ELECTRONIC TECHNOLOGY SERIES

L-C OSCILLATORS

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L-C
OSCILLATORS

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PREFACE

One of the most important parts of the study of oscillators is that of L-C oscillators. In itself an integral part of every curriculum in electronics, its importance stems from the wide and varied use of L-C oscillators in amateur, commercial, military and industrial applications.

Particular care has been taken to select topics that would make this work as comprehensive as possible within the practical limitations of size. Included are items of general information pertaining to L-C oscillators as they relate to oscillator elements, energy conversion, frequency range, stability, power considerations, oscillator efficiency, harmonic generation, series and parallel resonance, and critical damping. The chapter devoted to circuit analysis treats the factors affecting the feedback loop and the circuit requirements for an amplifier to reach a condition of oscillation. Detailed descriptions of the essential features of oscillator circuits utilize such mathematics as is necessary for a full understanding of the various criteria of oscillation. The concluding sections discuss a number of typical circuits, chosen for their relative importance among the many variations of L-C oscillator circuits that have been developed.

Grateful acknowledgment is made to the staff of the New York Technical Institute for its assistance in the preparation of the manuscript of this book.

New York, N. Y. A. S.
January 1957

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Chapter 1

GENERAL INFORMATION

1. Common Forms

Common forms of L-C oscillators now employ electron tubes as their amplifying devices almost exclusively, although transistors are beginning to appear in increasing numbers. Spark gaps, which once were the only practical means of producing high frequency oscillations, have now been virtually abandoned.

The output of most L-C oscillators is substantially sinusoidal in form. The problem of harmonic content, however, cannot be ignored and is therefore given careful consideration in this book.

2. Energy Conversion

The L-C oscillator is an energy converter that, as a rule, accepts d-c power, converting it into voltage, current, and/or power of predetermined frequency. During the conversion process, some of the power supplied is consumed in heating filaments and compensating for other losses in the oscillator circuit, while the remainder is delivered to the next circuit as useful output at the desired frequency. Normally, this conversion efficiency is quite low; it can be improved, however, by careful design, particularly in high-power applications.

3. Frequency Range

L-C oscillators may be constructed to yield output voltages having any of a wide range of frequencies from a fraction of a cycle per second to several hundred million cycles per second. A steady extension of the upper frequency limit has resulted from research and improvement in components over the past few decades. New circuits and new electron tubes especially designed for ultra-high frequencies are constantly being developed. As they are applied to practical equipment, they are bringing about a frequency spectrum wider than ever thought possible.

4. The Cycle

During one cycle, the output of the oscillator passes through all the positive and negative values of voltage and current which

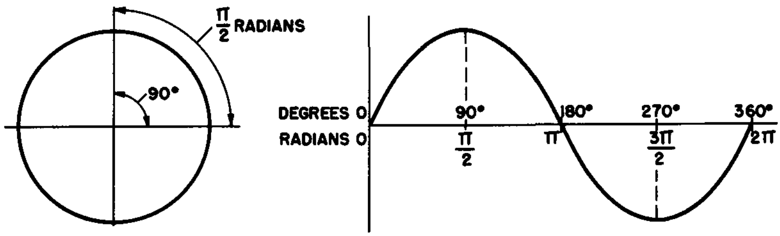


Fig. 1. Generation of a sine wave showing measurement in degrees and radians.

repeat in later cycles. The time required to complete one cycle, i.e. the *period* T, is an important consideration in oscillator discussions. It is related to frequency in the reciprocal equation:

$$T = \frac{1}{f} \tag{1}$$

where T is the period in seconds when the frequency, f, is given in cycles per second (cps).

5. Angular Frequency

It is often more convenient to express the cyclic repetition rate in terms of *angular frequency.* Angular displacement is measured in radians so that angular frequency is given in radians per second. A radian is the angle which subtends an arc equal in length to the radius of the circle on which the arc is chosen. Since the circumference of a circle is 2π times its radius, a 360° angle contains 2π radians. Thus 360° = 2π or (6.28) radians, one degree

= .01745 radian, and 1 radian = 57.2958 degrees. (See Fig. 1.) The lower case *omega* (ω) is conventionally used to express the number of radians per second traversed by a rotating vector in generating a projected sine-wave signal. The relationship is:

$$\omega = 2\pi f, \text{ or } f = \omega/2\pi \qquad (2)$$

Example: Find the angular frequency in radians per second of an oscillator whose period is .001 second.

$$f = \frac{1}{T} = \frac{1}{.001} = 1000 \text{ cps}$$

$$\omega = 2\pi f = 2000\pi \text{ radians per second}$$

6. Stability

More research has been devoted to the problem of improving stability than to any other aspect of oscillator design. Although amplitude stability is not generally a serious problem, achieving frequency stability (the degree to which an oscillator remains at a desired frequency) presents difficult aspects. The frequency stability of an oscillator is expressed in plus and minus deviations from a nominal frequency; for example, where the stability of an oscillator is given as 1000 $\pm$ 10 cycles, it means that the output frequency of the oscillator may vary between 990 cycles and 1010 cycles as a result of conditions that either have not been controlled or are not controllable.

Frequency stability is of the utmost importance because oscillators are often used as frequency standards and because there are many applications that demand high precision in the production of particular frequencies. As an example, a radio or television transmitter under the jurisdiction of the FCC that radiates a one-megacycle carrier is permitted by law a tolerance of only 20 cps, an accuracy of one part in fifty thousand. Special oscillators are now in use that can remain "on frequency" with no perceptible drift over long periods of time.

7. Power Oscillators

In applications where power delivery is the primary requisite, conversion efficiency must be given more than ordinary consideration. Once the oscillator circuit has been designed for the greatest possible efficiency, the problem becomes one of power transfer to the load which, of course, leads at once to considerations of efficient coupling methods, impedance matching, high-efficiency transmission lines, and other factors that are not a part of the oscillator proper.

Power oscillators are generally not expected to have high frequency stability and are not used where such requirements exist. When the goal is both high frequency stability and high power, multi-stage equipment is required, in which stability is obtained in a low power oscillator stage and the power requirements are satisfied by amplifiers.

8. Mode of Control

In most oscillators, frequency control is exercised by an L-C arrangement. Oscillation is sustained by controlling the electron stream in the amplifier tube electrostatically, electromagnetically, piezo-electrically, or by a combination of these methods. Armstrong or Hartley oscillators fall into the electromagnetic class, whereas the tuned-plate, tuned-grid circuit is electrostatic in nature. Very highly accurate oscillators are invariably piezo-electrically controlled by quartz crystals in constant-temperature ovens, and the special high-frequency oscillators described in Chap. 5 use modifications of these effects.

The microwave magnetron used in generating very high or ultra high frequencies for radar and allied apparatus is a highly efficient tube that employs both electrostatic and electromagnetic frequency control in addition to electron transit time effects. The klystron, another high frequency oscillator tube, is timed by the velocity of the electron stream within its envelope and is successfully used in many television transmitter and microwave circuits. Still another oscillatory arrangement called the atomic clock depends upon molecular resonance of ammonia gas present in a wave guide system to control the frequency of the electron tube oscillator.

9. Physical Forms of Tuning Inductance and Capacitance

Tuning inductors and capacitors may take a great variety of forms. In low frequency applications, the L-C elements are usually in the form of a lumped inductance and a lumped capacitance as discrete units. Either or both may be variable for frequency control. High frequency oscillators in the microwave region may be tuned by a transmission line section, real or simulated; or the tuning unit may be a cavity where the two surfaces form the capacitor and the path around the cavity between the surfaces is the inductor. (In the case of cavity resonators, it is not always easy to recognize the portions of the cavity that form the inductance and the capacitance.)

The behavior of a quartz crystal in a piezo-electric oscillator may be reduced to an equivalent circuit containing inductance, capacitance, and resistance. For this reason, the crystal element in its holder may be considered L-C components in a crystal oscillator.

10. Sine-Wave vs. Relaxation Oscillators

Oscillators in which the L-C elements are the principal frequency-determining components are called *sine-wave oscillators* because the voltages and currents that arise during oscillation have sinusoidal form. This distinguishes them from *relaxation oscillators* in which the waveform is markedly non-sinusoidal and in which considerable frequency instability is usually encountered, particularly at higher frequencies. Differentiating between these two types is not always an easy matter, since certain very popular oscillator circuits, such as blocking oscillators, make use of both L-C and relaxation characteristics.

11. Harmonic Content

Harmonics are integral multiples of the lowest frequency (the *fundamental*) that a given L-C combination can produce. When the energy content of an oscillatory circuit is predominantly sinusoidal (i.e. when the harmonic content is low), the oscillator may be classified as a *linear* device. Although no oscillator can ever produce perfect sine waves (be absolutely linear), approximately linear operation may be expected from a well designed system. Other L-C oscillators, either as a result of poor design or intentionally inserted harmonic-producing components, yield output waveforms with large harmonic voltages. In some cases, the presence of harmonics is desirable as, for example, in the frequency multipliers that follow the oscillator in certain types of transmitters.

In most situations, however, even and odd harmonics above the fundamental frequency must be minimized if good stability is to be realized.

12. Oscillator Elements

Regardless of its type, any oscillator may be divided into three basic elements: the frequency determining network (often called the "resonator"), the amplifier, and the load (or output circuit). When an oscillator circuit is to be functionally analyzed, it is usually easy to identify and distinguish between the resonator and the amplifier because the resonator is almost always an electromechanical device whereas the amplifier is essentially electronic in nature. Determining where the amplifier ends and the load begins is not quite as easy in some circuits, but careful analysis will always point to a demarcation line that permits development of an appropriate equivalent circuit.

From the point of view of good frequency stability, each of these elements is intrinsically important and, furthermore, the relationships between them have a dominant effect upon the oscillator's ability to remain "on frequency" under changing conditions of temperature, pressure, and humidity.

The resonator, for example, must be protected against temperature variations and must be insensitive to changes in tube parameters or characteristics. It should be sufficiently isolated from the load to be unaffected by variations in loading conditions, and it should be as free from losses as possible. (This, of course, means a high Q.) From the mechanical point of view, the resonator must be mounted so that vibration cannot affect its structure and electrostatic and electromagnetic shielding should be employed to reduce stray and body capacitance effects. Hermetic sealing minimizes the detrimental effects of moisture and pressure variations upon constant frequency.

13. The Basic L-C Oscillator Block Diagram

The essentials of a feedback type oscillator are shown in Fig. 2. This block diagram shows the electrical relationship between the amplifier, the feedback circuit, and the load. The output power of the amplifier, divided as it is between the load and the feedback loop, must be sufficiently large to supply both. A second requirement for maintaining oscillation is that the phase relationship between the feedback energy and the input energy of the amplifier must be correctly adjusted. These two specifications can usually be met at only one frequency since the resonator changes both the amplitude and phase of its output at frequencies other than the one to which it is tuned.

Starting with the *amplifier*, the assumption is made that some circuit disturbance such as shot effect or thermal inequalities in

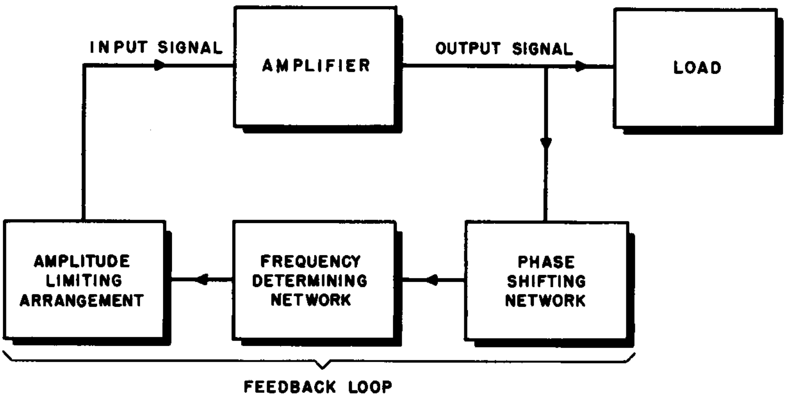


Fig. 2. Fundamental oscillator components.

cathode emission produces a small voltage change that constitutes *input.* The amplifier then acts upon this input signal to raise the output power to an adequately high level so that both the feedback circuit and the *load* are properly excited. The useful power output appears, of course, in the load. The feedback loop contains the remaining three elements: the *phase shifting network* satisfies the requirements of the resonator insofar as feedback phase (as related to input phase) is concerned; the *resonator* comprises the L-C network — either lumped or distributed — and establishes the cyclic period in which the oscillator operates; finally, the *amplitude-limiting arrangement* determines the amount of power that is to be circulated through the amplifier and feedback loop so that oscillation will neither cease due to insufficient feedback nor become unstable as a result of excessive feedback. The amplitude-limiting function may be performed by the biasing arrangement of the tube, by the adjustment of power supply voltages, or in some cases, by the selection of the electron tube type. The components of the feedback loop are not necessarily connected in the order shown; they have only to be present and connected in such a way that their action supports oscillation.

Figure 2 represents an "ideal" oscillator; that is, one in which (1) the signal fed back from the output of the amplifier *matches* the input signal; (2) the amplification is independent of the frequency generated by the oscillator and the level of the signal being amplified; (3) the resonator responds to only one specific frequency; and (4) the amplitude limiter is linear in function and so causes no appreciable re-shaping of the waveform. Although this set of ideal conditions is not encountered in practical oscillators, every effort is made to have the individual components approach ideal performance.

14. Oscillator Efficiency and Harmonic Generation

Efficiency is a basic consideration in establishing the operating conditions of an oscillator. In the interests of the highest possible efficiency, most oscillators of the power type are designed for Class C operation and, therefore, have outputs in which there is considerable distortion of the fundamental sine wave. To some extent, the frequency determining network acts to reduce the amplitude of the harmonics thus introduced, but the extent to which this correction is successful depends principally upon the Q of the tuned circuit, since high Q almost invariably means better rejection of frequencies other than the fundamental. Although low-Q circuits can be made to produce sustained oscillations, their tendency toward frequency drift and their high harmonic content are often objectionable.

15. Amplitude Limiting

The most popular method of automatic limiting – one that appears in most current oscillators – is grid-leak limiting. The proper choice of values for the grid resistor and grid capacitor may be used to establish the grid bias in the Class C region and to adjust the feedback power automatically so that the amplitude of oscillation remains essentially constant. This feature is discussed in detail in Chap. 3. Other oscillator designs discussed in Paragraph 45, use thermistors or other thermal-sensitive resistors to achieve amplitude limiting.

The limiter acts to prevent excessive feedback, which causes "racing", or insufficient feedback, which results in the complete cessation of oscillation. The losses in the feedback circuit should equal the gain of the amplifier or, more specifically, the sum of the load losses, losses in the phase-shifting network, losses in the resonator, and losses in the amplitude limiting network must just balance the gain of the amplifier if stable operation is to be realized. Moreover, the phase shift of the output signal must be such that it arrives at the input of the amplifier in phase with the signal originally impressed on the grid by the resonator.

Thus, the two requirements for oscillation stated in the most general terms are: (1) exact cancellation of all circuit losses by the gain of the amplifier tube and (2) perfect phase correspondence between the input and feedback signals.

16. Negative Resistance Oscillators

Despite the popularity of feedback L-C oscillators, other types such as *negative resistance* arrangements have a definite place in industry and communications. A negative resistance oscillator operates by virtue of a component or circuit in which a diminishing voltage produces an *increase* in current. This behavior suggests a reaction in which resistance is acting in a fashion opposed to its normal tendencies, hence the name *negative* resistance.

A pulse of energy fed to a tuned circuit causes oscillation at a frequency determined by the circuit constants. If the resonant circuit is of the passive type, i.e., one that has no internal source of energy, it will convert the energy of the initial pulse into heat and in a short time oscillations will cease. When a continuous source of energy is present, however, oscillations may be sustained by supplying power to the tuned circuit via a resistance-cancelling circuit or "negative resistor". The *dynatron* oscillator typifies this action and will be described in detail in Chap. 3.

17. Series Resonance

The voltage applied to the grid of a tube from a tuned circuit whose inductance is the secondary winding of a transformer is measured by the voltage across the capacitor. It is not always recognized that the tuned circuit, though drawn in a form that may resemble a parallel resonant arrangement, actually acts as a series resonant circuit. (See Figs. 3 and 4.) Whenever the generator is in the path around the L-C loop, the circuit is in series resonance; that is, the same current flows in each part — the generator, the inductance, and the capacitance. The condition of resonance is defined by the equality of inductive and capacitive reactance. For example, if $X_L = 100$ ohms, $X_C = 100$ ohms and $X_L = X_C$.

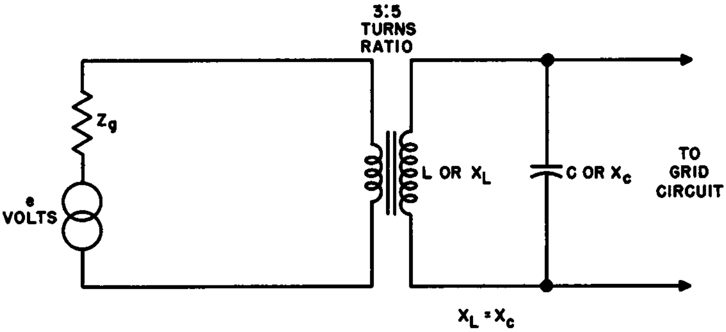


Fig. 3. Transformer coupled L-C grid circuit.

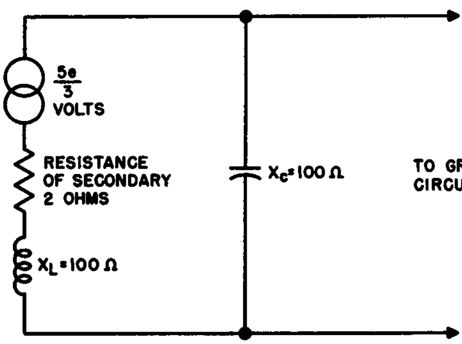


Fig. 4. Equivalent diagram of transformer-coupled L-C grid circuit.

Example: Figure 3 indicates an arbitrary transformer step-up ratio of 5/3 so that an input voltage, e, is increased to 5e/3 volts, assuming ideal transformer action. The equivalent circuit is given in Fig. 4. The generator is assumed to have infinite series impedance so that it does not contribute to the secondary resistance which, at the assumed frequency, is two ohms. As virtually all of the equivalent series resistance is in the coil, the equivalent circuit shows it in series with this branch rather than the capacitive branch. The current in a series circuit is everywhere the same so that, if e is taken as 6 volts, 5e/3 = 10 volts. Thus, the circulating current is:

$$I = \frac{E}{R} = \frac{10}{2} = 5 \text{ amperes}$$

The voltage across the inductance of the secondary winding of the transformer, expressed as a vector quantity,[1] is:

$$E_L = jIX_L = 5\,(+j100) = j500 \text{ volts}$$

The voltage drop is 500 volts across the pure inductance and leads the current by a phase angle of ninety degrees.

The voltage across the capacitor is:

$$E_C = jIX_C = 5\,(-j100) = -j500 \text{ volts}$$

These calculations are based upon the fact that the voltages across the reactances are equal and of opposite phase. Relative to the entire circuit, complete voltage cancellation occurs, but the potential across the terminals of the capacitor is still 500 volts lagging behind the current by 90 degrees. It is this voltage that is delivered to the grid of the oscillator tube. The total voltage gain is 500/6 = 83.3, of which only 1.67 is attributable to transformer action, the remainder being realized from series-resonant circuit action.

18. Parallel Resonance

An L-C circuit may be considered as parallel resonant if the generator is coupled into it as shown in Fig. 5, and if the frequency is so chosen that $X_L = X_C$. If the Q ($Q = X_L/R$) of the circuit is high, three distinct effects are obtained at its resonant frequency: the line current from the generator to the resonant circuit reaches a minimum value, the impedance presented to the generator by the L-C circuit becomes a pure resistance, and the reactances become equal, producing a phase angle of zero. Unless the Q is extremely small (10 or less), these effects occur at the same frequency; in circuits containing a large resistance in either the inductive or the capacitive branch, the frequencies at which these effects take place differ slightly from one another.

Example: Given a circuit in which parallel resonance is established by making the reactances equal and further assuming that there is no resistance in

1 The mathematics that follows employs the notation of vector quantities as complex numbers in which the resistive component is the real part and the reactive component (preceded by the symbol j) is the imaginary part. +j indicates that the reactive component of a current leads the resistive component by 90 degrees and −j indicates that it lags behind the resistive component by 90 degrees. The use of this notation permits algebraic solution of vectorial problems, since the real and imaginary portions of a complex expression are treated separately. To arrive at a numerical solution the real and imaginary portions are combined, using the familiar principle that the square of a vector is equal to the sum of the squares of the absolute values of its two components. In following these derivations it should be remembered that $j = \sqrt{-1}$, $j^2 = -1$, $-j^2 = 1$, $1/j = -j$, $1/-j = j$, etc.

either branch, the line current may be calculated by adding the currents in each branch (see Fig. 5):

$$I_L + I_C = \frac{E}{X_L} + \frac{E}{X_C} = -\frac{100}{10j} + \frac{100}{10j} = 0$$

The line current has two components of equal magnitude differing in phase by 180 degrees. Hence, cancellation results. From this it is evident that a parallel resonant circuit in which the resistance is zero (i.e. in which Q is infinite) at resonance satisfies all three conditions mentioned above: equal reactances, zero line current, zero phase angle.

When resistance is present in one of the branches, the situation changes. (See Fig. 6.) Computing the line current in a circuit where the resistance is numerically equal to the inductive reactance ($Q = 1$) we obtain:

$$I_L + I_C = \frac{100}{10 + j10} + \frac{100}{-j10} = \frac{1000}{200} - \frac{j1000}{200} + \frac{j100}{10}$$

$$= 5 - j5 + j10 = 5 + j5$$

$$= \sqrt{25 + 25} = 7.1 \text{ amperes (leading by 45 degrees)}.$$

The current is not at a minimum, nor is the power factor equal to one, hence the only condition for parallel resonance that is realized in this circuit is that $X_L = X_C$ (this was the supposition that permitted the substitutions in the first step). This is always the case when substantial resistance is present in one of the branches of a parallel resonant circuit and resonance is defined as the condition in which $X_L = X_C$.

19. Tuned Circuit with Infinite Q

An L-C circuit will start oscillating when any transient energy appears in it. Such transients may come from within the system,

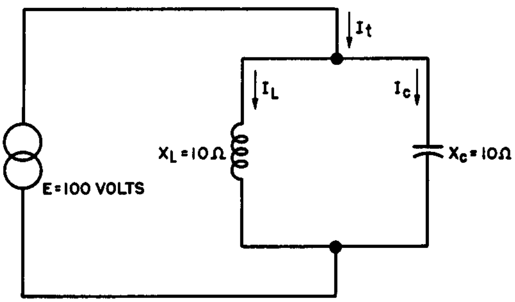


Fig. 5. Parallel resonance with equal reactances and no resistance in the reactive branches.

as previously described, or may originate externally. When a circuit such as that shown in Fig. 7 is set up, oscillations may be "shock excited" and will persist as long as the energy in the system lasts. The peak amplitude, rate of decay, and possibility of repetition of the resulting current depend upon the Q of the circuit.

The initial current I_0 is assumed to result from the current built up in the inductor while the switch was closed. The variations of the voltage e following the opening of the switch are plotted

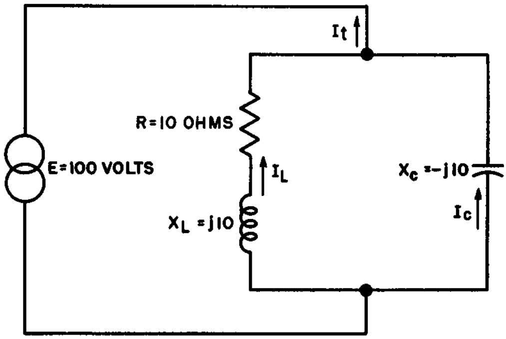


Fig. 6. Parallel resonance: equal reactances with resistance in the inductive branch.

in Figs. 8 and 9. (In this analysis, the values of L and C are not varied but R is changed to modify the Q for each of the curves.)

Let us first suppose that R is removed from the circuit of Fig. 7, making Q infinite. In this case the resultant current waveform

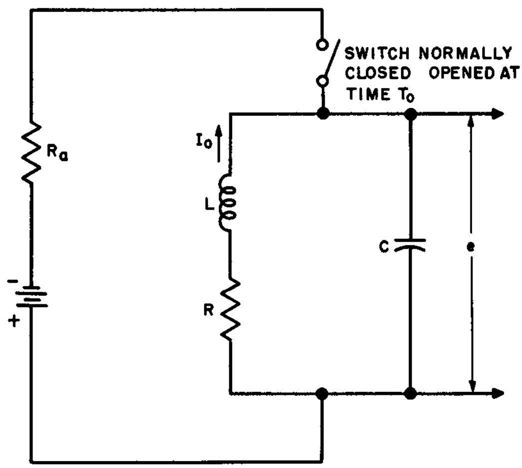


Fig. 7. Tuned circuit.

form (shown as a solid line in Fig. 8) is sinusoidal as explained below. When the switch is opened, the collapsing field around L causes current I_0 to flow from L into C. Its polarity matches the voltage that C had stored at the time the switch was closed prior to T_0. Therefore, the voltage across C increases. As the capacitor charges, the difference in the voltage developed by the collapsing field of L and the voltage on C becomes smaller, so the current I_0 diminishes. When the capacitor reaches the same potential as

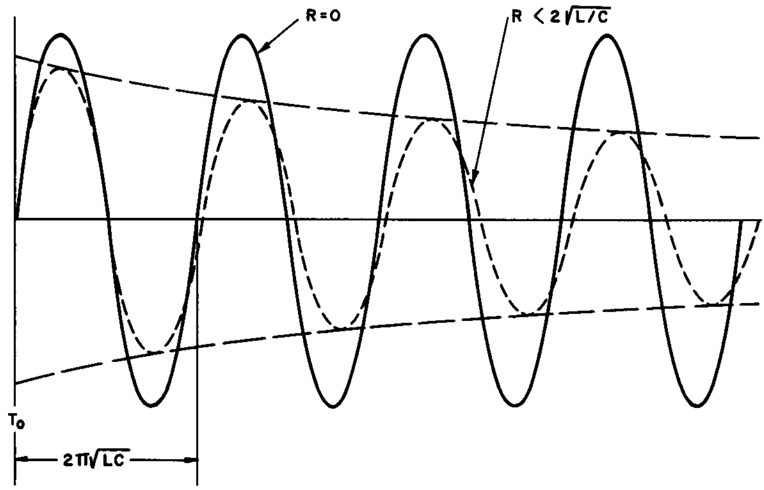


Fig. 8. Voltages across the capacitor in L-C circuits.

that produced by the collapsing field, I_0 becomes zero. Any further flow of current results from a reversal of direction and discharge of the capacitor.

When the inductor current arrives at zero, the capacitor potential is at its maximum, and it is considered that all the energy has been transferred and exists as the electric field of the capacitor. As the capacitor voltage decreases after reaching its peak, the energy is returned to the inductor, the restoration being complete when $e = 0$. The reverse current in L then charges C in such a direction as to make e negative. The process continues; energy passes from the fields of the inductor to the capacitor and back again, with e swinging (oscillating) above and below the zero axis. Since Q is infinite, (the circuit is lossless), energy is not dissipated and oscillation continues at constant amplitude forever. This action, although impossible to obtain without supplementary power in practice, illustrates the principle of sustained oscillation.

20. Tuned Circuit with Reduced Q

The presence of resistance in an L-C circuit causes the amplitude of the voltage produced by shock excitation to decrease with time as shown by the dashed line in Fig. 8. Such oscillation, known as *damped oscillation,* is characteristic of a system in which a certain amount of energy is dissipated in the resistance during each transfer of energy from L to C and back again. The maximum amplitude of the voltage on each oscillation decreases exponentially because the loss of energy during each half-cycle is propor-

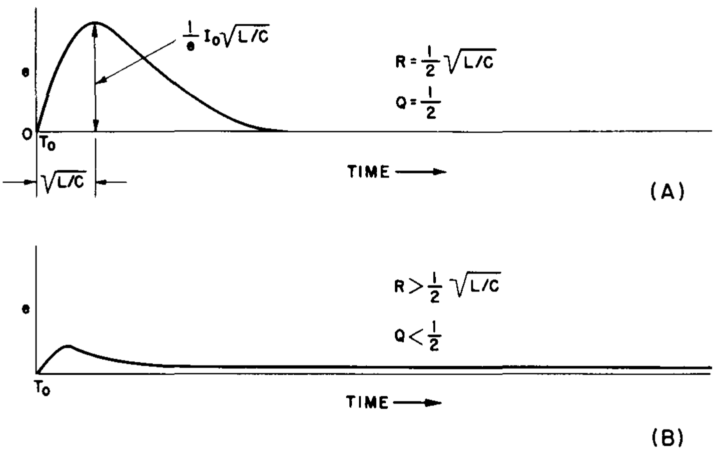


Fig. 9. Voltages in damped L-C circuits. (A) Critically damped, (B) Overdamped.

tional to the energy stored at the beginning of that half-cycle. The frequency of the damped oscillation is given by the equation

$$F_d = F_L \sqrt{1 - \left(\frac{1}{2Q}\right)^2} \qquad (3)$$

where F_d is the frequency of the damped wave in a circuit of finite Q, and F_L the frequency of the undamped wave in the same circuit if the Q were infinite.

Since the value of the radical in Equation 3 is always fractional, F_d is always smaller than F_L although the difference is not significant until the value of Q becomes quite small.

21. Critical Damping

As the value of R in Fig. 7 is increased, the rate of decay of the oscillations rises. As long as the variations of e remain oscillatory (swinging above and below the zero axis) the circuit is said to be *underdamped.* When R reaches the value $\frac{1}{2}\sqrt{L/C}$ (Q is then 0.5), the damping is so rapid that e does not swing below the zero axis at all (see Fig. 9A) and the circuit is said to be *critically damped;* e does not reach as high a positive maximum as in the undamped circuit because much of the energy initially present in the inductance is dissipated in the resistance during the rise of e.

When Q is made less than 0.5 by increasing R still further, the overdamped curve shown in Fig. 9 (B) is obtained. This form consists of two exponential portions: the quick rise of e immediately after zero time is described by the short time constant exponential $1-e^{-t/T}$; the slow return to zero is described by a long time constant exponential $e^{-t/T}$. As R is increased in value, the short time constant becomes shorter, the long one longer, and the peak value of e becomes smaller.

The shape of the curve arises in this way: During the period immediately following zero time, the inductor is a source of a current I_0. This current charges C to the voltage I_0R along the portion of the curve having the very short time constant RC. After reaching the value I_0R, e decreases slowly as the current in the inductor decreases. The decay of e is exponential, having the time constant L/R because the change is so slow that the current in the capacitor is negligible. If the overdamping is extreme, the response approaches that of an R-L circuit, and the capacitor merely prevents the perfectly vertical rise of e.

22. Review Questions

1. Name three devices used to generate oscillations.
2. Define oscillator stability.
3. In what forms does the tuned circuit occur?
4. List the three fundamental components of an oscillator.
5. What are the functions of the resonator?
6. How is limiting accomplished?
7. Define underdamping, overdamping, and critical damping.
8. Name nonelectronic devices which are analogies of electronic oscillators.
9. Is the transformer-coupled tuned circuit a series or a parallel resonant circuit?
10. Define parallel resonance.

Chapter 2

CIRCUIT ANALYSIS

23. The Electron Tube

The electron tube is used as an amplifier in standard L-C oscillator circuits. Its function is so important from the standpoint of frequency stability, power output, and general reliability of the oscillator that it warrants thorough study.

It is generally recognized that the elements of an electron tube are subject to appreciable change during use. The heat generated in the other elements by the filament of the tube and the power that must be dissipated during normal operation by the plate, screen grid, and control grid give rise to dimensional changes. As the emission of the cathode becomes weaker through use, the impedance characteristics of the tube are modified, often severely. Loss of vacuum due to release of absorbed gases from the metallic elements produces ionization effects that seriously affect operating characteristics. These effects add up to variations in gain, impedance, and distortion components, and even intermodulation effects. By using well-engineered circuitry and careful design, it is possible to hold these variations to a minimum – the feedback circuit is especially important in this respect.

Any reasonable approach to the design of a feedback loop must give careful consideration to the amplifier tube. The effect of the loop upon the internal tube impedances as well as the impedances into which it works, requires thoughtful planning. When the various interrelated impedances are incorrect, a circuit may oscillate only with certain of the terminating impedances removed, or it may not oscillate at all.

To illustrate some of the basic impedance problems often encountered in practice, consider first an amplifier without any feedback loop at all, Fig. 10. A source of signal voltage of the polarity indicated (E_s) having an internal impedance Z_s is applied to the amplifier. The portion of the source voltage present at the input is indicated as E_i and appears across the grid circuit of the tube. The input impedance Z_i is assumed to be very high. Output voltage E_o is applied to the load Z_L through the internal impedance

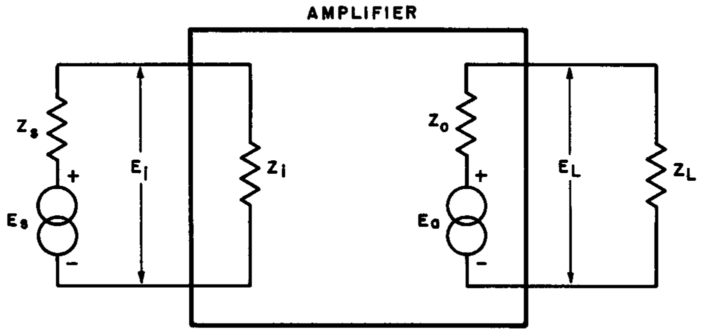


Fig. 10. Amplifier with its associated impedances.

(Z_o) of the output circuit of the amplifier. It appears as E_L across the load, Z_L, which represents all the circuitry outside the amplifier that is driven by the output voltage. One additional assumption the supposition that no distortion occurs if the input voltage E_s is small makes the treatment more straightforward. The conditions of high input impedance Z_i and the absence of distortion for small input signals are quite admissible, for example, in the case of Class A amplifiers.

The gain of the amplifier may be expressed in terms of E_s and E_L. Since Z_i is very large, the voltage drop across Z_s is negligible, and E_i very nearly equals E_s. That is:

$$A = \frac{E_L}{E_i} = \frac{E_L}{E_s} \tag{4}$$

where A is the *stage amplification.*

If no load is connected across the output of the amplifier, (i.e. if Z_L is open), the output voltage E_L may be considered to be equal to E_a. The ratio of the output voltage to the input voltage under these circumstances is often called the *gain* of the circuit. The relationship of circuit gain to the amplification factor (μ) and plate resistance (r_p) of the amplifier tube and to Z_L is given by

$$A = \frac{-\mu Z_L}{r_p + Z_L} \tag{5}$$

24. The Addition of Feedback

The connection of the impedance Z_b in the circuit shown in Fig. 11 from the output of the system to the input, constitutes an

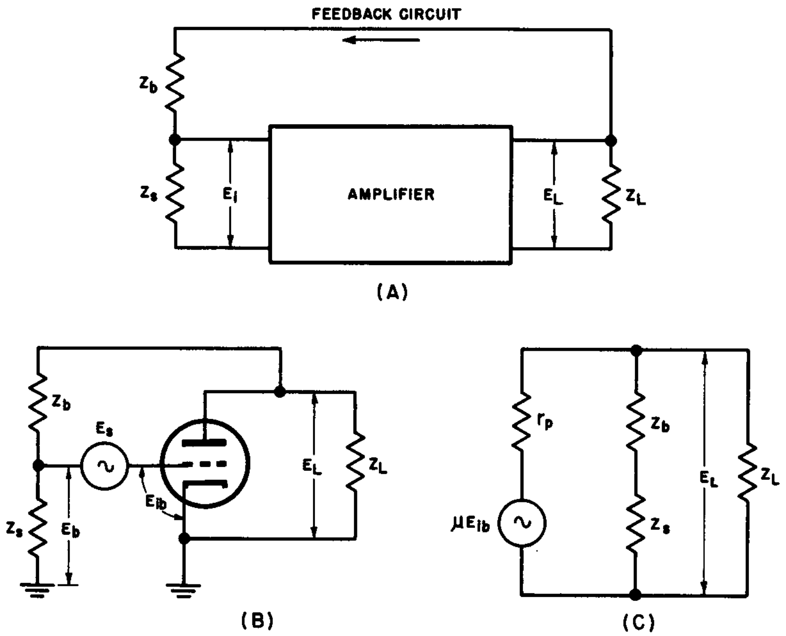


Fig. 11. An elementary form of feedback arrangement. (A) Block diagram. (B) Simplified schematic. (C) Equivalent circuit.

elementary form of feedback loop. The impedance of Z_b is considerably larger than either the input impedance Z_s or the output impedance Z_L. In this circuit the phasing of the system has been so arranged that the polarity of the feedback voltage corresponds to that of the input voltage. (Since a vacuum tube normally shifts phase by 180 degrees from input to output, it is assumed that an additional 180-degree phase-inverting network is present between the output and input to re-establish the original phase.)

The output voltage E_L is divided between Z_b and Z_s in proportion to the size of these impedances. The fraction of the output voltage that re-enters the amplifier input is then:

$$E_b = E_L \frac{Z_s}{Z_s + Z_b} \tag{6}$$

Since the Z_s is quite small compared to Z_b, its influence on the denominator of this fraction is negligible and it may be omitted to give:

$$E_b = E_L \frac{Z_s}{Z_b} \tag{7}$$

The input voltage E_i applied to the grid of the amplifier tube is the sum of the source voltage E_s and the feedback voltage E_b. Using the identity for E_b obtained in Equation 7 we have:

$$E_{ib} = E_s + E_L \frac{Z_s}{Z_b} \tag{8}$$

where E_{ib} represents input voltage with feedback. E_{ib} may be substituted for E_i in Equation 4 and the expression rewritten as

$$E_L = AE_{ib} \tag{9}$$

Substituting Equation 8 into Equation 9:

$$E_L = A\left(E_s + E_L \frac{Z_s}{Z_b}\right)$$

or

$$E_L = AE_s + AE_L \frac{Z_s}{Z_b} \tag{10}$$

Transposing terms and dividing through by E_L:

$$1 - \frac{AZ_s}{Z_b} = \frac{AE_s}{E_L} \tag{11}$$

Transposing once again:

$$E_L = \frac{AE_s}{1 - \frac{AZ_s}{Z_b}} \tag{12}$$

Dividing by E_s converts Equation 12 into a valuable expression for the gain A′ of an amplifier with feedback.

$$A' = \frac{E_L}{E_s} = \frac{A}{1 - \frac{AZ_s}{Z_b}} \qquad (13)$$

Equation 13 has several important implications. First, the denominator of the fraction always is smaller than unity. This means that the gain with positive feedback is always greater than the gain without feedback for any given amplifier.

Example: If the gain of a certain amplifier without feedback is 4000, the input impedance 60 ohms, and the feedback impedance 60 megohms, what is the gain of the amplifier?

$$A' = \frac{4000}{1 - \frac{4000 \times 600}{60{,}000{,}000}} = 4166$$

A second implication of Equation 13 is that if the feedback impedance Z_b is adjusted so that it is greater than the input impedance Z_s by a factor equal to the amplification without feedback A, the quantity AZ_s/Z_b in equation 13 approaches unity:

$$A\frac{Z_s}{Z_b} = A\frac{1}{A} = 1 \qquad (14)$$

As this value of Z_b is approached, the denominator of the entire fraction in Equation 13 approaches zero and A′ approaches infinity. When A′ becomes infinite, the amplifier has reached the *condition of oscillation.*

The ratio Z_s/Z_b is called the *feedback ratio* or *feedback factor* and is conventionally represented by the symbol β, while the product of feedback ratio and system gain without feedback, A, is known as the *loop transmission* of the circuit. Equation 13 may be rewritten in terms of β as

$$A' = \frac{A}{1 - A\beta} \qquad (15)$$

25. Review Questions

1. Define feedback ratio and loop transmission factor.
2. Explain, in terms of the approach of A′ to infinity, what is meant by the *condition of oscillation.*
3. Explain why source voltage E_s and input voltage E_i are used interchangeably in oscillator circuit analysis.
4. Distinguish carefully between positive and negative feedback. Which type is used in oscillatory amplifiers?
5. State the ratio that expresses the amplification factor of a circuit.
6. Throughout the discussions in the preceding chapter, the assumption is made that the input impedance Z_i is extremely high. Discuss the validity of this assumption.
7. Explain why a normal amplifier tube always produces a voltage phase reversal from input to output.

Chapter 3

ESSENTIAL FEATURES OF OSCILLATOR CIRCUITS

26. Class of Operation

The equations and basic concepts developed in the previous chapters are applicable to Class A operation of oscillators. The conditions for this class include a negative grid bias that places the quiescent tube in the approximate center of the linear portion of its grid transfer characteristic, an input grid signal sufficiently small to avoid the cutoff or saturation of plate current, and a very high input impedance (which, of course, virtually is equivalent to zero grid current). Class A oscillators are capable of very good sinusoidal output waveform, but are quite inefficient in performance.

A less perfect output waveform at vastly superior efficiency is obtainable from an oscillator operated in Class C. The requirements for this class are a grid bias two or three times more negative than the grid voltage required to cut off plate current and an input signal voltage large enough to reach the window[1] of the tube. (See Fig. 12.) It is evident from the figure that the bias on a tube determines the amount of amplification necessary to start oscillations. If the bias is large, the input voltage must also be large. Since the generation of oscillatory input depends upon tiny chance disturbances like shot effect and non-uniform emission, the

[1] The *window* of a tube is the point at which the tube just begins to conduct.

presence of Class C bias at the outset makes it virtually impossible for oscillation to start spontaneously. This situation is remedied, as a rule, by starting the cycle of events under conditions of low

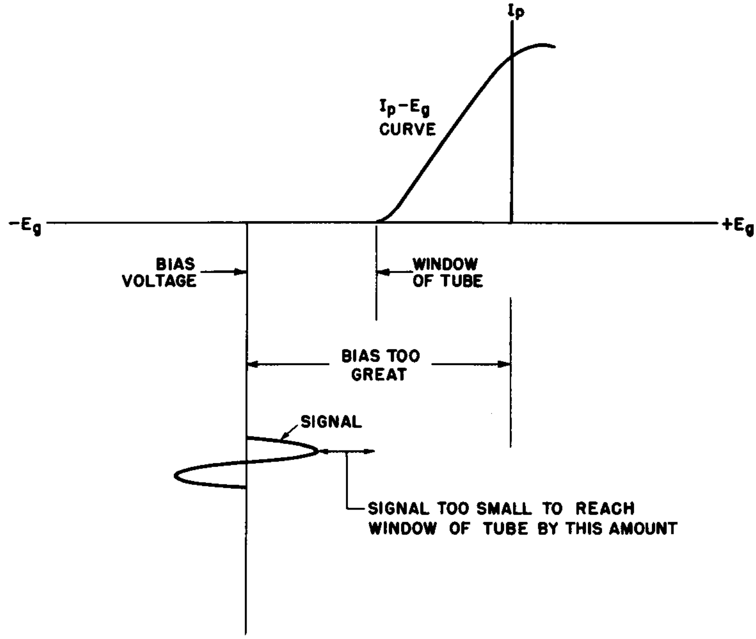


Fig. 12. Tube window and initial buildup of signal in Class C amplifier.

bias, building the bias up to Class C only after the input signal has become large enough. Simple biasing methods devised to do this automatically will be discussed in Paragraph 28.

27. Transconductance

The circuit conditions required to maintain oscillation in the circuit of Fig. 12 may be expressed by the equation:

$$\beta = \frac{1}{g_m Z} + \frac{1}{\mu} \tag{16}$$

in which μ is the amplification factor of the tube g_m is the transconductance of the tube, Z is the impedance looking toward the feedback loop, and β is the feedback ratio. (β is shown as a positive quantity since it is assumed that the coupling network re-inverts the output phase of the tube to produce positive feedback.)

Transconductance, defined as the ratio of a change in plate current to the causative change of grid voltage, is far from being a constant quantity even for a specific tube. In Fig. 13, g_m is given by the slope of the grid transfer characteristic. The slope of this curve varies. For example, for the small change in grid voltage, X, a

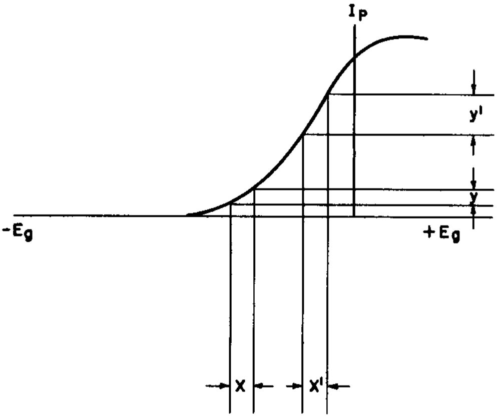


Fig. 13. Grid transfer characteristic curve.

large change, Y, occurs in the plate current. This indicates a large value for g_m. (The curve slopes sharply in this area.) An equal change in grid voltage X′ in another flatter area of the I_p-E_g curve yields a smaller plate current change, Y′, indicating reduced g_m.

The effect of g_m upon the conditions for oscillation may be seen from Equation 16. If g_m is made larger, the value of the first fraction in the equation decreases thereby diminishing β. This means that oscillation can occur with a smaller amount of positive feedback, or that oscillation is more likely to take place in a given circuit with a fixed feedback ratio. If the amplification factor, μ, is raised, the same result is obtained.

Example: An oscillator circuit is set up using a tube having a transconductance of 6000 micromhos; the amplification of the circuit is 20, and the impedance of the feedback loop is 10,000 ohms. Find the feedback necessary to sustain oscillation.

$$\beta = \frac{1}{g_m Z} + \frac{1}{A}$$

$$= \frac{1}{(6000 \times 10{-}6)\ (104)} + \frac{1}{20} = \frac{1}{60} + \frac{1}{20}$$

$$= \frac{1}{15} = 0.67$$

The variation of g_m with the operating point is sometimes used for amplitude limiting. If the tube is biased nearly to cutoff, when oscillation starts, g_m may be quite small. At this point, a grid potential change X causes an output current change such as Y in Fig. 13. As operation continues, a change in grid potential X′ of the same magnitude as X causes a larger change Y′ in the output current. As the signal voltage goes beyond this point, however, the tube again begins to work on the upper bend of the curve where the slope (or g_m) is reduced. This prevents the oscillator output from increasing further.

28. Grid Leak — Capacitor Bias

The use of Class C bias for most oscillators needs no justification other than that of the high efficiency possible under these conditions. As mentioned in Paragraph 28, the high negative bias

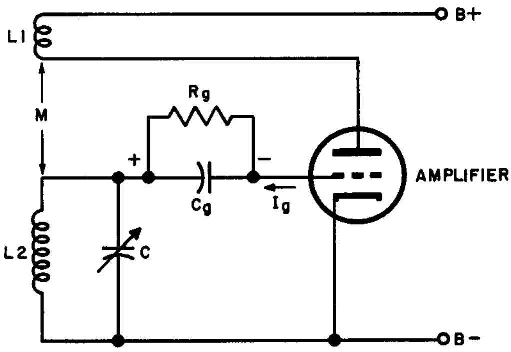


Fig. 14. Grid leak-Capacitor Bias.

required for Class C operation cannot be applied at the same instant oscillation is to start (unless it is practicable to apply an external starting voltage larger than the bias), since such bias prevents the random starting voltages from reaching the window of the tube. A simple capacitor-resistor combination used to produce bias can do away with these objections and yet permit Class C operation. The fundamental arrangement is shown in Fig. 14.

The grid of the amplifier is supplied with signal voltage via the feedback network. At the beginning of the process, the grid bias is zero with respect to cathode and the tube operates at a point on its curve where the g_m is reasonably high. These conditions encourage easy starting. As the amplitude of the oscillations grows, the alternating voltage appearing across L2 is applied to the grid in series with R_g and C_g. Owing to the rectifying action of the grid, direct current flows through R_g causing a voltage having approximately the value of the peak signal voltage to appear across C_g. The development of this bias voltage is shown in Fig. 15. The stable or "steady-state" bias in this drawing is approximately Class A but, by selecting the R-C components in the grid circuit correctly, Class C operation can just as easily be established.

Practical circuits utilizing grid leak-capacitor bias are usually protected from damage by incorporating some form of fixed or self-

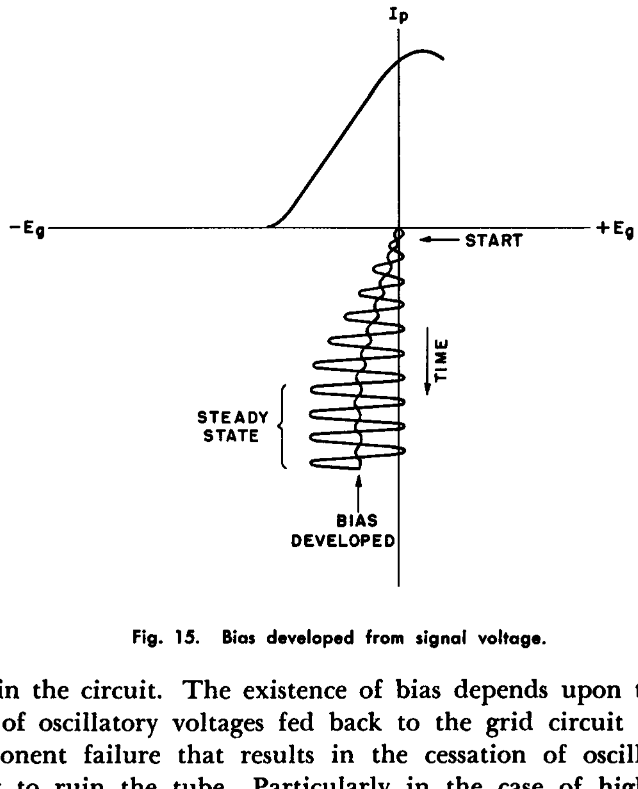


Fig. 15. Bias developed from signal voltage.

bias in the circuit. The existence of bias depends upon the presence of oscillatory voltages fed back to the grid circuit and any component failure that results in the cessation of oscillation is likely to ruin the tube. Particularly in the case of high power oscillators, the absence of bias causes excessive plate current.

The time constant of the R_g - C_g combination must be adjusted within reasonably close limits for optimum operation. The wavy line which serves as the axis of the grid pulsations in Fig. 15 is the grid-leak bias developed across C_g. During the intervals of zero grid current, the capacitor tends to discharge through R_g. With too short a time constant, no steady state d-c bias appears, since the capacitor closely follows the variations of the potential drop across R_g. At the opposite extreme, should the time constant be too large, a phenomenon called *blocking* takes place. As the oscillations build up, the voltage on the capacitor increases and, if it cannot discharge partially during each cycle, the bias may become sufficiently negative to stop oscillation. When this occurs, the capacitor slowly discharges until the circuit can operate again. This results in intermittent oscillation often called *superregeneration.* This *squelching* process is the basis of the superregenerative detectors used in the ultra-high frequency regions.

29. Loop Transmission and Feelback Phase

Equation 14 (as well as Equation 16) contains an expression for what is often termed a *criterion of oscillation:* oscillation takes place when the product $A\,(Z_s/Z_b)$ as it appears in Equation 14 and 15 (the loop transmission of the oscillator circuit) is equal to unity. This criterion is generally written:

$$A\beta = 1 \qquad (17)$$

If an oscillator were a rigorously linear arrangement and if the product $A\beta$ were greater than one, oscillation amplitude would become increasingly greater within the limits of the tube's ability to handle power. In real oscillators, however, it is found that the product must be slightly greater than one to allow for unpredictable and random variations in the tube's characteristic and the circuit parameters. As explained previously, there is no danger of "runaway" action under these circumstances because of the amplitude-limiting behavior of the non-linearity of the E_g - I_p curve of the oscillator tube.

We must not lose sight of the fact that feedback amplitude is not the only consideration that enters into the criterion for the condition of oscillation; the matter of the phase relationship between the feedback voltage and the input voltage of the tube must also be considered. The treatment given this subject in previous paragraphs enables us to summarize the phase requirements as follows: an oscillator that produces a sinusoidal output, functions only at that frequency for which the phase shift of the signal voltage around the complete loop is either zero or 360 degrees. Signals that pass through an L-C oscillator experience two distinct phase inversions or shifts of 180 degrees: the first occurs during normal amplifier action from grid input voltage to plate output voltage; the second shift of 180 degrees must take place in the coupling network, with the reactive components arranged to produce this condition.

30. Factors Affecting Frequency of Oscillation

Although the frequency of a lumped-constant oscillator is determined primarily by the values of L and C in the resonator circuit, any ambient variation that causes a change in physical size or conductivity in almost any component may produce frequency variation. Environmental factors that are responsible for much frequency instability are ambient temperature, barometric pressure, relative humidity, physical pressure, and vibration. In addition, the self-heating effects of vacuum tubes, resistors, coils, and even capacitors, and changes in the load impedance and source voltage are causes of instability, so the maintenance of a stable oscillator frequency is a difficult problem. Eliminating frequency drift in television receiver local oscillators, master oscillators of transmitters, and signal-generating test equipment are but a few examples of the problem's practical aspects.

31. Control of Oscillation Frequency

The effect of changing temperature upon frequency (within normal ambient limits) may, in most well-designed oscillators, be traced to the variation of the interelectrode capacitance (particularly that between the grid and plate) within the tube. As these tube elements form a part of the resonator network, the oscillator is susceptible to a substantial frequency shift during the warm-up period. This effect is minimized by making the tube capacitance a very small fraction of the tuning capacitance. The use of a large value for the C component of the L-C circuit (making the L-C ratio low) is beneficial from another point of view, since in Class C circuits, if the loaded Q is high the efficiency of the circuit is reduced, but frequency stability is much improved. The effective Q, with no load in the circuit, ($2\pi fL/R$) is quite different from the *loaded* Q, as an analysis of the following equation (derived from considerations involving parallel resonant circuits) shows.

$$Q_L = \frac{(E_{max})^2}{4\pi fLP} \qquad (18)$$

where Q_L is the loaded Q of the circuit, E_{max} the maximum voltage across the tank, f the frequency of operation, L the tuning inductance, and P the power delivered to the tank by the tube.

In a circuit that contains a given plate supply voltage and power, E_{max} is a constant. Let us also assume that the frequency at which this oscillator is to perform is also constant. Thus, the part of Equation 18 involving the quantities E_{max}, f, P, and 4π is fixed and may be denoted by "k," giving:

$$Q = \frac{k}{L} \tag{19}$$

The loaded Q of an oscillatory resonator is thus *inversely* proportional to the inductance used in the tank whereas the unloaded Q is *directly* proportional to it. To make the loaded Q high for a given frequency and power – the condition essential to good frequency stability – L must be low and, for a specific frequency, C must be large. This corroborates the statement made previously that a low L-C ratio leads to good frequency stability.

The effect of changing line voltage upon d-c output voltage from the source of power may be minimized by means of modern electronic voltage-regulator arrangements. In highly precise L-C oscillators it is often possible to insert a capacitor of the correct value into either the grid or plate circuit to neutralize the phase shift caused by changing plate voltage.

The avoidance of detuning by changing loads is generally based upon isolation principles. Master-oscillator-power-amplifier (MOPA) transmitters effect isolation between oscillator and load by means of one or more *buffer* stages. Electron-coupled oscillators (discussed in Paragraph 49) operate on this principle, although the buffering action is confined to the same tube as the oscillator.

The most precise oscillators in use today, those that control our time standards, broadcast and TV frequencies, and navigation services, are virtually all crystal-controlled. The crystal unit, including the piezo-electric plate of quartz and all the elements of the crystal holder, acts as a very high Q tank circuit for which an L-C equivalent may be drawn.[1] A Miller-type crystal oscillator circuit is shown in Fig. 16. The frequency of oscillation is governed by the physical dimensions of the crystal and by the orientation of its "cut" with relation to the axes of the mother stone

[1] See A. Schure (Ed.), *Crystal Oscillators* (New York: John F. Rider Publisher, Inc., 1955).

from which it comes. The L-C circuit acts as the plate impedance and is tuned to a frequency slightly higher than that of the crystal. With the crystal unit in a thermostatically controlled oven, this

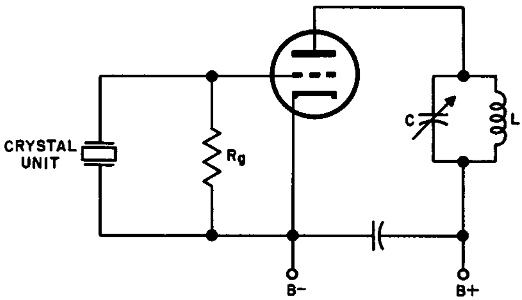


Fig. 16. Basic Miller-type crystal oscillator circuit.

oscillator has no equal for reliable "on-frequency" performance; its popularity is limited only because it requires a different crystal unit for each frequency and is thus not continuously tunable over a band of frequencies.

32. Input Admittance of an Amplifier

An understanding of the meaning of input admittance as applied to tuned amplifiers is helpful, if not essential, to a thorough comprehension of the principles of practical oscillators. Although the analysis of this subject applies particularly to tuned amplifiers, it is equally applicable to oscillators, especially those that make use of grid-to-plate capacitance for feedback.

The electron tube in an oscillator circuit is usually operated in Class C for reasons of economy and amplitude control. When the frequency of oscillation is high, the input impedance of the tube is an important factor, since it affects not only amplitude and gain but also the phase angle of the signal as it is passed through the amplifier and feedback loop.

The term *admittance* expresses the relative ease with which an alternating current flows through a given path. It is therefore the reciprocal of impedance and may be defined as the ratio of the alternating current flowing in a circuit to the voltage producing the flow.

"Looking into" the grid circuit from the input end, the signal source "sees" two different a-c paths. One is the path provided by the grid-to-cathode capacitance (C1 in Fig. 17) and the other is the path through the capacitance between the grid and plate (C2). The input admittance may be measured in terms of these two paths during normal Class C operation. Another path exists

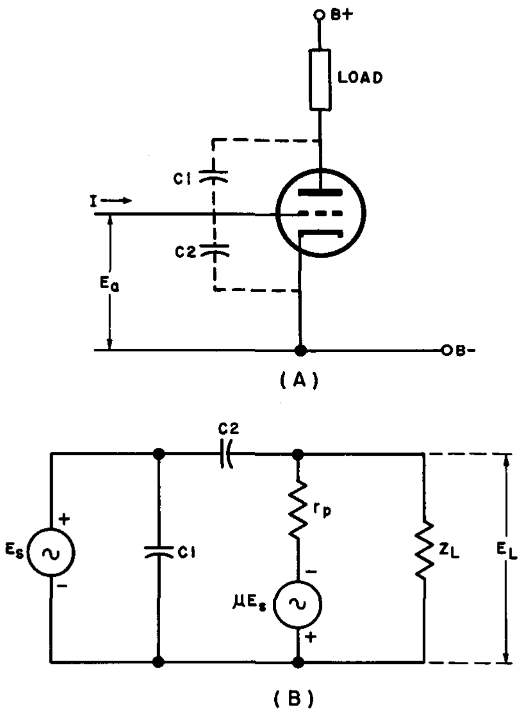


Fig. 17. Grid admittance paths. (A) Simplified schematic (B) Equivalent circuit.

during the small portion of the input cycle when the grid is driven positive, namely the resistive path through the grid return circuit when grid current flows. Although it is a factor in critical design work, the effect of this path is usually calculated separately as required.

Although C1 may be considered a simple capacitor and the current through it calculated by straightforward application of Ohm's Law, this is not the case for C2. The latter represents the capacitance between grid and plate, but it cannot be used as a simple parallel component. Due to the *Miller effect,* the equivalent grid-plate capacitance is actually larger than, say, the bridge-measured value by a factor determined by the amplification of the tube. The incorporation of this factor is given in the analysis that follows.

The total admittance of the input circuit is measured by the ratio I/E_s in the grid circuit. E_s is the signal voltage and I is the sum of the currents through the two capacitive paths as shown in Fig. 17.

Analysis of the equivalent circuit (Fig. 17B) yields an equation for input admittance

$$Y = j\omega C1 + j\omega C2\,(1 - A) \tag{20}$$

where, as in Equation 4, $A = E_L/E_s$.

Many practical oscillator circuits have purely resistive loads (a tuned plate circuit) and, since the amount of feedback and the phasing required to sustain oscillation depend upon the total input capacitance, an expression for total input capacitance in such circuits is of value. When Z_L is real and $1/\omega C2$ is very much greater than the parallel resistances and impedances, that is, if

$$\frac{1}{\omega C2} = \frac{r_p Z_L}{r_p + Z_L} \tag{21}$$

Equation 20 may be rewritten:

$$Y = j\omega C1 + j\omega C2\left(1 + \frac{\mu Z_L}{r_p + Z_L}\right) \tag{22}$$

If, in addition, r_p is very much greater than Z_L, the total input capacitance becomes

$$C_t = C1 + C2 + \mu C2 \tag{23}$$

33. The Tuned Plate Oscillator

To illustrate the application of many of the equations developed in this chapter, we shall thoroughly analyze a typical simple oscillator — the tuned plate type.

Figure 18 shows the basic *signal* circuit of the tuned plate oscillator in analysis form. The plate circuit contains a parallel resonant network (C, L, and R) which determines the frequency of oscillation. Grid excitation is established by inductive coupling, M, between plate and input circuit. Supply voltages and bias are not included to avoid complicating the signal picture. It is also assumed that there is no grid current flow; that is, the impedance of the grid circuit is very high, approaching open circuit condition.

The voltage applied to the grid by the feedback circuit is a function of the current in the inductance I_L and the impedance of the mutual inductance M or:

$$E = I_L Z_M \tag{24}$$

Z_M may be defined as $j2\pi fM$ and, taking phase angle into account by means of the j operator we may write:

$$Z_m = -j\omega M \tag{25}$$

in which $\omega = 2\pi f$. Thus, from this and Equation 24 we obtain:

$$E = -j\omega M I_L \tag{26}$$

Assuming, as previously stated, that the grid winding looks into an open circuit, the plate winding sees no load and the impedance looking into the parallel branches consists of the two

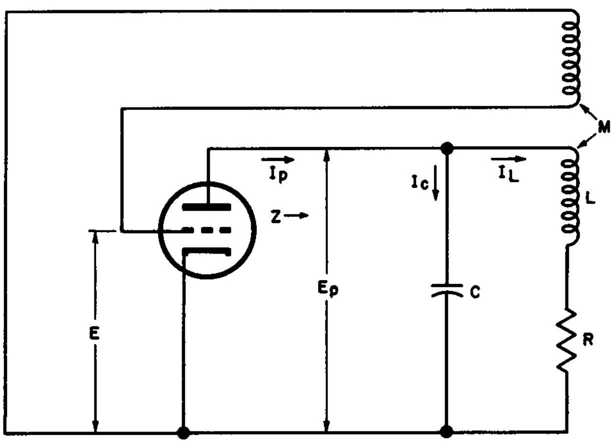


Fig. 18. Signal circuit of the tuned plate oscillator.

quantities: $R + j\omega L$ (the impedance of the inductive branch, Z_L) and $1/j\omega C$ (the impedance of the capacitive branch, Z_C). These quantities will be added properly later in this discussion.

To establish the conditions for oscillation, it is necessary to determine the values of A and β as given in Equation 17. The gain of an amplifier without feedback is $A = -\mu Z_L/(r_p + Z)$ (Equation 5). The feedback factor (see Fig. 18) is

$$\beta = \frac{E}{E_p} \tag{27}$$

E has already been determined as the product $I_L Z_M$. E_p is the product of plate current and plate load impedance or $I_p Z$. Hence

$$\beta = \frac{I_L Z_M}{I_p Z} \tag{28}$$

For high-Q circuits, parallel resonance includes three criteria: line current is zero, impedance is maximum, and the phase angle is zero. Using the first of these as a requirement in the plate circuit, it is clear that the current through the inductor must be equal to the current through the capacitor and that the voltage drops across these are also equal:

$$I_L Z_L = I_C Z_C \tag{29}$$

Since the total plate current divides between the two reactive components, then:

$$I_p = I_L + I_C \tag{30}$$

Solving for I_C and substituting into Equation 28:

$$\beta = \frac{Z_M\ I_L}{Z\,(I_L + I_C)} = \frac{Z_M\ I_L}{Z\left(I_L + \dfrac{I_L\ Z_L}{Z_C}\right)} = \frac{Z_M\ Z_C}{Z\,(Z_C + Z_L)} \tag{31}$$

When the product $A\beta$ is equal to one (Equation 17), oscillation is possible. Bearing this criterion in mind, and substituting our new values for A and β

$$A\beta = \left(\frac{-\mu Z}{r_p + Z}\right)\left(\frac{Z_M\ Z_C}{Z\,(Z_C + Z_L)}\right) = 1 \tag{32}$$

Cancelling Z's and multiplying out:

$$r_p\ (Z_C + Z_L) + Z\,(Z_C + Z_L) = -\mu Z_M Z_C \tag{33}$$

The total impedance of the parallel branches Z_C and Z_L is Z, which is related to the branch impedances by the familiar equation for parallel circuits:

$$Z = \frac{Z_L Z_C}{Z_L + Z_C} \tag{34}$$

When this value of Z is substituted into Equation 33 and the resulting statement simplified, we obtain:

$$r_p\ (Z_C + Z_L) + Z_C Z_L + \mu Z_M Z_C = 0 \tag{35}$$

Since transconductance, $g_m = \mu / r_p$, the equation may be altered thus:

$$(Z_C + Z_L) + \frac{Z_C Z_L}{r_p} + g_m Z_M Z_C = 0 \tag{36}$$

The vector expressions for impedance previously obtained may now be substituted in Equation 36 as follows:

$$R + j\left(\omega L - \frac{1}{\omega C}\right)\frac{R + j\omega L}{(j\omega C)\,r_p} + g_m\frac{j\omega M}{j\omega C} = 0 \qquad (37)$$

Collecting real and imaginary terms:

$$g_m\frac{M}{C} + R + \frac{L}{Cr_p} + j\left(\omega L - \frac{1}{\omega C} - \frac{R}{\omega Cr_p}\right) = 0 \quad (38)$$

Since Equation 38 was derived with Aβ set equal to one, it is an expression for the input impedance that meets the criteria of oscillation. The real parts express the conditions required to secure sufficient amplitude for oscillation and the imaginary parts specify those that make the phase of the feedback signal with respect to input signal zero or some integral multiple of 360 degrees.

Thus, the condition for adequate amplitude is:

$$-g_m\frac{M}{C} = R + \frac{L}{Cr_p} \qquad (39)$$

and the conditions needed for proper phase relationship are:

$$\omega L - \frac{1}{\omega C} - \frac{R}{\omega Cr_p} = 0 \qquad (40)$$

Equation 40 is very useful because it can be manipulated to provide an equation that expresses frequency of oscillation in terms of L, C, R, and r_p. This is accomplished by multiplying through by ω/L.

$$\omega^2 - \frac{1}{LC} - \frac{R}{LCr_p} = 0 \qquad (41)$$

Remembering that $\omega = 2\pi f$, this value may be substituted into Equation 41 and the resulting expression solved for f, the frequency of oscillation:

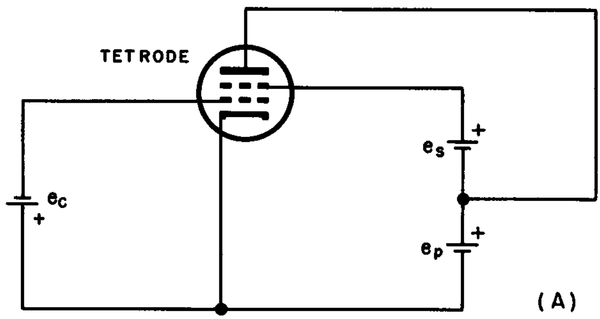
$$(2\pi f)^2 = \frac{1}{LC} + \frac{R}{LCr_p} = \frac{1}{LC}\left(1 + \frac{R}{r_p}\right)$$

$$f = \frac{1}{2\pi\sqrt{LC}}\sqrt{1 + \frac{R}{r_p}} \qquad (42)$$

The first part of this expression is the familiar equation for determining the resonant frequency of an L-C circuit. It is evident that the actual frequency of oscillation is somewhat higher than what one would expect from the values of L and C alone since $\sqrt{1 + R/r_p}$ is greater than one. Equation 42 also demonstrates that higher-Q tuned circuits yield frequencies closer to the basic L-C frequency. This is true because, in a high-Q circuit, R is small compared to r_p, which makes R/r_p small and the quantity under the second radical only slightly larger than one.

34. The Principle of Negative Resistance

The principle of feedback in which a vacuum tube amplifier compensates for resistive losses throughout the circuit may be viewed as a system in which the tube behaves as a *negative re-*



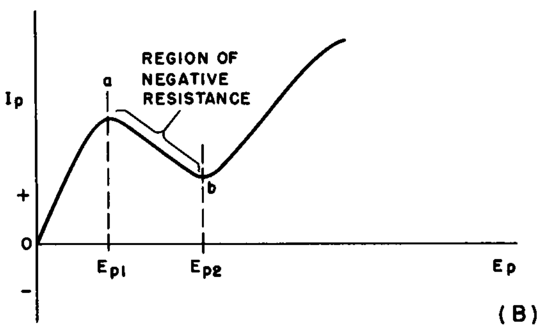
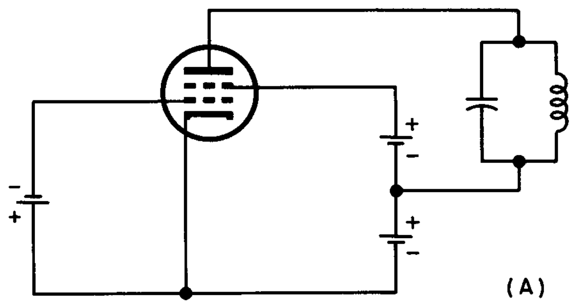


Fig. 19. (A) Tetrode amplifier (B) Region of negative resistance in the characteristic curve of the tube used in (A).

sistance. That is, an *increase* in current is obtained as a result of a *decreased* applied voltage. For sustained oscillation, such a negative resistance would have to have characteristics by which it could exactly neutralize all of the dissipative losses in the oscillator.

The plate characteristic curve of the tetrode amplifier shown in Fig 19 (A) has a negative resistance region as shown in Fig. 19 (B). If it is assumed that the screen grid is held at a positive potential of 100 volts and the plate voltage is varied, it is observed that plate current flows normally between zero plate potential and E_{p1}. As E_{p1} is passed, secondary emission from the plate begins. Since the secondary electrons move to the screen and thence into the screen grid circuit, this constitutes a reverse plate current flow that reduces the primary plate current. Thus, between points a and b on the curve, the effect of negative resistance as previously



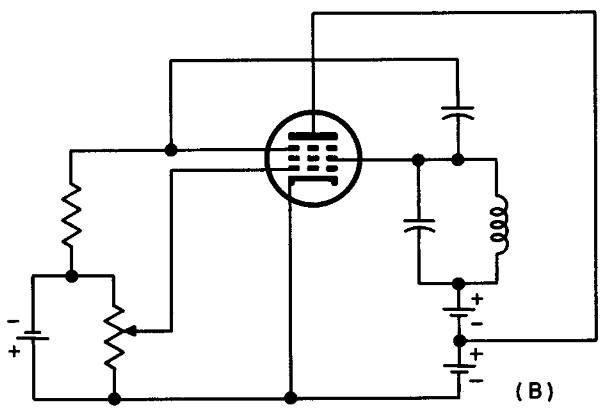


Fig. 20. Negative Resistance Oscillators. (A) Dynatron (B) Transitron.

defined takes place. (Beyond E_{p2} secondary electrons are drawn back to the plate since, at this potential, the electrostatic field of the plate is sufficiently great to hold them.) This negative resistance characteristic of a tetrode is used in oscillator designs such as the dynatron shown in Fig. 20 (A).

Pentodes may be made to exhibit negative resistance characteristics without having recourse to secondary emission at all. If the plate potential is made lower than the screen potential while the suppressor voltage is maintained slightly negative with respect to the cathode, the suppressor field causes many of the electrons that would normally go to the plate to return to the screen instead, thereby increasing the screen current. If the suppressor voltage is

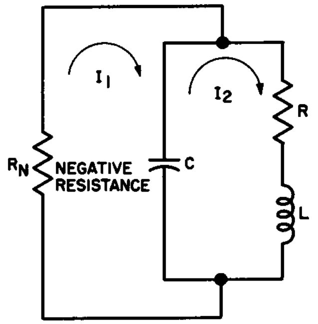


Fig. 21. Basic equivalent circuit of a negative resistance oscillator.

then made slightly less negative, electrons formerly repelled by the suppressor may now get through to the plate at the expense of the screen current. Thus, the increase of suppressor potential causes a decrease of screen current. To be considered a negative resistor, a circuit must display decreasing current with increasing voltage *at the same terminals.* Even if we raise the screen potential by the same amount as the suppressor potential, the influence of the latter is so much greater, that negative resistance is still evident in the screen circuit response. This idea is utilized in the transitron oscillator shown in Fig. 20 (B).

Other devices such as transistors and thermistors sometimes produce negative resistance effects and can be made to oscillate without electron tubes or feedback networks. As research along these lines continues, tubes will doubtless be displaced by lower-cost longer-lived elements in certain oscillator applications, particularly at lower frequencies.

35. Equations for a Negative Resistance Oscillator Circuit

Figure 21 is the equivalent circuit of a negative resistance oscillator. I_1 and I_2 are the currents flowing in the two-loop network. I_2, the circulating current in the tuned circuit when the arrangement is set up for oscillation, must be supported by I_1 for sustained oscillation. Unless r_p is a negative resistance, oscillation will quickly die out, of course, since there is no feedback path to make up for the resistive losses.

Since the derivation of the frequency equation for negative resistance oscillators involves complex Kirchoff substitutions and the solution of a differential equation, it will not be attempted here. An examination of the equation derived (Equation 43) is fruitful, however.

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}\left(\frac{r_p + R}{r_p}\right) - \frac{1}{4}\left(\frac{R}{L} + \frac{1}{Cr_p}\right)^2} \qquad (43)$$

The dependence of frequency upon L, C, R, and r_p is, of course, evident, so that in this sense, a negative resistance oscillator is similar in behavior to a feedback type (See Equation 42). It is further found that oscillations build up in amplitude gradually until a condition is attained where

$$r_p = -\frac{L}{RC} \qquad (44)$$

At this point, the amplitude of the oscillations becomes stabilized. If this value of r_p is substituted into the second term under the radical in Equation 43, this term disappears, and the remainder of the expression reduces to Equation 42, which was derived for the tuned plate oscillator.

36. Review Questions

1. What is meant by the term feedback?
2. Under what conditions does oscillation take place?
3. Is the waveform of an oscillator output always sinusoidal?
4. Name a few types of feedback.
5. How is amplitude control of the oscillator accomplished by the use of grid bias?
6. Can an oscillator biased below cutoff start by itself?
7. Is the time constant of the grid resistor-capacitor an important consideration?
8. How is the grid bias obtained in a grid resistor-capacitor type of biasing?
9. What affects the stability of the generated frequency?
10. Define admittance.
11. Explain the part a buffer amplifier plays in an oscillator output circuit.
12. What is the Miller effect?
13. Draw the circuit of the essential elements in a tuned plate circuit.
14. How does a negative resistance oscillator operate?
15. Name two negative resistance oscillators.

Chapter 4

LOW AND MEDIUM FREQUENCY OSCILLATORS

37. Introduction

Low- and medium-frequency oscillators differ from their high-, very-high-, and ultra-high-frequency counterparts chiefly in the physical arrangement of the L-C circuit. Lumped inductor-capacitor combinations are common up to approximately 50 mc, but beyond this frequency other approaches are favored. In these applications this often makes it difficult to identify the tuned circuit.

In a work of this size, it is impossible to analyze the multiplicity of oscillator circuits that have made their appearance during the last half century; in this chapter we shall discuss only the most representative and popular types of lumped-constant L-C circuits, reserving the analysis of distributed constant oscillators for Chap. 5.

38. Tuned-grid Oscillator

The oscillator shown in Fig. 22 is commonly called an Armstrong circuit, after Major Edwin H. Armstrong, to whom its invention is attributed. One of the first oscillators developed and still one of the most widely used, it satisfies the requirements for oscillation at low and medium frequencies up to and including the short wave bands. It is easy to lay out, oscillates freely even under adverse conditions, and carries no d-c power in the tuned circuit.

The L-C components in the grid circuit are in *series resonance* as explained in Paragraph 17. Considering only L and C, the resonant frequency is:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{45}$$

Equation 45 does not take into account other circuit elements that also influence the frequency of oscillation: L_p (the inductance

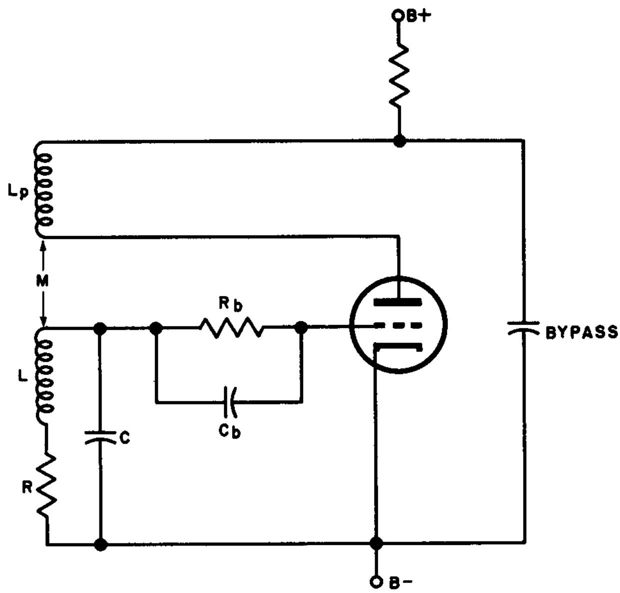


Fig. 22. Tuned-grid oscillator.

of plate or feedback coil), R (the resistance of grid inductor), and r_p (plate resistance of tube). When these factors are introduced, Equation 45 is modified to

$$f_o = \frac{f_r}{\sqrt{1 + \frac{L_pR}{Lr_p}}} \tag{46}$$

where f_o is the frequency of oscillation. The mutual inductance, M, governs the feedback coupling and may be varied above and below the point where there is sufficient power fed back for sustaining oscillations. The minimum value of M necessary for undamped operation depends upon the ratio given by the fraction under the radical in Equation 46, which we may call D, rewriting Equation 46 as

$$f_o = \frac{f_r}{\sqrt{1 + D}} \tag{47}$$

If μ is the amplification factor of the tube, g_m its transconductance, and M is $\sqrt{L_pL}$, the minimum value of M that will sustain oscillation in a circuit containing a reasonably efficient tube is given by

$$M = \frac{L_pD}{\mu(1 - D)} - \frac{CR}{g_m} \tag{48}$$

It is almost axiomatic that an oscillator that requires very little feedback to operate (i.e. one where M in Equation 48 is small) must be performing well. Hence, determining what makes M small provides the clues to methods of improving performance. It is evident from the first term that a diminution of the factor D to as small a value as possible will make the whole term appreciably smaller, as will increasing μ. Since $D = L_pR/Lr_p$ (Equation 47), keeping R very low and making r_p large will accomplish this. Thus, a high-Q circuit and a high-μ tube with a high plate resistance are indicated. The second term of the equation has less influence on M than the first term and is, therefore, usually ignored except in calculations requiring a high degree of precision.

It is interesting to note from Equation 47 that a finite positive value of D makes f_o smaller than f_r so that practical oscillators always operate at a frequency lower than that of the tuned circuit resonant frequency. As D approaches zero, f_o approaches f_r so that an ideal oscillator with a tank circuit of infinite Q would produce oscillations having the frequency dictated only by the values of L and C.

39. Shunt and Series Feed

Most (but not all) oscillators will perform satisfactorily with either *series* (Fig. 23A) or *shunt* (Fig. 23B) feed of plate power. In series feed, the tickler is in series with the plate supply. In shunt feed, plate voltage is applied through an isolating resistor and a radio-frequency choke directly to the plate of the tube. Effectively, the signal path through the tickler and the d-c path through the choke form a parallel (shunt) circuit. In practical oscillators, a radio-frequency choke is seldom needed in the series

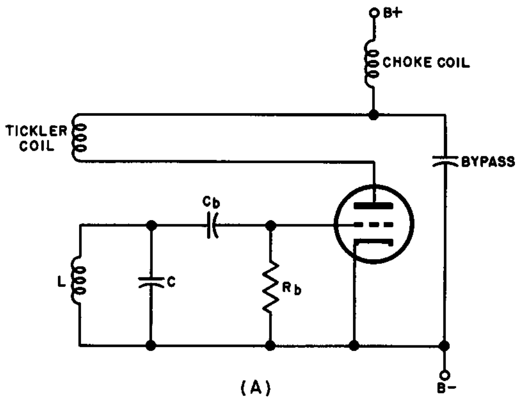
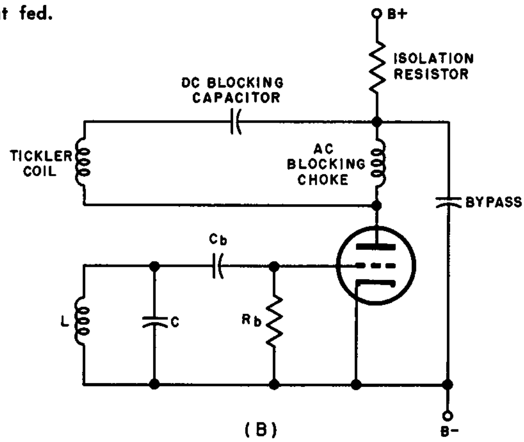


Fig. 23. Tuned—grid oscillators. (A) Series fed (B) Shunt fed.



feed arrangement, because the point of application of B+ is at signal ground potential due to the action of the by-pass capacitor. In the shunt fed circuit on the other hand, the choke is required in order to prevent a loss of oscillatory energy to the power source.

Although shunt feed requires more components, it is generally preferred to series feed, particularly in high power oscillators, since in shunt feed d-c potentials do not appear in the tuning system components.

40. The Colpitts Oscillator

Colpitts oscillators (Fig. 24) have been operated successfully at much higher frequencies than the tuned-grid type. Frequencies of several hundred mc are not uncommon. It is a relatively flexible

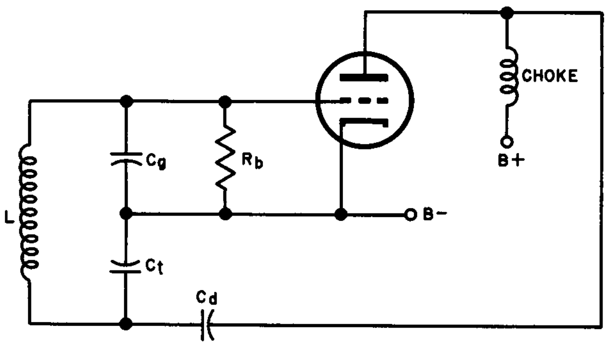


Fig. 24. Colpitts oscillator.

oscillator (in that various circuit configurations are possible), it may be made reasonably free of harmonics, and is easy to adjust.

The frequency determining network consists of L, C_g, and C_t, all connected in series. The plate circuit signal return path includes two parallel branches: one through C_t directly to the cathode and the other through the series combination of L and C_g. In this connection, the two tuning capacitors behave as a capacitive voltage divider, the amount of plate-to-grid feedback depending upon the ratio of C_g to C_t. To establish a chosen frequency with a given inductance, L, C_g and C_t must total to a specific capacitance; however, the smaller C_g is made and/or the larger C_t becomes, the greater the voltage coupled back will be. For this reason, both C_g and C_t are usually variable, enabling the operator to establish both the frequency and the feedback fraction.

When R_b is large enough (depending upon the bias required) it does not have much shunting effect upon the signal voltage applied to the grid; in certain circuits where R_b must be small, an additional choke is necessary and is inserted in series with R_b.

A high-power Colpitts oscillator of the type that might be found in a diathermy machine or dielectric or induction heater used for industrial purposes, is shown in Fig. 25. The basic principles of its operation have been discussed; it is of interest, however, to note the differences between this circuit and the one shown in Fig. 24.

The tuning network (L, C_g, and C_t) is isolated from both the plate and grid of the tube through capacitors C_d and C_b respectively. This isolation requires R_s to bleed off the static charges that tend to accumulate in the tuning system, especially on the coil L. R_s is quite high in value in order to avoid shunting effects during operation. Inductive coupling is used between L and the load.

Note the configuration around R_b, the grid leak resistor. L_m serves to prevent radio-frequency power losses in the grid circuit.

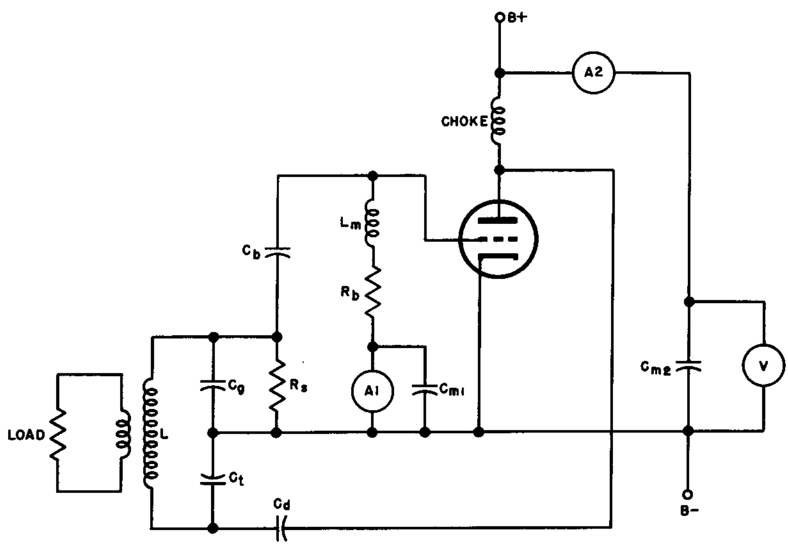


Fig. 25. Power application of Colpitts oscillator.

The meter A1 measures the rectified grid current of the tube and thus is a measure of the activity of the oscillator. C_{m1} is a positive safeguard against damage to the meter, providing a very low impedance path for r-f leakage currents that might get past L_m.

Provision is made for measuring plate current by means of meter A2 for the purpose of adjusting the C_g/C_t ratio during tune-up and to estimate the power while operating. Voltmeter V measures applied anode potential; it is protected against stray r-f by C_{m2}.

It is important to note that the grid leak is never connected in series with the tuned circuit but must be returned directly to the cathode. This is necessary because, in the Colpitts oscillator, there is no d-c path from grid to cathode through the inductance as there is in the tuned-grid and other oscillators. Another restriction that applies uniquely to the Colpitts circuit is that series-feed *cannot* be used owing to the absence of a d-c path between plate and cathode.

41. The Clapp-Gouriet Oscillator

The Clapp-Gouriet oscillator is a modification of the Colpitts circuit and operates on the same basic principles. Its principal advantage lies in the possibilities it offers for better frequency

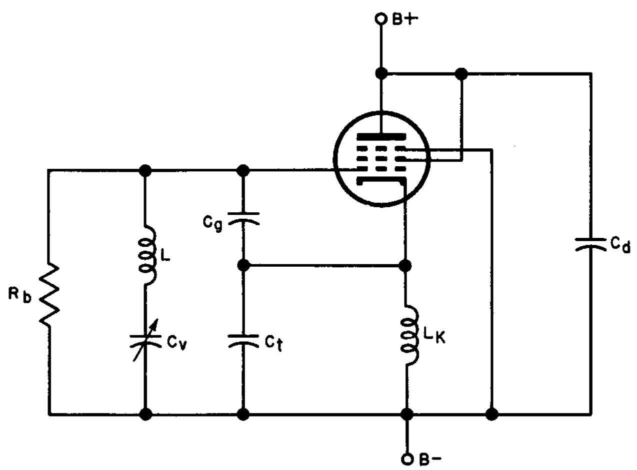


Fig. 26. Clapp-Gouriet oscillator.

stability if care is taken in its design and proportioning of its components.

As the circuit of Fig. 26 shows, the Clapp-Gouriet oscillator differs from the Colpitts in three major respects: the tube is a pentode, its plate is at a-c ground potential (due to the connection of C_d) while its cathode is held above ground by L_k, and a series resonant circuit for tuning purposes consisting of L and C_v takes the place of the simple inductor, L, used in the Colpitts circuit

Feedback occurs through the voltage divider action of C_g and C_t just as in Colpitts circuit. In the Clapp-Gouriet oscillator, however, these capacitors are fixed at the optimum ratio and are not disturbed for small frequency changes. Variation of C_v permits tuning over a reasonably large range. Although the Colpitts and Clapp-Gouriet oscillators are theoretically capable of approximately the same degree of frequency stability, the flexibility of the Clapp-Gouriet oscillator is superior. It is this flexibility that makes it possible for it to approach the theoretical limit of stability more closely than the Colpitts oscillator.

42. The Hartley Oscillator

For many years, the Hartley oscillator enjoyed a greater popularity among transmitter designers than any other simple L-C type. It uses relatively few components, has good frequency stability, is easy to adjust, and is quite reliable in its operation. The Hartley oscillator is very similar to the Colpitts in principle, except that it makes use of an inductive rather than a capacitive voltage divider in establishing feedback. In the circuit of Fig. 27 (A), the oscillator is series fed, which eliminates the isolating choke. A tap on the tuning inductor is adjusted until optimum feedback power is obtained. The advantage of this system over the Colpitts is evident: only one tuning capacitor is necessary, since the feedback ratio is governed by the position of the inductor tap.

Coil L is usually wound continuously, since mutual inductance between the two portions of the inductor is not necessary for operation. In high-power applications, the inductor may be fabricated of copper tubing or very heavy wire and the position of the tap experimentally determined by means of a clip lead before permanent connection is made.

The obvious disadvantage of the circuit of Fig. 27 (A) is that the tuning coil and capacitor are both at B+ potential, a condition that represents a serious hazard for operating personnel. To avoid this, the Hartley oscillator may be shunt-fed as shown in Fig. 27 (B). Although this method requires two additional components — the radio-frequency choke RFC and the blocking capacitor C_c — it is a worthwhile safety precaution that is almost always taken.

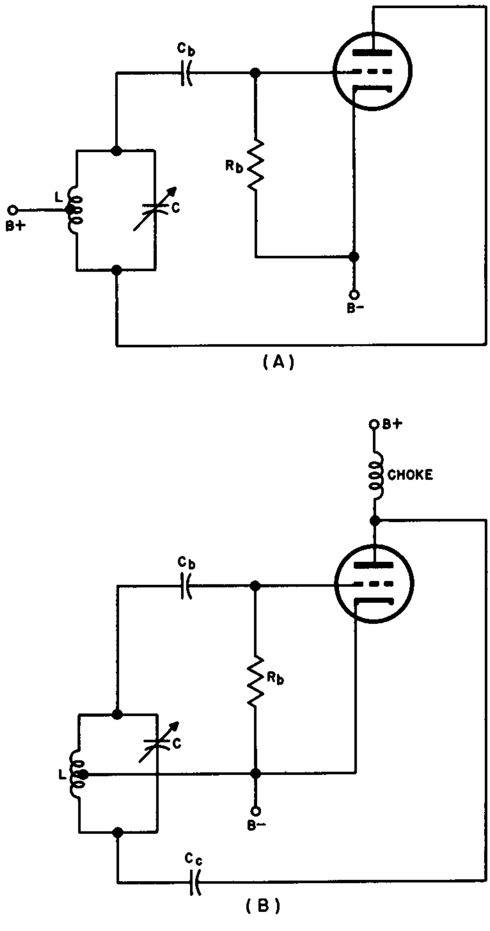


Fig. 27. Hartley Oscillators. (A) Series fed (B) Shunt fed.

43. The Tuned Plate Oscillator

This oscillator was mathematically analyzed in Paragraph 33. We shall now explore the practical aspects of the circuit and review the precautions that must be taken to realize optimum performance. The schematic diagrams of Fig. 28 show the tuned plate oscillator in series fed and shunt fed forms.

Resistor R drops the d-c plate voltage to a figure that matches the specifications of the particular tube, it isolates the oscillator from common connections that go to other circuits, and it provides

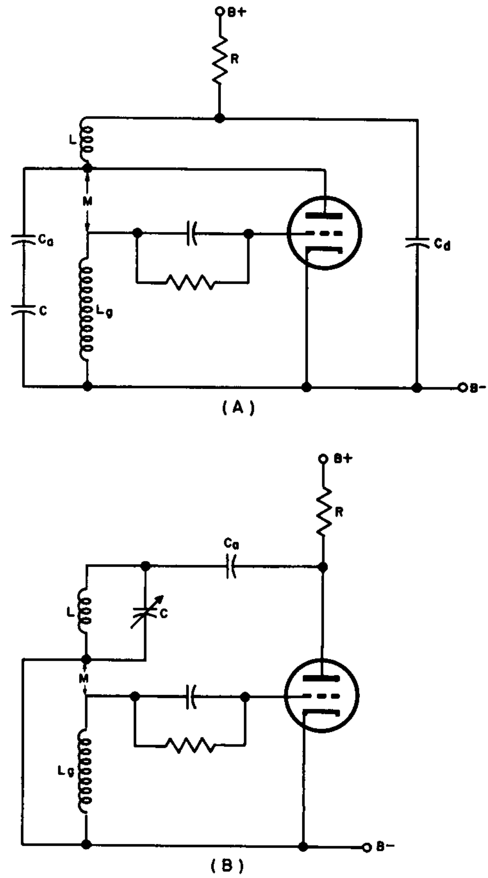
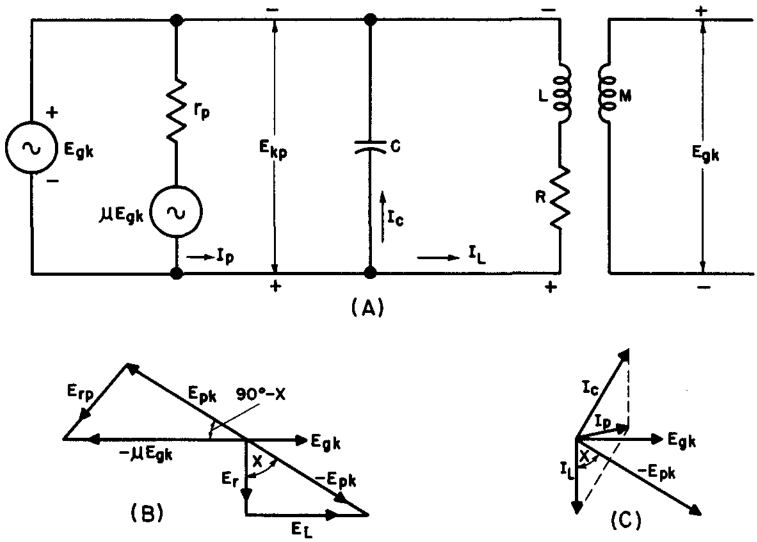


Fig. 28. Tuned–plate oscillator. (A) With series fed plate supply (B) with shunt fed plate supply.

some damping for the tuned circuit at higher frequencies. As the value of C is reduced, the basic oscillator frequency rises and the impedance of the tuned circuit increases. Under these conditions, the damping also becomes more effective and helps to hold the amplitude constant.

The grid coil L_g has few turns but is tightly coupled to L. (The inductance of L_g is kept at a minimum to avoid tuning the grid coil by its own distributed capacitance.) Capacitor C_a blocks d-c from the plates of the variable capacitor C, and C_d acts in conjunction with R as part of the filter network, while completing the a-c signal path. The use of a small inductance contributes to the performance of the circuit in another way: as the resonant frequency of L_g is quite high, it does not reflect an important



NOTES: $X = \tan^{-1}\frac{\omega L}{R} = \tan^{-1} Q$

$E_{gk} = M\frac{dI_L}{dt} = j\omega M I_L$

$I_L = \frac{1}{j\omega M}E_{gk}$ AND HAS ANGLE OF $-90°$ WITH RESPECT TO E_{gk}

$E_{pk} = (R + j\omega L)\,I_L = \frac{R+j\omega L}{j\omega M}E_{gk}$

Fig. 29. Vector analysis of the tuned-plate oscillator.

reactive component into the tuned circuit. This serves to isolate the latter and make it relatively free of effects which might be caused by small supply voltage variations.

The method of vector analysis presented in Fig. 29 and the text that follows is a valuable tool in the analysis of any oscillator circuit. It is included here to demonstrate the normal approach to problems of this type, and to show that a clear interpretation of voltages, currents, and the related phase angles is important to an understanding of oscillator function.

In the tuned plate oscillator, the angle x (Fig. 28) is commonly expressed:

$$x = \text{arc tan } \frac{\omega L}{R} = \text{arc tan } Q \qquad (49)$$

where L is the effective inductance of the tuned circuit and R is the resistive component of L. The feedback angle, (90 − x) degrees (i.e. the angle between E_{pk} and $-\mu E_{gk}$) must be small for sustained oscillation since this means that feedback occurs with very nearly 180-degree displacement. Complemented by the 180-degree phase inversion in the tube, this displacement produces a total turnover of 360 degrees for the complete circuit from grid through plate and back to grid. The following analysis shows that the feedback angle is indeed small. The angles have been somewhat exaggerated for clarity and the voltages are not to scale.

(a) An initial grid voltage E_{gk} produces a plate voltage $-\mu E_{gk}$ shown as a vector rotated 180 degrees from the causative grid voltage and larger in amplitude.

(b) $-\mu E_{gk}$ is resolved into two components; E_{rp} is the voltage across the internal plate resistance of the tube and E_{pk} is the voltage across the external circuit, shown as making an angle (90 − x) degrees with the "source" voltage μE_{gk}.

(c) $-E_{pk}$ is constructed equal and opposite in direction to E_{pk} and is the voltage that acts across the load components of the tuned circuit.

(d) $-E_{pk}$ is further resolved into $E_{\hat{R}}$, the a-c resistance in the tuned circuit (of which the d-c resistance R forms only a part) and E_L the voltage drop across the inductor. The angle between E_R and E_L is 90 degrees. The angle between $-E_{pk}$ and E_R is x.

(e) I_L, the current through the inductor L is shown displaced by the angle x from the voltage $-E_{pk}$.

(f) The second vector diagram in Fig. 29 shows the current in the capacitor 90 degrees in advance of $-E_{pk}$. This is the case because there is practically no resistance in the capacitive branch. In the inductive branch, the current I_L is displaced from $-E_{pk}$ by the angle x.

(g) The vector sum of the currents I_C and I_L is shown as I_p. The angle that I_p makes to the original E_{gk} is (90 − x) degrees, the feedback angle which, since x was defined as arc tan Q is small for high-Q circuits.

44. The Franklin Oscillator

This circuit, shown in Fig. 30, typifies an oscillator class that utilizes the phase reversal produced by a second tube, rather than a transformer, to complete the 360-degree shift input-output-input.

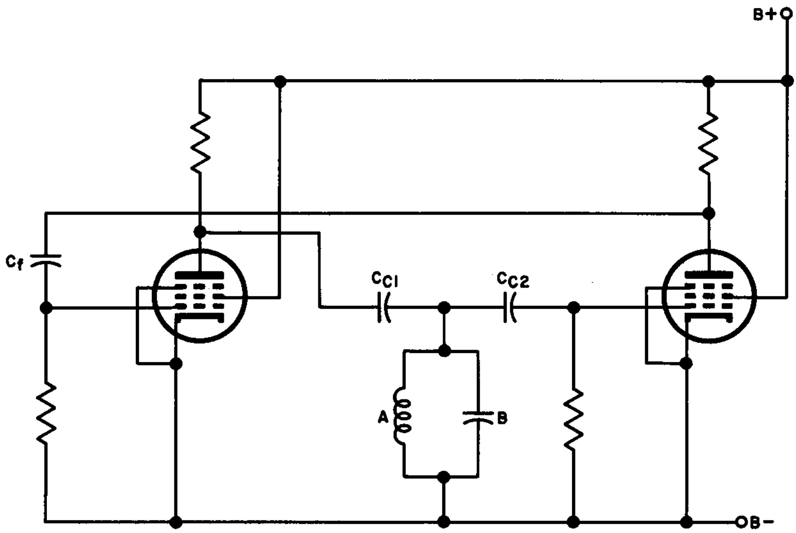


Fig. 30. Franklin Oscillator.

When properly designed, the Franklin oscillator is capable of good frequency stability.

The coupling capacitors C_{c1} and C_{c2} are very small (on the order of 1 or 2 $\mu\mu f$). This reduces the possibilities of interaction between the two tube circuits and diminishes the loading effect of the circuit on the L-C tank. Feedback occurs through capacitor C_f whose value is chosen so that it has little reactive effect upon the complete loop through the circuit. The second tube may be cathode-biased by inserting a resistor between cathode and B−. The tube current is thereby reduced so that the loading effect of the tube upon the tuned circuit is minimized.

45. The Level Controlled Oscillator

The variation of the tuned plate oscillator shown in Fig. 31 makes use of the "thermistive" curve of an incandescent lamp to stabilize the amplitude of oscillation. A tungsten lamp has a positive temperature coefficient: its resistance rises with increasing temperature. Should the amplitude of oscillation tend to rise, the current through the lamp increases and the filament temperature rises with an accompanying rise in resistance. This reduces the

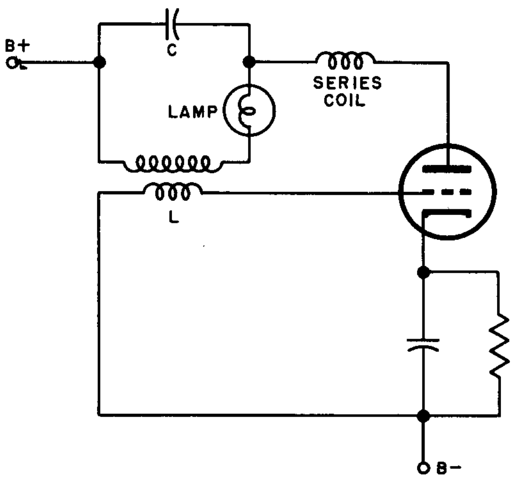


Fig. 31. Level controlled oscillator.

Q of the tuned circuit which, in turn, tends to reduce the amplitude of oscillations. In essence, this is a self-balancing thermistive loop that controls the level of oscillation.

Without the series coil, the changing Q of the tuned circuit would tend to vary the frequency as well as the amplitude of oscillations. If, however, the inductance of the series coil is made equal to the inductance of the tank coil, the frequency of oscillation becomes independent of the resistance of the lamp.

46. The Tuned-Plate Tuned-Grid Oscillator

This oscillator is unusual in that there are two tuned circuits, one in the grid and one in the plate, with *no mutual inductance* between coils. It oscillates by virtue of the feedback from the plate oscillatory system to the grid network through the interelectrode capacitance between the grid and plate. It is found that, when the tuned-plate tuned-grid oscillator is performing efficiently, both the resonant circuits are tuned *slightly below* the oscillatory

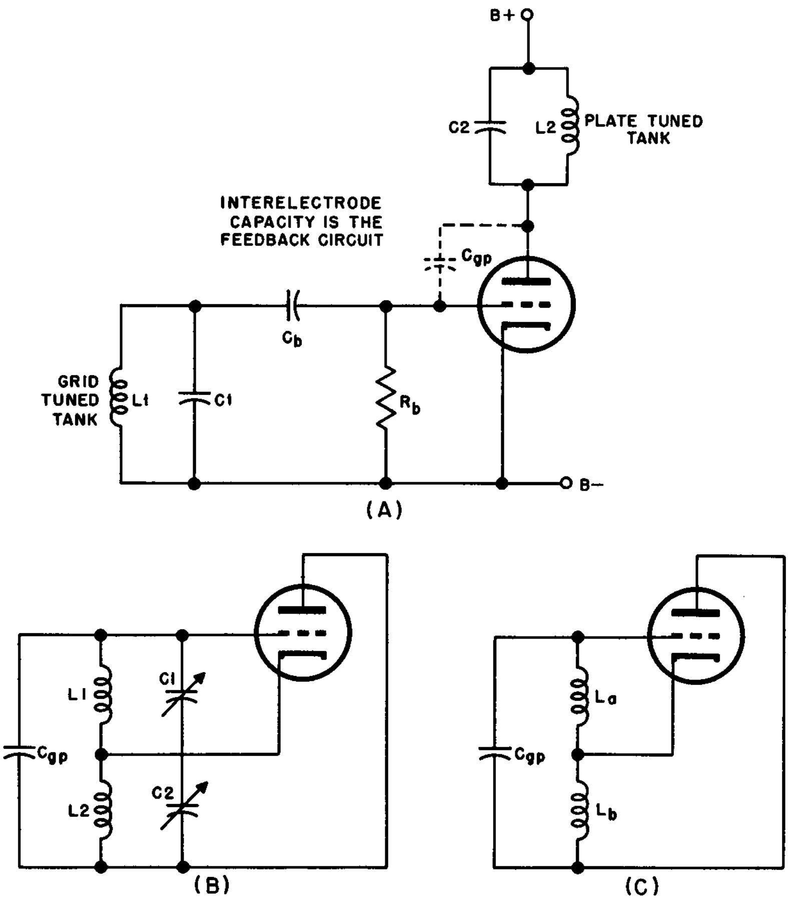


Fig. 32. Tuned-plate tuned-grid oscillator. (A) Schematic (B) Equivalent circuit (C) Simplified equivalent circuit.

frequency generated. This means that both these circuits are inductive, providing a clue that aids the qualitative analysis of tuned-plate tuned-grid operation.

Figure 32 (A) is a schematic diagram of the actual circuit and Fig. 32 (B) shows the circuit redrawn in equivalent form with the voltage source and bias components omitted for simplicity. Since both resonant pairs are inductive, the L_1-C_1 and L_2-C_2 combinations may be represented as pure inductances, simplifying Fig. 32 (B) to the form given in Fig. 32 (C). L_a is the net inductance of the grid tuned circuit and L_b is the net inductance of the plate tuned circuit with the grid-plate capacitance C_{gp} appearing across both

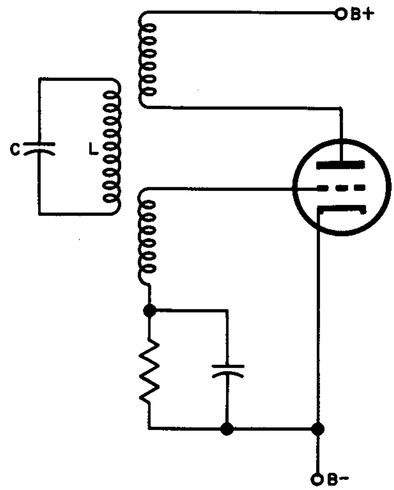


Fig. 33. Meissner Oscillator.

in series. The resemblance to a Hartley oscillator is very evident in this form. It should be noted that C_{gp} effectively resonates with the total residual inductance establishing the conditions required for proper feedback phase and sustained oscillation.

A supplementary, small capacitance is often connected directly from grid to plate. Its effect is to diminish the effect of tube changes upon resonant frequency.

47. The Meissner and Lampkin Circuits

Both of these circuits (Figs. 33 and 34) represent more or less unsuccessful attempts to design an oscillator in which the frequency-determining L-C network is isolated from the remaining components. If such isolation could be achieved it would, of course, do much to stabilize the frequency of the oscillator.

In the case of the Meissner circuit, the tank is inductively coupled to the plate and grid coils. To achieve reliable performance, the coupling must be so close that the concept of isolation is completely defeated. In addition, the Meissner oscillator tends to oscillate at spurious frequencies as well as its fundamental.

The Lampkin circuit is very similar to a shunt-fed Hartley circuit. The difference lies in the point of connection of the grid bias capacitor, which is to a tap on the coil rather than to its top end. It was originally felt that this design would be effective in reducing the influence that the remainder of the circuit has upon the natural frequency of oscillation. The anticipated results are in evidence to some degree at low and medium frequencies, but

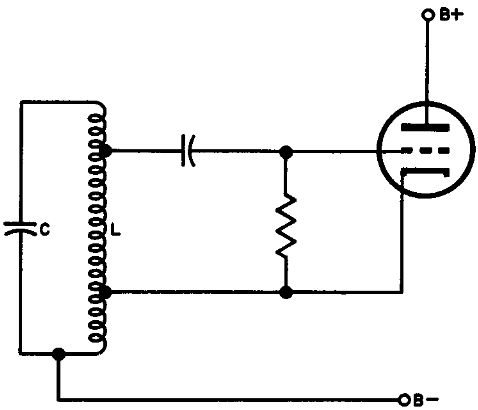


Fig. 34. Lampkin Oscillator.

the change accomplishes very little at high frequencies. The Lampkin oscillator, like the Meissner, is subject to parasitic oscillation when the coupling is not sufficiently close.

48. The Meacham Bridge Oscillator

No work on L-C oscillators would be complete without making mention of the Meacham bridge oscillator (Fig. 35). Although complete analyses of this circuit are available in specialized textbooks, they are much too complex and extensive to be presented here.

One of the most stable oscillators ever devised, the Meacham bridge circuit is now used almost exclusively as a crystal-controlled oscillator with a quartz crystal unit replacing the series resonant L-C circuit. Even without crystal stabilization however, the Meacham bridge outperforms other self-excited oscillators and was used as a primary frequency standard before the introduction of crystal circuits.

The bridge network is not only a frequency-determining assembly, but also serves as an amplitude limiter; frequency stability is vastly improved, as compared with other standard forms, as a result of the balancing action of the bridge. When the frequency tends to deviate, this balancing action gives rise to an increase of the effective Q of the series-resonant pair. As a result of this action,

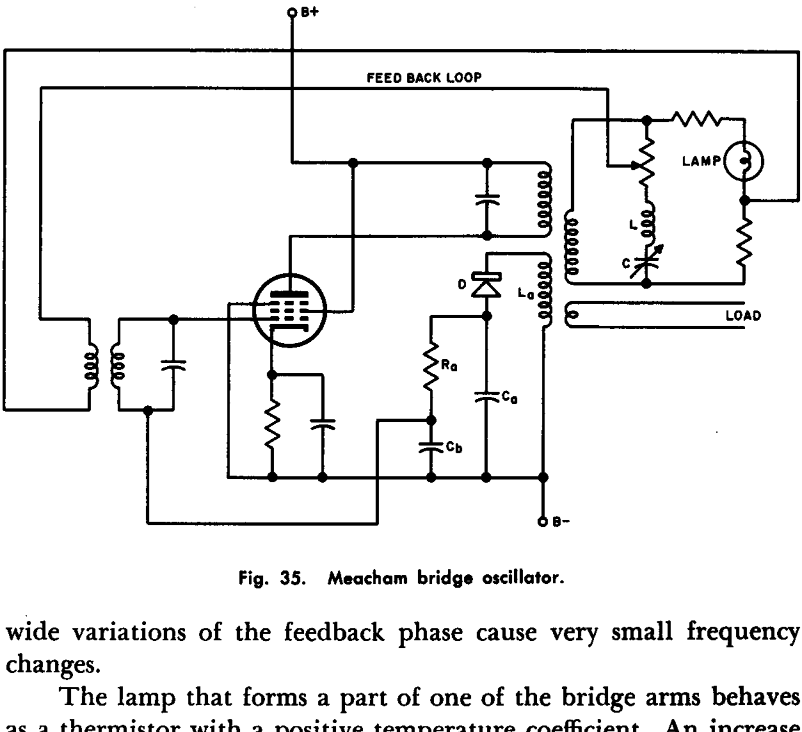


Fig. 35. Meacham bridge oscillator.

wide variations of the feedback phase cause very small frequency changes.

The lamp that forms a part of one of the bridge arms behaves as a thermistor with a positive temperature coefficient. An increase in oscillation amplitude results in an increase in temperature, which in turn elevates the total resistance of the arm. This reacts on the feedback network to reduce the grid signal and hence the total output.

Crystal diode D, inductor L_a, resistor R_a, and capacitors C_a and C_b are sometimes (not always, however) added to a Meacham oscillator to prevent any tendency it might have to oscillate intermittently. The network including these parts may be considered a corrective circuit necessary only when a particular oscillator displays this tendency.

49. The Electron-Coupled Oscillator

Electron-coupled oscillators are among the most popular types for low and medium frequency generators where both good stability and continuous tunability are required. (A crystal-controlled

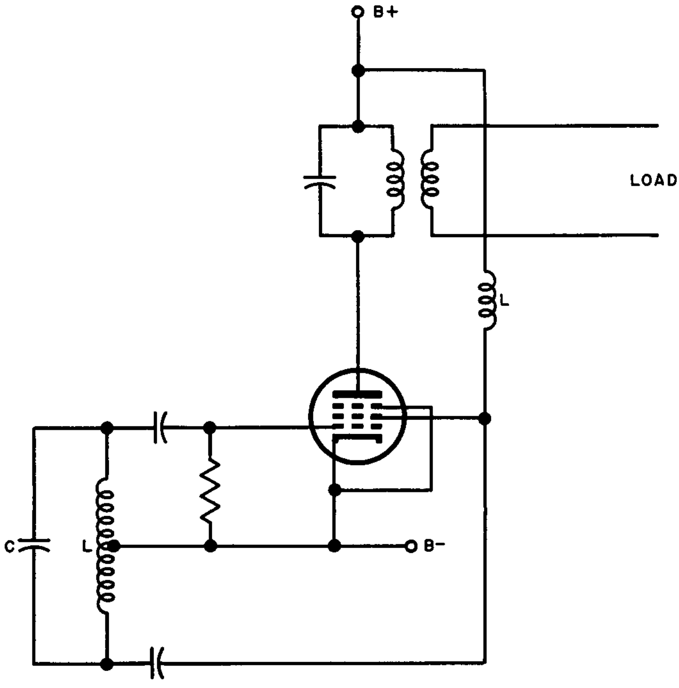


Fig. 36. Electron-coupled oscillator.

oscillator may be far more stable but it lacks the flexibility needed for use in alignment signal generators or the variable frequency oscillators in transmitting equipment.)

An ordinary triode oscillator such as a Hartley or Colpitts circuit is subject to frequency variation with changes of load. As the output requirements change, the plate current changes, causing a feedback phase shift that tends to make the frequency deviate. In addition to this, load changes are reflected to the oscillator through the grid-plate capacitance of the tube. Electron-coupled oscillators, such as the Hartley-type circuit shown in Fig. 36, are substantially unaffected by this action. The screen grid shields the output circuit from the oscillatory circuit so that the grid-plate capacitance is made virtually negligible and the plate current of a pentode is almost independent of the plate voltage, so that load variations have very little effect upon feedback phase angle.

Almost any type of L-C oscillator may be profitably operated as an electron-coupled type. For satisfactory results the tube must have good shielding and should have an externally available suppressor connection (in most designs, the suppressor grid is operated at a potential which is approximately as positive as the peak positive excursions of the cathode voltage). The inductor L is necessary only when the impedance of the plate supply is high and a relatively large power output is required.

50. Review Questions

1. Draw, from memory, the circuit of a tuned-grid oscillator. List its advantages and the range of frequencies over which it normally operates.
2. In the equation $f_o = f_r/\sqrt{1 + D}$, what is the ratio symbolized by D?
3. Differentiate between series feed and shunt feed. Illustrate your explanation by diagrams.
4. Which type of feed is normally employed in high power oscillators? What reasons can you give for your choice?
5. Draw, from memory, typical versions of the Colpitts and the Clapp-Gouriet oscillators.
6. What are the main features of the circuits drawn in answer to Question 5?
7. What advantages does the Hartley oscillator possess over the Colpitts, if any? Draw typical circuits for a shunt fed Hartley oscillator.
8. Draw the schematic of a tuned-plate tuned-grid oscillator and an equivalent circuit for analysis. Give the important characteristics of this oscillator using the equivalent circuit in your explanation.
9. What advantages does the electron-coupled oscillator possess over an ordinary triode oscillator?
10. What are the distinguishing features of (a) a Franklin oscillator (b) a level controlled oscillator?
11. Are triodes or pentodes preferred in inductive feedback type oscillator circuits? Capacitive feedback type oscillator circuits? Why?

Chapter 5

HIGH FREQUENCY OSCILLATORS

51. Introduction

This book is concerned principally with lumped-constant L-C oscillator principles and design; however, some mention should be made of the problems encountered in engineering and constructing the distributed-constant L-C oscillators used for very high frequency applications.

The circuits in themselves do not present particularly serious problems. Difficulties arise, however, in designing the components that form the circuit elements, particularly in the resonant section of the oscillator. In low frequency circuits the inductance is readily identified because it consists of a coil wound on some recognizable form. In high frequency circuits a straight piece of wire or a tube may have sufficient inductance to supply the requirements of the circuit. Regarding the tuning capacitor, what is considered negligible distributed capacitance in low frequency circuits may very well become the tuning capacitance at very high frequencies, making an additional capacitor unnecessary.

52. The Butterfly Resonator

The butterfly circuit shown in Fig. 37 is one form that a vhf resonator may take. The unit shown is tunable over a range of 200 to 1100 mc and consists of a system of stator and rotor plates typical of variable capacitors. The sections marked *inductor* form half-loops connected to what may be considered as capacitors in series as shown in the equivalent circuit. Thus, both the capacitance and inductance of the unit are changed as the plates are meshed or unmeshed.

The butterfly has an unusually large range of frequency coverage, the Q is quite high, and the absence of rubbing contacts improves the physical stability of the tuner. The extended range is explained by the fact that both capacitance and inductance change *in the same direction* as the plates are rotated. In going

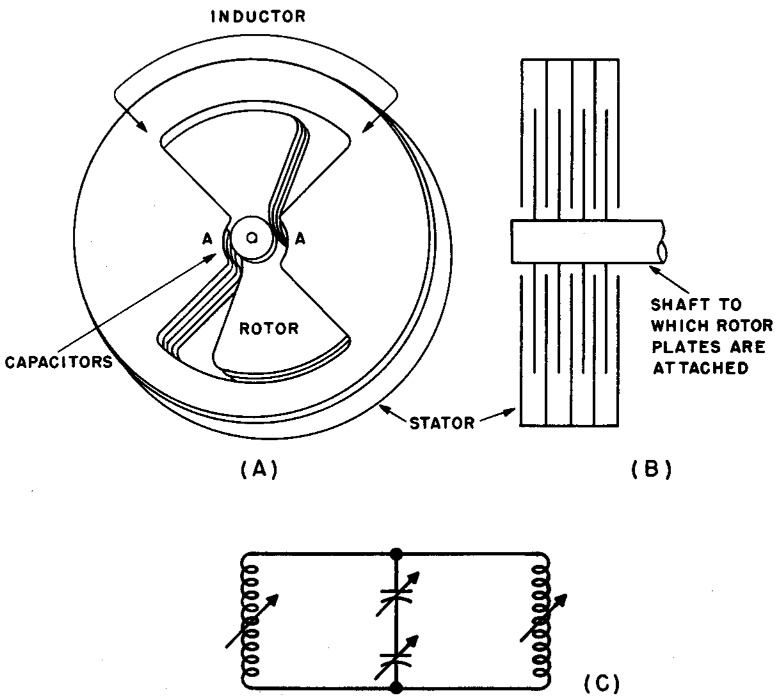


Fig. 37. Butterfly resonator. (A) Front view (B) Cross section (C) Equivalent circuit.

from high to low frequency tuning, the effective increase in C and L may be made to yield a ratio of the highest to lowest frequency of better than 4.5 to 1 in well designed butterflies.

A practical circuit in which a butterfly forms the resonant circuit is shown in Fig. 38. Plate and grid connections are made to the stator plates on opposite sides of the shaft; the B+ connection goes to a point on the "inductor" about midway between the curved stator edges. The output is obtained by means of a pick-up coil placed close to the point shown in the figure and oriented so that it links with the flux at that point.

53. Resonant Tuning Lines

Resonant tuning lines are used extensively in high frequency oscillators. If a source of high-frequency voltage is conected across the ends of two parallel wires or rods, it is found that the conductors present various impedances to the generator (vacuum tube, in this case) depending upon the length of the parallel line and upon whether or not it is short-circuited at some remote point.[1] For example, an open-circuited line less than 1/4 wavelength long presents a pure capacitive reactance to the generator while a short-circuited line longer than 1/4 wavelength is seen as a pure inductive reactance from the generator terminals.

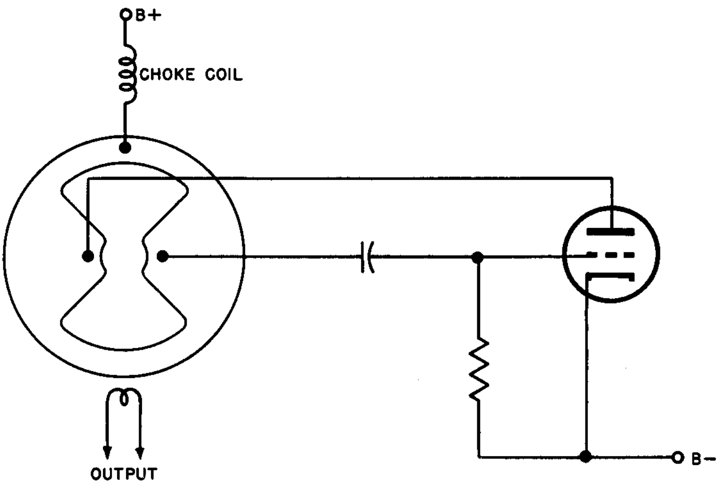


Fig. 38. Oscillator using a butterfly resonator.

In the circuit of Fig. 39, capacitor C is *not* a tuning capacitor, but rather a radio-frequency short circuit across the lines that acts as an open circuit for d-c to prevent grounding the positive

[1] See A. Schure (Ed.), *R-F Transmission Lines* (New York: John F. Rider Publisher, Inc., 1956), and *Resonant Circuits* (New York: John F. Rider Publisher, Inc., 1957).

side of the power supply. The distance between the terminals of C and the elements of the tube is made slightly greater than 1/4 wavelength by sliding the capacitor along the rods. The lines then present a pure inductive reactance to the tube. The grid-plate capacitance C_{gp} acts in parallel with this inductive reactance so that the two together comprise a parallel resonant circuit at the frequency to be generated.

The interelectrode capacitances C_{pk} and C_{gk} form a voltage divider which, just as in the Colpitts oscillator, serves to transfer energy from the grid to the plate circuit to sustain oscillation.

54. Other High Frequency Oscillators

An increasing amount of intensive research is being given to ultra-high frequency operation. The enormous progress made in this field since the beginning of World War II is attributable

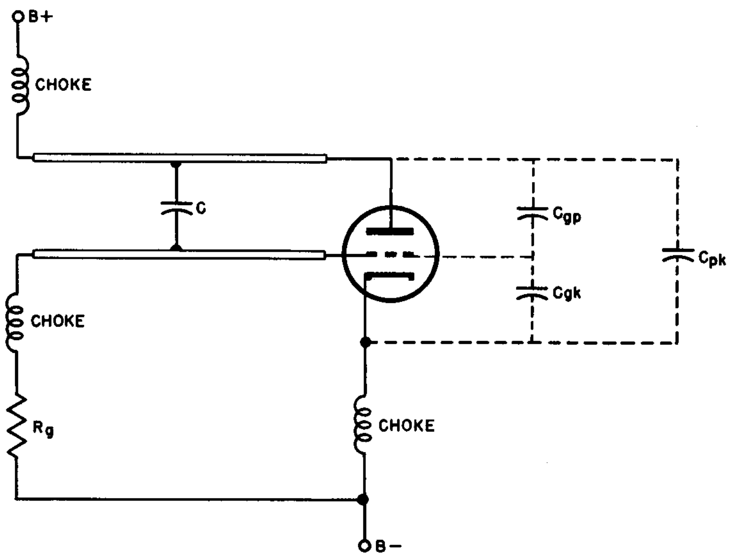


Fig. 39. Tuned line oscillator.

directly to the development of special tubes and components, some of which differ radically from conventional types. Since oscillators designed around these units cannot usually be classified as simple L-C types, they will not be covered in detail in this text. The following descriptions, however, give a brief summary of the more important of these special resonators:

Cavity resonator. An adaptation of a tuned resonant line oscillator in which a hollow conductor, usually of semi-cylindrical shape, acts as the tuned circuit. It may be used with conventional tubes.

Klystron. Generally used with cavity resonators, this tube produces oscillation by a process called velocity modulation. There are a number of different types of klystrons all of them being capable of producing oscillations up to about 3000 mc.

Magnetron. A cavity resonator oscillator that operates by virtue of the combined action of magnetic and electric fields. Magnetrons are capable of producing peak power outputs in the region of several kilowatts at frequencies well above 10,000 mc.

Lighthouse tube. Often called a "parallel-plane" or "disc" tube, this tube can reach frequencies of the same order as the klystron with an output up to about 1000 watts. It makes use of coaxial rather than cavity resonators.

55. Review Questions

1. What differences may occur in L-C units as the oscillators are designed for the higher frequency ranges?
2. Draw an oscillator circuit that uses a butterfly resonator. Explain the action and the characteristics of this oscillator.
3. Sketch a circuit illustrating the use of resonant tuning lines in high frequency oscillators. Describe the components forming the L-C arrangement.
4. What is (a) a cavity resonator; (b) a klystron; (c) a magnetron; (d) a lighthouse tube?

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