HARTLEY OSCILLATOR

$$\omega \approx \sqrt{\frac{1+\frac{R_1}{r_p}}{(L_1+L_2+2N)\,C}} = \omega_0\sqrt{1+\frac{R_1}{r_p}} \qquad \text{[Eq 12}$$

$$gm = \frac{C\,(R_1+R_2)\,(L_1+L_2+2M)}{(L_1+M)\,(L_2+M)} \qquad \text{[Eq 13}$$

$$\text{if } M=0: \quad gm = \frac{C\,(R_1+R_2)(L_1+L_2)}{L_1+L_2} \qquad \text{[Eq 14}$$

$$\text{Eq. 15]} \quad \text{or} \quad gm = \frac{CRL}{L_1\,L_2} \quad \text{where } R = \text{total tuned circuit resistance (in L)}$$

$$L = \text{total L in tuned circuit } (L_1+L_2)$$

$$M = \frac{L_1+M}{L_2+M} + \frac{Cr_p\;R\,(L_1+L_2+2M)}{(L_1+M)\,(L_2+M)} \qquad \text{[Eq 16}$$

ed that for equivalent coils, the stability would be better for the Hartley.

From the expression for u, it can be seen that the greater the ratio of the grid-to-cathode section of the coil to the plate-to-cathode section, the easier it is for oscillation to take place. However. the plate section cannot be too small, since then there will not be sufficient transfer of energy from the plate to the coil.

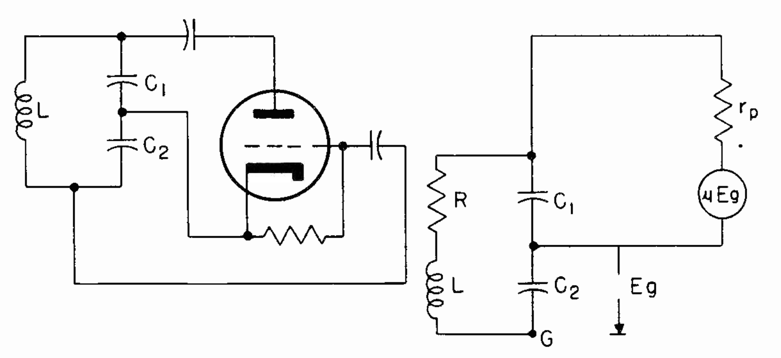
It is interesting to note that it is not necessary to have either grid-plate capacitance or mutual inductance between the sections of the coil to support oscillation. The expressions are derived containing M because such M is usually present. However, if the two sections of the coil are entirely separated oscillation takes place. In fact, oscillation is even more vigorous without mutual inductance. Of course, the number of turns in each section of the coil must be somewhat greater, to make up for the loss of M, if the same frequency is to be maintained with the same tuning capacitor.

The Colpitts oscillator is a variation of the Hartley principle in which the tuned circuit is divided by a capacitance voltage divider instead of a tap on the coil. It is shown with equivalent circuit in Fig. 8. The expressions for this oscillator are as follows:

$$\omega = \omega_0\sqrt{1+\frac{R}{r_p}+\left(\frac{C_2}{C_1+C_2}\right)} \qquad \text{[Eq. 17}$$

$$\mu = \frac{C_2}{C_1} + \frac{r_p\,R(C_1+C_2)}{L} \qquad \text{[Eq. 18}$$

$$gm = \frac{R\;(C_1+C_2)}{L} \qquad \text{[Eq. 19}$$



COLPITTS OSCILLATOR

FIGURE 8

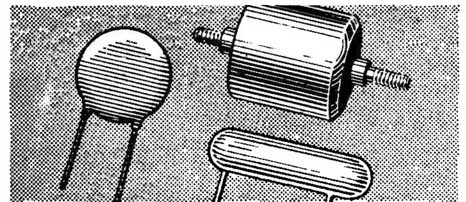
Note that the tuned circuit must be adjusted for a resonant frequency slightly below the actual frequency of oscillation. The expressions for u and gM are similar to those for the Hartley, except that they contain the divider capacitances instead of the sections of the coil. The values of both u and gM necessary for oscillation are small. In the expression for frequency, the capacitance values play an important part. It is noteworthy that a relatively high value for C_2 makes for less easy oscillation and poorer stability.

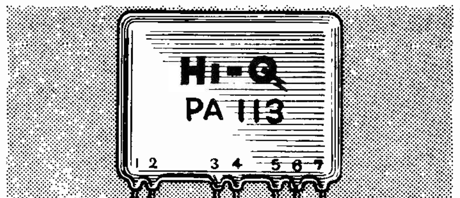
One of the important advantages of the Colpitts oscillator is the relatively large capacitances (C_1 and C_2) are shunted across the plate-to-cathode and grid-to-cathode interelectrode capacitances of the tube. This minimizes the effect of the latter on the stability of the oscillator, which depends almost altogether upon the external capacitances. The latter are within the control of the designer, whereas tube capacitance variations are not.

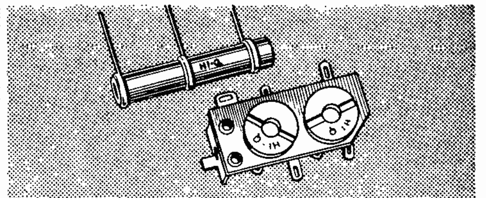
In this article we have discussed some of the more important factors influencing the operation, behavior and suitability of basic oscillator circuits. In the next article of this series we shall consider the use of oscillator circuits in low-frequency and short-wave AM radio receivers.

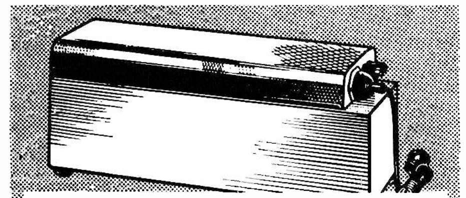
REFERENCES

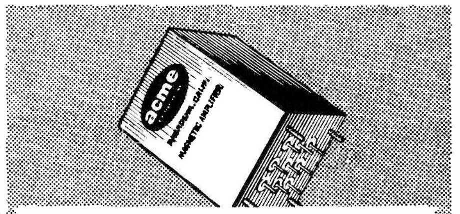
1—Eastman, Austin V — Fundamentals of Vacuum Tubes, McGraw-Hill 1949; pp. 441-452.
2—Edson, Wm. A. — Vacuum Tube Oscillators, John Wiley & Sons 1953; pp. 1-12, 158-169, 173-175.
3—Everitt, Wm. L. — Communication Engineering, McGraw-Hill 1937; pp. 598-615.
4—Glasgow, R. S. — Principles of Radio Engineering, McGraw-Hill 1936; pp. 228-236, 261-269.
5—Radiotron Designer's Hankbook, RCA-Victor Div. Radio Corp of America (for Amalgamated Wireless Valve Pty. Ltd.) 1952; pp. 49-53, 947-954.
6—Seely, Samuel — Electron-Tube Circuits, McGraw-Hill 1950; pp. 60-63, 244-253.
7—Sturley, K. R. — Radio Receiver Design, John Wiley & Sons 1949; pp. 37-53, 162-164, 241-252.
8—Terman, F. E. — Radio Engineer's Handbook, McGraw-Hill 1943; pp. 467-469.

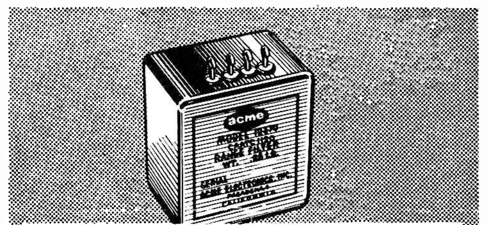


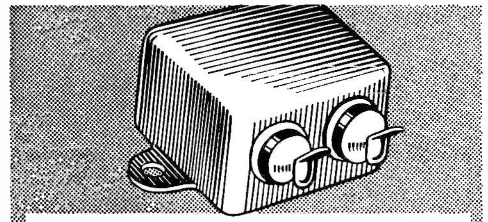


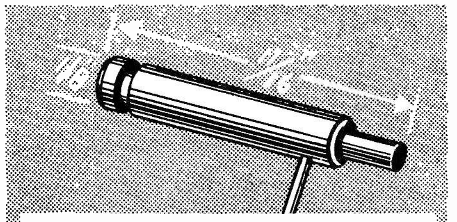


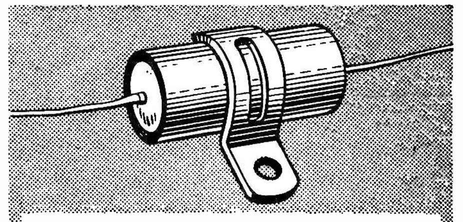


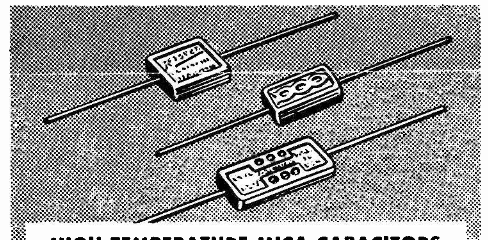


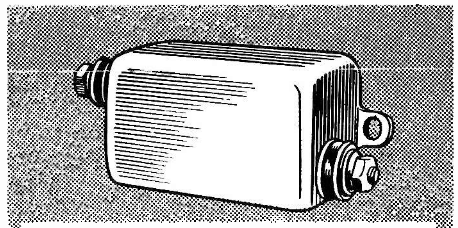


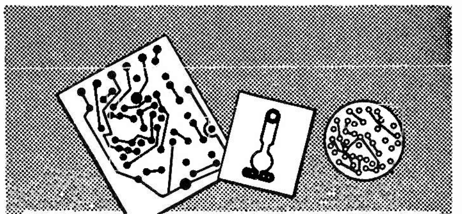












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Electronic Oscillators

Part 1

By the Engineering Department, Aerovox Corporation

IN the past 25 years of progress, probably no other basic electronic circuit has increased its scope and versatility as much as the vacuum tube oscillator. Practically every radio receiver contains at least one oscillator, and TV receivers normally contain three. Every transmitter must contain a carrier-generating and frequency-controlling oscillator, and special types (such as those employing single sideband output) employ several in many cases. The wide use of oscillators in test equipment, such as audio and radio frequency signal generators, frequency meters, grid-dip meters etc., and in magnetic recorders is well known.

The engineer, service technician, amateur and experimenter are thus vitally affected by the operation of oscillators in general, and important commonly-used types in particular. The object of this article, and those to follow in this series, is to review important fundamental concepts and design factors, and their application to every-day use of oscillators.

Definition of an Oscillator

An oscillator is any device which can be induced into cyclic repetitive action. Mechanically, an example is the clock pendulum; its electrical counterpart is a tuned resonant circuit. In both cases, the period of each cycle, and thus the frequency of oscillation is controlled, but energy must be added to overcome the loss in the device if sustained oscillations are to be obtained. Since we are primarily interested in sustained oscillations without damping, a complete oscillator must have two main parts: a frequency-controlling device which is usually a resonant circuit, and another part which applies energy to the frequency-controlling device in the proper manner to sustain oscillation. The latter is usually an amplifier.

The Institute of Radio Engineers defines an oscillator as

> A non-rotating device for producing alternating current, the output frequency of which is determined by the characteristics of the device. (Standards on Antennas, Modulation Systems and Transmitters, Definitions of Terms — IRE 1948.)

This definition is broad enough to cover all electrical oscillators. We are concerned here with the *electronic oscillator* which is an electrical oscillator employing one or more vacuum tubes.

An electronic oscillator requires input energy to overcome tube and circuit losses and to supply the required output power. This input energy it obtains by means of electrical energy or from the plate power supply, and indirectly from the heater or filament current to the tube. Basically, it can be considered a *converter* more properly than a generator, since it connects electrical energy from one frequency to another usually higher than the input frequency.

Negative Resistance Requirement

For oscillation, energy must flow from the output (usually the plate) circuit to the input circuit (usually the grid) in such magnitude and phase as to overcome the losses of the system. But the basic amplifying action of a vacuum tube is to produce plate voltage which is approximately (exactly with a resistance load) 180 degrees out of phase with the grid voltage which produces it. Part of this output voltage must be applied to the grid circuit in phase with the grid voltage. This is done by reversing the phase (either actually or effectively) of that part of the plate voltage fed back to the grid circuit.

When this condition exists the network develops a *negative resistance* in the circuit. In a negative resistance, the current increases as the voltage decreases; thus the current and voltage changes are out of phase 180 degrees.

There are three main ways in which a negative resistance can be provided in vacuum tube circuits for oscillation:

(1) By actually transmitting a desired portion of the output signal voltage to the input circuit in a feedback circuit which reverses the phase.

(2) By the design of a tube, or the adjustment of the applied poten-

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tials to the tube, so that it exhibits a negative resistance characteristic.

In this article, we will concern ourselves with the basic functional factors in types 1^a and 1^b. Type 2 will be considered later in a separate article.

A—*Inductively*

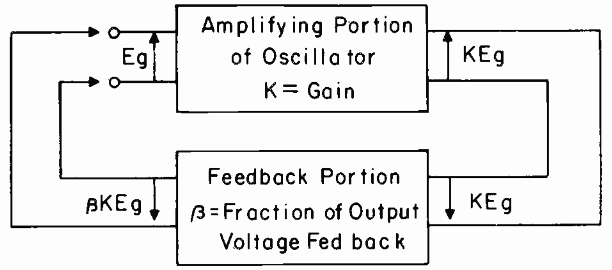
B—*Capacitatively, through the grid-plate capacitance or external capacitance*

Criterion For Oscillation

In the consideration of any given oscillator circuit, it is important to know under what conditions of circuit design and adjustment oscillation will take place, as these conditions are limited.

For any oscillator of the feedback type, the Barkhausen criterion of Fig. 1 is applicable. This figure shows the oscillator broken up into its two basic parts, the amplifier and the feedback link. The input voltage to the amplifier E_G is the voltage fed back through the feedback circuit. This simple derivation shows that the fraction of the output voltage which is fed back (B), must be equal to the reciprocal of the gain. Both of these factors are complex, because both the amplifier and the feedback circuits do, in general, introduce phase shifts. For oscillation, the phase shifts must cancel.

Equations 2 and 3 apply the criterion to a grounded-cathode amplifier. This expression is general, and can be applied to any particular circuit by evaluating load impedance and B in terms of the circuit parameters involved and substituting them in the general expression equation 3.



For sustained oscillation: $Eg = \beta KEg$

[Eq 1] or $\beta K = 1$ and $\beta = \frac{1}{K}$ (Barkhausen Criterion)

Let Z = eff. plate load impedance (with feedback network)

[Eq 2] Then, in general, $K = \frac{-\mu Z}{r_p + Z}$

[Eq 3] and $\beta = \frac{1}{K} = -\left(\frac{1}{\mu} + \frac{1}{g_m Z}\right)$ (K and β are usually both Complex)

BARKHAUSEN CRITERION FOR OSCILLATION

FIGURE 1

Inductive Feedback Circuits

From a theoretical standpoint, probably the most *dirεct* method of providing negative resistance for oscillation is by mutual inductance between coils in the plate and grid circuits respectively. The two most common circuits of this type are illustrated, along with their equivalent circuits, in Fig. 2 and 3 respectively. It will be noted that they differ only in the choice of which circuit is tuned.

These circuits can be analyzed either by setting up simultaneous equations equating the voltages around each loop, or by substituting appropriate expressions for Z and B in eq 3. For these circuits one method is about as easy as the other. The solution in each case results in an equation containing complex quantities. Equating the imaginary (j) terms provides an expression for the actual frequency of oscillation compared to the resonant frequency of the tuned circuit. Equating the real terms gives a relation showing the conditions necessary for oscillation. The detailed steps of the analysis are available in the literature, [6, 7] and will thus not be repeated here. The results are as follows:

As might be expected, the expressions have similar forms for the two circuits. However, one interesting difference is that in the tuned grid circuit the frequency of oscillation is lower than the tuned circuit resonant frequency (Eq. 4) while in the tuned plate oscillator it is higher (Eq. 7).

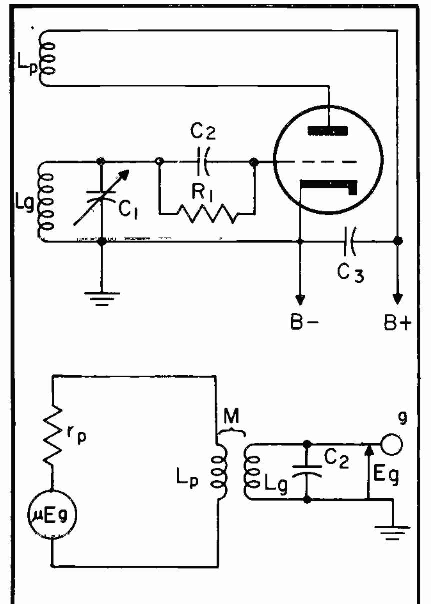
Tuned Grid Oscillator

$$\omega = \frac{\omega_o}{\sqrt{1+A}} = \frac{1}{\sqrt{L_pC(1+A)}} \quad \text{[Eq.4}$$

$$M \approx -\frac{A}{1+A} \quad \frac{L_p}{\mu} - \frac{CR}{qm} \quad \text{[Eq.5}$$

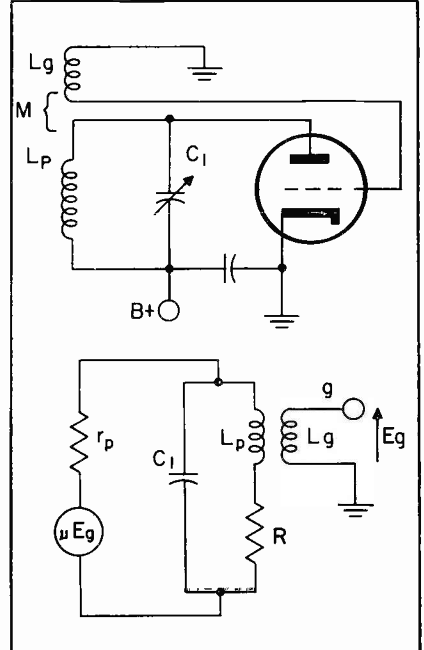
$$gm = -\frac{A}{1+A} \quad \frac{L_p}{Mr_p} - \frac{CR}{M} \quad \text{[Eq.6}$$

Where $A = \frac{L_pR}{L_g r_p}$ and $\omega = 2\pi \times$ actual osc freq, $\omega = 2\pi \times$ resonant freq of tuned cicuit



TUNED GRID FEEDBACK CIRCUIT

FIGURE 2



TUNED PLATE FEEDBACK CIRCUIT

FIGURE 3

Tuned Plate Oscillator

$$\omega = \omega_o\sqrt{1+\frac{R}{r_p}} = \sqrt{\frac{r_p+R}{L_pC}} \quad \text{[Eq7}$$

$$M = -\frac{L_p}{\mu} - \frac{CR}{gm} \quad \text{[Eq8}$$

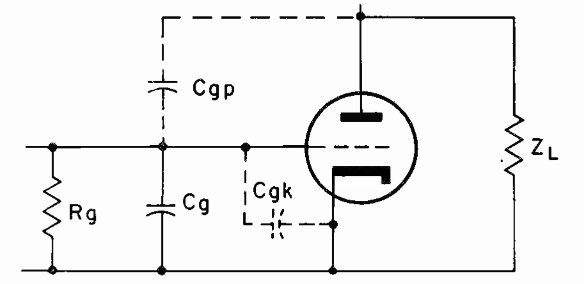
$$gm = -\frac{L_p}{Mr_p} - \frac{CR}{M} \quad \text{[Eq9}$$

These frequency equations are useful primarily in a qualitative way; quantitatively since w is ordinarily very close to Wo, the values of L and C are usually adjusted at least partly by empirical means, starting with values which by themselves resonate at the frequency of oscillation. But these expressions are important in indicating the direction of frequency change with change of Q and external loading.

In comparing the two circuits, the expression A is signicant. Because the feedback "tickler" coil L_P in the tuned grid circuit is usually much smaller than L_G and R is very much smaller than r_P, the value of A is for less than 1. Because of the presence of the ratio of inductances in A, and the fact that the plate coil is normally much smaller than the grid coil in the tuned grid circuit, it will be noted that the frequency of this circuit is less sensitive to changes in R (and thus Q) than in the tuned plate circuit. Also, in the expressions for M and g_M, the plate inductance appears in the numerator of the first fraction for both oscillators. Accordingly, since the plate inductance is relatively much smaller in the tuned grid circuit, the latter will oscillate with smaller values of M and g_M than will the tuned plate circuit.

In addition to the above-mentioned relative disadvantages, the tuned plate circuit requires of its designer that he make the unpleasant choice between (1) having plate d-c voltage applied to the coil and capacitor with series feed or (2) adding an r-f choke, with its added expense and danger of self-resonance somewhere in the tuning range, with shunt feed. On the other hand, in the tuned grid circuit, the plate coil is aperiodic, isolated from tuning adjustments, is easily insulated and adapts itself nicely to series feed, which is always used.

In defense of the tuned plate circuit, it should be said that it is less sensitive to power supply voltage variations. This arises from the fact that space-charge capacitance, a function of plate voltage, is greater between grid and cathode than between plate and cathode. The space-charge effect is thus greater upon the frequency when the frequency-determining circuit is connected to the grid than when it is connected to the plate.



[Eq 10] $Rg = \frac{1}{\omega C_{gp} K_i}$ K = amplification = $K_r + jK_i$

[Eq. 11] $Cg = Cgk + (1 - K_r)\,Cgp$

INPUT IMPEDANCE OF A TRIODE

FIGURE 4

It is important to note some of the assumptions made in the derivation of the equations 4 through 9. First, the effect of rectified grid current, present in nearly all oscillators, has been neglected. The vacuum tube and its circuit has been considered as a linear device, whereas ordinarily it must be non-linear for oscillator operation. However, this is not too bad an assumption. Nowadays, the power oscillator is a thing of the past except in special applications, and the usual circuit is designed for stability and flexibility. For the attainment of the best stability, the grid current must be kept relatively low, making the equations nearly valid.

Another assumption in the analysis of the inductive feedback oscillators is that grid-plate capacitance is negligible. This is a reasonable assumption, since, although it does add a certain amount of loading effect to the input circuit, this capacitance does not materially affect the action of the inductively-coupled feedback.

In general, an advantage of inductively-coupled feedback oscillators is that M provides a convenient parameter for adjustment of operating characteristics by adjustment of the size of the feedback coil and its physical position. A general disadvantage in multi-range circuits is that bandswitching is complicated by the additional coil terminals.

Capacitive Feedback Circuits

Under certain conditions, a deliberate circuit feedback path is not necessary for the support of oscillations. One common instance of this is the regenerative effect, especially in triodes, of the grid-plate capacitance. This effect becomes evident upon examination of the expression for the input resistance of a triode. Figure 4 illustrates the input impedance, which includes, in general, both a resistive and a capacitive component. The values of these depend upon the nature and magnitude of the plate load impedance as well as the grid-plate capacitance. When the plate load is a pure resistance, the resistive component of input impedance becomes infinite and the input impedance becomes a pure capacitance. (Amplification K depending upon plate load impedance.)

However, when the plate load impedance becomes inductive, and K_I becomes negative. the input resistance becomes negative. If the negative resistance exceeds grid losses, oscillation can take place. Thus a simple amplifier can become an oscillator if the plate load is inductive and the grid-plate capacitance is sufficient. As can be seen from Eq. 10, the frequency, grid-plate capacitance, and phase shift of gain are all interrelated in determining whether the input resistance is to be negative and oscillations will take place.

As in our previous discussions of inductive feedback oscillators, the effect of grid current is neglected and the tube is assumed to be a linear device, both permissable for most practical oscillators. It is also assumed that grid-plate capacitance has negligible effect on the gain.

About the only common type of oscillator depending primarily upon grid-plate capacitance for oscillation is the tuned-plate-tuned-grid type illustrated in Fig. 5, with its equivalent circuit. In essence, it is simply a tuned-circuit amplifier adjusted to oscillate. Sometimes an external capacitor is connected between plate and grid; its purpose would be either to increase feedback at low frequencies or to improve stability by reducing the effect of variations in the grid-plate capacitance.

From the equivalent circuit it will be noted that the feedback coupling is the result of the fact the grid circuit and the grid-plate capacitance are connected in series across the plate signal voltage.

As was explained above, this type of circuit will oscillate if the plate load is inductive. Since the plate load here is a parallel tuned circuit, the resonant frequency of this tuned circuit must be made *higher* than the expected frequency of oscillation. The net reactance of the parallel combination is then inductive as desired. It can also be shown that the grid tuned circuit must be tuned to be inductive, but slightly less inductive than the plate circuit.

The basic effective setup can perhaps be more clearly visualized by substituting inductances of the effective values for the two resonant circuits respectively, as illustrated in Fig. 6. It can be seen that for steady-state oscillation conditions, the effective inductances of the two tuned circuits and the grid-plate capacitance must resonate at the oscilltion frequency.

The tuned-plate-tuned-grid oscillator has the disadvantage of depending upon the grid-plate capacitance of the tube for a vital part of its operation. Its stability of frequency is thus affected by the thermal and other causes of variation of this factor. Besides, the fact that the grid-plate capacitance is fixed causes the degree of feedback to vary in an undesirable manner when an appreciable frequency range is to be covered. These difficulties, added to the inconvenience and expense of providing two tuned circuits, are undoubtedly the reasons that this circuit is not often encountered.

A slight varation of the tuned-plate-tuned-grid circuit is the "TNT" version, in which the principle is the same, but the grid circuit is adjusted to its proper effective inductance by the distributed capacitance of the grid coil, instead of the grid capacitor. Although this eliminates the need for one capacitor, this circuit still retains all the other disadvantages of the tuned-plate-tuned-grid circuit.

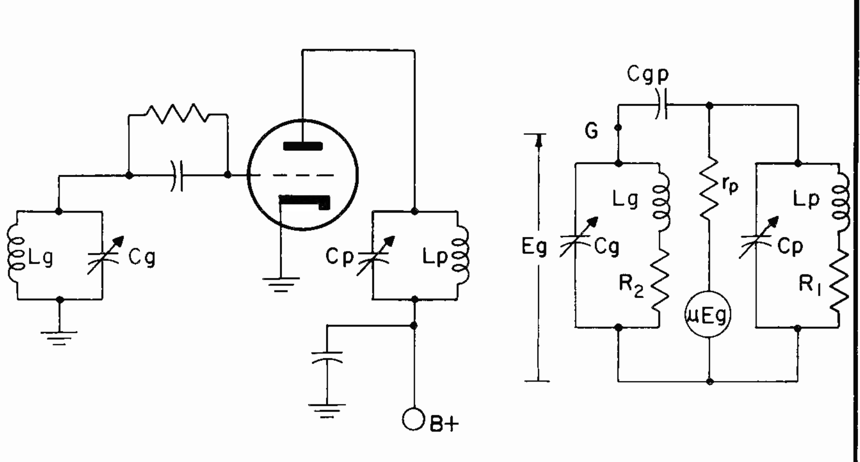
Tuned-Circuit Feedback

Other types of oscillators do not employ either inductive or capacitive feedback in the manner described above, but derive the feedback phase and amplitude relation from a tuned circuit. This tuned circuit is ordinarily the same one which determines the frequency of oscillation.

Probably the best-known example of this type is the Hartley, illustrated with its equivalent circuit in Fig. 7. The tuned circuit is divided into two parts by the cathode tap. Grid and plate signal voltages of opposite phase are then obtained from the two ends, respectively, of the resonant circuit.

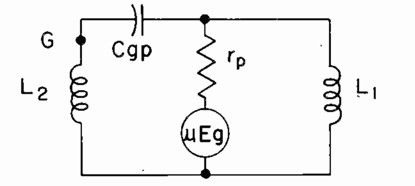
By analysis of the equivalent circuit in the same manner as for the inductive-feedback circuit earlier in this article, the following relations are obtained:

Note that the frequency relation Eq. 12 is the same as that for the tuned plate oscillator (Eq. 7) except that in this case it is the resistance of the plate section of the coil, instead of the total resistance of the coil, which influences frequency of operation. Thus it would be expect-



TUNED PLATE TUNED GRID CIRCUIT

FIGURE 5

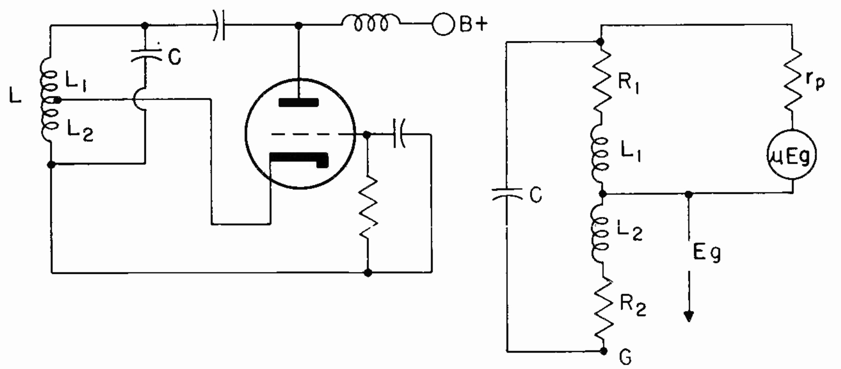


L_1 = Effective inductance of plate tank

L_2 = " " " grid "

SIMPLE EQUIVALENT OF TUNED PLATE TUNED GRID CIRCUIT

FIGURE 6



HARTLEY OSCILLATOR

FIGURE 7