NATIONAL RADIO INSTITUTE

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Lesson Text No. 16

INDUCTANCE AND CONDENSER DESIGN

Originators of Radio Home Study Courses
···Established 1914···
Washington, D. C.

"Make the most of yourself, for that is all there is of you."
—Ralph Waldo Emerson.

USEFULNESS AS A CRITERION

A Personal Message from J. E. Smith

Anyone, who is undertaking to study, whether he is going through a school or college course, or is going to study by himself at home, wants to take up subjects according to whether they will, in a large way, be useful to him.

He does not want to consider simply whether they will help him in his business, profession, or other occupation. That side is important.

He wants also, however, to look at his life outside his daily work. Knowledge is useful to a man, or a woman, it seems to me, even if he employs it only for his own pleasure. If one is really interested in a subject, that is sufficient reason for studying it.

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Complete Course in Practical Radio
NATIONAL RADIO INSTITUTE WASHINGTON, D. C.

INDUCTANCE AND CONDENSER DESIGN

In some of the earlier texts, the subject of *Inductance* and *Capacity* was discussed so that the student could gain some knowledge of what took place in a circuit containing inductance capacity. In practically all of the modern Radio receiving sets, inductances and capacities occupy a prominent position and in order to thoroughly understand the fundamental principles of Radio, it is necessary that the student have a detailed understanding of just what takes place in each of these component parts. It is the purpose, then, of this text to take up in detail, not only the theoretical principles of inductance and capacity, but to practically illustrate how these two components are used and the resulting action when they are included in a Radio circuit.

INDUCTANCE IN D. C. CIRCUITS

Specific cases and illustrations usually help to enlighten a student, and for this reason let us look at Figure 1 and study the effect of inductance.

First, let us study just what happens in an inductance or coil. It has already been learned that when an unvarying or direct current flows in a circuit, it encounters only the resistance of the circuit, and the magnitude of such a current is determined by the resistance and the applied voltage in accordance with Ohm's Law. Now when this current is forced through a coil, it sets up a magnetic field about the coil and this magnetic field is in proportion to the amount of current flowing and the number of turns in the coil. *By increasing either the current flowing in a coil or by increasing the number of turns of the coil, we can increase the strength of the magnetic field.* Therefore, the magnetic field is dependent upon the current and the number of turns. It seems reasonable, then, that if the field strength is proportional to the current and the number of turns that if we should in some way change the strength of the field, it would in some way react on the voltage and current applied to the coil.

Such is the case, because as stated previously, an electric current is always accompanied by a magnetic field and we can state the reverse of this by saying that a magnetic field always has the capability of producing an electric current.

If we have a steady, magnetic field and we place in this magnetic field, a wire or coil of wire, and cause this wire or coil to move, the lines of force of the magnetic field will induce in this wire or coil, a voltage and a current will flow in the coil or wire if the circuit be closed. Also, if the magnetic field is varied and the coil remains stationary, the lines of force will cut the wire of the coil and induce a voltage in the wire. Now let us see how this applies to an inductance coil alone.

When a current is passed through a coil, the magnetic lines of force of each wire interlink with those of the other and combine and set up a strong magnetic field. These lines of force, as they are starting to build up in the field, cut some of the other turns of the coil resulting in a voltage being induced in these turns. It then seems reasonable that a second voltage is present in this coil, and this is the case. The main point is, the induced voltage is in the opposite direction to the voltage applied to the coil. The reason for this is that the applied voltage to the coil forces a current through it and sets up a magnetic field in one direction; whereas the induced voltage set up in the coil is the result of the flux cutting the turns of the coil and hence a reversal of polarity between the two voltages.

This induced voltage which opposes the applied voltage is never as great as the applied voltage. However, in some Radio circuits it closely approaches the same value as that of the applied voltage. If the induced voltage of the back or counter E. M. F. (Electromotive Force), as it is sometimes called, should become as great as the applied voltage, no current could flow through the coil.

Suppose now that the applied voltage has overcome the induced or counter voltage and a steady rate of current is flowing through the coil. If the current should in some way be varied or the circuit broken so that current can no longer flow, the steady magnetic field surrounding the coil will collapse. As it collapses, the magnetic lines of force cut the turns of the coil and induce a voltage in the coil. In this last case, we have the applied current decreasing, and inducing another E. M. F. and in this case the E. M. F. is in the same direction as the applied voltage resulting in the induced E. M. F. tending to prolong the flow of current in the coil.

Summarizing the facts brought out together with the explanations, we have the proposition that when the current in an inductive circuit is increasing, the induced voltage is in such a direction that the total voltage acting in the circuit is decreased, and when the current is decreasing, the induced voltage acts to increase the total voltage of the circuit.

To more clearly impress this phenomenon on the mind of the student, it would probably be well to draw a comparison between inductance and something with which we are more familiar. *Inductance is very similar to inertia.* Inertia, as you know, is that property of a body which tends to keep it in a state of rest or to resist any change of momentum. Most all of us have had the experience of pushing a large ball or some object such as a roller used in rolling the grass on a tennis court;

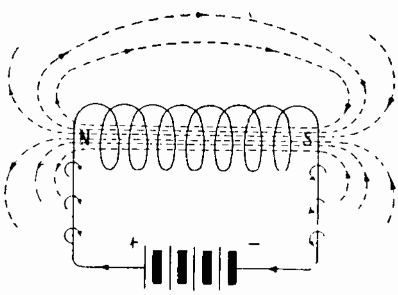


Fig. 1—Magnetic Field about a coil

in this case, we experience practically the same conditions as the electric current does in flowing through an inductance. When first trying to push the ball or roller and set it in motion, it takes a greater force to set it in motion than to keep it in motion. As soon as the roller has gained a certain amount of motion, if we decide to bring it to a sudden stop, it takes a greater amount of energy to stop it than it does to keep it in motion. This is just the same experience as the electric current has, because the applied voltage encounters a counter force when first trying to force the current through the coil and then when the current tries to decrease or stop, the force tries to prolong the current flow.

This phenomenon is referred to as "self-induction" or "self-inductance." "Inductance" is that magnetic property of a circuit that opposes any change in the flux and, therefore, any change in either the magnitude or the direction of the current in the circuit.

The unit of "self-induction" is defined as follows: If the rate of current change of one ampere per second gives an induced voltage of one volt, the coil has a self-induction of one unit. This unit is called the "henry"; *the "henry" is, however, too large a unit for most of the coils used in Radio work, so the sub-divisions of the henry are used. The millihenry is one thousandth of a henry* and the *microhenry is the millionth part of a henry.* The *prefix "milli" means the one-thousandth part of a unit and the "micro" means the one-millionth part of a unit.*

Sometimes, a still smaller unit is used, the *centimeter, which is the one-thousandth part of a microhenry.*

INDUCTANCE IN A. C. CIRCUITS

As the current in an alternating current (A. C.) circuit is periodically reversing its direction of flow, a moment's reflection will bring out the fact that inductance has a greater effect upon alternating current than it does upon direct current. In the direct current circuit, the inductance merely delays the current momentarily until the applied voltage can overcome the counter E. M. F. and then the current will assume a steady value until the circuit is broken or the current is decreased.

Previously it was brought out that whenever the current passing through an inductance changes, it causes a change in the magnetic field surrounding the inductance. The effect, then, of an inductance in an alternating current circuit is that the inductance causes two effects; one, the decreasing of the current and the other lagging of the current behind the voltage.

First, let us see just how the inductance decreases the current. *When a direct current flows through an inductance, it encounters only the resistance of the circuit, but when an alternating current flows through an inductance, the periodic reversals of the current are continually causing the field to change and in turn the field is opposing the flow of current.* This happens many times per second depending entirely upon the frequency of current reversals. This changing of the field represents a certain amount of work performed and in turn a certain amount of resistance to the flow of current is encountered. When speaking of this resistance that the inductance offers to the flow of alternating current, it is termed *reactance* instead of resistance. The symbol for reactance is usually the letter "X" and in order to differentiate between the different forms of reactances, a small letter "L" is sometimes placed to the right of the reactance, symbol, thus "X_L" to signify inductive reactance.

It can be seen, then, that the faster the current changes, the more the field is changed and it naturally follows that the more the number of changes in the field strength, the greater will be the reactance to the flow of current. The formula for the reactance of an inductance is as follows: $X_L = 6.28\ FL$.

In this formula, 6.28 is a constant which it is necessary to employ, F is the frequency of the current in cycles per second and L is the self-inductance in henries in the circuit. To illustrate this, suppose we have an inductance of 5 henries in an alternating current circuit and that the frequency of this current is 60 cycles per second. According to the formula, then, the reactance presented by the inductance is equal to 6.28 times 60 times 5 or 1884. The reactance is always expressed in ohms so that in this case the reactance presented by the inductance in the above example is 1884 ohms.

Now let us see what takes place if we increase the frequency. Suppose as in the previous example, we have an inductance of 5 henries in a circuit, and the frequency of the current is 1000 cycles per second. In this case, then, X_L or the reactance would equal 6.28 x 1000 x 5 which equals 31,400 ohms. It can readily be seen then that *if either the inductance or the frequency of the current is increased, the inductive reactance is also increased.*

The other effect which inductance has on an alternating current is that it causes the current to lag behind the voltage. Figure 2 illustrates a curve showing how the direct current builds up in an inductance and that it does not momentarily rise to its maximum value. If there were no opposing voltage, the current would immediately rise to its maximum value and the line A-B would be a straight vertical line (like CB) instead of a sloping curve.

In the right-hand side of Figure 2 you will see a curve (DF) showing how the coil affects the current whenever the current is decreased. In this case, it can be seen that a certain time exists before the current ceases to flow in the inductance and instead of suddenly decreasing to zero value, it gradually decreases to the zero value. The fundamental principle brought out is that when the voltage is applied to the coil, a certain time exists before the current can build up to its normal value. In this case, then, we have a condition where the voltage momentarily leads the current.

Now bear in mind that in an alternating current circuit just as soon as the current starts through the coil, it induces a voltage in the coil which opposes the flow of current and slightly delays the flow of this current. By the time the current tends to assume a normal value, the applied voltage already has started falling off so that we again have the magnetic field affecting the flow of current by inducing a voltage which tends to prolong it for a certain length of time. The exact relation is this; while the induced voltage is delaying the current, the applied voltage has already passed through its maximum value and has started to decline and the applied voltage has reached zero by the time the current reaches its normal value. This then shows that the voltage runs ahead of the current whenever alternating current passes through an inductance.

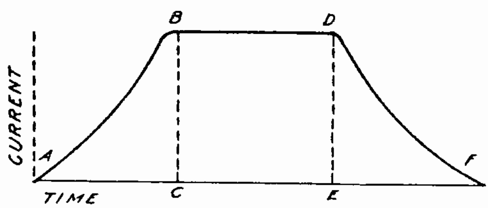


Fig. 2—Curve showing how an inductance affects the current in a circuit

MUTUAL INDUCTANCE

In one of the earlier paragraphs, it was stated that if a wire or coil was moved in a steady magnetic field, or if a coil was cut by a varying magnetic field, a voltage would be induced in this coil or wire. This, then, brings us to the second part of our circuit in which we include another coil such as in Figure 3. You can readily see that this is a part of a radio circuit. If the coil L2 is placed near the coil L1, and a varying current is passing through coil L1, the lines of force set up by the current passing through coil L1 will cut the second coil L2, and a voltage will be set up in this second coil. The amount of voltage set up in the second coil L2 is dependent upon the strength of the magnetic field of coil L1, and the proximity of the coil L2 to that of coil L1. If the second coil L2 is nearer the first coil L1, a greater number of lines of force will cut the second coil and the voltage induced in this second coil L2 will be much greater. Under the heading of "self-inductance," we learned that if the induced voltage was caused by the magnetism and current in the coil itself, the counter E. M. F. is then spoken of as the E. M. F. of self-induction. If the magnetism is due to some other coil, in proximity to the one in which the voltage is being induced, then the E. M. F. is spoken of as the E. M. F. of mutual induction.

This E. M. F. in the second coil, due to the *mutual induction,* is set up in the second coil whether the second circuit is open or closed. If, however, the second circuit is a closed one, then current will flow in it due to the induced voltage.

COUPLING THROUGH MUTUAL INDUCTANCE

From the foregoing, it would seem that there is some means of expressing the degree of coupling between two coils. Such is the case and this degree of coupling is sometimes spoken of

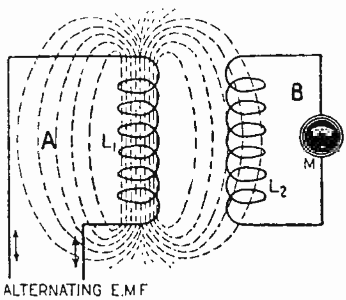


Fig. 3—Diagram illustrating the mutual inductance between Coil L1 in Circuit A and Coil L2 in Circuit B

as the co-efficient of coupling or merely coupling. The co-efficient of coupling is the coupling existing between two inductively coupled circuits and is the percentage of the number of lines of force of the first coil that cut the second coil. If all the flux produced by one coil threads with all the turns of the other, the coils are said to have 100 per cent coupling; if but a small fraction of the flux produced by the first coil threads the turns of the second, the coupling is less. The co-efficient of coupling, then, is a measure of the percentage of the flux of the primary which links with the turns of the secondary. This could be stated in another way—that is, coupling is a measure of the portion of the energy in one circuit which may be transferred to another by these flux interlinkages. Whenever two circuits are near each other so that a transfer of energy takes place between them, they are referred to as coupled circuits.

The coupling between two coils may be increased by moving the coils closer together, by placing the coils on the same iron core as in a power transformer, or by making the coils parallel to each other. By each of these methods, the mutual inductance is increased. The main use of mutual inductance coupling is that energy may be transferred between two insulated circuits due to the flux interlinkages. "Coupler," "Tickler" and "Oscillation Transformer" are names applied to various types of mutual inductance couplings in Radio work where energy is transferred from a coil in one circuit to a coil in another. Figure 4 shows how the coupling can be changed in various ways.

CAPACITY AND CONDENSERS

Whenever two metallic conductors are separated by an insulator (dielectic) these two conductors may maintain a difference of potential by applying a suitable electromotive force.

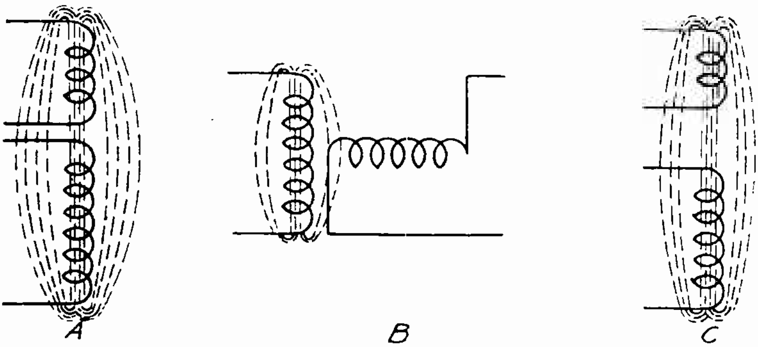


Fig. 4—Showing the affect of varying the coupling between coils

For instance, suppose A and B of Figure 5 are two conducting plates, with mica, air, or glass between them in the space C. *Such a device for storing electricity is called a condenser.* If the switch S is closed, it will be found that a momentary current will flow in the direction as shown, and indicated by the needle of the galvanometer G, but that this current will soon stop even though the battery still has an E. M. F. of 6 volts.

This stopping of current shows that the condenser has developed an electromotive force equal, but opposite, to the applied E. M. F. If the switch S be open and a suitable voltmeter applied to A and B, it will be found that the condenser has developed an E. M. F. of its own. In order that the difference of potential and an E. M. F. between A and B should exist, the electrons in the intervening space must have been re-distributed. We actually think that the plate A has a positive charge and the plate B has a negative charge, these charges having been set up by the current flowing for a certain time. Each plus charge on A is bound to equal minus charge on B, and we have established an electrostatic field between A and B, made up of charges bound by electrostatic lines. The electrons in the space C have been re-distributed, the strain between the electrons being represented by the electrostatic field.

DISCHARGE OF CONDENSERS

In Figure 5, we have a diagram showing how a condenser was charged. In Figure 6, we have connected to the previous circuit, another switch and a galvanometer. When switch S is closed and S-1 is open, the plates of the condenser will assume

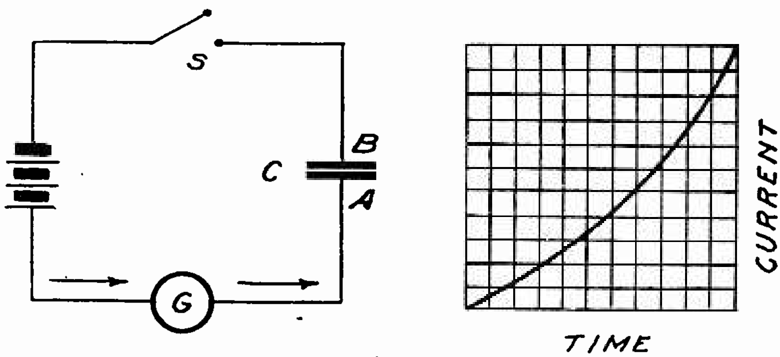


Fig. 5

a charge, the potential difference of which is the same as that of the battery. If switch S is then opened and switch S-1 is closed, the galvanometer G will indicate a flow of current. It was previously shown that the condenser developed a back pressure in opposition to the electromotive force of the battery. Naturally, therefore, the discharge current will flow in the opposite direction to the charging current. This flow of current will last for only a short length of time proving that the condenser has given up the charge which it held.

The discharge of the condenser is not momentary and it is illustrated by the curve shown to the right in Figure 6. In this case, you will notice that the condenser gradually gives up its discharge and that this curve is just the inverse of the charging curve shown in Figure 5. We will learn more about this slow discharging of the condenser later on.

ALTERNATING CURRENT FLOW IN A CONDENSER

By the definition of a condenser, no electrons can actually pass from one plate to the other; the plates are insulated from one another. If, however, a condenser is connected to a source of alternating E. M. F., current will flow in this circuit, as may be seen by the reading of an A. C. ammeter placed in series with the condenser.

Suppose a condenser having a certain capacity is connected to a line, the E. M. F. of which is periodically alternating. The condenser will, of course, take enough charge to bring the potential difference of its plate continually equal to that of the line to which it is connected. As this impressed E. M. F. continually rises in magnitude and direction, electrons must be continually running in and out of the condenser to maintain the plates at the proper potential difference. This continual charging and discharging of the condenser constitutes the current read by the ammeter. The electrons, the motion of which constitutes the current, do not actually pass from one plate of the condenser to the other through the dielectric; they merely flow in and out of the condenser. It can then be understood that the charging current of the condenser is dependent upon the frequency of the alternations. The greater the frequency, the greater the movement of electrons and hence, the greater the charging current. Other things being equal, the charging current of a condenser is directly proportional to the frequency of the impressed E. M. F. This should be contrasted to the inductive circuit in which the current varies inversely as the frequency.

The *reactance* (alternating current resistance) *of a condenser varies in an opposite manner to the reactance of an inductance.* The formula for the reactance of a condenser is given as follows: Xc equals $\frac{1}{6.28\ FC}$. In this formula, Xc represents capacity reactance of the condenser, 6.28 is a constant, F is the frequency of the current in cycles per second, and C is the capacity of the condenser in farads. The capacity reactance is expressed in ohms just as the inductive reactance was expressed in ohms. From this formula, it can readily be seen that the smaller the capacity and the lower the frequency, the greater is the reactance of the condenser and vica versa, the greater the capacity and the higher the frequency the smaller is the reactance.

To bring this out more clearly to the student, suppose we have a condenser of 1 mfd. capacity and we desire to determine its reactance when inserted in a circuit having a frequency of 60 cycles. As the microfarad is the one-millionth part of a farad, then the decimal .000001 farad is the same as 1 mfd. Substituting in the above formula, we then have

$$Xc = \frac{1}{6.28 \times 60 \times .000001}. \quad (1)$$

Solving the equation, we find that the reactance is approximately 2653 ohms. Now suppose that this same 1 mfd. condenser was

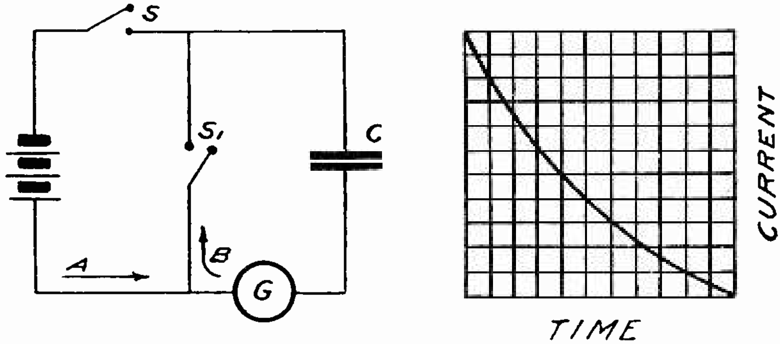


Fig. 6

inserted in an alternating current circuit, the frequency of which was 1000 cycles per second. From the above formula, then, we have

$$Xc = \frac{1}{6.28 \times 1000 \times .000001}. \quad (2)$$

Solving this equation, we find that the reactance at a frequency of 1000 cycles is only 159 ohms.

TYPE OF CONDENSERS

Fixed: The fixed condensers used in Radio circuits vary considerably in regard to the design. Each manufacturer has a special design which may or may not have its advantages. The capacity of the usual fixed receiving type of condensers is nearly standardized so that it is possible to buy a particular capacity designed to be used for a particular condition. The dielectric used in most of the ordinary receiving condensers is mica. However, paper is used considerably in the larger capacity condensers, especially those having a capacity of .1 mfd. or larger. Figure 7 illustrates several types of receiving fixed condensers.

VARIABLE CONDENSERS

It is generally more convenient to make a condenser continuously variable than to make an inductance of that kind, hence, the tuning of a Radio circuit is generally accomplished by using fixed inductances and a variable condenser. These variable condensers are usually made by having one set of the plates stationary and the other set of the plates can be rotated so as to intermesh the rotary plates between the stationary plates. There are three principal types of variable condensers

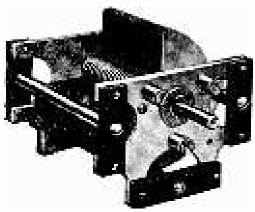
Fig. 7—Various types of Fixed Condensers

used in Radio receiving sets, the *straight line capacity type*, the *straight line wave-length type*, and the *straight line frequency type.*

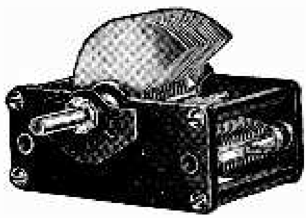
In Figure 8 the three different types are illustrated so as to show the shape of the plates used in each. There are, of course, several variations of each type but these illustrations will serve the purpose of bringing out the difference between the three types.

In the straight line capacity type, semi-circular rotor plates are used and the capacity is continuously variable, the capacity being in direct proportion to the angle of rotation of the rotary plates. When using a straight line capacity condenser in a tuned circuit, more than half of the Broadcast Stations will be tuned in at some point between zero and forty. This is due to the fact that the Broadcast Stations are separated 10 kilocycles apart and as the frequency increases very rapidly at the lower wave lengths, it can be easily understood that more than half of the available 10 kilocycle channels are between 200 and 300 meters.

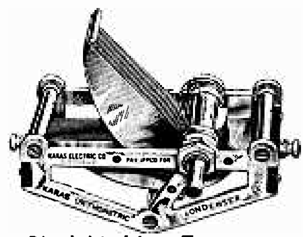
In the straight line wave-length type of variable condenser, the capacity is increased in such a ratio that the stations are tuned in at equal spaces on the condenser dial according to wave length. This is somewhat of an improvement over the straight line capacity type, but in this case also the stations are still crowded to a certain extent on the lower half of the condenser dial.



Straight Line Capacity Variable Condenser



Straight Line Wave Length Variable Condenser



Straight Line Frequency Variable Condenser

Fig. 8

The straight line frequency condenser as can be seen, uses a shaft which is placed to one side of the center so that the capacity is varied in such a way that the stations are tuned in on the condenser dial and equally spaced according to frequency.

OSCILLATORY CIRCUITS

In Figure 9, we have a capacity C in series with an inductance L and a resistance R. The resistance R represents the direct current resistance of the inductance. It is never possible to have an inductance without having it contain some form of direct current resistance, and in order to bring out some of the fundamental principles, this direct current resistance is shown separately. The battery "B" is connected to this circuit by means of two switches S and S-1. When S-1 is open and S is closed, we have already found that the battery will force a current through the resistance R, the inductance L, to the condenser

C, and in so doing, a re-distribution of the electrons in the circuit is caused and the condenser C will gradually assume a charge until the potential difference between the two plates is equal to the potential of the battery. From our previous study, we have found that if a circuit is provided so that the condenser can discharge, it will gradually give off whatever charge it holds until its plates come to a state where no potential difference exists between the two.

Now bear in mind all the former principles that have been brought out in this text so far and let us see what happens when we connect a condenser and an inductance in series. Suppose we open switch S-1 and close switch S. The battery will gradually charge the condenser until it finally assumes a potential equal to the battery. Now by opening switch S, the battery circuit is open and the condenser remains in a charged condition. Now let us close switch S-1 so that a complete circuit is provided for the condenser to discharge. We learned previously that the condenser does not discharge instantaneously.

As the condenser discharges the inductance tries to prolong the flow of current and prevent a decrease in current. In so doing, the inductance causes more electrons to be drawn from the condenser and the balance of the circuit, and the result is that the inductance forces a current through the resistance to switch S-1 and to the other side of the condenser, causing the condenser to be charged in an opposite manner. Instead, then, of the condenser coming to a normal zero potential, the inductance has forced it to assume a charge in the opposite direction. As the magnetic field of the inductance finally comes to rest, we find that there is a difference of potential between the plates of the condenser, and as a circuit is provided for the condenser to discharge, the condenser, therefore, tries to discharge and causes another re-distribution of electrons through the switch S-1, the resistance R, the inductance L and to the other side of the condenser. The inductance tries to retard the current at first but after the current has built up to a certain rate and starts to decrease, the inductance tries to prolong it. The result is, then, that wherever the condenser tries to discharge, the inductance prolongs the discharge until the condenser is actually charged in an opposite manner. From this, it would seem that this charging and discharging would continue indefinitely. However, it must be taken into consideration that in each case when there was a re-distribution of electrons in the circuit and the condenser was charging or discharging, that the current flow in each case was opposed by the resistance and a loss in potential occurred in forcing the current through the resistance. As the resistance causes a loss in potential, then each successive charge of the condenser is at a smaller potential than previously. If the resistance R is very high, the successive charging and discharging of the condenser will in each case be considerably less, whereas if the resistance R is small, each successive charge of the condenser more nearly approaches the charge in the previous instance.

By definition, *an oscillatory circuit is one in which oscillations* (periodic reversals in the direction of flow of current) *can take place.* From the foregoing explanation, it can be seen then

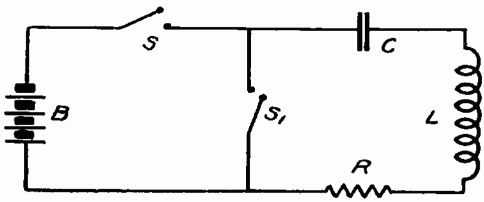
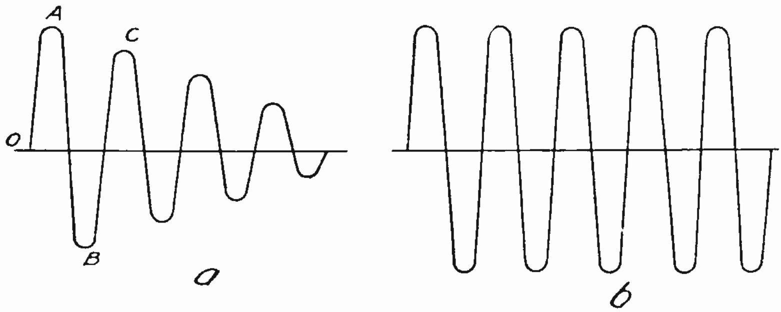


Fig. 9—Fundamental Oscillatory Circuit

that the circuit shown in Figure 9, composed of the condenser C, the inductance L and the resistance R, together with the switch S-1 composes an oscillatory circuit, because oscillations can take place in this circuit. In most cases, oscillations occur at a very high frequency and an oscillatory current is, therefore, a high frequency current which periodically reverses its direction of flow. In Figure 10, we have a graph or curve showing how the current circulates in an oscillatory circuit. When the condenser is uncharged, its potential is at zero just as shown at O. When the condenser is charging, a current circulates and the condenser gradually assumes a charge as represented by the line O-A. As soon as the switch S-1 is closed, the condenser begins to discharge and in doing so, the inductance tends to prolong the flow of current long enough for the condenser to be charged in the other direction as represented by the line from A to B. As the condenser has then been charged in the opposite direction, it tends to discharge and in doing so, the inductance tries to prolong the flow of current long enough for the condenser to become charged in the opposite direction as indicated by the line from B to C. It can be seen from this curve that the point C is not quite as high as the point A, and this indicates that the condition of the condenser when charged at the point C is not as great and it does not have as great a potential as when it was charged at the point A. These oscillations then gradually die away and each successive charge and discharge of the condenser is not as great as the previous one and the circuit finally assumes a normal condition where there is no current circulating in the oscillatory circuit.



Damped Wave — Undamped Wave

Fig. 10

Whenever a condenser discharges into an inductance and resistance, it creates such oscillations and these oscillations are known as damped wave oscillations because the amplitude of each successive charge is not as great as the previous one. This can be seen from Figure 10. *An undamped wave would be a wave in which all of the amplitudes are of the same height*—just as represented to the right in Figure 10.

This damping quality or the dying away of the wave is governed by the amount of resistance in the oscillatory circuit. The greater the resistance included in the oscillatory circuit, the shorter the time will be before the current in the circuit ceases to flow. If the resistance in the circuit is very low, the current tends to oscillate for a greater length of time. In Figure 11, we have an illustration of this showing how the oscillations are shortened or lengthened in time according to the amount of resistance in the circuit.

RESONANCE

So far in our discussion of an oscillatory circuit, it has been presumed that the proportion between the capacity and inductance in the circuit was such that oscillations could take place. Unless such a proportion between the inductance, capacity and resistance in the circuit exists, oscillations cannot take place, and we shall now learn just what are the conditions which must be met before these oscillations can take place. It was just pointed out that if the resistance was increased, the damping was increased, and the length of time that the oscillations existed in the circuit was dependent upon the resistance. Theoretically, if the resistance is too high, only a very few oscillations will take place, and the resistance can be increased to such a point that no oscillations will occur at all. The condenser will

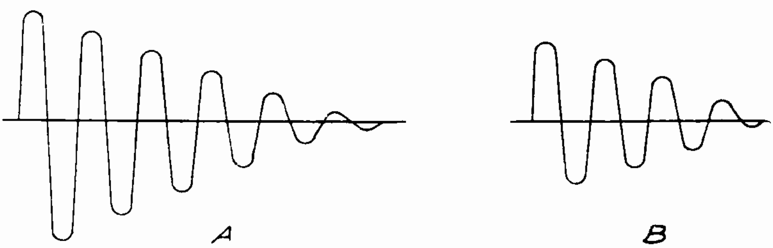


Fig. 11

merely discharge into the inductance and resistance and in doing so it will spend all of its energy in passing through the inductance and resistance and will not assume any charge in the opposite direction.

There is a balance between the inductance and the capacity which must exist and which governs the frequency of the oscillations. We previously learned that the reactance of an inductance was given as $X_L = 6.28 \times F \times L$. The reactance of a condenser is given as

$$X_C = \frac{1}{6.28 \times F \times C} \qquad (3)$$

By looking at these two formulas we can see that the inductive reactance increases with frequency, and that the capacitive reactance decreases as the frequency is increased. *Owing to this, there is a certain frequency at which the inductance and capacity reactance just balance each other resulting in a total reactance of zero.* Whenever such a condition exists, it is known as *"resonance"* because at that frequency the only resistance offered to the flow of alternating current is the direct current resistance included in the circuit. Without going into details as to the evolution of the formula, we find the formula for resonance is:

$$F = \frac{1}{6.28 \times \sqrt{LC}} \qquad (4)$$

From this formula, then, it is possible to determine the resonant frequency when the inductance and capacity of the circuit are known.

We have just discussed what is known as series resonance and this is the type of resonant circuit which is most used in Radio receiving circuits. In this case, the inductance L and the condenser C and the potential are all in series and this is known as series resonance.

There is another form of resonance known as parallel resonance and without going into detail, it can be stated that in parallel resonant circuits the opposite results are encountered as in the series circuit. In the parallel resonant circuit, the resultant reactance becomes infinitely high at the resonant frequency and the result is that the current is offered an infinitely high resistance and hence at this particular resonant frequency, the current is practically zero. As the series resonant circuits are much more common in Radio, the parallel resonant circuits will not be gone into at this time.

In Figure 12A we have a curve illustrating the current flowing in a series resonant circuit. At the resonant frequency when the two reactances balance each other, the current is at a maximum. It will be noticed that as resonance is approached from either direction, the current is rising and tends to increase. In Figure 12B we have another curve showing the effect of increased resistance on the resonance curve. It will be noticed that in this case the curve is not as sharp as in the previous case because the resistance has been increased and this materially broadens the resonance curve. Therefore, then, by decreasing the resistance in the oscillatory circuit, the resonance curve is sharpened and when the resistance is increased, the resonance curve is broadened. It would seem at first glance that the best oscillatory circuit for use in a Radio frequency receiver would be one which would have a very sharp resonance curve, but this is not always the case because it is generally desirable to amplify a certain band of frequencies instead of the frequency of the incoming carrier wave alone and since this is the case a slightly broader curve is more desirable. Figure 12C illustrates the ideal curve but this cannot always be obtained. It is, however, desirable to have the oscillatory circuit so designed that it will approach this type of resonance curve as nearly as possible.

DESIGN

The following *formulas, tables and curves given will enable one to design coils for use in Radio receiving sets.* Finding the inductance of a certain coil is an interesting problem and for that reason the formula for the inductance of a single layer close wound solenoid is given herewith:

$$L_S = \frac{A^2 \ N^2}{10b} \times K. \tag{5}$$

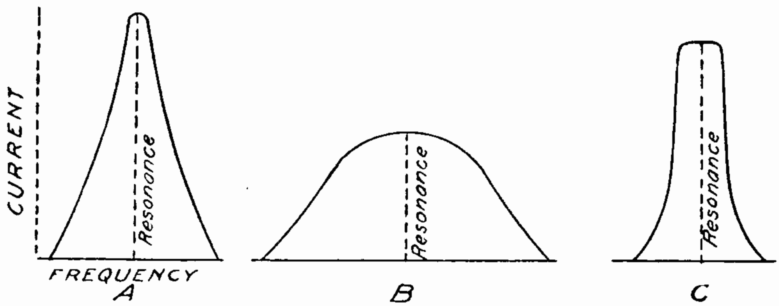


Fig. 12

In the above formula, Ls represents the self-inductance in microhenries of the coil, A is the radius in inches of the coil, N is the number of turns of wire, 10 is a constant, b represents the length of the coil in inches and K is a constant which is determined from the diameter divided by the length of the coil, the value of K for different values can be found from Table 1.

In order to clearly understand the formula and the use of the table, let us take a concrete example and work it out and find the self-inductance of a single layer coil. Suppose it is desired to find the self-inductance of a coil consisting of 82 turns of No. 24 DSC wire, the diameter of the winding being 2 inches. As No. 24 DSC wire can be wound with approximately 41 turns per linear inch, the coil will be approximately 2 inches long.

As K is a function of the diameter divided by the length, it is noted that the diameter is 2 inches and that the length is

2 inches, hence 2 divided by 2 equals 1. Now refer to Table 1 and in the first column, "diameter over length," you will notice the figure 1 in this column. To the right of this figure 1 in the next column under "K" you will find the fraction .6884. This then is the fraction which must be employed for this length and diameter coil in order to make the formula come out properly.

Substituting these values for the letters in the above formula, we then have

$$L_s = \frac{1^2 \times 82^2}{10 \times 2} \times .6884 \qquad (6)$$

Simplifying the foregoing, we have

$$Ls = \frac{1 \times 6724}{20} \times .6884 = 336.2 \times .6884 = 231. \qquad (7)$$

The result is just slightly over 231 microhenries but this is close enough for all average purposes.

Having thus learned how to calculate the inductance of a certain coil, the next step is to find out what combination of inductance and capacity will respond to a given wave-length or frequency. Earlier in the text the formula for the frequency to which a circuit would respond was given as

$$F = \frac{1}{6.28 \times \sqrt{LC}} \qquad (8)$$

In that case the inductance and capacity was given in henries and farads. As these units are much larger than ordinarily used in Radio receiving sets, the formula can be simplified by stating that

$$F = \frac{1,000,000}{6.28 \times \sqrt{LC}} \qquad (9)$$

In this case, then, the inductance and capacity are given in microhenries and microfarads. From this formula it can be seen that there is a certain constant representing LC or the square root of LC which will be a certain value for each frequency. That is, as the numerator of the fraction 1,000,000 is a constant and 6.28 is a constant then the inductance and capacity are the only values which vary. This is the case, however, should it be necessary to work this formula out in each case, considerable time would be spent, so tables are given which show the relation of the inductance and the capacity for certain fre-

TABLE 1

VALUES OF K FOR USE IN SELF-INDUCTANCE FORMULA

Diameter / Length	K	Diameter / Length	K
0.00	1.0000	1.75	0.5579
.05	.9791	1.80	.5511
.10	.9588	1.85	.5444
.15	.9391	1.90	.5379
.20	.9201	1.95	.5316
0.25	0.9016	2.00	0.5255
.30	.8838	2.10	.5137
.35	.8665	2.20	.5025
.40	.8499	2.30	.4918
.45	.8337	2.40	.4816
0.50	0.8181	2.50	0.4719
.55	.8031	2.60	.4626
.60	.7885	2.70	.4537
.65	.7745	2.80	.4452
.70	.7609	2.90	.4370
0.75	0.7478	3.00	0.4292
.80	.7351	3.10	.4217
.85	.7228	3.20	.4145
.90	.7110	3.30	.4075
.95	.6995	3.40	.4008
1.00	0.6884	3.50	0.3944
1.05	.6777	3.60	.3882
1.10	.6673	3.70	.3822
1.15	.6573	3.80	.3764
1.20	.6475	3.90	.3708
1.25	0.6381	4.00	0.3654
1.30	.6290	4.10	.3602
1.35	.6201	4.20	.3551
1.40	.6115	4.30	.3502
1.45	.6031	4.40	.3455
1.50	0.5950	4.50	0.3409
1.55	.5871	4.60	.3364
1.60	.5795	4.70	.3321
1.65	.5721	4.80	.3279
1.70	.5649	4.90	.3238

quencies or wave-lengths, which have been found from this formula.

In Table 2 these values are given so that if we merely multiply the value of the inductance in microhenries by the value of the capacity in microfarads we obtain a certain result and by referring to this table we can locate the product of the inductance and the capacity in the column marked "LC." Then by referring to the column under "wave-length" the same line, we can tell the wave-length to which the circuit will respond or under the column K.C. the frequency is found. It can be seen that since this product of inductance and capacity is constant for a certain frequency, we could vary either the inductance or the capacity, but so long as the product of the two is the same we have not altered the frequency to which the circuit will respond.

Let us take a concrete example and see just how this table is used. Suppose we have a .0005 mfd. variable condenser and desire to know what inductance will be necessary in order to have the circuit respond to a wave-length of approximately 545.4 meters (550 kilocycles). By referring to the table in the column under "LC," we find that the product of the capacity and inductance is, for this frequency, equal to .083734. If the capacity is .0005, then by dividing the fraction .083734 by .0005, we can determine the inductance necessary. Thus, we find that the inductance should be a trifle more than 167 microhenries. Now suppose that we desire to know the lowest wave-length to which the circuit will respond. Unless the minimum capacity of the condenser is known, it is only possible to estimate this. Roughly, the minimum capacity of any variable condenser is approximately 10% of its maximum capacity. Therefore, the minimum capacity of a .0005 mfd. condenser is approximately .00005 mfd. In some cases the minimum capacity is lower than 10%, however, this is an average figure especially taking into consideration the capacity of the connecting leads to the condenser, etc.

Now if we have an inductance of 167 microhenries and we desire to know the minimum wave-length the circuit will respond to when tuned by a variable condenser having a minimum capacity of .00005, we multiply 167 by .00005 and obtain a result of .00835. Trying to locate this last figure in the column under "LC" we note that this figure is lower than the lowest, or first figure, given in this column and, therefore, the circuit will respond to some wave-length less than 189.87 meters (1580 kilocycles).

TABLE 2

VALUES OF INDUCTANCE CAPACITY

Inductance in Microhenries, Capacity in Microfarads

Wave Length	K.C.	$\sqrt{LC}$	LC	Wave Length	K.C.	$\sqrt{LC}$	LC
189.87	1580	.10072	.010144	291.2	1030	.15452	.023876
191.08	1570	.10138	.010277	293.9	1020	.15603	.024345
192.30	1560	.10202	.010408	296.9	1010	.15757	.024828
193.54	1550	.10268	.010543	300.0	1000	.15915	.025328
194.79	1540	.10334	.010679	302.8	990	.16076	.025843
196.07	1530	.10402	.010820	305.9	980	.16240	.026022
197.36	1520	.10470	.010962	309.1	970	.16407	.026919
198.67	1510	.10540	.011109	312.5	960	.16578	.027483
200.00	1500	.10612	.011261	315.6	950	.16787	.028080
201.34	1490	.10681	.011408	319	940	.16931	.028665
202.70	1480	.10753	.011562	322.4	930	.17113	.029285
204.08	1470	.10826	.011721	325.9	920	.17474	.030534
205.41	1460	.10900	.011881	329.5	910	.17489	.030590
206.89	1450	.10976	.012047	333.1	900	.17684	.031272
208.33	1440	.11052	.012214	336.9	890	.17882	.031976
209.79	1430	.11128	.012365	340.7	880	.18084	.032703
211.26	1420	.11218	.012566	333.3	870	.18293	.033463
212.76	1410	.11283	.012831	348.8	860	.18506	.034247
214.28	1400	.11368	.012922	352.9	850	.18724	.035058
215.82	1390	.11451	.013112	357.1	840	.18947	.035896
217.39	1380	.11530	.013294	361.4	830	.19175	.036768
218.97	1370	.11617	.013495	365.8	820	.19409	.037670
220.58	1360	.11700	.013689	370.3	810	.19649	.038608
222.22	1350	.11789	.013898	375.0	800	.19894	.038768
223.88	1340	.11878	.014008	379.7	790	.20146	.040584
225.56	1330	.11966	.014318	384.6	780	.20608	.042468
227.27	1320	.12056	.014534	389.6	770	.20668	.042716
229.00	1310	.12149	.014759	393.4	760	.20932	.043820
230.76	1300	.12254	.015026	400.0	750	.21220	.045028
232.55	1290	.12337	.015190	405.4	740	.21722	.047184
234.37	1280	.12434	.015460	410.9	730	.21802	.047532
236.22	1270	.12531	.015702	416.6	720	.22104	.048858
238.09	1260	.12631	.016050	422.5	710	.22416	.050247
240.00	1250	.12732	.016210	428.5	700	.22736	.051692
241.12	1240	.12848	.016507	434.7	690	.23065	.053199
243.90	1230	.12939	.016731	441.1	680	.23429	.054890
245.90	1220	.13045	.017017	447.7	670	.23754	.056425
247.93	1210	.13153	.017300	454.5	660	.24114	.058148
250.00	1200	.13261	.017585	461.5	650	.24545	.060240
252.10	1190	.13376	.017891	467.0	640	.24868	.061741
254.23	1180	.13487	.018189	476.0	630	.25264	.063826
256.41	1170	.13602	.018503	483.8	620	.25670	.065894
258.62	1160	.13722	.018829	491.8	610	.26065	.067938
260.86	1150	.13840	.019154	500	600	.26525	.070357
263.15	1140	.13961	.019490	508.4	590	.26975	.073874
265.48	1130	.14084	.019835	517.3	580	.27440	.075295
267.85	1120	.14213	.020201	526.3	570	.27922	.077963
270.1	1110	.14340	.020511	535.7	560	.28421	.080774
272.6	1100	.14468	.020932	545.4	550	.28937	.083734
275.1	1090	.14601	.021318	555.5	540	.29476	.086883
277.6	1080	.14736	.021713	566.0	530	.30030	.090180
280.2	1070	.14874	.022223	576.9	520	.30607	.093678
282.8	1060	.15010	.022530	588.2	510	.31207	.097387
285.5	1050	.15157	.022973	600.0	500	.31830	.099023
288.3	1040	.15303	.023418				

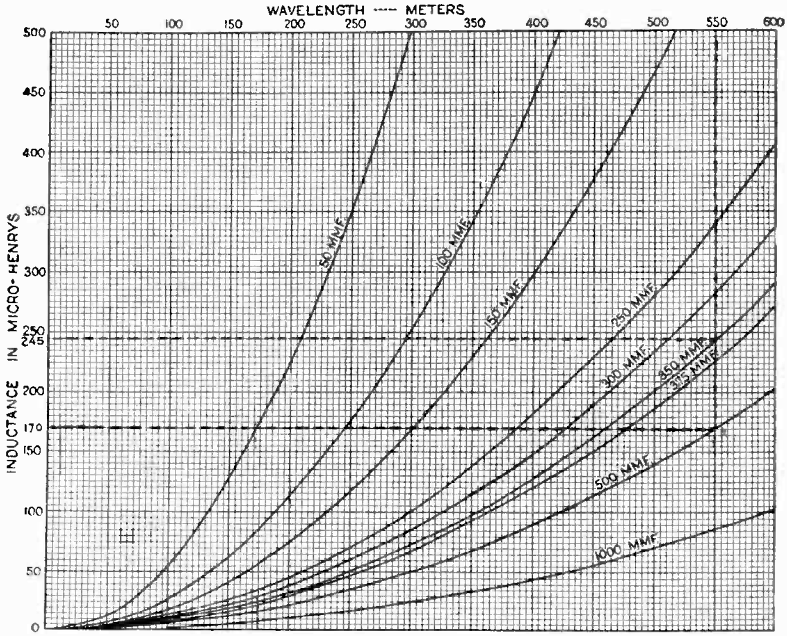
For those who are interested in designing coils by some means which does not necessitate the use of the formulas given, the following tables and charts will be found useful.

It might be interesting to take a few examples and work them out so as to show the flexibility of the charts. Suppose the receiver being designed requires a coil not more than 2 inches in diameter and 2½ inches long. In Figure 13 the 50 mmf. curve represents the curve for a .00005 mfd. condenser; the 100 mmf. a .0001 mfd. condenser; the 150 mmf. a .00015 mfd. condenser; the 250 mmf. a .00025 mfd. condenser; the 300 mmf. a .0003 mfd. condenser; the 350 mmf. a .00035 mfd. condenser; the 375 mmf. a .000375 mfd. condenser; the 500 mmf. a .0005 condenser and the 1000 mmf. curve a .001 mfd. condenser.

If the maximum wave-length to be reached with a .0005 condenser is 550 meters then locate this wave-length on the upper horizontal line and follow this point downward until it intersects the 500 mmf. curve. It will be noticed that the 550 meter line intersects the 500 mmf. line 4 spaces above the 150 line shown to the left representing microhenries. The dotted line running from the intersection of the 550-meter line to the left-hand column indicates then that the inductance should be 170 microhenries. Now refer to Figure 15 for coils 2″ in diameter and on the left-hand column locate the point 170 microhenries. Then following this to the right to the 2½″ curve, which represents coils 2½″ long, the intersection occurs directly under the line representing 30 turns per inch. Therefore, then, the coil should be wound with some wire having such a diameter that 30 turns to the linear inch can be wound. Referring then to Table 3, showing the number of turns per inch for the various size wire, we find that the coil could be wound with No. 20 enamel, No. 20 SS, or No. 22 DCC wire as all of these have a diameter so that approximately 30 turns per inch can be wound.

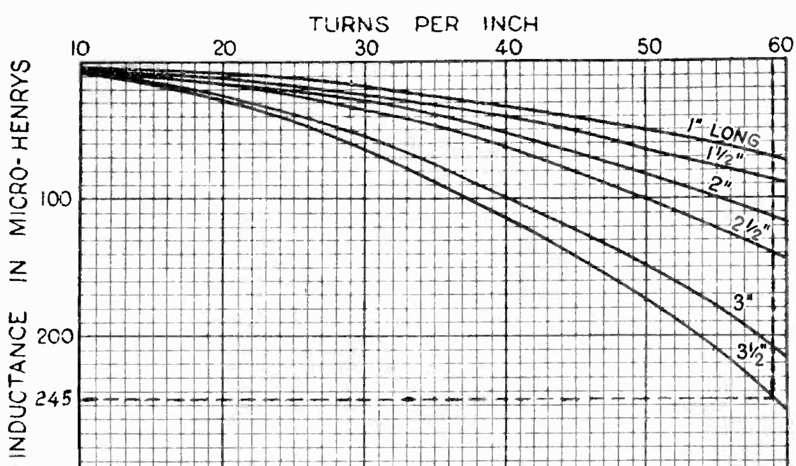
The given example shows that one can decide on the coil and determine the number of turns per inch for the most suitable condenser, or can decide on the condenser and determine the physical characteristics of the coil necessary to cover the desired wave band most suitably.

Let us work out a more practical example. Suppose we wish to use a variable condenser having a maximum capacity of 350 mmf. (.00035 mfd.). This is a good value and the curve for this capacity in Figure 13 is not too abrupt in its upward bend. If 550 meters is the highest wave-length we wish to reach, we



INDUCTANCE - CAPACITY CURVES

Fig. 13



COIL 1" DIAM.

Fig. 14

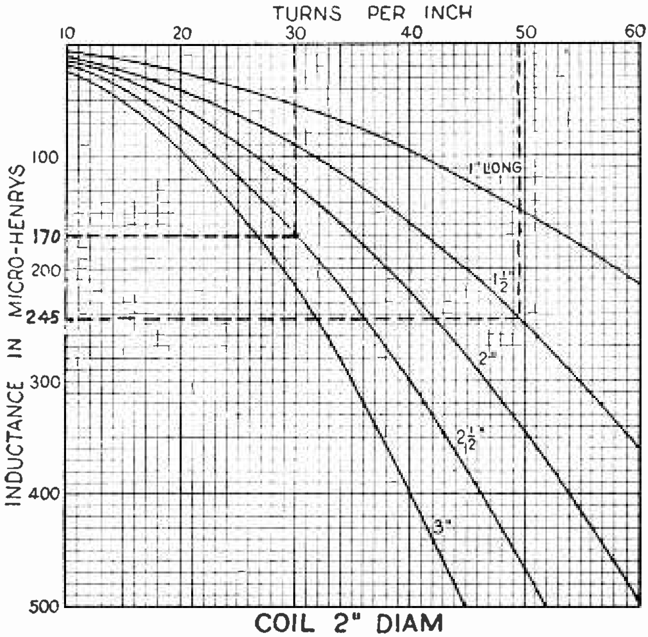

TURNS PER INCH
10
20
30
40
50
60
INDUCTANCE IN MICRO-HENRYS
100
170
200
245
300
400
500
1" LONG
1½"
2"
2½"
3"
COIL 2" DIAM

Fig. 15

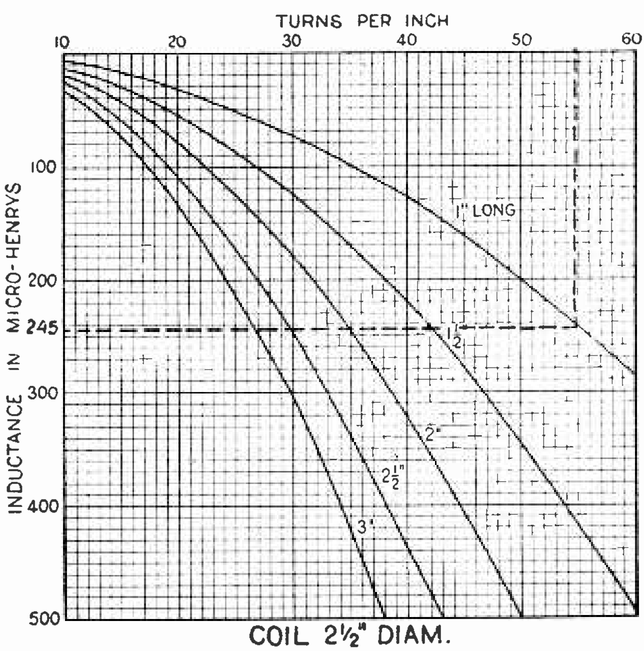
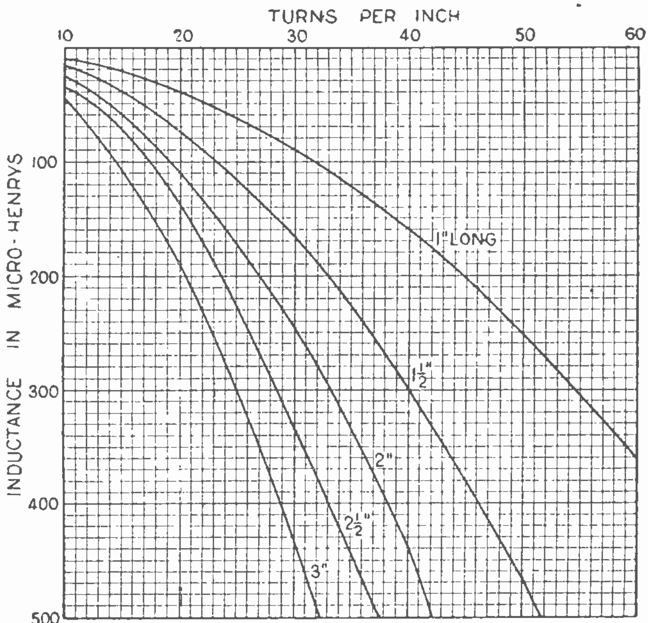
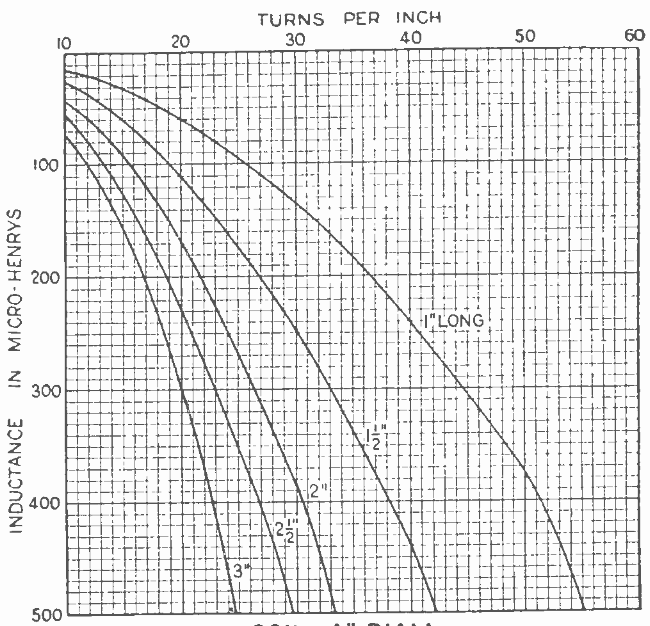

TURNS PER INCH
10
20
30
40
50
60
INDUCTANCE IN MICRO-HENRYS
100
200
245
300
400
500
1" LONG
1½"
2"
2½"
3"
COIL 2½" DIAM.

Fig. 16



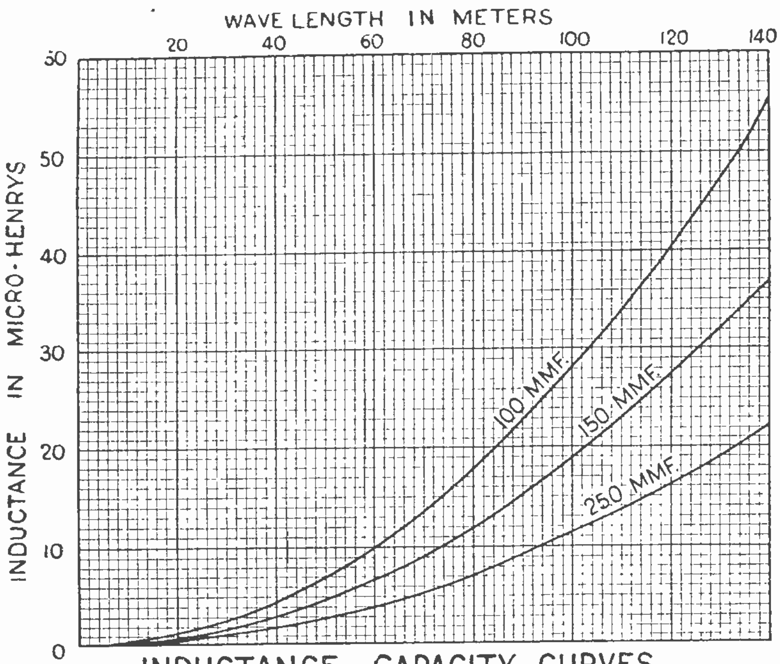
COIL 3" DIAM

Fig. 17



COIL 4" DIAM.

Fig. 18



INDUCTANCE - CAPACITY CURVES

Fig. 19

TABLE 3

WIRE TABLE

	TURNS PER LINEAR INCH				
B & S Gauge	Enamel	Single Silk	Double Silk	Single Cotton	Double Cotton
16	18.9	18.9	18.3	17.9	16.7
18	23.8	23.6	22.7	22.2	20.4
20	30	29.4	28.0	27.0	24.4
22	37	36.6	34.4	33.9	30.0
24	46	45.3	41.8	41.5	35.6
26	58	55.9	50.8	50.2	41.8
28	73	68.5	61.0	60.2	48.6
30	91	83.3	72.5	71.4	55.6
32	116	101	84.8	83.4	62.9
34	145	120	99.0	97.0	70.0
36	182	143	114.0	111.0	77.0
38	228	168	129	126.0	84.0
40	286	194	144	140.0	90.0

find that by referring to Figure 13 the value of the inductance required is a shade under 245 microhenries. Now, by referring to the chart of Figure 14, for a coil 1″ in diameter, it will be found that it is just possible to reach an inductance value of 245 microhenries by using a coil 3½″ long. However, a coil 2″ in diameter as shown by the curve in Figure 15 is satisfactory providing it is an even 1½″ long. If we increase the diameter of the proposed coil to 2½″, it need be only 1″ long (Fig. 16) to reach the required inductance, but a wire capable of being wound 55 turns to the inch would be required. The most satisfactory coil would probably be one with a diameter of 2″ and a length of 2½″. One of the reasons for this is that a coil of less length would require a small gauge wire in order to get the necessary number of turns per inch of coil.

The exact number of turns for the primary of a radio frequency transformer depends somewhat on the circuit in which the transformer is used and also the exact type of apparatus used in the construction of the entire receiver. If too many turns are used on the primary winding the Radio frequency tubes will oscillate. Therefore, the primary windings should be so designed that the tubes are just below the oscillation point.

Generally speaking, the primary winding is approximately one-third of the secondary winding. The exact number can be determined only by experiment, although 15 to 25 turns are generally used.

TEST QUESTIONS

Number your answer sheet 16-2 and add your **student number.**

Never hold up one set of lesson answers until you have another set ready to send in. Send each lesson in by itself before you start on the next lesson.

1. How may a voltage be induced in a coil of wire?
2. What is inductance?
3. What two effects does an inductance have upon an alternating current?
4. When are two circuits said to be coupled?
5. Define an oscillatory circuit.
6. What governs the damping of a circuit?
7. What term is used to denote that the inductive and capacitive reactance just balance each other?
8. What is the wave-length of a circuit when "LC" equals .028665?
9. What is the approximate value of inductance to use with a .00035 mfd. condenser in order to tune to a wave-length of 550 meters.
10. Give the size and kind of wire to use when it is desired to make a coil 1 inch long having 27 turns.

RADIO BY MAIL

National Radio Institute

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