixed, and with a given coil-condenser combination, a certain mutual inductance is required to start and maintain oscillations; the greater the resistance in the tuned circuit the higher the transconductance of the tube required to maintain oscillations with a given mutual inductance between grid and plate coils.

Problem 2-17. The mutual conductance of a power tube is 1500 micromhos, its amplification factor is 7.6 and its plate resistance is 3500 ohms. It is desired to generate oscillations of a frequency of 1000 kc. The coil to be used in a tuned plate circuit, as in Fig. 269, has an inductance of 200 μh and a resistance of 30 ohms. Calculate the mutual inductance required to maintain oscillations. If the peak plate current is 100 ma: What is the maximum current, i_L, that can exist in the oscillatory circuit? If the power in this oscillatory circuit is $i_L^2 \times r$ and r is its resistance (30 ohms) what is the power dissipated there?

345. Effect of coupling. If such a circuit as shown in Fig. 269 is set up in the laboratory, it will be found that oscillations occur over a rather wide range of coupling. Anyone who has operated a regenerative receiver for short, medium, or long waves knows that the loudest signals are received just before the tube stops oscillating because of too loose coupling between the secondary or grid coil and the tickler.

Looking at formula (3) we see that the induced grid voltage, due to the oscillatory current, is proportional to the coupling between the grid and plate coils. This induced voltage must be at least equal to the original voltage there due to the condenser discharge in order that the oscillations may be built up. If the induced voltage is less than the original voltage, oscillations will last longer than if the tube were not present, but they will finally die out. The effect is as though we had reduced the resistance in this oscillatory circuit but had not completely removed it. When the induced voltage is equal to the original voltage, we have in effect reduced to zero the resistance of the circuit, and oscillations can keep up, although feebly. If, now, the induced voltage is increased, all the losses in the input circuit will be neutralized by the power taken from the local batteries (the plate battery) and continuous oscillations will take place, gradually increasing in amplitude until the entire characteristic of the tube is used.

If we start oscillations, and then decrease the coupling, and if e_g (induced) is to remain the same, the oscillatory current must *increase*. Thus, when the coupling is loosened, but not enough to stop oscillations completely, the oscillatory current actually increases to make up the loss in induced voltage due to the decreased coupling. When the whole plate current characteristic is used by these oscillations, further decrease in coupling must decrease the exciting grid voltage, e_g, and oscillations cease.

If, on the other hand, the mutual inductance is increased, oscillations rise to a maximum and then fall off and finally cease entirely. The reason in this case for cessation of oscillations is different from the above reason. It is due to an increase in the effective resistance of the tuned circuit, so that greater exciting voltage is necessary to overcome the increased losses.

346. Dynamic characteristics. Because a change in grid voltage produces a change in plate voltage—just as in a resistance-coupled amplifier (Section 179), we cannot use the static characteristic curves to predict the action in the tube. We must use the dynamic curves. In Fig. 270 are the static characteristic curves of a low-mu oscillator tube. When the grid voltage increases in a positive direction owing to the exciting or induced voltage, e_g, the plate current increases but the voltage actually on the plate decreases because of the greater IR drop in voltage across the plate load. The operating point then may move along a curve like the dotted line. Because of the decreased slope of the dynamic curve compared with the static characteristic, the transconductance has decreased too, and it is not strictly correct to use the static value in equations (1), etc. It is approximately correct, however, unless the load in the plate circuit has a very high effective resistance, for example, a tuned circuit. In practice this load is made up of not only the resistance always in the circuit but also the resistance "reflected" into it by transformer action by coupling an antenna to the plate coil by means of a mutual inductance.

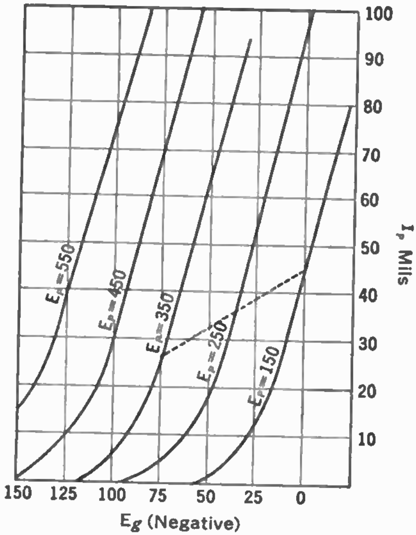


FIG. 270. Characteristic curves of power oscillator tube. The dashed line is the dynamic curve used when the tube oscillates.

The oscillator differs from an amplifier only in the fact that the grid voltage is derived from its own plate circuit instead of from an external source.

347. Efficiency of an oscillator. As in an amplifier when the grid is not excited, the power taken from the plate battery of a tube is equal to I_pE_p, and this power is dissipated in heating the plate of the tube. When oscillations take place the plate current and plate voltage vary about their average or non-oscillating values. The power taken from the battery does not change, but the power wasted in heating the plate decreases, part of it going into the load, just as in an amplifier.

If the operating point is such that when the tube oscillates its maximum alternating current is twice the value read in a d-c meter and once in each cycle is just reduced to zero-plate current, the efficiency is 50 per cent. In Fig. 268 the average plate current is 0.125 amp. The minimum value it can reach is zero and the greatest value it can reach is twice this value or 0.25 amp. At the same time the plate voltage variations are from zero to twice the average value. In other words, the variations in plate current are 0.125 amp plus and minus 0.125 amp, and the plate voltage is E_p volts plus and minus E_p volts. This is an a-c voltage whose maximum value is E_p volts, and an alternating plate current whose maximum is 0.125 amp.

The power, as in a resistive a-c circuit, is the product of the effective current and the effective voltage, or

$$P = \frac{E_p}{\sqrt{2}} \times \frac{I_p}{\sqrt{2}} = \frac{E_pI_p}{2}$$

and since the power supplied by the plate battery is E_pI_p, one-half the power taken from the battery is wasted in the tube and one-half is used in overcoming the resistance losses in the oscillatory circuit.

If we rate the efficiency of the plate circuit as the ratio between the total amount of power taken from the B battery, I_pE_p, to the power used in the oscillatory circuit, $E_pI_p/2$, we see that the above condition represents an efficiency of 50 per cent.

If the C bias of the tube is so adjusted that the operating point goes down on the lower bend, the steady plate current is small, and the power taken from the battery is small. As shown in Fig. 271, plate current flows only when the grid gets sufficiently positive to permit it, that is, when the operating point gets up far enough on the plate current curve for current to flow. Thus current flows during only a part of the cycle, and because the a-c components decrease less rapidly than the average value of current, the efficiency may increase above 50 per cent.

348. Harmonics. If a large C bias is used (as in a Class C oscillator), the form of the oscillatory current is no longer a sine wave and of course many harmonics are generated. Thus an

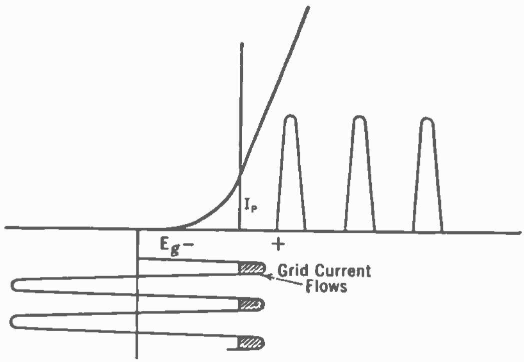


FIG. 271. Form of plate current waves when the tube is so biased that current flows in plate circuit on positive half-cycles of grid voltage.

oscillator generating a wave form like that in Fig. 271 may be thought of as an oscillator producing a pure sine wave plus many harmonics. If the oscillator is used to supply power to an antenna which is tuned to the fundamental frequency, these harmonics put little power into this antenna provided it is coupled loosely enough to the tuned circuit. This is due to the fact that the antenna is not in tune with the harmonic.

On short waves this is of great importance, because of the carrying power of high frequencies. Thus if a tube oscillates at 40 meters and puts out even a comparatively weak second harmonic on 20 meters, the latter signal can be heard over an area of many hundreds or even thousands of miles. A broadcasting station operating on 500 meters with a strong second harmonic can ruin another station's program operating on 250 meters, and so on.

There are times when it is desirable to generate a wave form that has many harmonics, or a particular harmonic of large amplitude. For example, a quartz plate may be used to control the frequency of a transmitter. Because the thickness of the quartz plate varies inversely as the frequency, for a high-frequency circuit the quartz is very thin and there is danger of its breaking. For this reason a thicker plate is used and a harmonic of the oscillator which it controls is used to drive a power amplifier which works into the antenna. The quartz circuit, then, is an oscillator which should generate a large second harmonic. By suitably adjusting the C bias such an output can be attained.

Such a highly biased tube will have strong harmonics of much higher order than the second, and if the frequency of the quartz plate is known these higher harmonic components of the output of the tube can be used as standards of frequency over a very wide range. It is frequently possible to count up to the 50th harmonic of such a circuit. Thus if the oscillator fundamental frequency is 500 kc, the tenth harmonic would be 5000 kc, and the fiftieth would be 25,000 kc.

349. Power output of an oscillator tube. The power output from an oscillating tube depends upon the efficiency of the circuit and the amount of power that can safely be dissipated at the plate. If the circuit is 50 per cent efficient and if the tube can safely dissipate 50 watts on the plate, the output power is evidently 50 watts. If, however, a high C bias is used and a larger plate voltage, the steady power taken from the battery may increase appreciably but a smaller proportion of it is lost in the tube and, of course, more power into the load (the tuned circuit) obtained. Thus if the tube is 70 per cent efficient, and can dissipate 50 watts internally, the output power can be 117 watts and the total power supplied by the battery 167 watts.

When an amateur manages to put into his transmitting tube twice the power for which it is rated, he may still be operating the tube as required by the manufacturer. He has increased the efficiency of his circuit by operating at a high C bias, and by making his output far from sine wave in form. The power lost on the plate may still be within the manufacturer's limit, and the power obtained from the plate voltage supply unit and usefully employed in putting signals into an antenna may be considerably increased. If, however, his tube stops oscillating suddenly, because of some maladjustment, the full plate battery power must be dissipated at the plate and it is quite likely to be melted and the tube destroyed.

Problem 3–17. An amateur desires to get 100 useful watts from a so-called 50-watt tube. This means that 50 watts can be safely dissipated at the plate. How efficient must his circuit be? If the plate voltage is 1000 volts, what will be the plate current? If his antenna has a resistance of 60 ohms at 40 meters, what antenna current must be put into it to radiate 100 watts?

Problem 4–17. The grid voltage necessary to excite a given transmitting tube is 100 volts. The frequency is 500 kc, the tuned circuit inductance, L_2, is 200 μh, the coefficient of coupling between grid coil and tuned circuit inductance is 0.3, the current in the tuned circuit is 1 amp. What must be the inductance L_g of the grid coil?

$$E_g = M\omega i_L = M\omega \times 1.0$$
$$M = \tau \sqrt{L_g L_2} = 0.3 \sqrt{L_g L_2}$$
$$\omega = 2\pi \times 500{,}000$$

Problem 5–17. The resistance of the tuned circuit when coupled to an antenna is 30 ohms. Its inductance is 300 μh, the mu of the tube is 8, its plate resistance is 5000 ohms, the frequency is 300 kc. What must be the value of M to make the circuit oscillate? On the assumption that the current in the oscillatory circuit is Q times the steady plate current (50 ma) calculate the current through L.

Problem 6–17. The normal plate current of a transmitting tube is 125 ma at a plate voltage of 1000. If the circuit is 65 per cent efficient, how much can the plate current be increased at this voltage without using more than 50 watts on the plate? What is the input and the output power under these conditions?

It is possible to get circuits of high efficiency by increasing the C bias so that plate current flows only during a part of the cycle when the grid is positive. At these times the plate current is high, but at the same time the voltage actually on the plate is low, because the grid and plate voltages are 180 degrees out of phase and because of the high voltage across the load when the current is high, and so the power wasted at the plate is low. If the voltage at the plate could be reduced to zero no power would be lost there and the efficiency would be 100 per cent. Such conditions cannot happen, of course.

350. Maximum power output of oscillator. As in an amplifier, the maximum power is converted from the battery to the load when the load resistance is equal to the tube plate resistance. Thus in Fig. 269 the effective resistance of the load is $L^2\omega^2/r$ which must be equal to R_p for maximum power output. This is not the condition for maximum efficiency, but is the condition for maximum power output under a given set of conditions. As a matter of fact the efficiency under these conditions is 50 per cent.

If the oscillator tube is operated as Class C, as it usually is, the plate resistance of the tube varies over the cycle appreciably. When the plate voltage is high, the plate resistance is low; when the plate voltage is low the plate resistance is high. Therefore it is difficult to use the expression above for computing the best value of the tuned circuit anti-resonant effective resistance.

351. Obtaining grid bias by means of resistance leak. During the part of a cycle when the grid is positive (shaded area in Fig. 271) the grid draws current. When the grid is negative it takes no current. There is in the grid circuit, then, an average grid current. This current can be made to flow through a resistance and, as in a detector tube, be used to maintain the grid at a negative potential with respect to the filament. Since grid current flows, it follows that some power must be wasted in the grid circuit. This power is that wasted in the grid leak, usually of the order of 5000 to 10,000 ohms, and that wasted in the grid-filament resistance of the tube itself. This power must be supplied by the plate battery. The over-all efficiency of the tube and circuit is lower than if no grid power is required. If the current is permitted to become very high the power dissipated in the grid may become too great for the grid to dissipate which may melt or begin to emit electrons. Or, on very high frequencies, the current flowing through the grid lead may heat or expand this lead and cause trouble. In high-frequency circuits, the grid-filament capacity has low enough reactance to conduct currents of considerable magnitude. These currents must flow through the grid-filament input resistance, and this represents another loss in power which must be kept below the value that is safe for the tube. A choke coil placed near the grid leak is one way to prevent unwanted oscillations occurring at a very high frequency partially determined by the tube capacities. (See Fig. 272.)

Problem 7-17. The grid bias required on a tube is 60 volts. If the bias resistance is 5000 ohms, what must be the grid current flowing? What power must the resistor be capable of dissipating as heat?

352. Practical circuits. There are a number of circuits by which an amplifying tube will produce oscillations, that is, transform d-c power from a battery or plate supply system into a-c power. All that is necessary is a tube that will amplify, coupling between input and output of proper phase and magnitude, and, of course, the filament, grid, and plate power.

The coupling between input and output can be through inductance, mutual inductance, capacity, or resistance, or through the plate-grid capacity of the tube itself.

353. Hartley oscillator. The simplest circuit, that is, the circuit which requires the least amount of apparatus, is the Hartley, Fig. 272. It requires only a coil with taps on it, a tuning condenser, the tube, and power supply. The coupling between plate and grid circuit is through mutual inductance between the two parts of the tuning coil, L_p and L_g. If the tuning condenser is placed only across the plate circuit, the circuit is exactly the same as Fig. 269. Alternating currents flowing in the plate coil, L_p, induce voltages in L_g, which are applied to the grid, amplified, and again applied to the plate coil. These voltages are 180 degrees out of phase because they are at opposite ends of the coil with the center grounded to the filament. In Fig. 272 the plate battery is placed in the center tap so that it is at ground potential. In Fig. 269 the plate battery, which has a high capacity with respect to ground, is connected to the plate and thereby partially shorts the plate of the tube so far as radio frequencies are concerned. A better way is to use the circuit in Fig. 273. Since this circuit would make the grid and plate at the same positive potential, which is the potential of the B battery, the grid is isolated, so far as direct current is concerned, by the blocking condenser. The proper bias voltage is secured through a grid leak to the filament or through a choke and C battery as in Fig. 273. The feedback between grid and plate circuits is

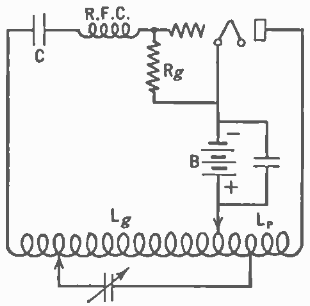


FIG. 272. Hartley oscillator. Grid current through R_g provides negative bias for the grid; choke R.F.C. prevents high-frequency oscillations.

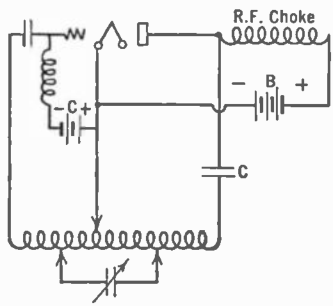


FIG. 273. Shunt-feed Hartley oscillator keeps high d-c voltage from the tuning condenser plates.

adjusted by varying the center filament tap. If more turns are in the plate coil a greater voltage will be induced into the grid coil ($L_g\omega I$) and so greater feedback from plate to grid circuits would result.

For covering a wide range of frequencies with plug-in coils, the Hartley oscillator is useful. It is used most frequently in laboratory apparatus.

354. Shunt-feeding oscillators. In Fig. 272 the B battery is in series with the plate coil. The terminals of the condenser, so far as direct current is concerned, are at the same voltage as the B battery and, of course, this is exceedingly dangerous since the operator, who is standing on the ground to which minus B is attached, may touch the plates or shaft of the condenser, and thereby provide a short within himself for the full plate voltage.

To prevent trouble of this kind the plate voltage may be fed into the tube through a separate path by means of a choke coil and blocking condenser as shown in Fig. 273. Now the d-c potential of the plate is kept from the tuning coil and condenser by the condenser *C*. The reactance of the condenser must be low compared with the reactance of the choke at the desired frequency so that the r-f current goes through the plate coil rather than through the plate power supply.

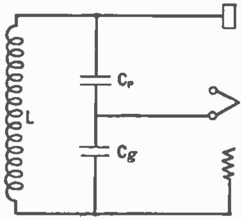


FIG. 274. Fundamental Colpitts circuit.

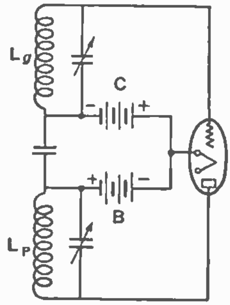


FIG. 275. Practical Colpitts circuit.

In a similar manner the use of a blocking condenser in the grid circuit and a choke for feeding the C bias into the grid is a shunt or parallel feed method of separating the direct and alternating currents and voltages. In Fig. 273 there are no direct currents or voltages on the tuning circuits, nor alternating currents in the C or B batteries.

355. Other oscillating circuits. If the inductances and condensers in Fig. 272 are interchanged, as in Fig. 274, we have the Colpitts circuits, a typical arrangement of which is shown in Fig. 275. In amateur practice the tuning condensers are on the same shaft which is grounded to the filament. The plate and grid d-c voltages are shunt fed under these conditions. Note that the full plate and grid battery voltages in series are across the fixed condenser between the grid and plate coils. This condenser must be able to stand this high voltage without breaking down.

In Fig. 276 is the tuned plate-tuned grid circuit. Input-output coupling is provided by the tube's grid-plate capacity—one of the few places in radio circuits where this unwanted and obnoxious capacity is put to use. Whenever the plate circuit is tuned so that it is sufficiently positive in reactance, the system will oscillate, and it is not when the plate and grid are both tuned to the same frequency as many amateurs think. Tuning the plate circuit to a higher wavelength or lower frequency than the grid is the same thing said in other words. This is because an inductive load in the plate circuit reflects a negative resistance into the grid circuit. If the plate circuit load is capacitive the tube is degenerative and it will not oscillate. This circuit has somewhat greater frequency stability because of the high-impedance plate load. In practice the C bias would not be shunt fed.

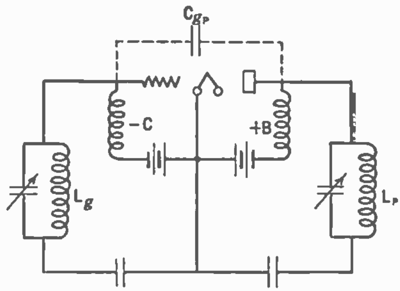


FIG. 276. In the tuned plate-tuned grid circuit C_{gp} acts as the feedback agency.

A resistance feedback that is employed in laboratory oscillations is shown in Fig. 277. As in all such circuits, the grid excitation is greatest when the largest coupling between grid and plate coils is used. Then the plate current variations are considerable in magnitude, they use curved parts of the characteristic, and harmonics are generated. In a laboratory oscillator where harmonic production is to be kept to a minimum, the coupling between input and output circuits should be adjusted at each frequency to the least possible amount that will insure stable

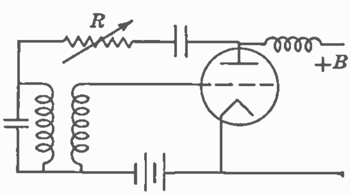


FIG. 277. Circuit often used in low- (audio) frequency oscillators. Feedback is provided by resistance, which also loads up the plate circuit and straightens out the E_g–I_p characteristic.

oscillations. The resistance feedback method is useful in such oscillators because of the mechanical ease of adjusting the feedback voltage. The feedback resistance increases the total resistance in the plate circuit and variations in tube resistance due to voltage variations are not so important. The circuit is, therefore, more stable.

In Fig. 277 the coils are iron-core inductances and the currents generated are at audio frequencies.

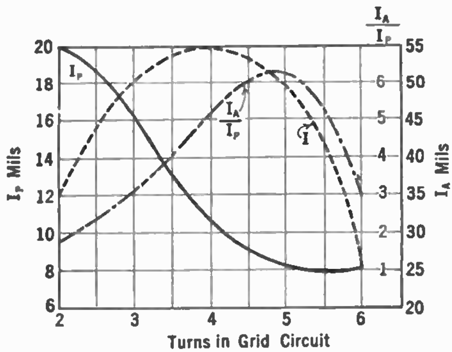


FIG. 278. Effect of varying grid turns, thereby changing excitation.

356. Adjusting the oscillator. When the oscillator is used to deliver power to an antenna it is desirable to attain the adjustment which will either deliver maximum output, or secure maximum efficiency so that greater inputs may be used. The tuned plate-tuned grid circuit has no adjustments. The operator tunes either the plate or grid circuits until the tube oscillates and there is nothing else he can do. In fact, if he does not tune the circuit to an oscillating condition the plate current may be very high unless the grid is biased with a battery and not through a grid leak and condenser.

In the Hartley circuit, however, it is possible to move the center filament tap and so to get some control over the strength of oscillations, the feedback voltage, etc. In Fig. 278 is illustrated the result of varying the filament tap on a simple 40-meter oscillator of the Hartley type. The curve gives the plate current, I_p,

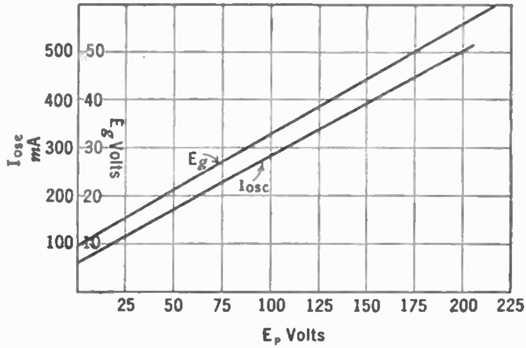


FIG. 279. Relation between plate voltage and oscillatory current and grid bias.

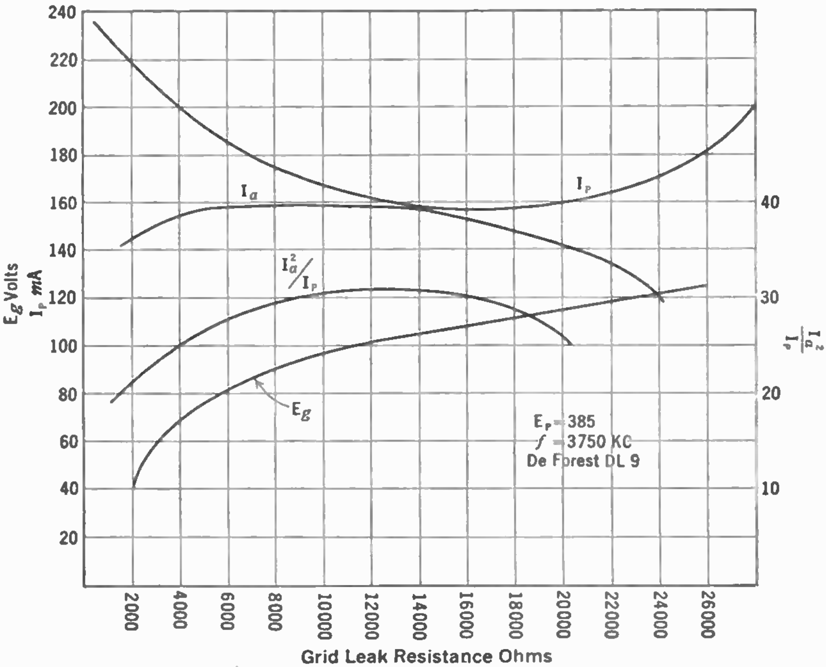


FIG. 280. Effect of varying grid-leak resistance.

the current, I_a, into an antenna coupled to the plate coil, and the ratio of antenna current to plate current as some measure of the efficiency of the circuit. What is wanted, from an amateur's standpoint, is much antenna current and little plate current. The greater is this ratio, the greater is the efficiency of his circuit.

The relation between plate voltage and oscillating current is shown by Fig. 279 to be linear. The grid bias measured across a 5000-ohm resistor is plotted too. The tube was a UX-210 oscillating at 1225 meters in a tuned plate circuit. The effect of changing the C bias resistor of a tube in the tuned grid-tuned plate circuit is shown by Fig. 280.

357. Frequency stability. When such circuits are used for transmission or for laboratory measurements where a constant frequency output is desired, complications set in. The frequency of such circuits is determined chiefly by the inductance and the condenser across it. This condenser is also shunted by the input capacity of the tube. This input capacity is a function of the plate load and the grid-plate capacity of the tube. In fact the input capacity C_i as a function of the load and this grid-plate capacity is

$$C_i = C_{gf} + C_{gp}\left(\frac{\mu R_o}{R_o + R_p} + 1\right)$$

which shows that any change in the plate resistance R_p of the tube, or in the grid-plate capacity of the tube, or the output load R_o produces a change in the grid-filament capacity which may have a share in determining the frequency to which the system oscillates. Changes in filament temperature, in C bias, or in plate voltage will affect the plate resistance of the tube and change its relation to the load resistance. Such changes produce a change in frequency of the oscillator's output.

One way to lessen this difficulty is to make the fixed input capacity of the tube which is across the tuned circuit so large compared with its normal grid-filament capacity that changes in the latter are unimportant. Thus, shunting a fairly large capacity directly across the grid and filament will increase the total effective input capacity so that small changes in the internal capacity of the tube will have little effect upon the tuning. This is accomplished by using a small coil and a large condenser in the tuned circuit, that is, a low L/C ratio.

Such circuits have large circulating currents in them, but small voltages, and at times are very inefficient.

358. Master oscillator systems. Where large amounts of power are to be transferred to an antenna or other load, a single large oscillating tube is replaced by a smaller oscillator and a large power amplifier driven by this tube. In other words, we have a self-excited oscillator and a separately excited amplifier. If the oscillator is carefully stabilized against frequency changes, the output of the amplifier will be constant too. Changes in the load (the antenna, for example) into which the amplifier works will not affect the frequency at which the oscillator is generating.

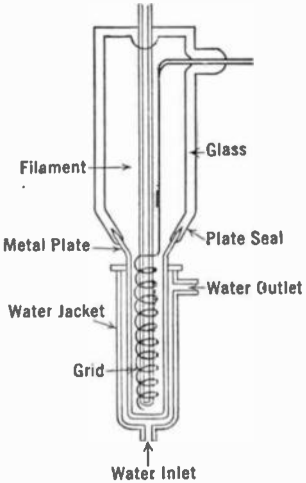


FIG. 281. Construction of water-cooled tube.

Such a system is called a "master oscillator, power amplifier" (MOPA) system and is used in all broadcasting stations and all transmitters of appreciable power. The oscillator can be of any conventional type; the amplifier may be a single tube, or it may be several in parallel, or push-pull, or several in cascade, just as in audio amplifiers. The chief difference lies in the fact that considerable power is being handled and so the circuits are made up of heavy conductors and use large water- or air-cooled tubes which may use plate voltages as high as 10,000 volts and several amperes of plate current.

The amplifiers may be neutralized—usually are—or they may use screen-grid power-amplifying tubes which have very low grid-plate capacities and so need no neutralization.

A simple master oscillator system is shown in Fig. 282. Here the power amplifier is a 50-watt tube which is to be operated at

50 per cent efficiency. That is, 50 watts go into the load, and 50 into the tube. If the plate voltage is 1000 and the instantaneous voltage on the plate is to be just reduced to zero once in each cycle, the peak a-c voltage will be 1000. If the mu of the tube is 25, the a-c grid voltage must be at least 40, and if the inductance of the oscillator plate circuit is known it is a simple matter to calculate the current that must flow through it to set up a voltage of 40 with which to drive the following tube. New tubes

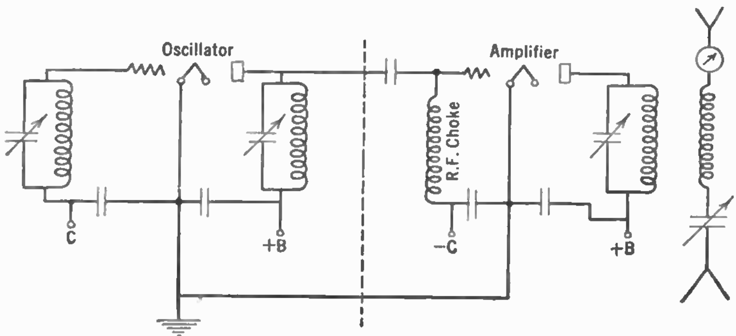


FIG. 282. Master oscillator-power amplifier transmitting circuit.

of the multi-grid type require very little excitation voltage to deliver a considerable power output.

359. Crystal control apparatus. A quartz plate (crystal) cut with proper respect to its optical axis can control the frequency of an oscillator to a remarkable degree. When such a slab of quartz is compressed mechanically, an electrical difference of potential is generated across its two faces. Conversely, when such a difference of potential is set up across its faces, it tends to change its size. It may be thought of as a tuned circuit whose frequency is fixed by the dimensions of the crystal. The thicker it is, the longer the wavelength to which it resonates. The manner in which the crystal is cut is of utmost importance; if it is cut in one manner, the relation between frequency and thickness is 2.64 meters per thousandth inch, and if cut in another, the relation is 3.87 meters per thousandth inch. A crystal quartz plate 1.0 mm thick will resonate to 2860 kc.

If connected as in Fig. 283 it takes the place of the tuned grid coil in the tuned plate-tuned grid circuit. For several degrees of the plate-tuning condenser the output frequency is that of the crystal, and so changes in plate resistance of the tube, battery voltages, etc., will have a relatively small effect on controlling the frequency at which the circuit oscillates.

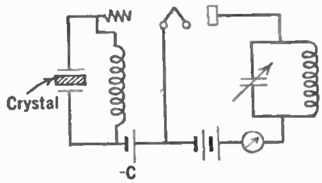


Fig. 283. Quartz plate or crystal in oscillator circuit to maintain frequency of oscillation constant.

The frequency at which the crystal resonates depends to some extent upon the temperature of the crystal. In the best transmitting stations, the crystal plate is maintained at constant temperature by complicated thermostats and electrical heating coils. Then the frequency of a broadcasting station can be maintained within 5 cycles of its assigned frequency, say 1000 kc. This is an accuracy of 5 parts in one million or 0.0005 per cent. The effect of temperature on a small oscillator may be

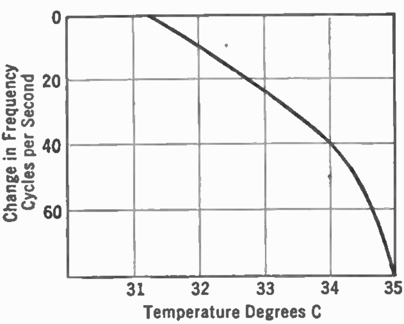


Fig. 284. Effect of temperature on frequency.

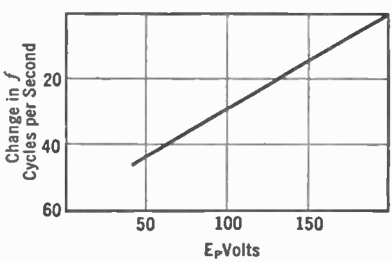


Fig. 285. Effect on frequency of changes in plate voltage of a crystal-controlled oscillator.

seen in Fig. 284, and the effect of changes in plate voltage on the oscillator tube in Fig. 285.

Quite good stability may be secured in an oscillator without using crystals provided certain precautions are taken. The input tuning capacity should be large so that variations in tube input capacity will be negligible in affecting oscillator frequency.

360. Frequency multipliers. The amount of power a crystal can control is limited. If the crystal is called upon to handle too much power it is likely to crack. The power that can be controlled is about the output of a 5-watt tube on broadcast and higher frequencies where the quartz plate is very thin, and certainly not over 50 watts can be controlled with safety.

The crystal oscillator is followed by amplifier stages until the required amount of power is ready for the antenna. These stages of amplification can be single tubes neutralized if necessary; they may be push-pull tubes, they may be tubes in parallel. The purpose of each succeeding tube is to provide a voltage at the required frequency and of the required magnitude to drive the grid of the next tube.

For high frequencies the problem of crystal breakage and that from oscillation in the amplifier stages become serious. The method usually followed is to use a fairly large crystal which drives an oscillator. Let us suppose the antenna is tuned to 40 meters. The crystal may oscillate at 160 meters. The tube is so biased that it generates a strong second harmonic, or 80 meters. This 80-meter output is fed into the grid of the next tube, whose output may be tuned to the second harmonic of 80 meters, or 40 meters. Neither of these amplifiers shows much tendency to oscillate because of the fact that the input and output circuits are tuned to different frequencies. By proper values of C bias a strong harmonic can be secured and the final power tube driven by a 40-meter voltage.

Such transmitters can operate from either alternating or direct current. If they are to be used for telephone transmission, broadcasting, for example, pure direct current is necessary. For code transmission some slight ripple in the output is probably desirable if the signals are to be copied by ear at the receiving station. If they are to operate a relay and mechanical apparatus, the character of the signal may be adapted to the receiving apparatus, or ignored entirely. A "frequency doubler" is shown in Fig. 286.

361. Self-rectified transmitters. When a-c voltages are applied to an oscillator tube, it rectifies them and plate current flows during the time the plate is positive. In other words, the circuit oscillates half the time. On the negative half-cycles the circuit is non-operative. The signal as it is heard at the receiving station has a characteristic note depending upon the frequency of the transmitter power supply and the adjustments at the transmitter. A transmitter of this type is called a self-

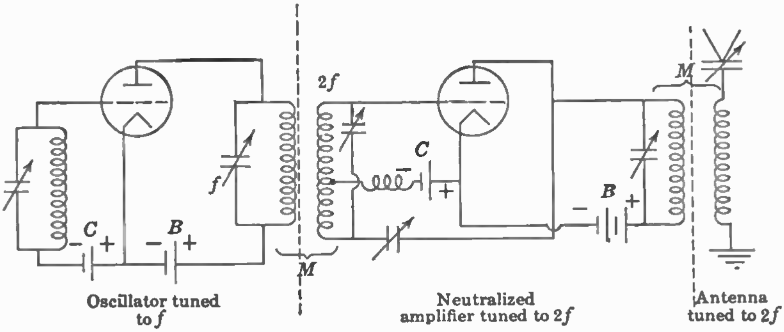


FIG. 286. A frequency doubler. A second harmonic (2f) voltage in the plate circuit of the oscillator drives the following amplifier.

rectified circuit because the tube furnishes its own plate voltage by rectifying an a-c wave. Two such tubes may be used in push-pull or "back to back" to rectify and oscillate on opposite halves of the a-c cycle. The transmitted note then will have double the frequency of a single-wave rectified transmitter.

Such transmitters take up more room in the ether than is desirable, and even though controlled by crystal seem to vary from their assigned channel because of variations in the a-f modulations. A transmitter using 500-cycle source of plate voltage will require a channel width of 1000 cycles when holding the key down. Ether space required for it depends upon adjustments of several factors. Transmitters now are required by law to use pure direct current on the plates of the tubes.

362. Adjusting the oscillator to the load. Although the condition for maximum transfer of power from the oscillator to the load is attained when the load resistance and the tube resistance are equal, this condition is difficult to figure in advance unless the tube is operated as Class A, which is seldom the case. There is a best impedance for the tuned plate or grid circuit, however. This impedance is a function of the resistance, the inductance, and the capacity of this tuned circuit. If the impedance of the tuned circuit (known as the "tank" circuit) is not correct for the tube, but is dictated by other considerations, the tube and load may be coupled by proper transformer action.

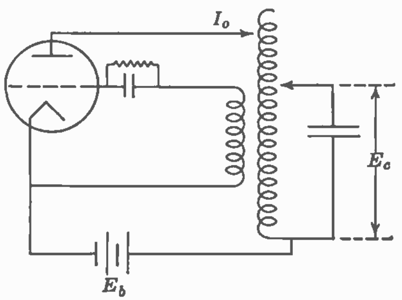


FIG. 287. By means of taps on plate tank coil, the best circuit operating conditions between tube and load can be secured.

Consider the circuit in Fig. 287 which is a tuned-plate circuit with grid feedback. Note that there is a primary and a secondary to the inductance of the tuned circuit, obtained by using this coil as an auto-transformer. By varying the tap connected to the tuning condenser the frequency to which the circuit resonates may be controlled and the ratio of L to C may be fixed for best operation. Then the tap connected to the plate of the tube may be varied until maximum power appears in the tank circuit. Now if an antenna or other load is coupled to the tank coil, the impedance of the tank will change and a new position of the plate tap will be required.

The d-c power supplied to the tube from the plate voltage supply system will be

$$P = E_b I_b$$

The power into the tank will be

$$P_0 = \frac{E_0 I_0}{2}$$

where E_0 is the peak alternating voltage across the tank and I_0 is the peak plate alternating plate current. If this amount of power is being fed into the tank, the effective resistance of the tank must be

$$R_0 = \frac{E_0}{I_0}$$

Since the impedance of the anti-resonant tank circuit is equal to $L^2\omega^2/r$ in which r is the series resistance of the tank inductance and includes the effective resistance of any load coupled to the tank circuit R_0 should equal this value. Since the plate circuit must also supply whatever power is required to excite the grid, these losses must also be included in the effective series resistance of the tank circuit.

Fixation of the plate tap on the tank inductance is a matter of cut-and-try to determine the best operating conditions.

363. Plate current when oscillator is connected to load. When the load is coupled to the tank circuit, power begins to be transferred to the load; and the tube will be required to furnish more power. The tube plate current will rise since more power (E_bI_b) must now be supplied by the plate voltage supply system and this is indicated by a larger flow of current from the system (since the voltage remains the same whether load is increased or not). Therefore the change in plate current may be taken as some sort of indication of the amount of power being fed to the load by the tube.

It is no longer legal to connect an antenna directly to the output of an oscillator but in the days when this was the conventional system, a transmitter operator could judge the approximate power into an antenna in this manner. Suppose the plate current was 100 ma and the plate voltage 1000 volts. This represented a power input to the tube of 100 watts. Now suppose the antenna was coupled to the tank circuit, and suppose the plate current increased to 150 ma. The power to the tubes was now 150 watts. It was assumed that 50 watts was now going into the antenna. This was only roughly true but did provide some indication of the fact that power was going into the antenna.

364. Keying a transmitter. There are several methods of modulating the oscillations of a transmitter so that they may convey intelligence from one operator to another. The tube may be caused to cease oscillations, the antenna circuit may be broken or closed, or the frequency to which the oscillator is tuned may

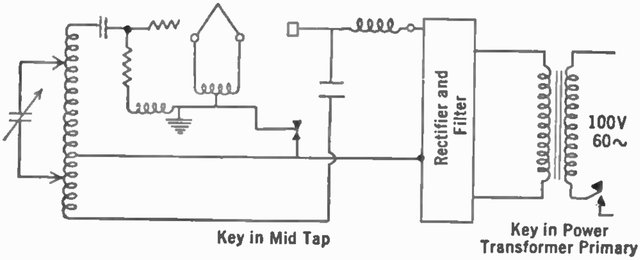


FIG. 288. Keying in "center tap" or in transformer primary.

be changed in accordance with the manipulations of the key. A key placed in the plate voltage supply (Fig. 288) will cut off the power. This method is not successful with well-filtered systems because of the time taken to discharge completely the condensers. An alternative place for the key is the grid circuit, as in Fig. 289. If the grid leak or the C bias lead is opened by the key, there will be no path for the electrons trapped on the grid to escape. The grid will then assume a large negative voltage which will reduce the plate current to such low value that oscillations cease.

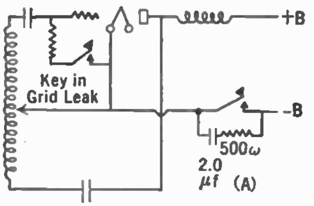


FIG. 289. Two methods of keying transmitter. Note "thump" filter in $-B$ lead.

If the key is placed in the plate lead it must break the full power to the tube, and its contacts must be able to handle the current without heating and without breakdown from the voltage drop across the key as it is opening.

The voltages and currents in the grid circuit are much lower. Both these methods of starting and stopping the oscillations are abrupt and provide the near-by ether with profound shocks known among the amateur fraternity as "key thumps" and cordially hated by listeners to other transmissions. Various thump filters have been devised to start and stop the oscillations in the tube less abruptly. One method is to let the tube oscillate feebly during the periods the key is up by placing a high resistance across the key contacts. Another is to place a resistance, capacity, and inductance across the key contacts. The condenser charges and discharges slowly and prevents the abrupt opening of the plate power circuit. The inductance (about 0.5 to 2 henries) slows up the start of oscillations.

Keying can be accomplished as in Fig. 288 but generally the break is made *between* the filament and the connection to minus B, which is also attached to the grid. In other words, only the filament is cut loose. This is called "keying in the common lead."

When master oscillator-power amplifier systems are used, keying may be accomplished in the oscillator circuit. This requires that all succeeding stages be biased by fixed voltages rather than relying on grid leak bias. This is because the bias in the latter case depends upon presence of excitation and the plate current will rise too high when the key is up unless the amplifier-tube bias is independent of excitation.

365. Modulation. A transmitter may be designed either for code or voice transmission. More apparatus is required for the latter means of communication. In addition to the oscillator tubes and amplifiers which may finally feed power into the antenna, there must be a modulating system. One method is to put the audio voltage variations into the grid circuit of the oscillator. These variations are, then, superimposed upon the alternating plate current and so the output into the antenna is varied at the a-f rate.

Another system is known as the Heising or constant-current system. In it the plate voltage to an oscillator, whose frequency is the carrier or high frequency, is varied by the a-f modulating voltages. Since the oscillating current and hence the antenna current is proportional to the plate voltage, this current will vary with the audio variations.

Consider Fig. 290, in which the reactance of the choke L is high at all audio frequencies compared with the two resistances. The resistance R_{mod} is the resistance of what later will be seen to be the modulator tube, which is simply a power amplifier operating at audio frequencies. The resistance R_{osc} is the resistance of the oscillator tube. Suppose the resistance of R_{mod} is caused to vary at some audio rate. The current taken from the B battery will not vary at this rate because of the large choking effect of the inductance L. The total current, then, from the battery is constant. If the resistance of the modulator tube, R_{mod}, increases, less current will be taken by it and more can be taken by the oscillator tube. On the next half-cycle, the resistance of the modulator tube decreases and more current will be taken by it. The current taken by the oscillator then must decrease.

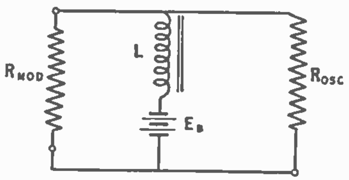


FIG. 290. Equivalent of Heising modulation system.

If the variations in resistance of the modulator tube are at some audio frequency, say 1000 cycles, the current taken by the oscillator will vary at this rate too—which is another way of stating that the r-f currents generated by the oscillator and transferred to the antenna will be modulated at the rate of the audio variations in the modulator circuit.

The actual circuit is shown in Fig. 291. When the r-f output of the oscillator is completely modulated, it looks as in Fig. 292 (taken from Heising, *Proceedings Institute of Radio Engineers*, August, 1921), and the power in the antenna is 1.5 times as great as when no modulation occurs. The antenna current meter will read the effective value of the current, or the square root of the power, and so will increase 22.6 per cent when the wave is completely modulated. (The square root of 1.5 is 1.226, which is 22.6 per cent greater than 1.0.)

The modulator may be thought of simply as an audio amplifier coupled to its load by means of a choke coil. The load is the effective resistance presented to the modulator by the oscillator.

The modulator acts as a Class A amplifier and the theory of such amplifiers is adapted to this type of modulator. The modulator causes the plate voltage of the oscillator to vary at an audio rate. There should be a linear relation between oscillatory cur-

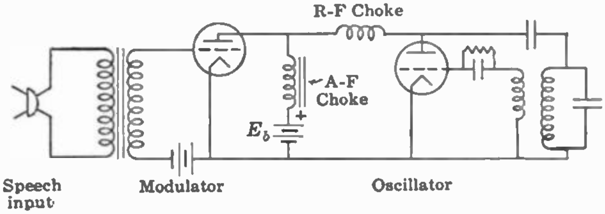


Fig. 291. Complete Heising modulation system.

rent and plate voltage and a similar linearity between plate voltage and plate current.

To modulate completely the oscillator requires that the modulator plate current be reduced to zero at one instant in the audio cycle and at the next half-wave peak the current must be

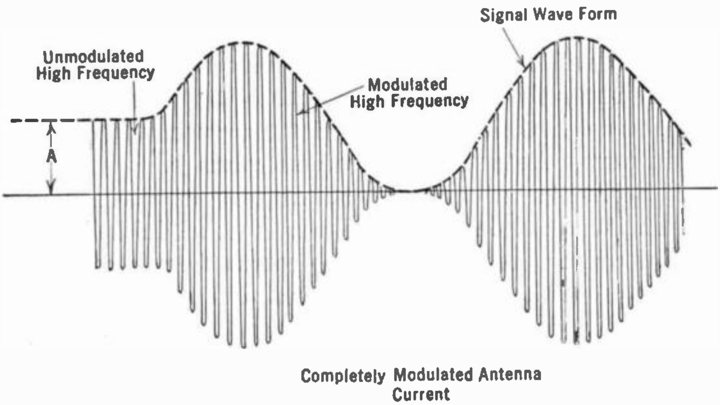


Fig. 292. A radio-frequency wave before and after complete modulation.

doubled. Now in a Class A amplifier it is impossible to reduce the plate current to zero without causing severe distortion. Therefore a tube having the same power rating as the oscillator will not completely modulate the oscillator in this circuit. If, however, the modulator is supplied with a higher voltage than the oscillator, so that it operates with a higher zero-signal plate current, or if the choke is replaced by a step-up transformer complete modulation may be accomplished.

One trouble with modulating the oscillator is that the frequency generated by the oscillator is not independent of the plate voltage. Since the plate voltage to the oscillator varies from zero to twice the plate battery voltage, the frequency of the oscil-

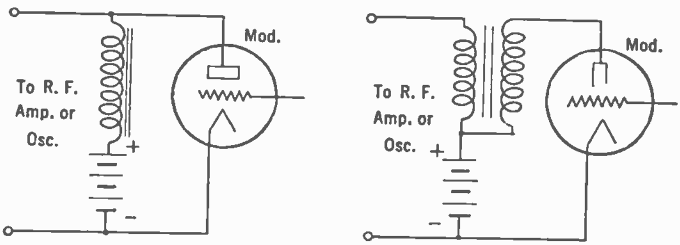


FIG. 293. Conventional Heising modulator and on right, method of increasing percentage modulation and decreasing saturation of core.

lator varies over the audio cycle. This produces frequency modulation which is not permitted on the broadcasting bands. It is no longer the practice to modulate the oscillator for this reason, except in the laboratory, or for other uses where the variation in carrier frequency is not a disadvantage.

366. Economics of modulation. Instead of modulating the oscillator it is possible, with some benefit, to modulate a Class C amplifier which is amplifying at the carrier frequency. But the difficulty of getting enough power out of the modulator is as serious here as modulating an oscillator.

As stated in Section 365 the power in the tank circuit of the oscillator increases with modulation, becoming 50 per cent greater at 100 per cent modulation. This additional power must be supplied by the modulator. Now a Class A modulator is rarely over 25 per cent efficient. Thus if two tubes of the same type are used, one for oscillator and one for modulator, trouble will be had in completely modulating the oscillator. For example, suppose a 5000-watt oscillator is to be modulated 100 per cent. The additional power to be supplied by the modulator is 2500 watts. Four tubes, operating at 25 per cent efficiency, of the same type as the oscillator will be required as modulators to furnish this modulating power.

Thus the cost of a modulating system of this type is very high, and for this reason, if for no other, the constant-current system of modulation has been abandoned in place of more efficient modulation systems. Of course, the modulation with the constant-current system can take place at low power and then all the succeeding stages must be capable of handling the 50 per cent increase in average power contained in a completely modulated carrier. The problem is one of deciding between the costs of building a large modulating equipment operating at audio frequencies and a correspondingly smaller r-f amplifier, or to build a low-power audio modulator and a higher power r-f amplifier.

367. Other types of modulator circuits. The more efficient methods of modulation involve varying the C bias to an r-f amplifier operating in Class C. The r-f and a-f voltages are supplied to the grid in series. The advantage of this method over plate modulation is that only a small amount of modulating power is required. It is difficult, however, to secure complete modulation by this method. Modulation may be applied to the suppressor or screen grids of pentode tubes, as well as to the signal grid.

A system capable of low distortion and fairly good efficiency can be made up of a Class A amplifier driving a Class B audio amplifier which in turn furnishes the power required to modulate a Class C r-f amplifier.

368. Analysis of modulation. In the antenna of a broadcast station flow alternating currents of the frequency of the carrier of that station. So long as the transmitter is not modulated, the amplitude of these alternating currents is constant, as shown in Fig. 292. When, however, the microphone is spoken into or the station is otherwise modulated, the plate voltage on the oscillator or modulated amplifier changes, the currents in the plate circuit and in the tank circuit change and the currents in the antenna change. This is the essence of modulation—a variation of the carrier current by the audio frequencies spoken or played into the microphone. The antenna current increases and decreases in accordance with the frequency of the modulating tones.

The percentage modulation is the ratio between the audio peak current and the radio peak current. When they are equal the transmitter is modulated 100 per cent; the peak currents flowing in the tank and antenna circuits will have doubled; the peak power developed by the transmitter will have quadrupled; the average power in the antenna will have increased by 50 per cent. More power is actually radiated at these instants.

A modulated wave form like that in Fig. 292 is the equivalent of a single carrier frequency plus two "side band" frequencies displaced from the carrier by the audio frequency. Thus if the carrier is 1000 kc, and if a pure 1000-cycle tone is impressed upon the modulator grid, the antenna will radiate the three frequencies, 1000 kc minus 1 kc; 1000 kc, and 1000 kc plus 1 kc, and a sensitive and selective detector will find these frequencies in the ether.

If the station is a broadcast station accepting all frequencies up to 10,000 cycles, for example, the side bands of the station occupy the region between the carrier minus 10,000 cycles and the carrier plus 10,000 cycles. This is why the carriers of broadcast stations cannot be placed closer together than the highest modulating audio frequency. Otherwise their side bands will overlap and create interference and distortion in the listeners' receivers.

369. Increase of antenna current with modulation. The antenna current of a transmitter will increase when that station is modulated because the power into the antenna increases by the amount of the modulation. Therefore the increase in antenna current can be taken as a measure of the amount of modulation in percentage. This additional power is represented by the side bands of modulation.

The average power in the carrier is $I^2R/2$. The amplitude of the current in each side band is the current in the carrier multiplied by $m/2$, where m is the percentage modulation. Therefore the power in each side band is $m^2I^2R/8$, and the total power for

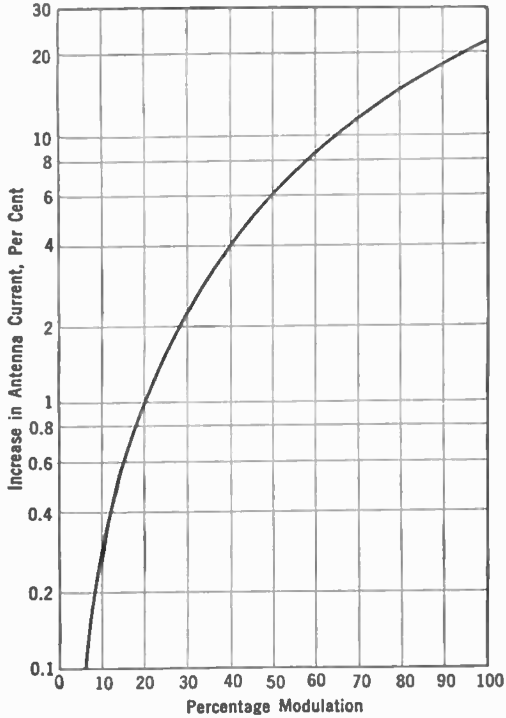


FIG. 294. Increase in antenna current as a function of the percentage modulation.

the carrier and side bands, on the basis that each side band is a replica of the other, is

$$\text{Total antenna power} = \frac{I^2R}{2}\left(1 + \frac{m^2}{2}\right)$$

and since the current is proportional to the square root of the power the current at any degree of modulation is proportional to

$$\sqrt{1 + \frac{m^2}{2}}$$

Thus the following table can be calculated.

Percentage Modulation	Percentage Increase in Antenna Current	Percentage Modulation	Percentage Increase in Antenna Current
0	0.0	50	6.0
10	0.22	60	8.7
20	1.00	70	11.7
25	1.6	80	15.0
30	2.2	90	18.7
40	3.9	100	22.6

The relation between modulator and oscillator (or r-f amplifier) in a Heising system may be understood from the following analysis. When the oscillator is working properly, not being modulated, its apparent resistance is the plate voltage divided by the plate current, or the plate voltage squared divided by the watts taken by the tube. Thus

$$\text{Oscillator resistance } R_o = \frac{E_p}{I_{po}} = \frac{E_p^2}{W_o} \qquad [1]$$

Oscillator and modulator both draw power from the plate battery. Thus:

$$\text{Total power from battery} = \text{power to modulator} + \text{power to oscillator}$$

$$= P_M + P_o$$

$$P_M = E^2/R_M$$

$$P_o = E^2/R_o$$

where

E^2 = battery voltage

R_M = apparent resistance of modulator

R_o = apparent resistance of oscillator

Now if $R_o = R_M$, most power will be transferred to the oscillator.

$$P_M + P_o = \frac{E^2}{R_M} + \frac{E^2}{R_o} = \frac{2E^2}{R_M} = \frac{2E}{R_M} \times E$$

By definition the percentage modulation, m, is the ratio between the peak a-c voltage delivered to the oscillator, divided by the battery voltage.

$$m = \frac{\sqrt{2}\, e_p}{E}$$

and

$$E = \frac{\sqrt{2}\, e_p}{m}$$

$$e_p = \text{a-c voltage developed by the modulator}$$
$$= \tfrac{1}{2}\, \mu e_g$$

since $R_m = R_o$.

Therefore,

$$E = \frac{\sqrt{2}\, \mu e_g}{2m}$$

$$P_M + P_o = \frac{2\sqrt{2}\, \mu e_g}{2m\, R_M} \times E = \frac{\sqrt{2}\, \mu e_g}{m\, R_M} \times E$$

$$P_o = P_M + P_o - P_M = \frac{\sqrt{2}\, \mu e_g}{m\, R_M} E - \frac{E^2}{R_M}$$

where μ = amplification factor of modulator,
R_M = plate resistance of modulator,
m = desired percentage modulation,
e_g = rms signal to modulator grid,
E = plate voltage applied to modulator and oscillator.

This, then, is the power that can be modulated to a given percentage by a modulator tube.

Example. Assume the following data on an 842 which is to modulate a tube from a 350-volt source of supply.

$E_c = -88$ $\qquad$ $e_g = 88/\sqrt{2} = 48$

$E_p = 350$ $\qquad$ $I_p = 14$ ma

$r_p = 2400$ $\qquad$ $\mu = 3$

$$W_o = \frac{\sqrt{2} \times 3 \times 48 \times 350}{0.6 \times 2400} - \frac{350^2}{2400}$$

$$= 44.4 \text{ watts}$$

when $m = 0.6$ or 60 per cent.

The load of the modulator, which is the apparent resistance of the oscillator, is given by

$$R_o = \frac{E_p^2}{W_o} = \frac{350^2}{44.4} = 2260$$

The peak voltage produced by the modulator across the oscillator load is

$$\sqrt{2}\, e_p = m\, E_p = 0.6 \times 350 = 210 \text{ volts}$$

Somewhat greater percentages of modulation may be obtained by using an auto-transformer in place of the choke as the coupling between modulator and oscillator. Furthermore, the two windings of the transformer may be properly proportioned to match the impedances on either side of the coupling unit, and by properly poling the windings the flux in the core may be decreased considerably below that required in a single winding.

370. Frequency modulation. The method of modulation we have just discussed is called **amplitude modulation** because the amplitude of the carrier power is varied by the modulation. This is not the only way by which a carrier can be modulated so that it will transmit intelligence from one place to another.

Suppose, for example, we vary the frequency of the carrier instead of its amplitude. Now a detector at a distant point could be rigged up so that the variations in frequency could be interpreted in the same way we can interpret variations in power or amplitude. This would be called **frequency modulation.** This could be done rather simply by varying the position of the plates of the tank-tuning condenser so that the frequency generated by the oscillator varied according to some desired modulation—speech, for example.

Now there are very great advantages to frequency modulation. In the first place, static is largely amplitude-modulated noise. Not much of it is frequency modulated. Furthermore, the power of the carrier of the transmitter can be operated at a constant value equal to its full-power output rating. It will be remembered that the power of an amplitude-modulated transmitter varies, and that at 100 per cent modulation the peak power radiated is four times the non-modulated carrier power. But this peak power is called for by the modulation at rare intervals, so that the average modulation of a broadcast transmitter is about 30 per cent. Therefore, much of the power-handling ability of the transmitter is called upon only at rare intervals. The rest of the time it is sitting idly by, waiting for these few peak requirements.

If the total power could be radiated all the time, better signals would be received at the distant point, or, conversely a transmitter with less power would be needed to deliver the same service if it were modulated 100 per cent all the time instead of 30 per cent on the average. Furthermore, the ratio of desired to undesired signals for good reception need be only 6 db compared with 35 db in an amplitude-modulated system.

Frequency modulation has one disadvantage. It requires a wider band in the ether. This makes it virtually impossible to use on standard broadcast frequencies. It must be used on the short waves. But there is another advantage in this—there is less natural static on the short waves. Here there is a wide band of frequencies available, and the wider the band used the less the trouble from static, and the wider the band the greater the signal-to-noise ratio.

Frequency modulation on short waves, therefore, offers a virtually static-free system operating at full power all the time and capable of transmitting a very wide band of audio frequencies. It is the real opportunity for a high-fidelity broadcasting system.

371. Technique of frequency modulation. Numerous methods have been suggested for producing frequency modulation. In the present wide-band system of Armstrong, the rate at which the carrier frequency is changed is a function of the audio modulations whereas the amount the carrier shifts above and below its average frequency is dependent upon the strength of the audio modulation. In other words, if the carrier has a mean or average frequency of 42 megacycles, a 1000-cycle modulation may be applied and its strength adjusted until the full deviation (plus or minus 75 kc) is obtained. Then the frequency of the carrier will shift 1000 times per second and in terms of frequency, it will shift from 42 megacycles plus 75 kc to 42 megacycles minus 75 kc. How can this be accomplished?

Suppose a condenser microphone be connected across the tuning condenser in the oscillator tank circuit. Then as the capacitance of the microphone is varied at an audio rate by speech or

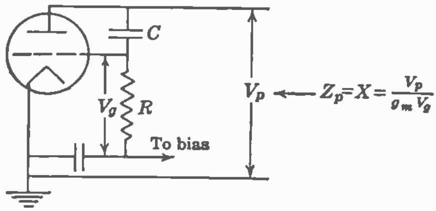


FIG. 295. Reactance-tube circuit. Compared to an external circuit the tube plate circuit looks like an impedance instead of a pure resistance.

music, the frequency generated by the oscillator will vary. In a condenser microphone the displacement of one electrode with respect to another (in magnitude) depends upon the loudness of the signal impinging upon the microphone. The louder the acoustic signal, the greater the displacement and therefore the greater the change in capacity. The rate at which the capacity changes per second depends upon the frequency of the acoustic signal which the microphone picks up.

The carrier of the f-m station, then, swishes back and forth about the average frequency as a center. The rate at which it swishes depends upon the rate at which the movable electrode of the microphone is moved, that is, the modulation frequency. The extent or deviation of the swish depends upon the magnitude of the microphone signal.

This is not a practical method, but a reactance change similar to that produced by a condenser microphone is used.

Consider Fig. 295 which is a reactance-tube circuit. The grid is supplied with voltage from the plate circuit after going through a phase-shifting network to bring the grid and plate voltages 90 degrees out of phase with each other. Then the impedance of the plate circuit is very nearly a pure reactance whose magnitude is equal to

$$X = \frac{V_p}{V_g g_m}$$

where g_m is the transconductance of the tube.

The transconductance is varied by varying the grid bias by the modulating signal. This variation in g_m produces a change in the magnitude of the reactance represented by the plate circuit of the tube. This tube is shunted across the tank circuit of the transmitting oscillator.

372. Receiver circuits for frequency modulation. Some means must be provided at the receiver for changing variations in frequency into amplitude variations so they may be detected in the ordinary manner. This is done in several ways. One is to use a tuned circuit and instead of utilizing the whole resonance curve, only one-half is utilized. Thus in Fig. 296 note that the operating point is about halfway up the side of the curve. As the frequency varies, the current varies. Thus we have changed a variation in frequency into a variation in current.

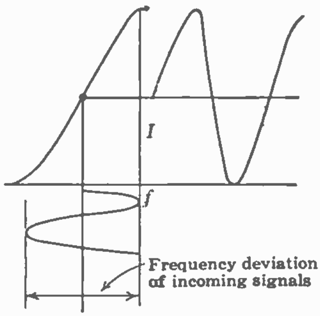


FIG. 296. Use of resonance curve to convert variations of frequency into variations of voltage or current.

In the receiver is also placed a tube known as a **limiter.** This is very much like an avc system. It prevents changes in amplitude from affecting the circuit. By means of it any amplitude modulation that may be on the incoming signal is prevented from delivering a demodulated signal to the audio circuits. If the r-f input signals are high enough to operate the limiter, then any increase in signal, as by amplitude change, will not have any effect for the output of the limiter is "limited"—nothing more can be got out of it no matter how much the signal increases.

Since the incoming signals, if pure fm, will not vary in amplitude, the limiter has no effect upon the desired signals.

CHAPTER XVIII

ANTENNAS, TRANSMISSION

Now that we have generated oscillations and induced r-f currents in an antenna, how is it that these currents convey intelligence to a receiver perhaps thousands of miles away? What is the character of this process? What is the character of the invisible and often unpredictable medium between transmitter and receiver?

373. Radiation resistance. Let us suppose that two wires about 30 ft long and about a foot apart are coupled to a 40-meter transmitter through any of the familiar coupling methods, perhaps by means of a coupling coil as in Fig. 297. The current into this double-wire system will rise to a maximum when the tuning condenser has been adjusted so that the product of L and C is equal to the product of L and C of the oscillator. Suppose this current is 1 amp. Now let us separate the ends of the two wires farther and farther until finally they are stretched out straight. More and more power will be required from the plate battery to maintain a constant value of current in the wires.

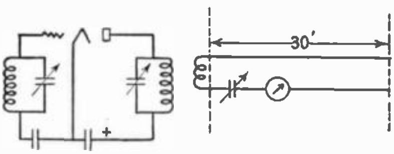


Fig. 297. Experimental diagram to demonstrate existence of radiation resistance.

At the same time we shall note that the capacity and inductance have changed somewhat so that some minor changes must be made in the tuning condenser to keep the wires in resonance with the oscillator—but these changes cannot account for the greater power required from the battery to maintain the same current in the wires. In the first place, the changes in capacity and inductance are balanced out each time by readjusting the tuning condenser to resonance. Then there is only resistance to impede the flow of current. Every time the reactances have been balanced against each other. Clearly the resistance of the wires has increased. At the same time, if we installed a small receiver near the oscillator and kept moving away from it so that the signals picked up were of constant strength, we should find that the greater the power taken from the battery and hence the greater the power into the antenna, the farther away we could hear the signals.

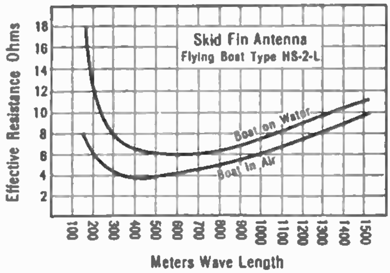


FIG. 298. Antenna resistance.

It is apparent that if the current is still 1 amp but twice as much power is taken from the battery to produce the 1 amp, the resistance of the wires has doubled. The useful part of this resistance is called the **radiation resistance** of the wires, which may now be called the antenna. The power that goes into this resistance is the power that is effective in carrying intelligent communication from the transmitter to the receiver.

The total resistance of an antenna may be measured by the same method used to measure the high-frequency resistance of a coil. (Section 137.) If enough resistance is added to our 40-meter antenna system to halve the current, this added resistance is equal to the resistance already there. If the resistance is measured at several wavelengths we shall get a curve similar to that in Fig. 298 (taken from the *Proceedings Institute of Radio Engineers*, February, 1920, by T. Johnson, Naval Aircraft Radio). This resistance is made up of the ohmic resistance of the wires, the losses in the dielectric of the antenna capacity, the loss of energy due to radiation, and other small losses. An efficient antenna is one which has a very high radiation resistance and a low resistance of all other sorts. Then most of the power put into the antenna from the oscillator will be radiated. This method of measuring antenna resistance is fairly accurate if very loose coupling and a sensitive meter are used.

374. The radiation field. The energy which is taken by the radiation resistance is used in setting up about the antenna a **radiation field.** This radiation field moves away from the antenna with a speed equal to the velocity of light, and its strength at any distance is inversely proportional to the distance minus any losses of power in absorbing media.

When the lines of force making up this radiation field cut a conductor such as a receiving antenna, a voltage is induced in this conductor and, if amplified and demodulated, it becomes the received part of the communication thrust upon the ether by the transmitter.

How does energy put into an antenna at one location produce a field at a distant point, perhaps thousands of miles from the transmitting location?

Consider first any piece of electrical apparatus, say a coil. It is a concentrated piece of equipment, and every attempt is made to concentrate into small space the lines of force spreading from it. Leakage flux is kept to a minimum. At each reversal of the direction of the current through the coil, the field reverses and if the current is removed from the coil, the field collapses and the field energy is given back to the coil.

In an antenna, however, exactly the opposite is desired. It is desired to project the field to great distances to prevent them from collapsing back on the source of energy. How is this accomplished?

It takes finite time for the field of lines of force to be propagated from one point to another. The greater the distance, the greater the time required, even if the field does move with the speed of light. Thus the events in the field of force lag behind the events in the parent circuit which produce the field. If, however, the parent circuit has its energy removed, as by cutting off a current, this distant field will collapse and return to the vicinity of the parent.

Suppose, however, that sufficient time is taken to establish the field at a distant point and then that we do not remove the parent circuit but reverse, instantly, the direction of current flow in it. Now a field opposite in polarity to the original field moves away from the antenna. The distant field, however, cannot get back to the antenna instantly; when it does, it finds a field of opposite direction surrounding the antenna and moving out to meet the returning field. Thus this distant field is detached from its parent circuit and becomes a free wave of energy traveling in space.

In an actual antenna the direction does not reverse instantly, but less quickly. Some of the distant field does return to the antenna but some becomes free. That portion of the energy which returns is called the *induction field* and the detached portion is called the *radiation field.*

In our experiment of stretching out a linear wire we have unbalanced the circuit, so to speak. If two wires are laid side by side and energized, equal and opposite charges are set up on the two wires and neutralize each other. There is no radiation field, but when the wires are spread apart the balance of charges is upset. The ultimate is a simple straight wire which is fed energy in any one of the ways to be described below.

Radiation, then, may be looked at as energy which is sent out from the antenna and which is prevented from getting back by production of new energy of an opposite polarity.

375. Types of antenna. All antennas may be thought of as made up of two very simple types, the Hertz half-wave radiator and the Marconi quarter-wave radiator. The Hertz antenna is also called a doublet or a dipole. They are called half-wave antennas because they are of such a physical and electrical length that one-half of a complete wave of current (or voltage) appears along them. Thus in Fig. 299 is seen the result of measuring the current in each portion of a half-wave radiator and plotting this current as a function of the distance from one end of the wire. The antenna is excited by a generator or by other means so that it is operating as its resonant frequency. Note

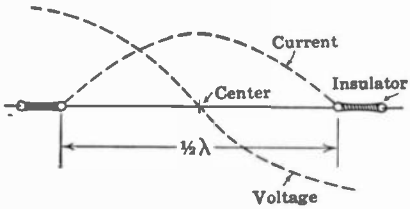


Fig. 299. Voltage and current along a half-wave radiator or doubler.

that the current is zero at the two ends and rises to a maximum at the center.

The antenna acts like a resonant circuit and since it has capacity and inductance it is natural that it will resonate to some frequency. This capacity and inductance, however, are distributed throughout its length and not concentrated as in a coil or a condenser.

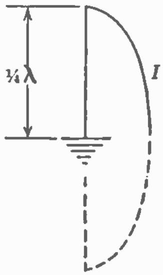


Fig. 300. Grounded quarter-wave antenna looks like a half-wave radiator, one half of which is in the ground.

The Hertz antenna, then, is a half wavelength long. It may be erected vertically or horizontally.

The Marconi antenna is a quarter wavelength long, but the antenna is not used alone. It is either grounded at one end, or used with a *counterpoise*, which is a series of wires suspended under the antenna, or actually buried in the ground. Under these conditions the current distribution along the wire will be such that it will look like one-half of a half-wave antenna, the other half being an image of the antenna and located underground as an imaginary extension of the real wire aboveground. A grounded quarter-wave antenna, then, acts like an ungrounded half-wave antenna.

A long wire may be thought of as a series of half- or quarter-wave antennas. Directional antennas are made up of numerous sections of quarter- or half-wave antennas, all properly connected so that the currents are in phase with each other. Thus the elementary sections add up their individual components of radiation, producing a sum total much greater than the effect of any individual. If, at the same time, the individual elements are directive and if a reflector behind the antenna can be used to cancel the radiation in a direction opposite to the desired direction, or can turn the energy around in the proper phase to go along with the desired radiation, the directive effect may be exceedingly great—equal to one hundred times the power of a single antenna in the desired direction.

The physical length of the antenna depends upon the frequency or wavelength of the desired radiation, the nearness of the antenna to surrounding objects. But a free wire in space will have a length as shown below. If a wire in free space is excited by a transmitter in such a way that one complete wave of current exists along its length, this length will be

$$\frac{1}{f\sqrt{LC}}$$

where L and C are the inductance and capacity per unit length of the wire and f is the frequency.

The actual physical length of a half-wave doublet in feet is given by

$$L = \frac{468}{f}\text{ ft}$$

where f is the frequency of operation in megacycles.

The corresponding length for a quarter-wave antenna from the far end to the ground or to the counterpoise is

$$L = \frac{236}{f}\text{ ft}$$

where f is the frequency in megacycles.

376. Antenna characteristics. Antennas have inductance, capacitance, and resistance. The only useful part of the resistance is the radiation resistance; the rest of the resistance, made up of the ohmic resistance and the loss of energy in dielectrics near the antenna, represents energy wasted. The radiation resistance may be represented by resistance which, inserted in place of the antenna, would absorb as much power as the radiated energy represents. If this radiated energy could be measured, and if the current at the center of the half-wave antenna or at the base of the quarter-wave antenna could be measured, then the radiation resistance would be

$$R = \frac{P}{I^2}$$

where P is the radiated power and I is the antenna current.

Now if a wire is stretched out straight and fed with current at the center, and if the frequency of this current is increased, it will be found that the radiation resistance (and hence the radiated power) will increase.

Now the longer the wavelength to be transmitted, the larger must be the physical structure of the antenna to resonate to this wavelength. On the very long waves it is practically impossible to make the antenna big enough to be resonant to the transmitting wavelength, and resonance is secured by "loading" the antenna with inductance.

An antenna operated at its natural wavelength (a half-wave antenna) is very efficient because its radiation resistance is high at this point, but an antenna which is small compared to its resonant wavelength is inefficient because most of its resistance is ohmic resistance and losses other than radiation. Therefore most of the power poured into it goes to heating the wire and the surrounding physical objects rather than into radiation.

This is one of the reasons why the short waves are so efficient —it is possible to make antennas to operate on these frequencies which are in themselves very efficient. Most of the power put into the antenna goes into radiation.

A half-wave antenna operating at 40 meters will have a physical length of approximately 67 ft. A similar antenna to operate on 15,000 meters would be 23,400 ft long. Imagine the difference in the ohmic resistance between these two antennas! The two will have the same radiation resistance and will radiate the same power into the ether, provided enough power input is applied to overcome the waste in the ohmic resistance of the longer antenna.

As a matter of fact, the large antennas used at long waves have radiation resistances of the order of 1 ohm or less, and so several hundred kilowatts of energy must be fed into them to get any appreciable radiated power.

The most efficient antenna, then, is one operating as a half-wave doublet in free space. Its impedance, measured at the center, will be approximately 70 ohms, which means that the power source should have an impedance of this order or be coupled to the antenna through a transformer, so that it looks like 70 ohms to the antenna. Then the most efficient transfer of energy will take place.

377. Directional characteristics of antennas. The simple dipole antenna is not an all-direction radiator. For example, a vertical doublet will radiate into a doughnut-shaped pattern. No radiation will come off the end of the antenna, and the maximum coming from the sides is at right angles to the antenna, less radiation occurring at angles other than 90 degrees to the antenna. A horizontal half-wave doublet will have the same pattern only it will be oriented up and down rather than in a horizontal plane.

If the antenna is lengthened so that it is one wavelength long, instead of a half wavelength, at the operating frequency, the pattern becomes more complex, there being two elongated doughnuts at an angle of 54 degrees to the line of the antenna. If the antenna is still further lengthened, more and more lobes of radiation occur, the strongest radiation occurring in a lobe which gets nearer to the direction of the antenna as the length increases. These same effects may be obtained by operating a given antenna at a higher and higher frequency, so that it is several wavelengths long at the operating frequency.

An antenna operated at a frequency higher than that which makes it a half-wave radiator tends to radiate its energy nearer and nearer the horizon if the antenna is horizontal, or more nearly vertical if the antenna is vertical.

Presence of ground or other objects changes the pattern of radiation from an antenna, and very precise use is made of this effect when erecting highly directive antennas for reception or transmission.

Where it is necessary to receive signals over a wide range of wavelengths, as in the home where signals over the whole broadcast band must be picked up, or on shipboard where quite a large spectrum must be covered, no attempt is made to use antennas resonant to any particular wavelength. A vertical or horizontal wire, straight or bent, or a wire around the molding of the room —practically any metallic object—may be used. This is not so efficient as an antenna which can be tuned to each frequency to be covered. The loss in efficiency, however, can easily be made up by greater r-f amplification in the receiver.

When two or more lobes of energy are radiated from an antenna, one lies nearer the horizon than the other. This directivity in a vertical plane may be made use of, depending upon whether the *ground* wave or the *sky* is the more useful. For example, in short-wave work where long distances are to be covered, the high-angle radiation is most useful. This wave, directed skyward, is reflected by the ionized layer high up in the atmosphere and it is on its downward path that it is received. The angle at which the radiation leaves the antenna governs the point on the earth's surface where it returns.

On the other hand, broadcast station radiation is directed along the ground as much as possible so that people near the antenna will get the best possible service. The sky wave is repressed so that it will not return to earth at some distant point where it may be out of phase with the ground wave and cause intermittent fading as the reflected wave varies in strength. Broadcast antennas are usually operated below their natural wavelength, i.e., the antenna is not a half-wave long. This keeps the ground radiation more effective than the skyward radiation. On the other hand, short-wave antennas, where the useful wave is to be reflected back to earth, are operated at harmonics of the natural wavelength, which means that the antenna is very much larger than a half wavelength for the desired radiated frequency.

378. Antenna arrays. When it is desired to direct radiation in a given direction, as for point-to-point service where the greatest possible energy is to be received at a given location, combinations of half- and quarter-wave antennas are built up into arrays, with each element properly connected to the others so that all the energy adds up. To reduce the power in an unwanted direction, arrays may be used to absorb the radiation 180 degrees back of the desired direction. Then the same channel can be used for two transmitters working in opposite directions without too much interference. The reflector may also be used to redirect the energy into the desired direction.

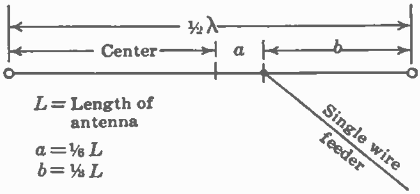


FIG. 301. Proper place to correct a single-wire feeder wire to a half-wave antenna.

Antenna arrays can be extremely complex structures and the gain, expressed as the increased power required to deliver the same result from a single half-wave antenna, may be very great, as much as one hundred times or more in power.

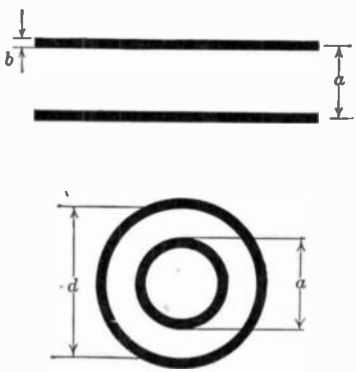


FIG. 302. Two-wire and concentric tube transmission lines. Inner conductor of the latter may be solid.

379. Getting energy into an antenna. Since the best type of simple transmitting antenna is a half-wave dipole high in the air and in free space, the problem is one of getting power into it. No power should be lost in the connecting system between the antenna and the transmitter. This calls for a low-loss transmission line of the proper impedance. The impedance of a half-wave antenna at the center is approximately 70 ohms. This impedance increases towards the ends, becoming 2400 ohms at the end. The transmission line, therefore, should have an impedance of 70 ohms or should be coupled to the antenna so that the line looks like 70 ohms to the antenna.

At the other end the transmission line must be coupled to the transmitter so that the latter looks like 70 ohms to the line. This calls for a transformer of some sort, perhaps merely a tap on the output-amplifier tank circuit.

Since the impedance of the antenna varies from one point to another, lines of higher impedance than 70 ohms can be used, provided they are connected to the antenna at the proper point.

380. Transmission lines. Three types of lines are used to get energy from the transmitter to the antenna, single-wire lines, two-wire lines, and coaxial cable lines. With the average amateur antenna, situated an average distance above ground and an average distance from surrounding objects, a single wire may be attached to a point where the impedance is approximately 500 ohms. Such a single wire will have an impedance of this value.

Two-wire lines have an impedance varying between 400 and 800 ohms according to the formula.

$$Z = 276 \log_{10} \left(\frac{2a}{b} \right)$$

where Z = the impedance in ohms,
a = the spacing between wire centers in inches,
b = the wire diameter in inches.

For example, a pair of No. 14 wires, spaced 5 in. apart; has an impedance of approximately 500 ohms.

Coaxial line is made up of two conductors, one located within the other, maintained in its position by insulating spacers. The impedance of such a line is lower than that of the open wire line and may be found from the formula

$$Z = 138 \log_{10} \left(\frac{a}{d} \right)$$

where Z = the impedance in ohms,
a = the outside diameter of the inner wire in inches,
b = the inside diameter of the outer conductor in inches.

For example, a/d is equal to 0.31 for a 70-ohm line. If the two conductors have diameters of ¾ and ¼ in., the impedance is 66 ohms.

The loss in energy in these lines is very low if they are well made. The two-wire line has a loss of $k\sqrt{f}$ db per 1000 ft, where k varies from 0.1 to 0.2, depending upon the insulating material used, etc. The loss in coaxial cable is $0.256\sqrt{f}/d$ per 1000 ft, where d is the outer conductor diameter, and in both formulas f is the frequency in megacycles.

In Fig. 303 are shown two ways by which two-wire lines may be connected to a half-wave antenna. Of course, a 70-ohm concentric cable line may be connected directly to the center of a half-wave antenna since its impedance is of this approximate value.

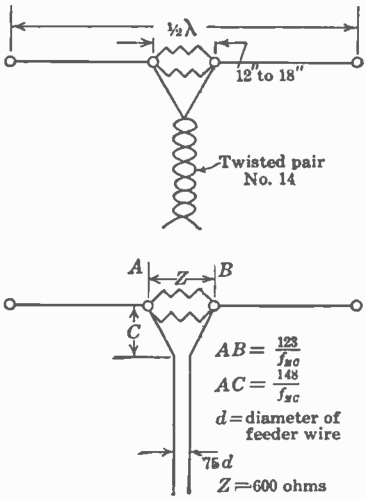


FIG. 303. Ways by which power may be fed to an antenna.

381. Quarter- and half-wave lines. Transmission lines of a particular length for the frequency for which they are designed have very interesting and useful characteristics. A quarter-wave line has such a physical length that it is a quarter wavelength long at the operating frequency. Now all lines have a characteristic impedance and for minimum loss in the line the impedances between which it works should be equal to the impedance of the line. If, however, two unequal impedances are to be connected, say a generator and a load, then a quarter-wave line having a characteristic impedance equal to the geometric mean of the two unequal impedances may be used as the connecting link, very much as a transformer is used. The impedance of the line should be equal to $\sqrt{Z_1Z_2}$, where Z_1 and Z_2 are the impedances connected to the two ends of the line.

For example, if impedances of 600 ohms and 70 ohms, such as a 600-ohm transmission line and a 70-ohm doublet, are to be connected, a quarter-wave line may be used between them to minimize loss due to impedance mismatch.

A half-wave line, on the other hand, has a quite different quality. The impedance looking into a half-wave line is equal to the impedance terminating the other end of the line. This is true, regardless of the impedance of the line itself. Thus a half-wave line looks like a one-to-one ratio transformer and may be used as such. It is understood that a line is a half- or quarter-wave line at only one frequency. Thus the physical length of a quarter-wave line is equal to

$$L = \frac{246V}{f} \text{ ft}$$

where V varies from 0.56 to 0.95, depending upon the kind of transmission line used (coaxial, $V = 0.85$; two-wire line, $V = 0.975$) and f is the frequency in megacycles.

382. The loop antenna. The loop is a directional antenna. It receives better in the direction towards which the narrow dimension points. For example, its pickup ability is such that when it is pointed east-west it will pick up very little energy from a north-south direction. In connection with a sensitive receiver, it may be used to determine the direction whence the signals come. It is the heart of the **direction-finding** stations which are situated along the coasts of the world. When a ship wants bearings, its signals are picked up by the coastal station which determines the position of its receiving loop which gives the least signal. A compass is attached to the base of the loop and the indicator then points out the bearing of the vessel. A receiving operator in another location also swings his loop on the vessel and thus two bearings will be obtained. From them the master of the ship can tell where he is with regard to the coast line.

There is one disadvantage of the loop when used alone. Its directivity pattern is composed of two equal loops, so that the operator can tell that a signal is coming from a north-south direction rather than an east-west direction, but he cannot determine whether the signal is coming from south or from the north. The addition of a single vertical antenna whose output is properly added to that produced by the loop adequately solves this problem. The difference in phase between the signal picked up

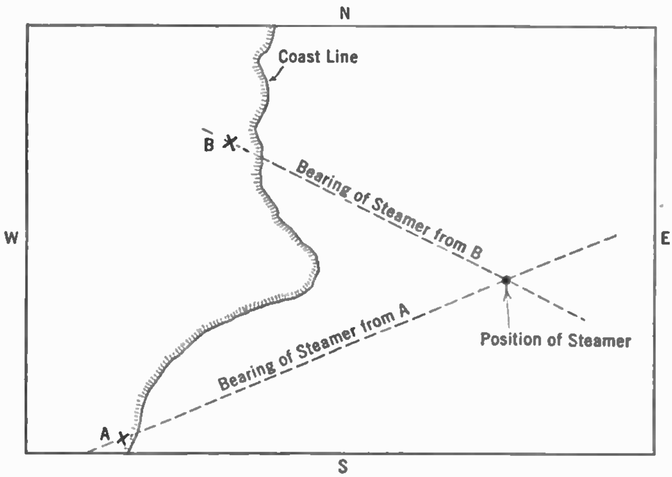


FIG. 304. Method of plotting a ship's position by obtaining two bearings from land stations.

by one side of the loop and the vertical antenna is used to add to or subtract from the current in this half of the loop. The resultant directional characteristic is shown in Fig. 305.

The 180-degree ambiguity may be avoided by the use of a pair of loops crossed so they are at right angles to each other.

383. Loading an antenna. If an antenna does not have the required inductance to bring its wavelength to the desired value, additional concentrated inductance can be placed in the down lead and the antenna "loaded" up to the desired wavelength. Since the coil cannot radiate to any extent and since its resistance must be added to the resistance of the antenna system, loading makes the entire system inefficient.

384. Decreasing the wavelength of an antenna. If the antenna is too large to tune to the desired wavelength, its natural wavelength can be reduced by placing a condenser in series with it. This reduces the effective capacity and as a result reduces its wavelength. The wavelength cannot be reduced below one-half the natural wavelength. Here again, loss in power in the condenser must be subtracted from the power that would go into the radiation resistance, and so the losses in the condenser must

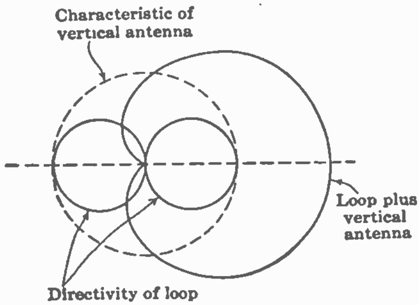


FIG. 305. Directional characteristics of loop, vertical antenna, and two combined.

be paid for in inefficiency. Fortunately, it is possible to build a condenser whose resistance may be very low at the frequency at which it is to be worked, and so a series capacity does not add much resistance to the antenna.

385. Short-wave transmission. For many years the high-frequency portion of the r-f spectrum was considered worthless. It was largely for this reason that amateurs were permitted to operate there. No one else wanted the short waves. Strangely enough, these short waves, once thought worthless, are now being fought for by radio communication companies the world over.

The radiation field as it goes out from the antenna is absorbed by all conductors which exist in its field. According to theory, the shorter the wavelength the greater the absorption so that for waves shorter than 100 meters very little energy arrives at a receiver any distance away. Amateurs, however, discovered that these waves did arrive at much more distant points than theory permitted and a new theory had to be developed.

Waves are radiated from the antenna at all angles to the horizontal. The **ground wave** which the old theory dealt with goes near the surface; some radiation leaves the antenna at a high angle and shoots off into space. Some distance above the earth is an ionized layer which is a fairly good conductor of electrical disturbances. It therefore reflects a certain amount of the **sky wave** which returns to earth and may be received by any antenna in its path.

The ground wave is soon absorbed. The sky wave does not come down to earth in the immediate vicinity of the transmitter. Between the area covered by the ground wave and the sky wave there is a dead spot known as the **skip distance.** Signals are not received there except with the greatest difficulty and with considerable irregularity. In the daytime this skip distance is about 200 miles at 40 meters wavelength and 800 miles at 20 meters. Beyond the skip distance the signals are audible and fall off in intensity until they are again inaudible.

By properly choosing the frequency for the time of day it is possible to maintain a continuous communication with another station at any given distance. In other words, distance, time of day, season, and frequency are related.

It is because of the sky wave that amateurs working with less than 100 watts in an antenna are frequently able to communicate over several thousand miles on waves below 80 meters. On waves longer than 300 meters the skip distance is negligible; the sky wave is not so important, except as noted in Section 386.

386. Fading. The Kennelly-Heaviside layer, as the ionized conducting layer which is about 100 miles above the earth is called, varies in height and density from moment to moment, from day to day, and from season to season, and so the reflected wave varies in intensity. This is one cause of fading. Fading occurs most on short waves. It is of some importance on broadcast frequencies but at lower frequencies becomes of less and less value. When the sky wave and the ground wave arrive at a receiving station out of phase with each other, the received signal will be decreased in strength. This accounts for fading experienced on broadcast frequencies.

The automatic volume control discussed in previous sections will eliminate much of the troubles due to fading. The result of fading to the listener will be the apparent rise and fall of noise; when the signal gets weak the sensitivity of the amplifier rises bringing in more noise, and vice versa. The avc system, or the unlimited increase of power at the transmitter, will not eliminate fading in which the side bands fade less than the carrier with the effect that the carrier as it arrives at the receiver is over-modulated, with resultant distortion.

Fading that varies with the frequency of modulation sometimes occurs. Nothing can be done to correct it at the receiver.

387. Comparison of night and day reception. The shorter the wavelength the greater the difference between night and day transmission and reception. On long waves there is little difference. At night signals are somewhat louder. On broadcast frequencies the difference is marked, especially in winter. Signals can be heard at night which are inaudible during the day. On short waves the skip distance becomes much greater at night. Why is this?

During the day the sun pours radiation into our atmosphere ionizing the particles which constitute it. These ionized particles absorb radiations of all kinds. Once absorbed, their energy is lost and they cannot transmit intelligence to distant receiving stations. At night this ionization ceases, the absorption of radio waves decreases and signals again reach out. The Kennelly-Heaviside layer of ionized particles which reflects the sky wave on the frequencies above 3000 kc is very low in the daytime. The skip distance is not so great then as it is on a winter night when the reflecting layer is high, 100 miles or more above the earth.

388. Static. Static is part of the noisy background that is sometimes of sufficient strength to interfere with the reception of signals. It is caused by natural phenomena, such as discharges of electricity between clouds at different potential or from clouds to earth. It is not the same noise that is caused by a leaky transmission line, defective power transformers, wires rubbing in trees and sparking, or other noises which come under the heading of man-made static. All the latter noises can be eliminated. Static cannot be eliminated but its effects can be reduced.

The loop antenna which can be pointed at the desired signal, or any other directional antenna, will not pick up static or unwanted signals from other directions and will produce a greater signal to static ratio. It has the effect of reducing static.

A number of schemes have been devised to reduce the static to the level of the signal, but none has yet been made that will completely eliminate the static without also eliminating the signal. Both are produced by the same fundamental phenomenon—the charge and discharge of a condenser. One is produced in a broadcasting station by man, the other in the sky by nature. Wide-band frequency modulation is the nearest approach to static elimination. With sufficient power at the transmitter, good limiters in the receivers, static is practically gone, so far as the listener is concerned.

Static is more bothersome during hot summer weather when the clouds are highly charged. The more sensitive one's receiver the further away the storms can be and still disturb reception. Man-made static is bothersome at all times of the year and at any time of the day or night. In the future all man-made static will be illegal, just as it is now illegal to operate an automobile without a muffler.

389. Elimination of man-made interference. Considerable advance has been made towards the elimination of radio interference from all manner of sparking machines. The sparks must be eliminated or the electric waves they set up must be prevented from radiating much energy. If the sparks occur in a large system of wires the energy radiated may be considerable and may ruin radio reception over a large area. This radiated energy may be strongest at the natural frequency of the radiating wires but, because of the high resistance of the spark gap, the disturbance may cover a very wide band of frequencies.

Condensers across the place where the spark occurs reduce both spark and interference; inductances in series with the power wires leading to the electrical machine creating the disturbance prevent the radiations from getting into the power lines and hence from having much of a radiating system. Combinations of inductances and condensers may filter out the radiations by reducing or preventing sparks, by shunting them into the ground, and by preventing them from getting into power lines.

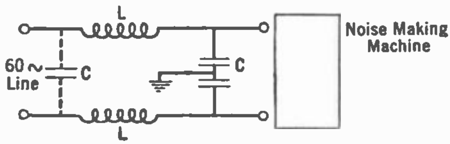


FIG. 306. Use of noise filter.

To tell whether noise in a receiver comes from outside or from the receiver or power equipment itself it is only necessary to disconnect the antenna. If the noise persists, its origin is within the receiver or power supply. If it is reduced, it is being picked up by the antenna. A directional receiver may be used to determine first its general direction and finally its exact location. Noise in a-c operated or electric sets may come in over the power wires and then it will be heard even though the antenna is disconnected.

The complete elimination of interference from true static and from man-made radio disturbances is one of the few big radio problems that have not yet been solved.

390. Anti-static antenna systems. If a receiver must be operated in a noisy location so that the desired signals are immersed in man-made static, resort must be made to a rather elegant antenna system put into quite wide use in 1933. This system consists of a good antenna erected in as high and clear a location as possible and connected to the receiver by means of a transmission line of low impedance.

If the antenna is connected to the receiver by a shielded down lead, most of the desired signal will be lost on the way down through the capacity between the down lead and the shielding which will be more or less at ground potential. If the down lead is not shielded it will pick up the local noise, for example with elevator-motor noise, the high clear antenna will be wasted.

If, however, the shielded down lead is connected to the antenna by means of an impedance-adjusting device, a transformer for example, the down lead will be a low-impedance affair and will not lose its signal energy, and since it is shielded it will not pick up local noise.

At the lower end, another transformer steps up the signals so that they go into the receiver just as they would if coming di-

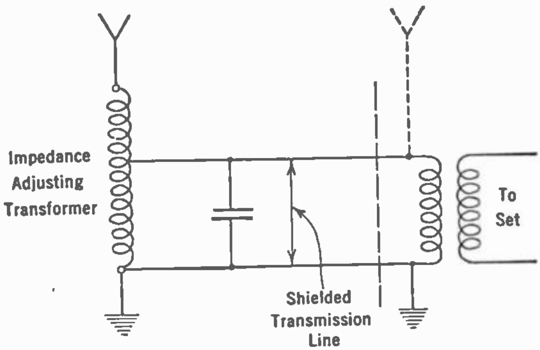


FIG. 307. Method of connecting a good antenna to a receiver in a poor location by means of a shielded transmission line.

rectly from the higher-impedance antenna instead of the low-impedance line. If the antenna has a capacity of 200 $\mu\mu$f, an inductance of 20 μh, and a resistance of 25 ohms, it will have an impedance of 1460 ohms at 550 kc and 345 ohms at 1500 kc. The receiver will have an input impedance that is nearly pure resistance, because the input is usually tuned to resonance with the incoming signal, and if the first transformer has a primary of 2 to 3 millihenries, the primary resistance will be approximately 125 ohms at 1000 kc. If the primary has few turns the input of the set will look like approximately 1.2 ohms.

The input impedance of the receiver in these cases will be approximately five times the resistance of the primary coil; hence an antenna system of this type must be connected to the receiver with knowledge at hand of the input transformer characteristics.

Such a system will make clear reception possible in a location where little else but noise is heard with an ordinary antenna.

391. Automobile antennas. Antennas for mobile services as in automobiles and aircraft present a difficult problem. In the first place, the effective height possible is small; secondly, the structure must be simple and rigid.

In aircraft the antenna is a simple pole mounted rigidly over which the wire is strung and insulated from the ship proper. Similarly in police radio systems working on short waves, a simple rod is mounted in the rear or the front of the automobile chassis and is tuned to the desired wavelength. In pleasure automobiles the first aerials were sections of chicken wire or netting imbedded in the roof. The advent of all-metal bodies, however, put a stop to this practice. Metal plates suspended under the running boards and other types of under-car antennas were successfully used. The practice of police cars putting a flexible steel rod outside the car, however, showed the way to success, and at present the tendency is toward such vertical rods or metallic devices which run up from the center of the windshield and form additional decoration for the car top. These have fair pickup and are out of the noise field of the ignition system.

CHAPTER XIX

FACSIMILE AND TELEVISION TRANSMISSION

A new factor enters when pictures or television images are to be transmitted over wire or radio circuits. This is the factor of *time*. Picture transmission is much like code transmission; television is more like voice or music transmission—but both picture and television are more complex than the earlier methods of transmitting intelligence.

In code transmission the listener gets one letter after another and after recording them he may form an accurate idea of what the sender has in mind. In picture transmission the receiver puts down small pieces of the final picture in the order in which the sender transmits them, much like a crossword puzzle, and after a certain *time* he gets an accurate idea of what the original picture is.

In voice or music transmission, time enters to a limited extent only, since the listener is not called upon to remember the exact sound that he has just heard. He is interested only in the tone or sound that at a given instant is impressing itself upon his ears. But if we wish to transmit 10 orchestras simultaneously, 10 transmitters, 10 channels and 10 receivers are required. Here is where the factor of time enters. A single channel could transmit all 10 orchestras provided they could play one after another.

392. The problem of picture transmission. There is no known method of transmitting a picture so that the listener sees it all simultaneously with the sender. All known methods consist in taking the picture apart, transmitting the parts, and then in putting them together again at the receiver. In facsimile transmission the time required may be fast or slow. It may take a week to transmit a single picture or it may be transmitted in a second, but in the latter case a high premium must be paid for speed.

In television we must perforce transmit the pictures at a high speed. Not only does the problem of chronological transmission enter but also the problem of simultaneity as well.

393. Picture elements. If one looks at a newspaper photograph with a hand lens he will see that it is made up of small dots of ink, and he will realize that there is not much detail in the picture. If he looks at a photo in a high-class magazine he will discover that much greater detail is present—in other words, the dots are smaller and are placed closer together. If he looks at a photograph he will see almost infinite detail since the dots are microscopically small and almost infinitely close together.

It takes about 50 dots across and 50 dots down a picture to make a face recognizable. If there are five times this number of dots in the same space the picture will have much greater detail. If this mosaic of 50 $\times$ 50 or 2500 dots is placed in an area the size of a postage stamp the picture may be viewed at close range; but if it is put on a screen 10 feet across, each dot being multiplied in size accordingly, the same degree of detail will be present but the picture must be viewed at a much greater distance.

Newspaper cuts have detail corresponding to about 55 dots per linear inch; high-class magazine cuts have about 100 to 200 dots per inch; a 4- by 5-in. photograph may involve as many as 100,000,000 separate dots of light and darkness.

Let us consider the 50-dot-per-inch picture. If this picture, say 1 in. square, is to be transmitted in one second, all the dots must be sent in this time. That is, 2500 dots or impulses per second may be transmitted and received. This will give us a picture 1 in. square. If the picture is to be 10 in. square and therefore include more objects, the number of impulses per second will be 2500 $\times$ 100 or 250,000.

These figures correspond to 2500 and 250,000 cycles per second, and if transmitted by carrier frequency, the side-band width must be 5000 cycles and 500,000 cycles wide, respectively. In this manner one of the most serious problems of television enters —to transmit good detail in a short space of time requires a very wide band of frequencies, and apparatus and a medium that will handle this wide band.

The second problem is, how large shall be the field of view—not how large shall be the ultimate picture, but how much shall be included in the picture? Obviously a 1-in.-square picture may be enlarged at the receiver but it will contain no more information than the original 1-in.-square picture.

The third problem is the time available in which the picture is to be sent and received. If time is of no importance, as many dots as desired can be sent, and greater detail will be possible, but if the time is limited then the detail must be limited or a very wide frequency band must be used and the apparatus must be correspondingly complex. If a wide band is to be transmitted by radio, fading within that band may erase part of the picture; and of course there is always the problem of the available space in the r-f spectrum.

394. Frequency band required. The highest frequency that must be transmitted for a given picture is determined from the equation

$$\text{Highest frequency} = \frac{NA}{2t}$$

where N is the number of elements per square inch,

A = size of the picture in square inches,

t = time in seconds for transmission.

Example. The Bell system of picture transmission enables a very beautiful picture 5 by 7 in. with equivalent detail of 10,000 elements per square inch to be transmitted in approximately 7 minutes. What is the highest frequency necessary, and what band width is required?

The total number of elements is $10{,}000 \times 35 = 350{,}000$

The time available is $7 \times 60 = 420$ seconds

Therefore the highest frequency required is $\dfrac{350{,}000}{2 \times 420} = 420$ cycles (approx.)

and the frequency band required $= 840$ cycles (approx.).

395. Method of taking the picture apart. Since the picture is to be transmitted piecemeal, some method must be available for taking the picture apart. In the Bell system (as used by the Associated Press) the photograph, or a film, may be placed upon a drum which revolves in front of a small carefully focused light source. As the drum rotates, it moves along in front of this light, and the beam either goes through the film, or is reflected from the finished print into a photocell.

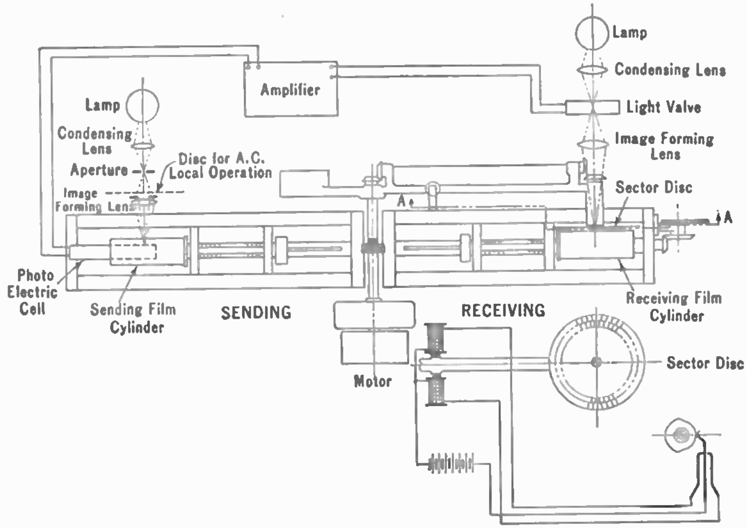


FIG. 308. Bell system of photograph transmission.

Since the amount of light that gets to the photocell is a function of the light or shade of the picture, each portion of the picture is translated from a visible shade into an electrical current, more light causing more current to flow from the photocell. These variations in the photocell current are amplified and transmitted to the receiver where a similar piece of unexposed paper, or an unexposed film, is rotated on a drum at exactly the same speed as the transmitter drum. As the variations in current come from the transmitter they are translated back into variations in intensity of light which is permitted to shine upon the photographic film and thus expose it in exact accordance with the picture at the transmitter.

This method of taking the picture apart is called *scanning*, and in all facsimile, photograph, or television systems some scanning scheme must be employed. In all such schemes a photocell is employed to translate the variations in light to variations in an electric current which after amplification may be transmitted to the receiver over a wire or may be used to modulate a carrier of a radio transmitter.

The frequency band calculated in the above example is the narrowest possible band; if good detail is desired, higher frequencies corresponding to the higher harmonics of the highest frequency must be transmitted. Thus when a picture is composed of alternate white and jet-black portions, the photocell gets a sudden illumination, or a steep wave front, and the electric current coming from the photocell must have a similar wave front. This means that the current must start and stop suddenly—and such circuits are extremely difficult to obtain and to maintain. Any inductance and capacity in the circuit would tend to flatten this steep wave front with the result that the received picture would not have as white a white, nor as black a black, as the original. In other words, distortion would result. Steep wave fronts imply tones with numerous harmonics. Therefore the second or third harmonic of the highest fundamental tone should be transmitted for high fidelity.

396. Putting the picture together again. Once the picture is in the form of variable electrical currents and transmitted to the receiver it becomes necessary to reconvert these impulses into a visible picture. One method is to use a sensitive galvanometer which carries a mirror whose movements, under the variations in incoming current, cause more or less light to fall upon a sensitive photographic film.

In another system (Cooley) the incoming signal caused a high-frequency, high-potential spark or corona discharge to spark through a paper, thus burning minute holes in it in accordance with the original picture. Or these sparks may be made to turn some chemical dark in color and thus leave an impression on the receiving paper.

In still other methods hot jets of air are turned on or off in accordance with the modulations of the transmitter; these jets (which may be other liquids than air—ink, for example) produce some visible change in the paper on the receiving drum.

The great difficulties in the way of general usage of such systems lie both in technical and economic problems. Once the technical problems are solved there remains the problem of who is to pay for the pictures and how much they will pay and whether this amount will finance the development of the method, pay for the expensive circuits and terminal equipment.

FIG. 309. Picture transmitted by very simple 1933 system (Hogan).

At present a considerable amount of picture transmission takes place among newspaper and news-gathering associations. Rapid travel by air or train has made transmission by radio or wire less necessary than was formerly thought. It is possible, however, to connect facsimile or picture systems to existing broadcast stations, the receivers to be placed in the listener's home. Such systems can transmit pictures during the night when the broadcast transmitter ordinarily is off the air. The program might be news services, advertisements, weather reports, stock-market reports, entertainment features such as Krazy Kat, etc. Although such systems are in occasional use, the public has not been sold on the value of such a service as a home entertainment feature. For spot news, and for pictures of big events such as fires, floods, important gatherings, or wars, picture transmission is a useful service.

397. Television—rapid picture transmission. Television does not differ fundamentally from picture transmission. In this method of communicating intelligence many pictures are transmitted per second, each slightly different from the preceding so that the observer thinks he sees a continuously changing picture much as he *thinks* he sees a continuous picture in the moving-picture theater.

Television and motion pictures are possible because of a peculiar characteristic of the eye. If two pictures exactly alike are transmitted at a rate exceeding sixteen pictures per second, the observer thinks he has seen but a single picture. In other words, the visual system has a certain inertia in it, such that a picture snapped off suddenly persists for a fraction of a second. This is called "persistence of vision." It has become general practice to transmit at least sixteen pictures (frames, as they are called in the movies and in television) per second. Otherwise the pictures seem to flicker.

At once we begin to see why television is a difficult art. Not only must we transmit a picture of desired detail, and of desired field of view, and without distortion, but we must also do it in a sixteenth of a second. Now let us see what this problem is from the standpoint of the required band width.

Example. Suppose we are to send television pictures of the quality of the Bell System photographs. What is the highest frequency required? How many broadcast channels would be required?

$$\text{Time available } \tfrac{1}{16} \text{ second} = \qquad 0.06 \text{ second}$$

$$\text{Highest frequency} = \frac{10{,}000 \times 35}{2 \times 0.06} = 2{,}915{,}000 \text{ cycles}$$

$$\text{Band width} = \qquad 5{,}830{,}000 \text{ cycles}$$

And since the carrier frequency should be about 10 times the frequency of the modulation, the carrier would have to be about 60,000 kc, and to transmit 5- by 7-in. pictures with 10,000-element detail in 1/16-second intervals would require a band at least equal to 583 present-day broadcast station channels.

Such is the problem of television. The tremendous band width required was a fundamental obstacle to high definition television until the realm of the short waves was available. The calculations above show that our television channel would have to be on 60,000 kc or 60 megacycles, and until recent years no one thought it would be possible to generate appreciable amounts of power at these frequencies.

398. Television research. Many lines of research have converged on the television problem. Some of them were necessary to advance knowledge and practice for other purposes; some of them were useful only to television. Many investigators have had their hand in this development and, like radio, it will be impossible to state who invented it when television becomes a useful service.

It was realized that the very high frequencies must be used as the television carrier. Therefore it was necessary to find methods of generating power at these frequencies, to get it into the ether and to get it out again. This called for new types of tubes, for studies of the characteristics of the transmission path between transmitter and receiver.

It was realized that some way must be provided for getting television programs from a central point, the studio, out to stations which might be miles away from the place where the show is going on—just as in sound broadcasting. This meant that new types of wire circuits must be developed. Here is where the telephone engineers' work on the coaxial cable came in handy. New types of antennas were developed, and it was realized that getting the short-wave antenna up in the air as high as possible was necessary since these waves travel only as far as the eye can see, being cut off, like a ray of light, by the curvature of the earth.

Then, most difficult of all, it was realized that the early mechanical methods of television would have to be modified or discarded if high definition television were to become a practical service. First let us see how the mechanical systems worked.

399. Scanning the image. In general there were two methods of scanning the image. In one the image was brightly illuminated by several sources of light. The image was focused upon a rotating disk which was pierced with a series of holes in a spiral as shown in Fig. 310. As the spiral rotated the holes traced across the image, which had been greatly reduced in size by the lens, one after another in a series of parallel lines. The light that got through the holes fell upon a photocell and was translated into electric currents. In one complete rotation of the disk the holes traversed the entire picture, or frame.

In the other general method a single high-intensity source of light shone through the holes upon the image, and the reflected light was viewed by several photocells. Thus a single spot (the flying spot) traced itself across the image from one side to another and from top to bottom.

Experiments of Dr. H. E. Ives of the Bell Laboratories show that the first method would require that the object be illuminated

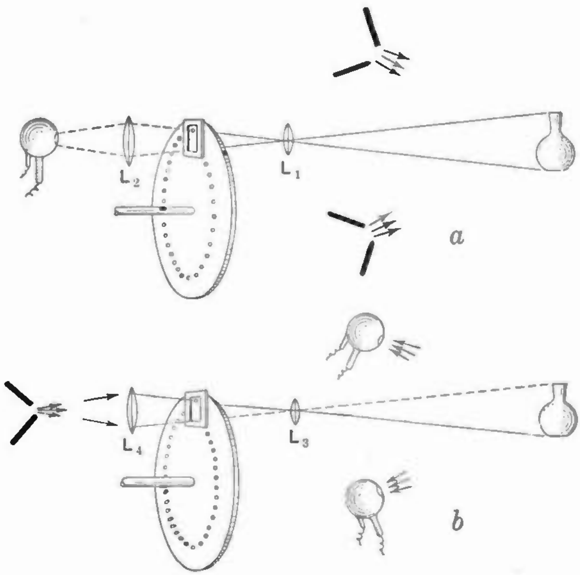


FIG. 310. Two methods of illuminating and scanning an object. The lower is the "flying spot" system.

with a 16,000-candlepower arc at a distance of about 4 ft to secure an image bright enough that the currents from the photocell would be above the noise level. Therefore the flying-spot method was more generally used.

Lenses in place of holes in the disk improve the efficiency somewhat, but the difficulty of making, say, 48 lenses of exactly the same focus and of placing them in the periphery of a disk so that they line up their individual images properly increases the technical and mechanical problems appreciably. Deep blue light has been used to illuminate the object to prevent too intense illumination on a person's eyes, for example. Photocells especially sensitive to blue were utilized in this scheme.

400. The receiving system. Another scanning disk was used at the receiver. It was operated in exact synchronism, usually by operating on the same power circuits with the transmitter. The image was viewed in a neon-filled lamp consisting of two flat metallic plates about 2 in. square placed in the neon atmosphere. The voltage across these electrodes was modulated by the incoming signals so that as the holes in the disk were rotated in front of the plate, the observer's eyes saw, momentarily, each portion of the lamp which was bright or dull according to the voltage across it. The color of the image was red, characteristic of neon.

Small disks, say 1 or 2 ft across, were used. The picture was seldom over 2 in. square, although projection systems were designed which gave a screen picture as large as 6 ft across. The detail, however, in the larger pictures was no greater than was contained in the smaller home-type receivers. To increase the amount of light falling on the photocell at the transmitter, holes in the scanning disk were replaced with lenses but the difficulty of getting sufficient light to the photocell so that the output in current was greater than the inherent noise level was very great.

The mechanical difficulties of the disk scanning system are summarized as follows by D. G. Fink in *Principles of Television Engineering:* One mechanical problem is raised by the required speed of scanning motion. In a 441-line picture (characteristic of modern television detail) sent 30 times per second, 13,230 lines are scanned each second. If the picture width at the plane of the scanning apertures is 2 in., the apertures must move 26,460 in. per second. If the rotating disk or drum is 3 ft in diameter, such a scanning speed can be obtained only at a rotation of about 14,000 rpm. This is a high rate of rotation and necessitates careful dynamic balancing to prevent mechanical distortions which would displace the scanning apertures.

401. Electronic scanning. The difficulties of mechanically scanning pictures when high detail is required led engineers to look for other means at an early date in the history of television.

Electronic scanning is the alternative to mechanical scanning. The use of electrons and their motions has many advantages. The electron may be moved with tremendous speed and may have considerable acceleration imparted to it. This is because of its small mass. The amount of energy required to move the electron is relatively small. The whole transmitting and receiving scanning mechanisms may be small and fairly efficient. Lack of mechanically moving parts has obvious advantages.

The **cathode-ray tube** is the electronic analog of the mechanically rotated disk. This tube consists of a cathode like any other electronic tube. This cathode emits electrons which are drawn toward an anode on which is a positive potential. On the way to the anode the electrons may be deflected from their normally straight path so that they may hit any portion of the anode and in fact may be caused to spray over (scan) the anode in a regular to-and-fro manner starting at the upper left, going across to the upper right, dropping down a fraction of an inch while the beam of electrons is returned to the left side, then going across again to the right for the second line, and continuing this motion until the entire anode has been covered. The intensity with which the electrons hit the anode depends upon the voltages impressed upon the anode. The place where the electron strikes is controlled by other voltages placed on deflecting plates, or coils, placed along the path of the electrons.

When the electron hits the anode, it causes a momentary glow of light to be seen by an observer. This is accomplished by painting the anode with certain fluorescent chemicals. If the anode, or screen, is hit with electrons which arrive at constant velocity, the screen is uniformly bright. But if the electron stream is momentarily cut off during part of the to-and-fro motion the screen will be dark. Intermediate shades between light and dark are obtained by voltage variations. The color of the screen can vary over a range. Standard cathode-ray tubes used for electrical measurements have green screens; for television the screens are usually white since the observer seems to enjoy a black and white picture more than a green and white picture.

At the transmitter, the cathode-ray tube is somewhat different from that used at the receiver. Here the cathode and deflecting system are essentially the same, but the anode is entirely different.

402. The transmitter cathode-ray tube. Within the large end of the cathode-ray tube, to be used at the sender, is a square plate about 4 by 5 in. in size. This plate is covered with thousands of minute light-sensitive surfaces or photocells. The picture to be televised is focused by a lens, external to the evacuated space, upon this plate. Between the front light-sensitive surface of these individual photocells and the rear of the plate exists a small capacity which may be charged by the current flowing from the individual photocell under action of the picture focused upon it.

Suppose, therefore, we focus a still picture upon this plate. The photocells translate this picture of varying light and shade into electrical charges existing in the tiny condensers associated with the cells. Now suppose we aim at this plate a beam of electrons (a cathode ray) and sweep it across the plate, across and up and down. In other words we shall make the cathode-ray beam scan this plate of photocells. Each time it strikes the photocell it discharges the condenser associated with that photocell. The discharge current may be amplified, transmitted to the receiving station, and utilized there to modulate another cathode-ray beam which is sweeping across, or scanning, a screen which lights up momentarily when an electron hits it. If these two cathode-ray beams are operated in synchronism the picture will be re-created at the receiver.

The advantages of the cathode-ray scanner are that it is more efficient from the standpoint of using the available light—for the entire picture is illuminated all the time in this case and not just momentarily; and the cathode-ray beam can move with extreme rapidity. Further advantages are saving of space and freedom from the troubles of rotating machinery.

But not all the problems of television are solved by the cathode-ray tube. The transmitter and receiver are complex and expensive; and the programs are vastly more expensive than programs which are merely heard and not looked at.

The problem of space in the ether for high-quality transmission points to the ultra-high frequencies as the only solution. Other, and probably more important, services already tax the available frequencies above 10 meters wavelength. Between this wavelength (30,000 kilocycles) and 5 meters (60,000 kc) there are 1000 channels three times as wide as existing broadcast bands, and there are 30 channels each 1,000,000 cycles wide, which is sufficient for good television. But already other services are making demands upon some of these channels. Nineteen channels have been allocated to television between 44 and 294 megacycles. To date only the lowest of these frequencies has been utilized.

All members of the radio industry—engineers, executives, broadcasters, set manufacturers, and government officials—realize the importance of preserving a space in the ether for television. Fortunately the channels reserved can be used several times within the confines of the United States. Therefore one channel can support several stations provided they are spaced widely enough apart.

Engineers of several companies have spent many hundreds of thousands of man-hours of work and millions of dollars in research, all leading toward the ultimate realization of man's desire to see at a distance.

Standards have been set up for the number of lines to be used (525 for the entire picture), the channels are available, transmitting stations have been erected and tested in New York, Philadelphia and San Francisco. RCA and NBC, Farnsworth, and Philco in this country have demonstrated high-quality television numerous times. These demonstrations have been of cathode-ray systems, both studio scenes and film programs being given.

The Bell Laboratories have developed the coaxial cable, and a first installation between Philadelphia and New York has been made. This is composed of two conductors, one in the center of the other which is grounded. The inner conductor is maintained at the center by insulating spacers. The cable has the property of conducting currents of very high frequency such as are necessary for television channels.

There are still problems, and although vast strides have been made in overcoming them, it is highly doubtful that any appreciable proportion of the area of the United States will be covered with television signals for many years.

403. Problems at ultra-high frequencies. Television brought engineers into intimate contact with the very high frequencies. The desire for greater power at still higher frequencies further instigated research into waves only a few centimeters in length.

Some of the problems are mentioned on page 364. With the problems have come possibilities. Consider a transmission line. If the frequencies sent over it are high enough, the wavelength of the waves traveling through it become of the same dimensions as the diameter of the line. Now the inner conductor may be eliminated—and currents still travel through it. The line is now a pipe, and current can be sent through it just as sound can be sent through an acoustic pipe. Thus we have "wave guides," pipes through which electric waves pass.

Ultra-short waves can be sent on extremely narrow beams because the dimensions of reflectors for these waves are small enough to be physically convenient. Thus a small amount of energy, properly directed to a desired point, may become as useful as a vast amount of energy undirected.

Suppose two condenser plates have a high-frequency charge oscillating between them. With correct dimensions of the condenser with respect to the wavelength of the electric currents, standing waves will exist between these plates. Instead of a single conductor (inductance) connecting the plates into a tuned circuit, all four sides of the plates may be connected with a continuous conductor so that a box results. Still the charges oscillate—we now have an electric resonator.

The end of the war will see these new techniques put to wide use.

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Relation between Wave Length in Meters, Frequency in Kilocycles, and the Product of Inductance (in Microhenries) and Capacity (in Microfarads)

Meters	f in Kc.	L×C	Meters	f in Kc.	L×C	Meters	f in Kc.	L×C
1	300,000	0.0000003	450	667	0.0570	740	405	0.1541
2	150,000	0.0000011	460	652	0.0596	745	403	0.1562
3	100,000	0.0000018	470	639	0.0622	750	400	0.1583
4	75,000	0.0000045	480	625	0.0649	755	397	0.1604
5	60,000	0.0000057	490	612	0.0676	760	395	0.1626
6	50,000	0.0000101	500	600	0.0704	765	392	0.1647
7	42,900	0.0000138	505	594	0.0718	770	390	0.1669
8	37,500	0.0000180	510	588	0.0732	775	387	0.1690
9	33,333	0.0000228	515	583	0.0747	780	385	0.1712
10	30,000	0.0000282	520	577	0.0761	785	382	0.1734
20	15,000	0.0001129	525	572	0.0776	790	380	0.1756
30	10,000	0.0002530	530	566	0.0791	795	377	0.1779
40	7,500	0.0004500	535	561	0.0806	800	375	0.1801
50	6,000	0.0007040	540	556	0.0821	805	373	0.1824
60	5,000	0.0010140	545	551	0.0836	810	370	0.1847
70	4,290	0.0013780	550	546	0.0852	815	368	0.1870
80	3,750	0.0018010	555	541	0.0867	820	366	0.1893
90	3,333	0.0022800	560	536	0.0883	825	364	0.1916
100	3,000	0.00282	565	531	0.0899	830	361	0.1939
110	2,727	0.00341	570	527	0.0915	835	359	0.1962
120	2,500	0.00405	575	522	0.0931	840	357	0.1986
130	2,308	0.00476	580	517	0.0947	845	355	0.201
140	2,143	0.00552	585	513	0.0963	850	353	0.203
150	2,000	0.00633	590	509	0.0980	855	351	0.206
160	1,875	0.00721	595	504	0.0996	860	349	0.208
170	1,764	0.00813	600	500	0.1013	865	347	0.211
180	1,667	0.00912	605	496	0.1030	870	345	0.213
190	1,579	0.01015	610	492	0.1047	875	343	0.216
200	1,500	0.01126	615	488	0.1065	880	341	0.218
210	1,429	0.01241	620	484	0.1082	885	339	0.220
220	1,364	0.01362	625	480	0.1100	890	337	0.223
230	1,304	0.01489	630	476	0.1117	895	335	0.225
240	1,250	0.01621	635	472	0.1135	900	333	0.228
250	1,200	0.01759	640	469	0.1153	905	331	0.231
260	1,154	0.01903	645	465	0.1171	910	330	0.233
270	1,111	0.0205	650	462	0.1189	915	328	0.236
280	1,071	0.0221	655	458	0.1208	920	326	0.238
290	1,034	0.0237	660	455	0.1226	925	324	0.241
300	1,000	0.0253	665	451	0.1245	930	323	0.243
310	968	0.0270	670	448	0.1264	935	321	0.246
320	938	0.0288	675	444	0.1283	940	319	0.249
330	909	0.0306	680	441	0.1302	945	317	0.251
340	883	0.0325	685	438	0.1321	950	316	0.254
350	857	0.0345	690	435	0.1340	955	314	0.257
360	834	0.0365	695	432	0.1360	960	313	0.259
370	811	0.0385	700	429	0.1379	965	311	0.262
380	790	0.0406	705	426	0.1399	970	309	0.265
390	769	0.0428	710	423	0.1419	975	308	0.268
400	750	0.0450	715	420	0.1439	980	306	0.270
410	732	0.0473	720	417	0.1459	985	305	0.273
420	715	0.0496	725	414	0.1479	990	303	0.276
430	698	0.0520	730	411	0.1500	995	302	0.279
440	682	0.0545	735	408	0.1521	1000	300	0.282