SECTION 7

OSCILLATOR CIRCUITS

PART A. ELECTRON TUBE CIRCUITS

L-C OSCILLATORS.

The L-C type of oscillator uses a tuned circuit consisting of lumped and distributed inductance and lumped and distributed capacitance connected as a series or parallel resonant (tank) circuit to determine the frequency of operation. Series resonant tanks are sometimes, but not often, used depending on the oscillator circuit selected. Operation is normally in the radio-frequency range (operation in audio range may occasionally be used). Oscillation is achieved by the application of positive (regenerative) feedback from plate (or any other element) to grid through external or internal capacitance or inductive coupling, depending upon the particular circuit configuration.

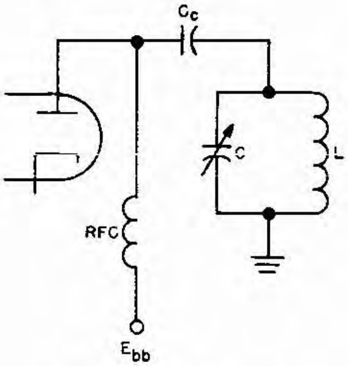
Class C operation is usually employed for power oscillators, and Class A operation is used for test equipment oscillators where waveform linearity is important. Class B operation is normally not used, but may occasionally be encountered.

Efficient circuit operation and maximum frequency stability are achieved with a tank circuit having a high loaded Q (this is equivalent to low Q, or high C to L ratio). This is produced for parallel-tuned tanks by using a large tuning capacitance (high C) with a small inductance. For series-tuned tanks a high L to C ratio is used to achieve the same effect. Normally the inductance of the tank circuit remains fixed, and the capacitance is the variable tuning element. Inductive tuning may be encountered, particularly in the low- and very-low-frequency r-f ranges.

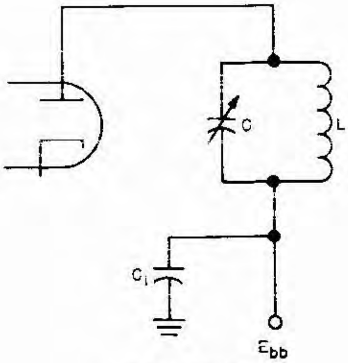
Grid-leak bias is generally used for self-excited oscillators and may be either shunt or series (see Section 2, paragraph 2.2.2), with the series form predominating. Either shunt or series type plate feed is employed, with shunt feed being used for those applications where it is desired to isolate the tank circuit from dc. Generally speaking, oscillator operation is basically independent of the type of bias or method of plate feed. For design purposes the oscillator is considered as a Class C amplifier with a feedback loop, operating at the same voltages and currents as an amplifier, but with a lower over-all power output because of feedback and circuit losses.

Although there are a number of types of L-C oscillators, and each type has a particular advantage or feature claimed for it, they are usually all operable over the range for which tuned circuits can be developed. Therefore, their ranges of operation many times overlap, and the particular circuit used may be selected only because of the designer's preference or previous familiarity with the circuit. In addition to the constant frequency, and thermal and mechanical considerations afforded by the tank circuit, the plate resistance and amplification factor of the tube used, plus tube element capacitances and stray wiring capacitances, determine the oscillator performance to a great extent. Most circuits can be arranged so that the tuning element can be grounded to prevent hand capacitance effects, although it may be mechanically or economically unfeasible to use some of these circuits.

The figure shows both series and shunt plate-voltage feed arrangements. The series feed arrangement is easily recognized by the fact that the plate voltage is applied through the tank circuit. Capacitor C_1 bypasses the tank to ground for rf, so one end of the tank is at r-f ground potential, and the tuning capacitor is effectively grounded to eliminate hand capacitance effects. The tank, however, is at full d-c (and r-f) potential and dangerous if touched (for high applied voltage). The identifying characteristic of the shunt feed arrangement is that the plate of the tube is connected to B+ through an r-f choke, and coupled through C_c to the tank. Effectively, the tank is isolated from dc, but is coupled for rf. In most shunt-feed circuits the tank capacitor can be grounded directly rather than through a bypass capacitor. Usually shunt feed is avoided where a large range of frequencies is to be covered (particularly at the higher frequencies) because of parasitic oscillations, or dead spots, resulting from unwanted resonances of the r-f choke and tube or wiring capacitances.



SHUNT FEED



SERIES FEED

Methods of Plate-Voltage Feed

TICKLER-COIL OSCILLATOR.

APPLICATION.

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The L-C tickler-coil oscillator is used to produce a sine-wave output of relatively constant amplitude and fairly constant frequency within the r-f range. The circuit is generally used as a local oscillator or beat-frequency oscillator in a superheterodyne receiver.

CHARACTERISTICS.

Utilizes an L-C tuned grid circuit to establish the frequency of oscillation. Feedback is accomplished by mutual inductive coupling between the tickler coil and the L-C tuned grid circuit.

Operates Class C with automatic self-bias.

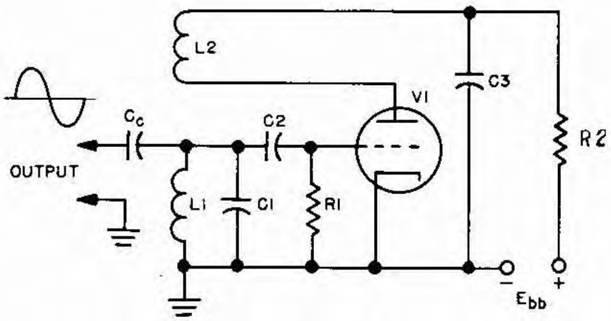
Frequency stability is fair.

Output amplitude is relatively constant.

CIRCUIT ANALYSIS.

General. Oscillations of a tuned circuit will tend to die out at an exponential rate and will finally cease, unless energy is replaced at regular intervals. For oscillations to be sustained, sufficient energy must be supplied to overcome circuit losses. The use of an electron tube as an amplifier provides the additional energy necessary to sustain oscillations. The energy applied to the tuned circuit must be of the correct phase relationship to aid the initial oscillations and of sufficient amplitude to overcome circuit losses in the tuned circuit.

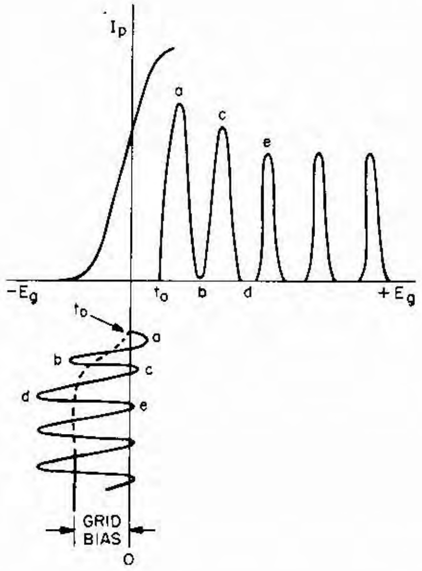
The circuit used to provide this type of feedback is called a **regenerative circuit**, and the energy supplied is called **positive feedback.** In the accompanying circuit schematic the tuned L-C circuit is designated as L1, C1; the tickler (feedback) coil is designated as L2.



L-C Tickler-Coil (Armstrong) Oscillator

Circuit Operation. The accompanying circuit schematic illustrates a triode electron tube in an L-C tickler-coil oscillator circuit. Inductance L1 and capacitor C1 form the resonant grid circuit. Inductance L2 is the plate, or tickler, coil and is mutually coupled to L1, to couple a feedback voltage to inductance L1 by transformer action. Capacitor C2 and resistor R1 form an R-C circuit which is used to develop the operating bias. Capacitor C3 functions as an r-f bypass to place the B+ terminal of tickler coil L2 at signal ground potential. Resistor R2 isolates the B+ line from the r-f signal and also serves to reduce the input voltage applied to the oscillator circuit. Capacitor C_c is the output coupling capacitor.

For the following discussion of circuit operation, refer to the accompanying illustration of oscillator grid-signal voltage and plate-current waveforms.



Theoretical Grid-Voltage and Plate-Current Waveforms

Initially the tube is at zero bias (t_o on waveform illustration) to permit the circuit to be self-starting. When input power is applied to the circuit, the tube conducts because of the lack of operating bias. As the plate current increases through tickler coil L2, an expanding magnetic field is built up around the tickler coil. This expanding field causes an increasing voltage to be induced in inductance L1 of the tuned circuit, and this voltage is of such polarity that the grid of V1 is made positive with respect to the cathode. The positive grid condition increases the flow of plate current, which further increases the field about tickler coil L2; consequently, the voltage induced in inductance L1 increases and the grid is driven further in the positive direction. This process continues until saturation is reached, at which time no further increase in plate current can take place (point **a** on waveforms).

During the period of time that a charging voltage is induced in inductance L1, capacitor C1 charges to maximum; also, capacitor C2 receives a charge as the result of grid-current flow through the low internal cathode-to-grid resistance of the tube.

When the plate current reaches saturation, a steady (unchanging) magnetic field is produced about tickler coil L2, and, as a result, a voltage is no longer induced in inductance L1. With no induced voltage present, capacitor C1 begins to discharge through inductance L1, and capacitor C2 begins to discharge through resistor R1 (and L1). The positive voltage on the grid of V1 decreases as capacitor C1 discharges through inductance L1, and this decrease in the grid voltage causes the plate current to decrease below the saturation value. The decrease in plate current through tickler coil L2 causes the magnetic field about the tickler coil to decrease and start to collapse, and thus causes an increasing voltage to be induced in inductance L1. However, the polarity of the induced voltage is reversed from that originally induced in L1 when the magnetic field about tickler coil L2 was expanding. Hence, the induced voltage causes the grid of V1 to be driven negative with respect to the cathode, and the plate current is further decreased, causing the magnetic field about tickler coil L2 to collapse completely. As this occurs, the grid of V1 becomes increasingly negative until a value is reached which prevents any further decrease in plate current (point **b** on waveforms). (The voltage induced in L1 during this time also aids the discharge of C1.)

At this instant, capacitor C2 starts to discharge through resistor R1 (and L1), decreasing slightly the negative potential existing between the grid and cathode of V1. Also, capacitor C1 discharges through inductance L1, producing an expanding magnetic field about inductance L1; when capacitor C1 is completely discharged, the magnetic field begins to collapse. The collapsing magnetic field about inductance L1 again produces a voltage across the inductance which charges capacitor C1 and also drives the grid of V1 in a positive direction. As the grid of V1 becomes positive with respect to the cathode, plate current begins to flow through tickler coil L2. The magnetic field produced about tickler coil L2 again increases and induces a voltage in inductance L1, which drives the grid still further into the positive condition. Grid current again flows through the internal cathode-to-grid resistance of the tube to produce a negative charge on capacitor C2. Plate current again rises to maximum, at which time no further increase in plate current can take place (point **c** on waveforms).

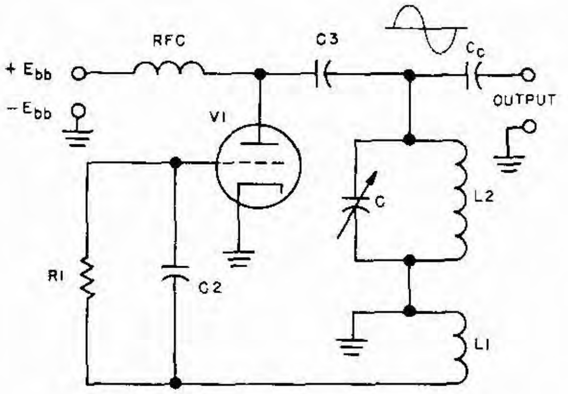
The entire process repeats as described above, with the bias voltage continuing to build up across capacitor C2 until a steady value of Class C bias, effectively across resistor R1, is reached. The interchange of energy at the resonant-frequency rate between inductance L1 and capacitor C1 of the tank circuit maintains the oscillations during the period of time that plate current is cut off and no energy is supplied to the tuned circuit through the tickler-coil feedback circuit.

As oscillations build up, the maximum signal across the resonant circuit becomes increasingly greater. Note that the grid-leak and capacitor combination, R1 and C2, is used to develop the operating bias, to permit Class C operation of the tube. When the circuit is placed in operation, a stable operating point is quickly reached where the positive signal peaks are of sufficient amplitude to cause grid current to flow and to charge the grid capacitor, C2. Momentarily, when the signal is less positive, grid current ceases to flow, and capacitor C2 discharges slowly through grid-leak resistor R1. Since the value of R1 is large, only a small amount of charge is lost by capacitor C2 before the signal again is sufficiently positive to cause the grid to again draw current. As a result of this automatic charge-discharge action, an average value of negative bias, approximately the value to which capacitor C2 is being charged, is developed across R1, between the grid and cathode. Whenever the signal amplitude tends to increase, additional grid current flows through the internal cathode-to-grid resistance of the tube, and, therefore, capacitor C2 is charged to a higher value. Consequently, the bias voltage also increases, and the resulting effect is to decrease the gain of the tube. As the gain of the tube decreases, the output-signal level also decreases and returns to approximately its original amplitude. Similarly, when the signal amplitude tends to decrease, there is a decrease in bias voltage and an accompanying increase in the gain of the tube. As the gain of the tube increases, the output-signal level also increases and returns to its original amplitude. Thus, through the regulating action of grid-leak bias, the circuit operation is stabilized, and the amplitude of the output is held essentially constant.

The oscillator output frequency is determined primarily by the values of inductance L1 and capacitance C1 at resonance ($f_0 = \frac{1}{2\pi\sqrt{LC}}$), although interelectrode capacitances of the electron tube and distributed capacitances and inductances of the circuit also have an effect upon the oscillator frequency. In most circuits a variable capacitor is used to change the frequency; however a variable inductance can be used with a fixed capacitor to accomplish the same purpose.

The oscillator output, which is taken from the tuned circuit, is generally capacitively coupled (C_c) to the associated load circuit; however, inductive coupling may also be used with the output coupling coil being mutually coupled to L1 near its ground end.

Tuned-Plate Version. The circuit description above covered the basic Armstrong circuit, in which the tank coil is in the grid circuit (tuned grid) and the tickler coil is in the plate circuit. Another circuit version in which these conditions are reversed is called the tuned-plate circuit. In this circuit, the tank is in the plate circuit and the tickler (feedback) coil is in the grid circuit. The operation of this oscillator is identical to that of the tuned-grid circuit, except for limitations imposed by coupling between the plate and grid. This coupling limits the range of oscillation in the tuned-grid version, but not in the tuned-plate version. Actually, the tuned-plate oscillator is considered less susceptible to frequency changes caused by power supply voltage changes than the tuned-grid oscillator. The schematic of the tuned-plate circuit is shown in the following illustration.

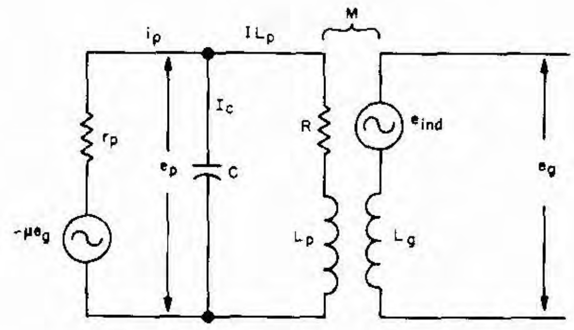


Tuned-Plate Armstrong Oscillator

The parts in the tuned-plate oscillator are labeled the same as in the illustration of the tuned-grid oscillator, for comparision. The differences are the use of shunt plate feed in the tuned-plate circuit instead of what is essentially series plate feed in the tuned-grid circuit and the use of series grid-leak bias instead of shunt grid-leak bias. Actually, the use of shunt or series feed does not change the method of operation; it merely illustrates possible circuit variations. Grid-leak components R1 and C2 operate in the same manner as described for the tuned-grid version, and C3 is a plate blocking and coupling capacitor instead of an r-f bypass. Note that plate dropping resistor R2 is replaced by radio-frequency choke RFC, which keeps the r-f from being shunted to ground via the power supply filter capacitors. When the circuit is energized, the flow of plate current produces tank circuit variations through L2, and an in-phase voltage is fed back through grid (tickler) coil L1 to sustain feedback exactly as described under L-C circuit operation for the tuned-grid circuit previously discussed. The grid leak formed by R1 and C2 controls the amplitude and grid bias.

Detailed Analysis. Since the oscillator is considered to be a Class C amplifier with a feedback loop, a rigorous mathematical analysis is complex because the circuit operation is inherently non-linear. The analysis can be greatly simplified by using the equivalent plate circuit, together with a few assumptions. This method of analysis is helpful in determining the conditions necessary to produce sustained oscillations and in determining the basic frequency of oscillation. With this approach, it is customary to neglect the flow of grid current, but to bear in mind that its effect must be considered and the final results modified to take the grid current into account. Actually, losses due to grid current can be treated as an equivalent loss in the tuned circuit.

The a-c equivalent circuit for the tuned plate oscillator is shown below. Assuming that the currents are sinusoidal and neglecting grid current flow, Kirchhoff's laws and Thevenin's theorem can be applied to this circuit to obtain the limiting parameters that determine oscillation and frequency.



Tuned Plate Equivalent Circuit

Mathematical analysis of the equivalent circuit for the tuned-plate oscillator shows that the critical value of coupling is:

$$M = \frac{L_p + CRr_p}{\mu} \qquad (1)$$

which gives the minimum value that M can have and still allow the circuit to oscillate. To satisfy this condition, M must be positive and:

$$g_m = \frac{RC}{M} + \frac{L_p}{Mr_p} \qquad (2)$$

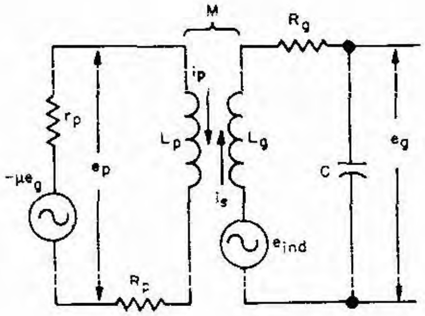
Thus, the coupling between grid and plate coils must exceed the minimum value indicated in equation (1), and must have the sign to produce a positive grid voltage component when I_{L_p} is increasing (this is the condition required for regenerative feedback). The frequency of oscillation is determined by:

$$\omega = \sqrt{\frac{R + r_p}{L_p C r_p}} = \omega_0 \sqrt{1 + \frac{R}{r_p}} \text{ or } f = \frac{1}{2\pi\sqrt{LC}} \cdot \sqrt{\frac{R + r_p}{r_p}}$$

It is evident from (3) that the frequency of oscillation is affected to some extent by the resistance of the load, as well as the plate resistance of the tube. With $r_p >> R$ to provide better frequency stability (which condition normally exists), we can say that for all practical purposes,

or $f = \frac{1}{2\pi\sqrt{LC}}$, where C includes all of the stray and distributed capacitance that tunes L_p.

A similar analysis of the tuned-grid circuit can also be made by using the equivalent circuit shown below.



Tuned-Grid Equivalent Circuit

In this instance it can be demonstrated that the requirement for oscillation is:

$$g_m = \frac{RC}{M} + \frac{M}{L_p r_p} \qquad (4)$$

Since the quantity M appears in the denominator of one term and in the numerator of the other, the value of g_m is large for both high and low values of M, with a minimum value existing somewhere between. This is to say that in the tuned-plate circuit, while there is a critical value of coupling below which oscillation will not occur, there is no limit to the maximum value of coupling; although plate current and output may be reduced as a consequence, oscillation will still occur. For the tuned-grid circuit there exists both a lower and an upper limit; thus if the value of coupling is too low or too high, the circuit will not oscillate. This upper limit on M could be a practical disadvantage; however, it appears to be of academic interest, since it is only true for large values of L_p and C. That is, it actually applies only to low r-f or audio frequencies. At the higher radio frequencies the effect of tube capacitance and distributed circuit capacitance makes the value of M required to satisfy this condition so high that it is impractical or impossible to obtain. Thus, although there is a difference between the plate- and grid-tuned circuits, theoretically, it is of no practical consequence.

The frequency of oscillation for the tuned-grid oscillator is given as:

$$f = \frac{1}{2\pi\sqrt{\dfrac{C\,(L_g r_p + L_p R_g)}{r_p}}} \qquad (5)$$

From this expression it may be seen that if R_g is very small as compared with r_p, the quantity $(L_g r_p + L_p R_g)$ is nearly identical with $L_g r_p$. Equation (5) may then be rewritten as:

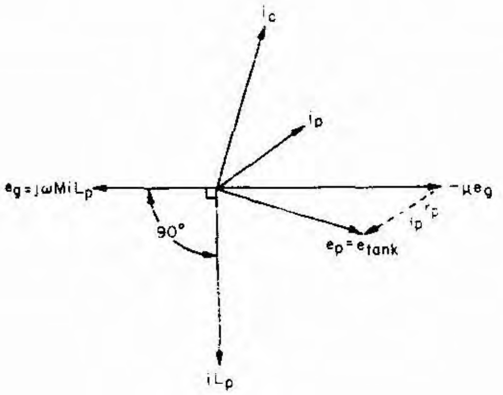
$$f \cong f_o = \frac{1}{\sqrt{2\pi \quad L_g C}} \qquad (6)$$

The tuned-grid circuit is similar to the tuned-plate version in that the ratio rp/R should be as large as possible for good frequency stability. One other fact may readily be seen if equation (5) is rewritten as:

$$f = \frac{f_o}{\sqrt{1 + \dfrac{L_p R_g}{L_g r_p}}} \qquad (7)$$

where f_o is the same as in equation (6).
Since the operating frequency of the oscillator is equal to the tank resonant frequency divided by a number slightly greater than unity, the operating frequency is slightly less than the natural resonant frequency of the tank circuit. On the other hand, the tuned-plate version has a higher frequency of oscillation than its tank circuit, as shown by equation (3). Thus, at the operating frequency, the tuned-grid tank appears as an inductive reactance, and the tuned-plate tank appears as a capacitive reactance (neglecting the effect of resistance, which is of academic interest only).

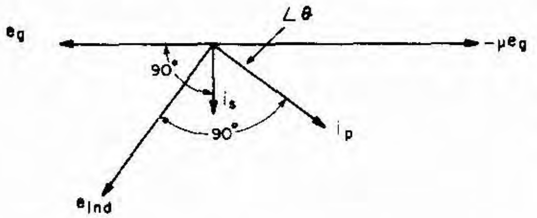
Vector Diagram. It is sometimes more helpful to use vectors to show the relationships of the various currents and voltages in the circuit. The figure below shows the vector diagram for the tuned-plate circuit. In this figure,



Tuned-Plate Vector Diagram

The voltage $-\mu e_g$ is used as a reference. e_g is about 180° out of phase with $-\mu e_g$, as indicated by the negative sign preceding the real quantity $-\mu e_g$. The direction of i_{LP} may be established from the fact that e_g (the voltage induced in L_g) equals $-j\omega M i_{LP}$, and must lag i_{LP} by 90° because of the -j coefficient. Similarly, it can be seen from the a-c equivalent circuit, that i_{LP} will lag e_p by something less than 90° because of the resistance R in series with the coil. The amount of phase difference between e_p and i_{LP} will depend on the Q of the coil, being closer to 90° with higher values of Q ($\omega L/R$). This makes e_p lag $-\mu e_g$ by some small angle, which is dependent on the circuit Q. i_C, since it is considered purely capacitive, will lead e_p by 90°. The vector sum of $i_p r_p$ and e_p must equal $-\mu e_g$. For this to be true, $i_p r_p$ must lead $-\mu e_g$ by some small amount, and since the current through a resistance is in phase with the voltage drop across it, i_p may be shown as leading $-\mu e_g$. Thus with i_p having a leading phase angle, the tuned plate circuit is shown to be capacitive as was also proven in the mathematical analysis. Note that i_p is the vector sum of i_C and i_{LP}; therefore, i_C must be the larger quantity.

The tuned grid circuit may be similarly represented by means of a vector diagram as shown below:



Tuned-Grid Vector Diagram

As with the tuned-plate oscillator, the vector representing the voltage $-\mu e_g$ is used as a reference; e_g is again shown displaced 180° from $-\mu e_g$. Since the plate circuit is inductive and resistive in nature, plate current i_p will lag $-\mu e_g$ by a small angle, θ. This angle will be small because $r_p >> j\omega L_p$. The voltage induced in the secondary circuit, e_{ind}, will lag i_p by 90° since e_{ind} equals $-j\omega M i_{LP}$. The voltage e_{ind} may be represented by a generator in series with the grid circuit. It was shown in the mathematical analysis that the oscillator operates slightly below the tank frequency; therefore, the capacitive reactance of C will be slightly larger than the inductive reactance of L_p. Viewing the grid circuit as a series circuit in relation to e_{ind}, it is seen that the secondary current (i_s) is slightly capacitive and will lead e_{ind} by a small angle. Since grid voltage e_g is the same as capacitor voltage e_C, it will lag current i_s through the capacitor by 90°. From inspection of the vector diagram, it can be seen that angle θ is the same as the angular difference between e_{ind} and i_s. Higher values of circuit Q will tend to diminish this angular difference, thus diminishing angle-θ and improving the stability of the oscillator.

FAILURE ANALYSIS.

No Output. If the circuit is in a non-oscillating condition, negative grid bias will not be developed; as a result, the applied plate voltage will be below normal because of the passage of additional current through the dropping resistor, R2. Excessive circuit losses present in the resonant circuit or the tickler (feedback) coil will prevent sustained oscillations. Reduced tube gain will also affect stage regeneration; changing values of the grid-leak bias components, R1 and C2, will directly affect the operating bias and, hence, the Class C operation and gain of the tube.

Reduced or Unstable Output. A relative indication of oscillator output is provided by the amount of bias voltage developed across R1. This negative bias voltage is normally from 2 to 40 volts, depending upon circuit design and the applied plate voltage.

A reduction in the applied plate voltage will cause the output to be reduced. An unstable voltage source will cause the output to be unstable in amplitude, and may also produce some frequency instability. Losses in the tickler (feedback) coil, due to shorted turns or poor soldered connections, can cause reduced output or unstable operation resulting from changes in amplitude of the feedback signal coupled into the resonant circuit (L1, C1).

Incorrect Output Frequency. Normally, a small change in output frequency can be compensated for by realigning or adjusting the variable component of the L-C resonant circuit, assuming that all component parts of the circuit are known to be satisfactory. Since L1 and L2 are mutually coupled, any change in inductance of one coil will have an effect upon the inductance of the other. Thus, if several turns of tickler coil L2 should become shorted, the resonant frequency of L1, C1 will likely be affected and the output frequency will change. This condition is also likely to reduce the oscillator output, since L2 is the means by which feedback or regeneration is accomplished. Furthermore, changes in distributed circuit capacitance, changes in the value of output coupling capacitor C4 and its associated circuit load, or changes in the value of r-f bypass C3 will produce a change in the resonant frequency of L1, C1; thus, the output frequency will depend upon the amount of reactance reflected into the tuned circuit (L1, C1).

HARTLEY OSCILLATOR.

APPLICATION.

The Hartley oscillator is used to produce a sine wave output of constant amplitude and fairly constant frequency within the r-f (and sometimes audio) range. The circuit is generally used as a local oscillator in receivers, as a signal source in signal generators and as a variable-frequency oscillator over the medium- and high-frequency ranges.

CHARACTERISTICS.

Uses an L-C parallel-tuned circuit to establish frequency of oscillation, with the inductance connected as an autotransformer between grid, cathode, and plate to provide the feedback needed for oscillation.

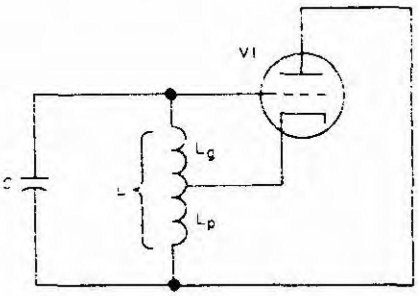
Operates Class C with automatic self-bias for ordinary, or power, operation and Class A when output waveform linearity is important.

Frequency stability is only fair, but better than that of the Armstrong oscillator.

CIRCUIT ANALYSIS.

General. A sine-wave output may be obtained from an oscillator utilizing a tuned L-C circuit. The L-C circuit (commonly called a tank circuit) determines the frequency at which oscillation will take place. At any particular instant of time, the opposite ends of a tuned inductance are at different polarities, or 180 degrees out of phase. Likewise, the grid and plate of a triode are 180 degrees out of phase. Therefore, connecting the tuned circuit to the grid and plate of the triode will not affect the polarity of operation. When the cathode is tapped to the inductance of the tuned circuit and cathode current flows, a magnetic field will be produced between the cathode-to-plate turns of the inductor. A voltage will be induced in the turns of the inductor connected between the cathode and grid by the cathode current flow, and the polarity of the induced voltage will be in the proper direction to cause an increase of cathode current. Thus, a positive regenerative action is produced by the tapped, tuned-tank circuit connected between the electron-tube elements. As long as feedback is sufficient to supply the losses in the tuned circuit, continuous, undamped oscillations are produced.

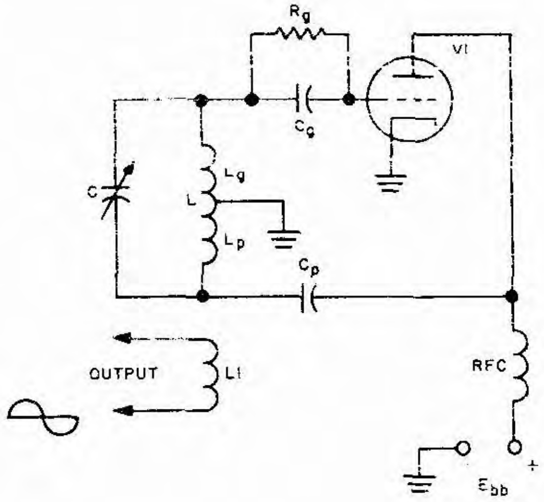
Circuit Operation. The basic Hartley oscillator circuit is shown schematically in the following illustration.



Basic Hartley Circuit

Bias and plate feed arrangements will be discussed later. The tuned (tank) circuit consists of the L_g and L_p portions of inductance L, which is parallel-connected with capacitor C. Feedback is usually accomplished by transformer action between Lp and Lg operating essentially as an autotransformer, with the turns ratio (from about 0.6 to 1) determining the feedback amplitude. (Electrostatic coupling through the tank capacitor can also provide the feedback for oscillation.) Tapping the cathode closer to the plate increases the feedback when the feedback is primarily accomplished by electrostatic coupling through the tank circuit capacitance, with the size of the plate load, L_p, determining the feedback amplitude. Tapping the cathode closer to the plate reduces the plate load and the feedback amplitude. The manner of feedback is determined by the basic construction of the tank circuit inductance.

Shunt-Fed Hartley. The circuit for the shunt-fed Hartley oscillator is shown in the following illustration. Grid bias is developed by R_g and C_g, connected in series between the tuned circuit and the grid of the triode tube. *Shunt plate feed is accomplished by connecting the tuned* circuit to the plate through C_p, which isolates the tank for dc, but connects it to the plate for r-f current flow. Radio-frequency choke RFC offers a high impedance to the rf, which flows through the tank circuit and not through the power supply, but it permits the dc to flow to the plate.



Shunt-Fed Hartley Circuit

The manner in which oscillations occur and the automatic amplitude regulation by grid-leak bias are identical for both the Hartley and the Armstrong oscillators. Refer to the previous discussion of the L-C tickler coil oscillator for an explanation of this action, and assume that the L_p *portion of inductor L is the tickler coil.*

The use of a high-C tank circuit, consisting of C and L connected between the grid and plate of the electron tube, effectively swamps the tube electrode capacitances and produces better frequency stability. The operating frequency is determined by the values of L and C at resonance

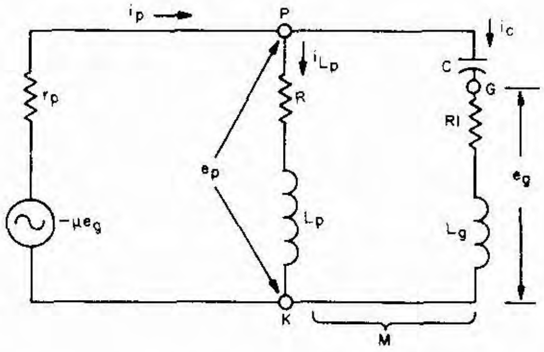
$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

where L is equal to $(L_g + L_p + 2M)$.

Inductive coupling to the load through L_1 at the grounded end of the tank is usually used, but it does not preclude the use of capacitive coupling to the tank circuit where desired.

Series-Fed Hartley. The shunt-fed circuit may be easily modified to a commonly used series plate feed arrangement, by moving the ground connection from the cathode to the bottom end of L_p, and connecting the cathode to the top end of L_p. Thus plate current will flow directly through L_p. Plate capacitor C_p, in conjunction with radio-frequency choke RFC, then serves only to bypass the rf around the plate voltage supply. The operation of the circuit is otherwise identical to that of the shunt-fed circuit previously described.

Detailed Analysis. The analysis of the Hartley oscillator is similar to that of the tuned-plate Armstrong oscillator previously discussed. The equivalent circuit is shown below labelled exactly as in the previous example. Since the tank coil is now tapped, the total tank inductance, L, is $L_p + L_g + 2M$. Resistors R and R_1 are equal to the r-f resistances of L_p and L_g, respectively.



Hartley Equivalent Circuit

Analysis of the Hartley circuit shows that the angular frequency is:

$$\omega = \omega_o \sqrt{\frac{R + r_p}{r_p + R(\mu + 1)}} \qquad (1)$$

$$\text{where: } \omega_o = \sqrt{\frac{1}{L_T C}}$$

As in the case of the tuned-plate oscillator, when no power is taken from the circuit, the frequency is practically given by:

$$f = \frac{1}{2\pi\sqrt{L_T C}} \qquad (2)$$

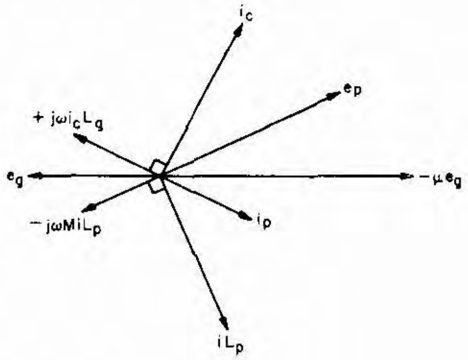
where $L_T = L_p + L_g + 2M$, or the resonant frequency of the tank circuit. Thus while the oscillation frequency is slightly lower than the tank frequency, if a high r_p and a small R are used, the tank will govern the frequency.

The criteria for oscillation is that:

$$g_m = \frac{\mu(R + R_1)\,CL_T}{(L_p + M)\ [\mu\,(L_g + M) - (L_p + M)]} \qquad (3)$$

Examination of equation (3) indicates that even with M at zero the equation will be satisfied; therefore, oscillation can occur even when there is no inductive coupling between the plate and grid circuits, the feedback being capacitively coupled through C. As might be suspected, since the criterion for oscillation is not critical, the Hartley circuit oscillates easily.

Vector Diagram. The relationships between the currents and voltages in the circuit are shown in the vector diagram below. Refer to the equivalent circuit drawing for easier understanding of the development of the vector diagram.



Hartley Vector Diagram

The voltage $-\mu e_g$ is used as a reference vector, and e_g is 180° out of phase. It was pointed out in the mathematical analysis that the Hartley circuit operates slightly below tank resonance; therefore, the tank circuit will appear resistive and inductive, causing i_p to lag $-\mu e_g$ by a small angle, and e_p, the voltage across the tank, to lead by a small angle. The current i_{LP} will lag e_p by some angle less than 90° dependent on the Q of that branch. The current i_C will lead e_p by some angle less than 90° since that branch is largely capacitive. The voltage induced in the grid coil, $-j\omega M i_{LP}$, lags i_{LP} by 90° as indicated by its -j coefficient, while the positive component $(+j\omega i_c L_g)$, will lead i_c by 90°. Grid voltage e_g is the vector sum of the voltages developed across the grid coil L_g. Note that with higher values of circuit Q the voltages developed across the grid coil will more closely approach in-phase quantities, and the angle between i_p and e_p will also diminish, thereby improving oscillator stability.

FAILURE ANALYSIS.

No Output. If the circuit is in a non-oscillating condition, negative grid bias cannot be developed; as a result, the applied plate voltage may be below normal because of the additional current drain unless the power supply is well regulated. For this condition, the plate current will be much higher than normal. Excessive circuit losses in the resonant tank circuit will prevent sustained oscillations. Reduced tube gain (if sufficient) will also affect oscillation. Changes in value of the grid-leak bias components, C_g and R_g, will directly affect the operating bias, and hence the class of operation and overall gain of the tube. Such changes, if sufficient, may cause a loss of oscillation. Too high a value of grid leak resistance may cause intermittent operation or "motor-boating". Shorted turns of the oscillator coil (s), in addition to affecting output amplitude and frequency, may cause loss of oscillation because of loading effects. A leaky plate capacitor C_p may also load the oscillator sufficiently to stop operation. In the shunt-fed circuit, a defective radio-frequency choke RFC or coupling capacitor C_c may stop oscillation since the oscillator is dependent on these components for development and application of feed-back voltages.

Reduced or Unstable Output. A relative indication of oscillator output is provided by the amount of bias voltage developed across R_g. Variation from the manufacturer's rated value is indicative of abnormal operation.

A reduction in applied plate voltage will cause a reduced output. Therefore, an unregulated voltage source will produce output amplitude variations and probably frequency changes or instability. Losses in feedback, due to shorted turns or poor soldered connections, can cause reduced output or unstable operation. A leaky plate capacitor, C_p, may cause reduced or unstable output by loading the oscillator or by reducing plate voltage by adding to the normal current flow through a series resistance. Care should be used in selecting a replacement for a defective r-f choke, since an improper replacement choke may cause unwanted oscillations by resonating with distributed circuit capacitances or with the distributed capacitances of its own windings. Similar care should be exercised in replacing a defective tube in those oscillators operating in the higher frequency ranges where interelectrode capacitances may consitute a considerable portion of the tuned circuits. Variations of this physical capacitance from one tube to another may, in addition to affecting output frequency, cause the oscillator to shift from one mode of operation to another as the oscillator is tuned through its frequency range. For example, a Hartley oscillator could shift to Colpitts operation under the right conditions. This shifting may cause frequency jumps and/or dead spots in the tuning range of the oscillator. At the higher frequencies it is good practice to try more than one replacement tube if the first substitution does not achieve the desired results in frequency of operation and stability. Realignment of circuit components to compensate for a tube substitution should be avoided wherever possible.

Incorrect Output Frequency. Normally, a small change in output frequency can be compensated for by realigning or adjusting the variable component of the L-C resonant tank circuit, assuming that all component parts of the circuit are known to be satisfactory. Changes in distributed circuit capacitance or reflected load reactance will affect the frequency to some extent. Thus, an increase in capacitance will lower the frequency, and a decrease in capacitance will increase the frequency. Therefore, care must be used in the removal and replacement of parts in order not to disturb the distributed capacitance of the circuit which is inherent in the placement of physical parts and the wiring of the circuits. Large changes in ambient temperature may affect the operating frequency of the oscillator. Such changes could come about through failure of an oscillator oven, changes in filament supply voltage, etc. The effects of tube substitution on oscillator frequency were discussed above.

COLPITTS OSCILLATOR.

APPLICATION.

The Colpitts oscillator is used to produce a sine-wave output of constant amplitude and fairly constant frequency within the r-f range. The circuit is generally used as a local oscillator in receivers, as a signal source in signal generators, and as a variable-frequency oscillator over the low- and very-high-frequency ranges, especially where inductive tuning is desired.

CHARACTERISTICS.

Uses a parallel-tuned L-C circuit to determine the frequency of oscillation, with a capacitance voltage divider form of feedback to control oscillation.

Operates Class C with automatic self-bias for ordinary or power operation, and Class A where output waveform linearity is important.

Frequency stability is fair; it is roughly equivalent to the stability of the Hartley circuit, except it is considered somewhat better at the lower frequencies.

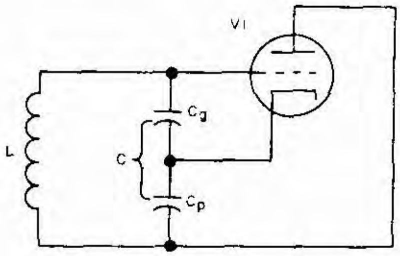
CIRCUIT ANALYSIS.

General. When a tuned L-C (tank) circuit is connected between the grid and plate of an electron tube, the phasing is of the correct polarity to sustain oscillation. The capacitor of a tuned tank circuit may be a single capacitor, or it can be two series-connected capacitors with a total capacitance equivalent to that of the single capacitor. In either case, the frequency of oscillation is the same. The two series-connected capacitors will form a capacitance voltage divider across the tank circuit. Tapping the cathode of the tube to this voltage divider provides a convenient electrical (and mechanical) connection, and a means of controlling feedback between the grid, cathode, and plate elements. The ratio of the capacitances used will determine the amount of feedback, and the total capacitance value will determine the resonant frequency for any particular value of tank inductance. Varying the inductance is a convenient method for tuning the tank over a range of frequencies with a fixed amount of feedback. The use of capacitive tuning involves the simultaneous tuning of both capacitors to maintain the proper ratio of feedback. For tuning over a limited range, capacitive tuning is sometimes employed.

Circuit Operation. The basic Colpitts oscillator circuit is shown schematically in the following illustration. The tuned tank circuit consists of C_g and C_p, in series, and the parallel-connected inductor, L. Feedback is accomplished by the capacitive voltage-divider action of C_g and C_p (or by the use of a variable capacitor shunting C_g and C_p). The feedback ratio varies as

$$\frac{C_g}{C_g + C_p}$$

thus, increasing the value of C_p decreases the feedback.

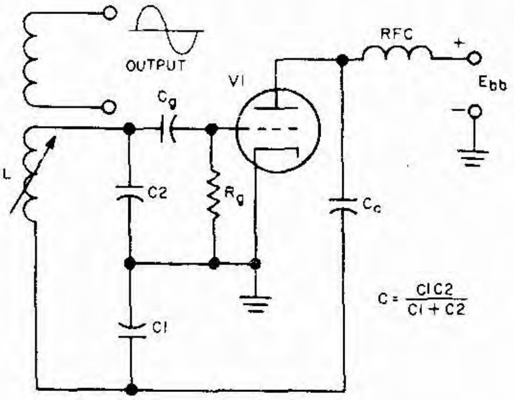


Basic Colpitts Circuit

The capacitive ratios vary with circuit design and frequency, from about a 1:1 ratio to a 1:4 ratio, with the larger capacitor being C_p. For high-frequency use, the capacitance voltage divider may consist of only the interelectrode capacitances of the electron tube. The circuit may be arranged for grounded grid, cathode, or plate operation without affecting performance; the grounded-cathode configuration is probably the most frequently used circuit.

For simplicity, biasing and plate-voltage feed methods are not shown in the basic circuit, but are discussed where applicable in the following circuit variations.

Shunt-Fed Colpitts. The circuit for the shunt-fed Colpitts oscillator is shown in the following schematic. Grid bias is developed by R_g and C_g in the shunt grid-leak bias arrangement. Shunt plate feed is also used, with C_c serving as the plate blocking and coupling capacitor, and RFC as the r-f isolating choke. The tank circuit consists of inductor L and capacitor C, which are parallel-connected between the grid and plate of the electron tube. Capacitor C consists of two series-connected capacitors, C_1 and C_2, which are external to the tube and form a feedback voltage divider to which the cathode is connected.



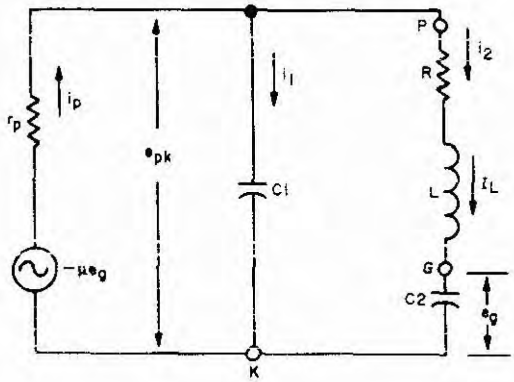
Shunt-Fed Colpitts Oscillator

The manner in which oscillations occur, as well as the automatic regulation of amplitude by grid-leak bias, is the same as explained in the previous discussion of the L-C tickler coil oscillator, except that feedback is obtained from a capacitive voltage divider instead of an inductive voltage divider. Assume that the tank circuit consists of L and C where C represents C_1 and C_2 in series. The tank circuit then is identical with the tuned grid circuit of the tickler-coil oscillator previously described. Since the tank is connected between the plate and grid of the electron tube, and C_1 and C_2 form a capacitive voltage divider, it is evident that there will be a division of feedback voltage in inverse ratio to their capacitance. For a specific frequency the larger capacitor will have the lowest impedance, and the smaller capacitor the highest impedance. For equal capacitors, the voltages across the capacitors will be equal. Thus, with the cathode connected to the common connection of the capacitors, the tank voltage will be divided between cathode-and-grid and cathode-and-plate in accordance with the ratio of C_2 to C_1. Any voltage change in the plate circuit will appear across C_1 and be fed back through C_2 in the correct phase to drive the grid in that direction to increase the initial change. That is, if the plate voltage is increasing, the grid change will cause a further increase, and if decreasing, a further decrease. This is exactly the same result that is achieved by the plate-grid coils of the Armstrong circuit or the tapped inductor of the Hartley circuit, as discussed previously, and sustained oscillations will occur.

Since the tank capacitance is composed of series-connected capacitors, each capacitor will be larger than the total capacitance that is effective in tuning the circuit. Since these series capacitors are connected in parallel with the grid-to-cathode and plate-to-cathode tube capacitances, they will swamp out the interelectrode capacitance variations and thereby increase the frequency stability. Note, however, that as the capacitance of the feedback capacitors approaches the value of the tube element capacitance, this swamping effect is decreased. Stability therefore, is at a maximum at the lower frequencies. The grid-plate capacitance, which is usually larger than the other element capacitance, remains in shunt with the tank inductor and will not be compensated for. If desired, capacitive tuning can be achieved by using a shunt tuning capacitor across L and leaving the feedback capacitors fixed. The advantage of the Colpitts circuit, however, is in the use of large variable inductors and fixed feedback-tank capacitors for operation in the low- and medium-frequency r-f ranges, where the greatest stability is obtained.

For high-frequency use, the Colpitts can be employed as an oscillator controlled mainly by the capacitance between the tube elements, so that inductance alone is needed to achieve oscillation. This arrangement results in higher frequencies of operation than with other L-C circuits, and is exemplified by the series-fed version of the Colpitts known as the ultraudion circuit, which is discussed as a separate circuit later in this section. The output coupling may be either inductive or capacitive, as desired.

Detailed Analysis. The equivalent plate circuit for the shunt-fed Colpitts oscillator is shown below. Assuming that the RFC has infinite reactance, neglecting the grid capacitor reactance, and assuming that the circuit has an infinite grid leak with no grid current, it can be seen that:



Colpitts Equivalent Circuit

$$i_p = i_1 + i_2$$

$$e_{gk} = \frac{i_2}{j\omega C_2}$$

$$e_{pk} = \frac{i_1}{j\omega C_1} = i_2\,(R + j\omega L) + \frac{i_2}{j\omega C_2}$$

$$-\mu e_{gk} = r_p\,i_p + \frac{i_1}{j\omega C_1}$$

The analysis of the Colpitts oscillator is similar to that of the Hartley, except that the capacitive reactance of capacitors C1 and C2 is substituted for L_p and L_g, and the inductive reactance for C. The angular frequency is:

$$\omega = \omega_o\sqrt{1 + \frac{R}{r_p}\cdot\left(\frac{C_2}{C_1 + C_2}\right)}$$

For all practical purposes, the frequency is:

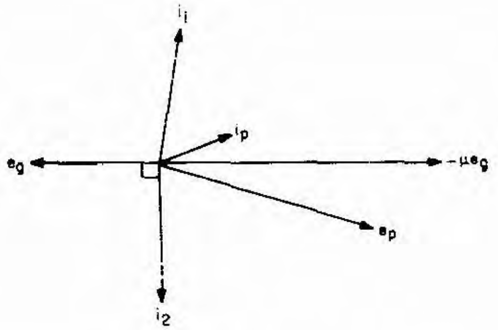
$$f = \frac{1}{2\pi\sqrt{L\,\frac{C_1 C_2}{C_1 + C_2}}}$$

The criteria for oscillation is that:

$$\mu = \frac{C_2}{C_1} + \frac{r_p R\,(C_1 + C_2)}{L}$$

Capacitors C1 and C2 form a capacitive voltage divider across L, causing the grid excitation voltage to be proportional to $\frac{C_2}{C_1 + C_2}$.

Vector Diagram. The relationships between the currents and voltages are shown in the vector diagram below. Refer to the illustration of the equivalent circuit for development of the vector quantities.



Colpitts Vector Diagram

The voltage generator $-\mu e_g$ is the reference voltage, e_g being 180° out of phase. It was shown that the Colpitts oscillator operates above the tank frequency. Therefore, the tank circuit appears slightly capacitive, and i_p leads $-\mu e_g$ by a small angle while e_p lags $-\mu e_g$. The current i_1 through capacitor C_1 will lead e_p by 90°. Current i_2 through the branch containing L and C_2 is primarily inductive and will lag e_p by an angle less than 90° determined largely by the Q of L. The voltage e_g, since it appears across capacitor C_2, will lag i_2 by 90°, thereby satisfying the conditions for oscillation. It can be seen that with higher values of circuit Q, the phase difference between i_p and e_p will be diminished.

FAILURE ANALYSIS.

No Output. If the circuit is in a non-oscillating condition, the negative grid bias will be much less than it is in the oscillating condition, because it will consist of contact-potential bias only, which will allow the tube to operate at approximately zero instead of at cutoff or higher. Thus the plate current will be much higher than normal. Excessive losses present in the resonant tank circuit will prevent sustained oscillations. Reduced tube gain, if sufficient, will also affect oscillation, but will not be as noticeable as in the inductive feedback circuits. Changed values of grid-leak bias components R_g and C_g will directly affect the operating bias and change the amplitude of the oscillations; if the change is large, oscillation may even be prevented; if small, the effect may not be noticeable. A defective radio-frequency choke RFC or coupling capacitor C_c may cause loss of oscillation since the circuit depends on these components for the development and application of the feedback voltage.

Reduced or Unstable Output. A relative indication of oscillator output is provided by the amount of bias voltage developed across R_g. Variation from the standard operating value is an indication of abnormal operation. A reduction of applied plate voltage will cause a reduced output. Therefore, an unregulated voltage source will produce output amplitude variations and probably some frequency change or instability. Losses in feedback due to shorted turns, poor soldered connections, or changing values of feedback capacitance can also cause reduced output or unstable operation. Care should be used in selecting a replacement for a defective r-f choke, since an improper replacement may cause unwanted oscillation by resonating with the capacitance of its own windings or with distributed circuit capacitances.

Incorrect Output Frequency. Normally, a small change in output frequency can be corrected by adjusting the variable component of the L-C resonant tank circuit, provided that all component parts of the circuit are known to be satisfactory. Changes in distributed circuit capacitance or reflected load reactance will affect the frequency of operation to some extent, being most noticeable on the higher-frequency ranges. Changes in stray capacitance which parallels the tank circuit will have a greater effect in changing the frequency than grid-cathode or plate-cathode capacitance changes (provided that they are large enough to overcome the tank swamping effect). Care should be used in replacing a defective tube, particularly in oscillator circuits operating in the higher frequency ranges. It is good practice to try more than one replacement tube if the first substitution does not achieve the desired results in frequency of operation and stability. Realignment of circuit components to compensate for a tube substitution should be avoided wherever possible. Large changes in ambient temperature may affect the operating frequency of the oscillator. Such changes could come about through failure of an oscillator oven, changes in filament supply voltage, etc.

CLAPP OSCILLATOR.

APPLICATION.

The Clapp oscillator is used to produce a sine-wave output of constant amplitude and fairly constant frequency within the r-f range. The circuit is used as a beat frequency oscillator in receivers, as a master oscillator in transmitters, and generally as a variable-frequency oscillator over the high- and very-high frequency ranges. It is also employed as a crystal controlled oscillator in frequency meters and in signal generators.

CHARACTERISTICS.

Uses a separate series tuned L-C circuit to determine the frequency of oscillation, with a capacitance voltage divider form of feedback to control oscilllation.

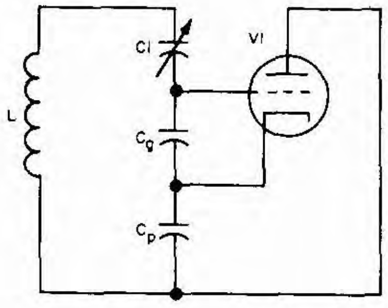
Operates as Class B or C with automatic self-bias for ordinary or power operation, and as Class A where output waveform linearity is important.

Frequency stability is good. The circuit is considered to have better stability than the Colpitts circuit.

CIRCUIT ANALYSIS.

General. The Clapp circuit is considered to be a variation of the Colpitts circuit discussed previously. It uses the stabilizing effect of a series tuned tank circuit, coupled loosely to the tube feedback loop, to provide better frequency stability. It incorporates capacitive tuning which require the use of only one tuning capacitor. It also offers a convenient method of tuning over a small band of frequencies where band-spread or vernier-type tuning is desired.

Circuit Operation. The basic Clapp oscillator circuit is shown schematically below. The tuned tank circuit consists of series-connected components L and C1 in parallel with the basic capacitance feedback voltage divider, C_g and C_p. For simplicity, the biasing and plate feeds are not shown in this basic circuit, but are discussed as necessary in the following circuit discussion.



Basic Clapp Circuit

The capacitance ratio for the voltage divider which provides the basic feedback (as in the Colpitts circuit) may vary with the circuit design and the frequency. Usually it is 1:1 with C1 being smaller (about one-tenth C_g for high-frequency operation).

The circuit may be arranged for grounded grid, cathode, or plate operation without affecting performance; the grounded-plate configuration is the most frequently used.

The frequency of operation is dependent upon the values of the three capacitors and inductor as follows:

$$F = \frac{1}{\sqrt{2\pi \; L \; C_1}} \cdot \sqrt{1 + \frac{C1}{C_g} + \frac{C1}{C_p}}$$

Thus it is evident that when the ratios of C_1/C_g and C_1/C_p are very small, the resonant frequency will be primarily determined by the values of L and C_1 alone. This is the condition usually desired.

Since the resonant frequency is primarily determined by L and C_1 when C_p and C_g are comparatively large, the Clapp circuit may employ much larger values of capacitance in the feedback voltage divider than can the equivalent Colpitts. The larger values of capacitance much more effectively swamp interelectrode capacitances; it has been estimated that as much as a 400 to 1 reduction of change in capacitance by temperature or tube variations may be obtained.

As in the other L-C circuits, the most stable operation is obtained with a high loaded Q, which is produced for a series resonant circuit by a high L to C (not C to L ratio.

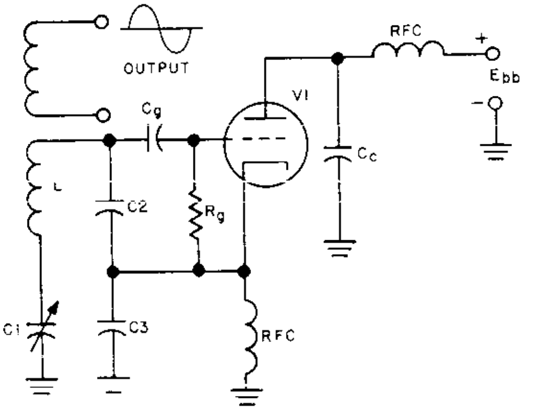
Thus, for a given frequency, the tank inductance is larger than that used for the previously discussed circuits. Since it is easier to produce a high-Q coil when the inductance is greater than the usual high-C tank affords, the Clapp oscillator benefits from the low-C tank. While the capacitance voltage divider consisting of C_g and C_p does not offer any greater stability in this Clapp circuit than in the Colpitts, the ratio of C_g to C_p is chosen to afford the greatest possible stability in conjunction with the higher Q offered by the series tuned tank. Tuning capacitor C1 is chosen to have the desired tuning range, with sufficient capacitance to sustain the feedback loop at the higher frequency (feedback increases with decrease of frequency).

Since the basic frequency-determining portion of the Clapp circuit is the tank inductor (C_1 merely tunes over the desired range), which is coupled capacitively through C1 to the tube, the Clapp tank is generally considered to be more loosely coupled than the tank circuit of the other oscillator configurations. Thus tank circuit changes are normally minimized. This factor, in combination with the higher circuit Q obtainable, provides the Clapp oscillator with very high stability in the presence of supply voltage variations, the frequency changing only a few parts per million for a supply voltage variation of 15 percent.

Variations of the Clapp oscillator circuit may be encountered. For example, an RFC may be inserted between cathode and ground to keep the cathode at a high impedance above ground, and offer a d-c return path to the cathode. Usually this choke is chosen to resonate with its distributed capacitance at the fundamental frequency, and occasionally a trimmer is included to adjust the parallel resonant choke circuit for proper impedance. In special circuit versions, the cathode tank may be used for frequency doubling. These circuit variations, however, are not a part of the basic Clapp oscillator circuit design.

Shunt-Fed Clapp. The complete schematic for a shunt-fed Clapp oscillator is shown below. Series plate feed is never used in this circuit and will not be discussed. Shunt grid-leak bias is used (R_g and C_g), with shunt plate feed. Capacitor C_c is the plate blocking and coupling capacitor, and inductor RFC is the r-f choke. The combination of C_c and RFC provide an r-f bypass to isolate the power supply from rf. The plate is grounded to rf, and L and C_1 form the tank circuit, which is connected across the feedback divider consisting of C_2 and C_3. The cathode RFC provides a d-c return path to ground for the cathode, and offers a high impedance to rf to prevent any shunting of divider capacitor C_3.

Operation of the circuit and automatic regulation of the amplitude by grid bias are the same as described in previous oscillator discussions. Oscillation is caused by feedback through the capacitance voltage divider, C2-C3, as in the Colpitts oscillator, but the ratio of the capacitors is chosen for the best frequency stability. The output coupling is usually inductive, but it may be capacitive.



Shunt-Fed Clapp Oscillator

FAILURE ANALYSIS.

No Output. High plate current will be indicative of non-oscillation and consequent loss of operating bias, with the tube operating at essentially zero (contact) bias. Reduced tube gain, if sufficient, will also affect oscillation. Changes in the value of the bias resistor and capacitor will directly affect the operating bias and the amplitude of oscillating—if the changes are large, oscillation may be prevented; if small, the effect may not be noticeable. Shorted turns of oscillator coil, in addition to affecting output amplitude and frequency, may cause loss of oscillation because of loading effects. A defective radio-frequency choke (RFC) or coupling capacitor (C_c) may stop oscillation since the oscillator is dependent on these components for the development and application of feedback voltages.

Reduced or Unstable Output. A relative indication of oscillator output is provided by the amount of bias voltage developed across R_g. Variation from the standard operating value is an indication of abnormal operation. A reduction of plate voltage will decrease the output amplitude. Therefore, an unregulated voltage source will produce output amplitude variations and possibly some frequency change, although the Clapp circuit is considered to be less affected in this manner than the Colpitts (a change of only a few parts in a million for a 15 per cent plate supply fluctuation is claimed). A partially open plate blocking capacitor will reduce the grid-to-plate coupling and feedback and thus affect the output or oscillation. At the higher frequencies it is possible for weak feedback to occur through the grid-to-plate tube capacitance and sustain oscillation even though the plate blocking capacitor is faulty. A leaky plate capacitor may cause reduced or unstable output by loading the oscillator or by reducing plate voltage by adding to the normal current flow through a series resistance. Care should be exercised in selecting a replacement for a defective r-f choke since an improper replacement choke may cause unwanted oscillation by resonating with distributed circuit capacitances or with the distributed capacitances of its own windings.

Incorrect Output Frequency. Changes in distributed circuit capacitance or reflected load reactance will affect the frequency of operation to some extent, although the design of this circuit provides fixed swamping capacitances to eliminate such changes. The largest change will be produced by a change of the tank circuit Q caused by shorted turns or poor soldered connections in the tank circuit. An incorrect output frequency resulting from a change of tube transconductance with age is normally corrected by slight readjustment of the tuning capacitor. Large changes in ambient temperature may affect the operating frequency of the oscillator. Such changes could occur through failure of an oscillator oven, changes in filament supply voltage, etc.

TUNED-PLATE TUNED-GRID OSCILLATOR.

APPLICATION.

The tuned-plate tuned-grid (TPTG) oscillator is used to produce a sine-wave output of constant amplitude and fairly constant frequency within the r-f range. This circuit is generally used as a variable-frequency oscillator over the high- and very-high-frequency r-f ranges. It is not often encountered in Navy electronic equipment.

CHARACTERISTICS.

Contains two parallel-tuned L-C circuits — one in the grid circuit and the other in the plate circuit of the electron tube — and uses the internal grid-plate tube capacitance for feedback.

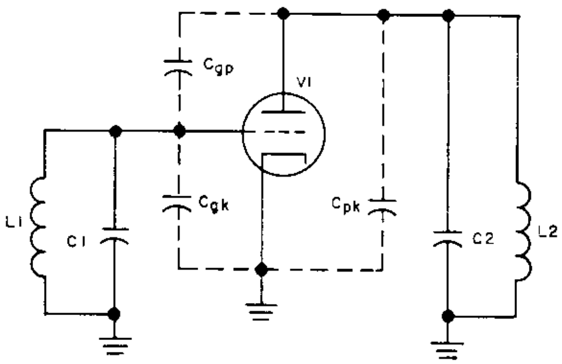
Operates as Class C with automatic self-bias for ordinary, or power, operation and is seldom used for linear waveform applications.

Frequency stability is good when properly adjusted.

CIRCUIT ANALYSIS.

General. When a tuned L-C tank circuit is connected between the grid and cathode of an electron tube and a similar tank circuit is connected between the plate and cathode of the tube with coupling existing between them, sustained oscillation will occur when these tuned circuits are resonated to the same frequency. The amplitude of the oscillation is determined by the amount of feedback from plate to grid, and is also affected by the tuning of the two circuits. To provide the proper phase to sustain oscillation, both the grid tank and the plate tank are tuned to a slightly higher frequency than the resonant frequency at which operation is desired. At the operating frequency both tanks then offer an inductive reactance, and the phase shift through the grid-plate tube capacitance is of the proper polarity to sustain oscillation. The condition for proper phasing is that the inductive reactance of the grid tank circuit be less than the capacitive reactance of the grid-plate interelectrode capacitance at the operating frequency. To sustain oscillation, it is only necessary to supply the losses in the grid circuit, which because of the high-Q grid tank are relatively small. Consequently, only a small capacitance is needed to supply sufficient feedback, and the grid-plate interelectrode capacitance of the triode tube is adequate for this purpose. When a pentode is employed in the circuit, it is usually necessary to supply an external capacitor to provide the feedback, because of the low electrode capacitance inherent in the pentode.

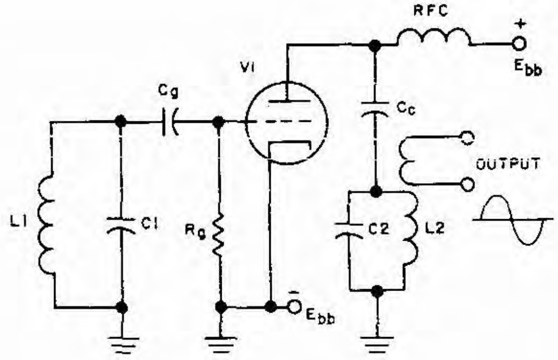
Circuit Operation. The basic tuned-plate tuned-grid oscillator circuit is shown schematically below. The grid tank consists of C1 and L1, while the plate tank consists of C2 and L2, no mutual inductance existing between L1 and L2. Feedback occurs through the plate-grid capacitance, C_{gp} (shown in dotted lines), when both tanks are tuned to the same frequency. The feedback amplitude can be controlled by detuning the grid tank with C1. Thus, differences in interelectrode capacitance between tubes can be accommodated with no adverse effects.



Basic Tuned-Plate Tuned-Grid Oscillator

For simplicity, biasing and plate voltage feeds are not shown in the basic circuit, but are discussed when applicable in the following discussion. Since capacitive feedback determines oscillation, this circuit is a better oscillator at the higher frequencies and is not often used in the low- or medium-frequency ranges. Although other configurations may be used, this circuit lends itself conveniently to grounded-cathode operation. The grid tank basically controls the excitation and operating stability, and the grid-cathode tube capacitance is in parallel with the tank, being effectively swamped by the tank capacitance. Likewise, the plate tank capacitor effectively swamps the plate-cathode tube capacitance, and the plate tank is primarily used to determine the operating frequency. Once oscillation occurs near the desired frequency, the plate tank is tuned to set this frequency to the desired value, while the grid tank is adjusted for proper excitation and maximum stability.

Upon examination of the shunt-fed tuned-plate tuned-grid oscillator circuit, it is evident that shunt grid-leak bias (C_g, R_g) and shunt plate feed are used, with C_c serving as the plate coupling and blocking capacitor. The radio-frequency choke, RFC, keeps the rf out of the plate supply. L1, C1 is the grid tank and L2, C2 is the plate tank. The grounded-cathode connection is shown since it permits grounding the tuning-capacitor rotors to eliminate any body capacitance effects on tuning. The use of shunt grid-leak bias isolates the grid tank as far as dc is concerned and reduces circulating grid current, although series grid bias could be used as well. Sometimes a series resistor is included between cathode and ground, to provide protective bias in the event of non-oscillation. Both the plate and grid capacitors are sufficiently large so that the tank circuits are effectively coupled to the grid and plate for rf, yet isolated as far as dc is concerned. Grid-leak bias ac-

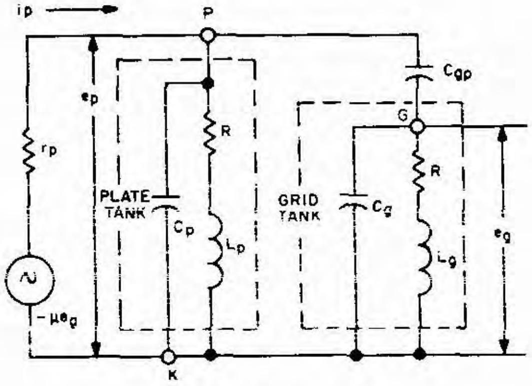


Shunt-Fed Tuned-Plate Tuned-Grid Oscillator

tion and automatic amplitude regulation are the same as described previously in other oscillator discussions. The feedback action takes place as described above, making use of the coupling between the plate and grid tanks provided by the grid-plate tube capacitance. At radio frequencies which require the use of relatively large inductors and when appreciable power is used, it is important for the tanks to be shielded or turned at right angles to each other, to prevent possible inductive coupling effects which would deteriorate circuit performance.

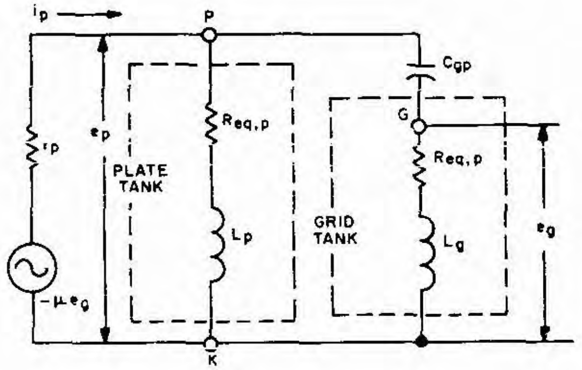
Output is obtained by inductive coupling to the plate tank, although a capacitive connection may be made if desired.

Detailed Analysis. The equivalent circuit of the tuned-plate, tuned-grid oscillator is shown below.



Basic TPTG Equivalent Circuit

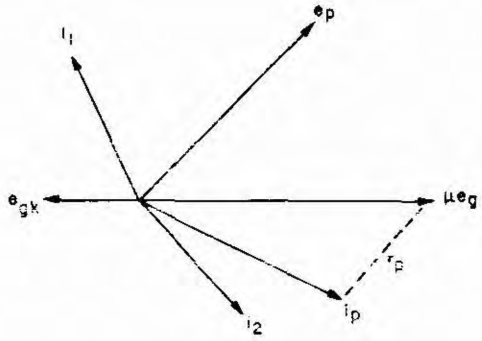
Since the oscillator operates below the resonant frequency of the tank circuits, both the plate tank and the grid tank will appear resistive and inductive to the signal source $-\mu e_g$.



Modified Tuned-Plate, Tuned-Grid Equivalent Circuit

The figure above shows the tank circuits replaced by their equivalent values of modified equivalent resistance and inductance at the operating frequency. Notice that this equivalent circuit closely resembles that of the Hartley oscillator which was shown previously. Therefore, the operation of the TPTG oscillator, at the operating frequency, is basically that of a Hartley oscillator without the benefit of mutual *inductance. However, adjustment* of the tuned circuits to meet this condition is rather critical. Note from the equivalent circuits that the basic frequency-determining components are the plate tank and the plate-to-grid capacitance of the tube, C_{gp}. The plate tank, therefore, is tuned to establish the frequency of operation, while the grid tank is tuned to establish the proper phasing and amount of feedback voltage for grid excitation.

Vector Diagram. The relationship between the current and voltages in the circuit is shown by the vector diagram below.



Tuned-Plate Tuned-Grid Vector Diagram

The constant voltage generator output μe_g is the reference voltage. It is assumed that there is no inductive coupling between the plate and grid tank circuits and that the frequency of oscillation is slightly lower than the resonant frequency of the tanks. Since the tank circuits are tuned to a higher frequency than the oscillation frequency, they offer an inductive reactance. Also, since the feedback must occur through the grid-plate inter-electrode capacitance, the grid tank must offer a lower inductive reactance than the capacitive reactance of the electrodes (the grid-cathode and plate-cathode capacitance is assumed to be a part of the tuned circuits). Therefore, the inductive plate tank causes e_p to lead μe_g by some angle dependent on the circuit values, and $i_p r_p$ lags. The inductive plate tank current i_2 also lags e_p somewhat less than 90 degrees. Since the reactance of C_{gp} is greater than the grid tank reactance, i_1 leads e_p by almost 90 degrees. Voltage e_{gk} is developed across the inductive grid coil (tank) and, therefore, leads i_1 by almost 90 degrees. This voltage is exactly 180 degrees out of phase with μe_g, satisfying the requirement for oscillation.

FAILURE ANALYSIS.

No Output. If something happens to either of the tank circuits so as to cause a large enough shift in that tank's resonant frequency, the circuit will not oscillate, and only contact bias will be developed. Plate current, therefore, will be higher than normal and the standard operating value of grid bias will not be obtained. Excessive losses if present in the tank circuit will prevent sustained oscillation. Changes in the values of grid-bias components R_g and C_g will affect the operating bias and change the amplitude of oscillation. A large change may prevent oscillation, whereas a small change may not have any noticeable effect. Although loss of tube gain will reduce the amount of feedback, the TPTG circuit is a vigorous oscillator when properly adjusted, so that considerable reduction in tube amplification is necessary to reduce oscillation. Too close coupling of the output circuit to the plate tank will produce the same effect as a lossy tank circuit, and reflected reactance may cause sufficient detuning to prevent oscillation. In the shunt-fed circuit, a defective radio-frequency choke RFC or coupling capacitor C_c may cause loss of oscillation since the oscillator depends on these components for isolation from the low a-c impedance of the plate supply and for coupling of the a-c signal to the tuned plate tank.

Reduced or Unstable Output. A relative indication of oscillator output is provided by the amount of bias voltage developed across R_g. Variation from the standard operating value is an indication of abnormal operation. A reduction of applied plate voltage will decrease the output. Therefore, an unregulated voltage source will produce output amplitude variations and probably some frequency change or instability. In this respect, the tuning of the grid tank is important, as it has a great effect on the stability of operation. A leaky coupling capacitor C_c may cause reduced or unstable output by loading the oscillator or by reducing plate voltage by adding to the normal current flow through a series voltage dropping resistance. Care should be used in selecting a replacement part for a defective r-f choke, since an improper replacement may cause unwanted oscillation by resonating with distributed circuit capacitances or with the distributed capacitances of its own windings. Similar care should be exercised in replacement of a defective tube since the oscillator depends on interelectrode capacitances as a part of the tuned circuits. Variations of this physical capacitance from one tube to another may be enough to seriously detune the oscillator. It is good practice to try more than one replacement tube if the first substitution does not achieve the desired results in frequency of operation and stability. Realignment of circuit components to compensate for tube substitution should not ordinarily be necessary.

Incorrect Output Frequency. Assuming that all component parts of the circuit are known to be satisfactory, changes in output frequency can be compensated for by realigning or tuning the tank circuits. Detuning effects caused by reflected load reactance will affect the frequency of operation to some extent, being most noticeable on the very-high-frequency ranges. Changes in tank inductance caused by shorted turns, particularly in the grid circuit, will result in a different frequency of operation, if oscillation still occurs. Large changes in ambient temperature, such as may occur through failure of an oscillator oven or changes in filament supply voltage, may affect the operating frequency of the oscillator. Changes in distributed circuit capacitances will also affect the operating frequency. Therefore, care should be used in the removal and replacement of parts, in order not to disturb the distributed capacitance inherent in the physical parts and wiring of the circuit. The effects of tube substitution were discussed above.

SERIES-FED TUNED-PLATE TUNED-GRID. Series plate feed is easily accomplished with the tuned-plate tuned-grid circuit by connecting B + and the RFC in place of the ground to L2 (refer to shunt-fed schematic), connecting the plate directly to the top of L2, and bypassing the bottom end of L2 to ground with C_c. Circuit operation and failure analysis are exactly the same as for the shunt-fed circuit with two exceptions: (1) With the series connection, unwanted low-frequency (or high-frequency) parasitic oscillations caused by resonances of RFC and C_c or of RFC and C_{pk} are eliminated. (2) The effect of dc in the tank circuit must be considered; since the capacitor and inductor must withstand both d-c and r-f voltages, their insulation to ground becomes an important factor.

ELECTRON-COUPLED OSCILLATOR.

APPLICATION.

The electron-coupled oscillator is used to produce an r-f output of constant amplitude and extremely constant frequency, usually within the r-f range. The circuit is generally used in any type of electronic equipment where stability is required, and the output waveform need not be a sine wave, as some distortion of waveform is normal.

CHARACTERISTICS.

Uses the shielding effect between the plate and screen grid in a tetrode or pentode to isolate the plate load from the oscillator, and employs the electron stream between the screen grid and plate to couple the oscillator output to the plate load.

Operates with practically any circuit configuration of the L-C or R-C type, but is mostly used with L-C circuits.

Frequency stability of circuit is very good — better than that of the previously discussed types of oscillators.

CIRCUIT ANALYSIS.

General. In the triode-type oscillator, variation of the plate supply voltage and reflected load reactance causes slight frequency variations because the plate is involved in the feedback loop. By using the cathode, grid, and screen grid of a tetrode or pentode as the oscillator, the plate is eliminated from the feedback loop. Since the plate current in the tetrode or pentode is relatively independent of plate voltage changes and remains nearly constant for a specific value of screen voltage, variations in the plate load circuit have practically no effect on the other elements. Connecting the screen grid as the plate of the triode oscillator electrostatically shields the plate of the pentode or tetrode, and couples the output of the oscillator to the load through the plate electron stream.

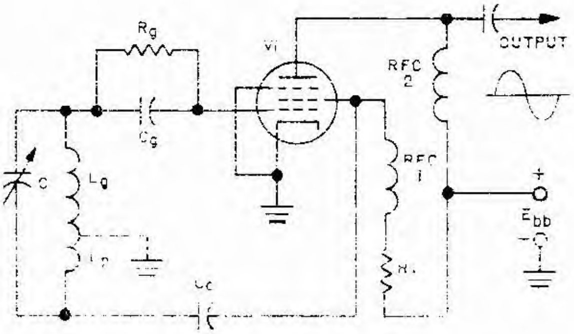
Any of the previously discussed oscillator circuits may be used for the oscillating portion of the electron-coupled oscillator circuit, and the electron tube can be either a tetrode, a pentode, or a beam-power tube.

The tetrode is a four-element tube, which uses a screen grid to accelerate the flow of electrons from the cathode to the plate under control of the control grid. As the electrons pass through the screen grid to the more positive plate, some of them impinge on the screen grid and produce a screen-grid current, which amounts to about one tenth of the plate current. Secondary electrons are emitted by the portion of the electron stream striking the screen grid and by the stream striking the plate. Normally, when the plate voltage is higher than the screen-grid voltage, these secondary electrons are attracted to the nearest element, plate or screen, and merely increase their respective currents. When the plate voltage is near or below the screen-grid voltage, space charge forms a virtual cathode between the screen grid and plate and thus nullifies the effect of electron coupling. Therefore, the screen grid is usually supplied from the plate source through a series voltage-dropping resistor, and it is bypassed to ground with a capacitor to provide an electrostatic shield. The beam-power tetrode uses special construction and beam-forming plates connected to its cathode to provide the same effect. The pentode utilizes a fifth element (the suppressor grid), usually connected to the cathode internally and located between the screen grid and plate, to eliminate secondary-emission effects. In some tubes the suppressor grid connection is brought out externally, and may be connected to ground, screen grid, or plate as desired. In the electron-coupled oscillator, it is always connected to provide an effective electrostatic shield between the screen grid and plate, in order to eliminate coupling of load variations back to the oscillator circuit. When a pentode with an internally connected suppressor is used in the electron-coupled circuit, the cathode is always grounded; otherwise, full electron coupling is not obtained and a less stable circuit results.

The electron-coupled plate load may be another tuned tank circuit, a radio-frequency choke, or a resistor. The tuned plate tank may be operated on the same frequency as the grid tank, or it may be tuned to a harmonic, operating as a frequency multiplier. In test-equipment applications, a choke or a resistor (instead of a tank circuit) is usually used with light loading to assure maximum frequency stability. A properly designed electron-coupled oscillator provides the stability of a master oscillator-power amplifier circuit combination with only one tube, and it has the power output of an equivalent triode operating at the same plate voltage and current.

When a resistor or choke is used in the output circuit, the waveform is not exactly sinusoidal because the plate current does not vary linearly with the screen-grid current. Although the control grid varies the screen-grid current linearly, and these oscillations effectively modulate the electron stream between the screen grid and plate, not all of the current controlled by the grid reaches the plate. Some of the electrons in the screen-plate region are attracted back to the screen grid, while others are shunted to the cathode by the suppressor electrode. Therefore, at any particular instant when the screen-grid current is being slightly increased, the plate current may or may not be increased by the same amount — in fact, it may actually decrease. Hence, the output waveform, which is the result of plate current flow through the load resistance, will not be exactly like the screen-grid waveform; it will be similar, but distorted. If a plate tank or an L-C filter is employed, the distortion will be corrected and a nearly sinusoidal waveform will result.

Circuit Operation. The schematic of an electron-coupled oscillator using a pentode tube is shown below. The oscillator section utilizes the basic Hartley shunt-fed circuit, with a series grid leak as discussed previously in the Hartley oscillator circuit, and with the screen of the pentode acting as the triode plate.

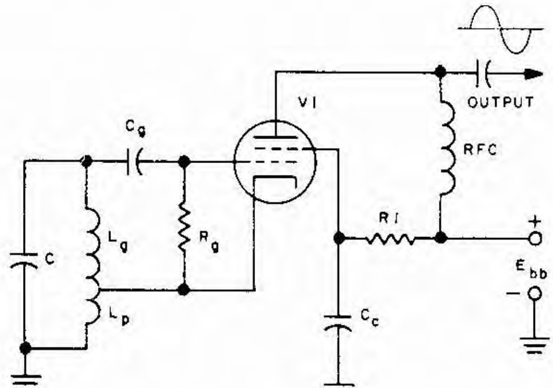


Pentode Electron Coupled Oscillator

The E.C.O. load is taken from the plate circuit of the pentode. Operation of the oscillator portion is identical to that of the previously discussed Hartley oscillator. In the electron-coupled version, however, plate voltage is applied to the pentode through RFC2 to keep rf out of the power supply, and the output is capacitively coupled to the load (usually the next r-f amplifier stage). To insure that the screen of the pentode remains at a lower minimum d-c potential than the plate, a dropping resistor, R1, is generally used, but may be omitted in some versions of this circuit. Since the screen is above ground at r-f potential, RFC1 is necessary to block the rf from the power supply. If R1 is a high-value resistor of say 5000 ohms or more, RFC1 may be omitted, because the high resistance of R1 is comparable to the reactance offered by the r-f choke. Note that the suppressor element is connected to the cathode, which is grounded. If the cathode were above ground, the suppressor could not be connected to the cathode or it would capacitively couple the oscillator into the plate circuit and destroy the shielding effect of electron coupling. Since in this instance the cathode is grounded, the suppressor performs its normal function of eliminating secondary emission and isolating the plate and the screen grid.

The oscillator normally operates Class C, and for each pulse of oscillation a corresponding pulse is produced in the plate circuit through modulation of the electron stream. Thus electron coupling exists between the screen grid and plate. Plate load variations produce plate voltage and current changes, but, since a change of pentode plate voltage has little effect on plate current, these changes have negligible effect on the screen-grid voltage and current. Hence, the stability of the oscillator remains relatively unaffected by load variations. It should be noted that, although the pentode is considered to be unaffected by supply voltage variations, only the tetrode circuit can be designed by selection of proper plate and screen voltages to be completely independent of supply variations. The advantage of the pentode arrangement is that grounded-cathode operation can be used to provide an electrostatic shield between plate and grid or screen, and secondary emission effects need not be considered.

The tetrode version of the electron-coupled oscillator which is particularly applicable to beam-power tubes is the grounded-screen circuit shown below. In this circuit, the shunt-fed Hartley is used; the operation and components of the circuit are the same as just described for the pentode E.C.O. illustrated above, with the following exceptions:

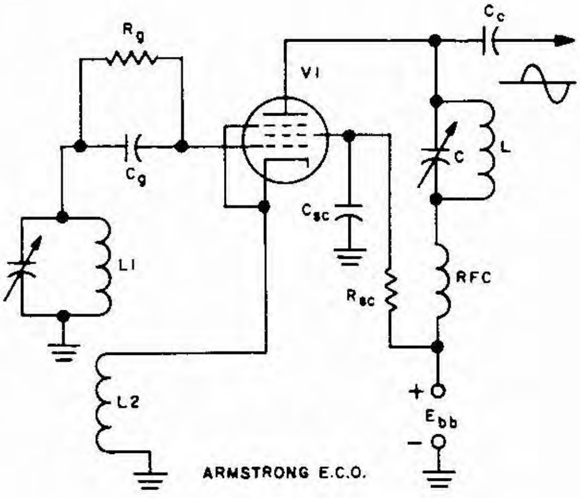


Tetrode Electron-Coupled Oscillator

Since there is no suppressor element in a tetrode tube, secondary emission effects are encountered. Therefore, R1 is needed to keep the plate voltage always higher than the screen-grid voltage, in order to avoid formation of a virtual cathode within the space-charge region between the screen grid and plate. Because the screen is grounded by C_c, an electrostatic shield is provided between the oscillator and output sections. Since the cathode is above ground and cathode current flows through the L_p portion of the tank, the full current of the tube is utilized to provide feedback through the tank inductor. Actually, this is a series plate-fed connection. Since the plate current of the tetrode is independent of plate voltage, being controlled by the potentials on the screen and control grids, no undesired coupling results from the flow of cathode current through L_p. The original derivation of this circuit utilized a variable resistor as R1, and the screen-grid voltage was adjusted for maximum stability. Since a slight increase of screen voltage (caused by supply or load variations) decreases the frequency, while a similar change of plate voltage increases the frequency, R1 can be adjusted for specific screen voltage where a frequency change in one direction will cancel a corresponding change in the other direction and result in freedom from frequency changes due to supply voltage variations.

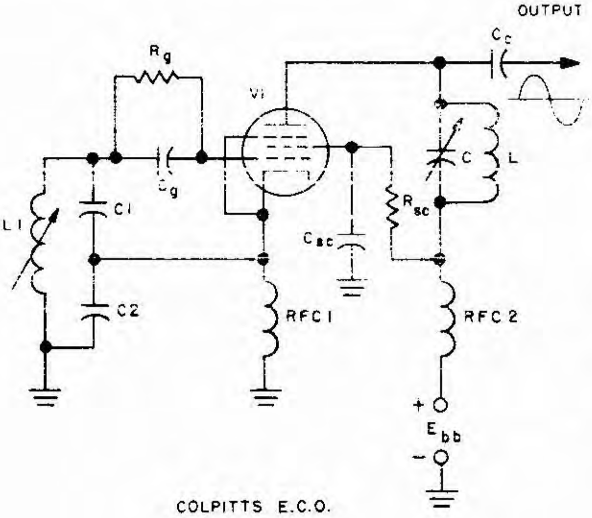
It should be noted that, if a pentode is used in the tetrode circuit, the suppressor should not be connected to the above-ground cathode, or capacitance coupling will exist between the suppressor and ground and inject an undesired coupling between the oscillator and output sections. Instead, the suppressor grid should be tied to the screen or the plate, making the tube effectively into a tetrode; a pentode with an internally connected suppressor is not usable in this circuit.

A number of electron-coupled-oscillator variations using the oscillators previously discussed are also illustrated. These circuits are drawn in their most usually encountered form; namely, with a plate output tank which may be operated either on the fundamental or a harmonic. Circuit operation is the same as discussed for the basic oscillator with the addition of the electron-coupled circuit theory just com-

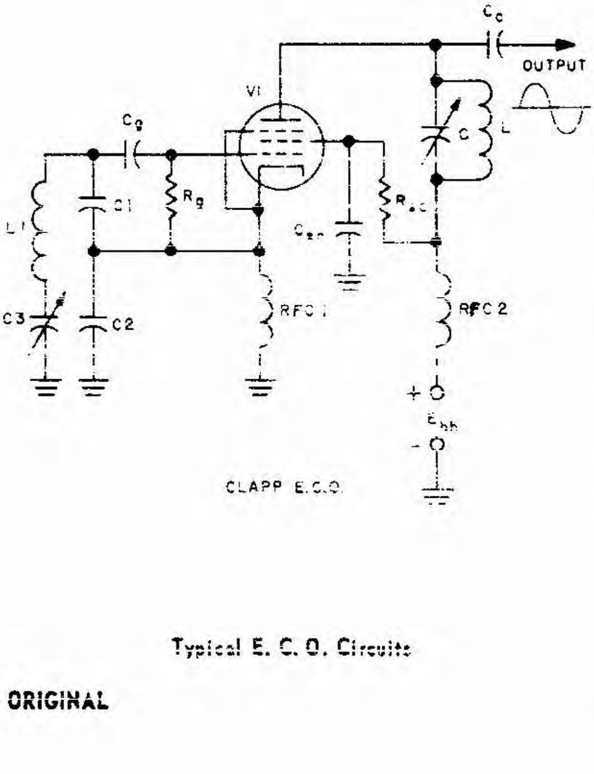


ARMSTRONG E.C.O.

pleted. The tuned-plate tuned-grid version is not shown because it is usually in the form of a crystal-controlled electron-coupled oscillator, in which the grid tank is replaced by the crystal and the plate tank is the output of the oscillator. This circuit version is discussed later in this section.



COLPITTS E.C.O.



CLAPP E.C.O.

Typical E. C. O. Circuits

FAILURE ANALYSIS.

No Output. Failure of oscillation would cause no output, and could result from the same effects described in the failure analysis section of the Hartley oscillator. In addition, lack of supply voltage caused by open components or a short from plate to ground would effectively stop output. Actually, in this type of circuit tube emission could drop to the point where there is sufficient current for the oscillator section, but practically none for the plate. Therefore, the circuit should be considered as basically a two-section tube, and checked for oscillator output first and then for continuity through the plate circuit. If the plate output circuit is [illegible] complete with [illegible] components in good operating condition, and the oscillator is operating, lack of plate output indicates a faulty tube.

Reduced or Unstable Output. In addition to those causes indicated for the basic oscillator in the Hartley oscillator circuit discussion, the following should be considered: If the basic oscillator is unstable or has a reduced output, then, with all other conditions equal, the plate output will also be unstable or reduced. Thus the oscillator should first be investigated for proper operation. Since the screen voltage determines the amount of plate current drawn by the tube, a reduction of screen voltage would have a more noticeable effect on the output before it dropped below the point where oscillation could be sustained. An increase in resistance of the screen dropping resistor, if used, is a primary cause of reduced output. Where the plate voltage is supplied through a load resistor, it is common for a high resistance to develop, reducing both the plate voltage and the output. This condition can result in instability if the plate voltage becomes lower than the screen voltage. If the output circuit of the plate includes a tuned tank circuit, a normal increase of output is to be expected when the tank is tuned to the same frequency as the oscillator or to a low-order harmonic. Therefore, any effects causing tank detuning will immediately result in a reduced output. When instability is produced by load variations, it can immediately be assumed that the electron coupling is involved; in this case, the circuit should be checked for capacitive coupling between screen and plate or for a change in voltage ratios due to an excessive voltage drop or a short circuit in either the screen or plate. When the screen current increases abnormally, secondary emission effects or a defective (open) plate circuit can be suspected.

Incorrect Output Frequency. Since the output frequency is determined basically by the oscillator portion of the tube, any change in frequency with normal output amplitude indications would indicate that a change of oscillator components or voltages is the most probable cause. If the oscillator frequency change is not due to components in the oscillator itself, the electrostatic shielding between the plate and screen sections has probably deteriorated because of open or shorted bypass capacitors, changes in tube voltages, or the presence of stray capacitive coupling from other causes.

ULTRAUDION OSCILLATOR.

APPLICATION.

The ultraudion oscillator is used to produce a sine-wave output of constant amplitude and fairly constant frequency within the r-f range. It is generally used as a variable-frequency oscillator on the very-high and ultra-high-frequency ranges.

CHARACTERISTICS.

Uses a parallel tuned L-C circuit to determine the frequency of oscillation, with a capacitive voltage divider form of feedback to control oscillation.

Operates Class C with automatic self-bias for ordinary operation.

Frequency stability is fair - similar to that of the Colpitts operating at high frequencies.

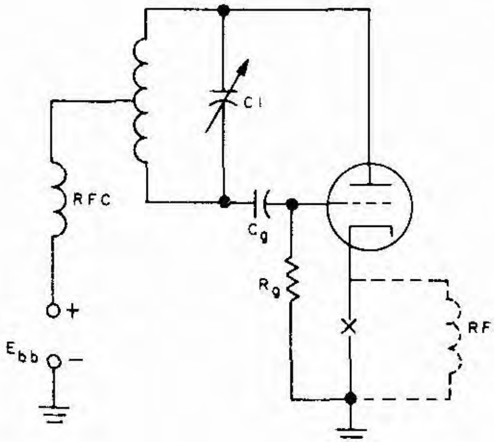
Oscillates easily at frequencies which are too high for other types of oscillators, or at which they are very unstable.

Has only one tuning control, and requires only two leads for connections between the tank and the tube.

CIRCUIT ANALYSIS.

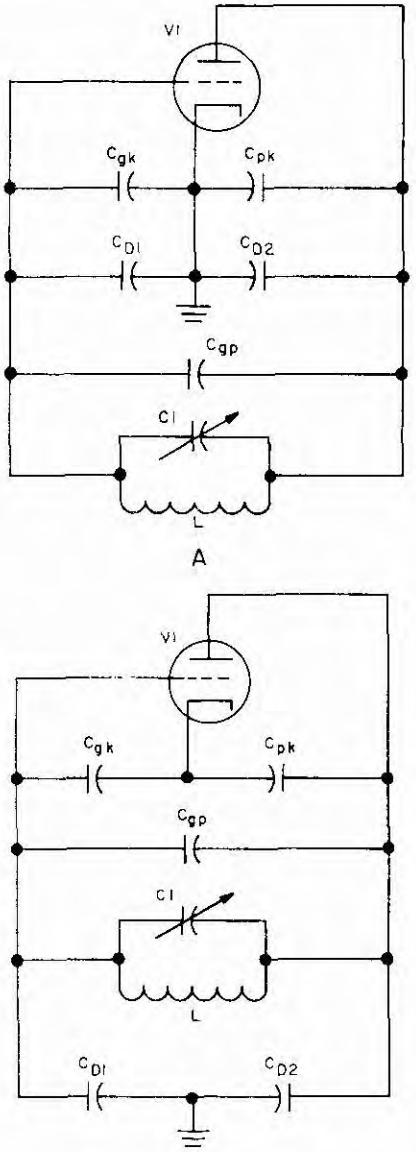
General. The ultraudion circuit is essentially a series-fed Colpitts oscillator with a parallel-tuned tank circuit for determining the frequency of operation. The previous discussion of the Colpitts oscillator circuit is generally applicable to the ultraudion oscillator. The following discussion will be limited to pointing out the basic differences of operation between the two circuits and any special considerations necessary for high-frequency operation.

Circuit Operation. The ultraudion circuit is shown schematically below. The tuned tank circuit consists of L and C1, connected between the plate and grid of the tube. Shunt grid-leak bias is used (C_g and R_g) because of the series plate feed.



Ultraudion Circuit

The radio-frequency choke shown in dotted lines in the the cathode circuit is sometimes inserted (open cathode lead at x), to minimize the effects of stray wiring capacitance; it is usually self-resonant at the frequency of operation. Although the frequency is determined by the tank circuit, the feedback is controlled by the ratio of grid-cathode and plate-cathode electrode capacitance plus any stray wiring capacitance. Operation is exactly the same as previously discussed for the Colpitts oscillator circuit. To visualize the circuit operation and component relationships, refer to the equivalent circuits shown in the illustrations. Figure A shows the basic ultraudion without the cathode RFC, and figure B shows the arrangement when the cathode choke is used; each circuit will be discussed separately.



A

B

Simplified Equivalent of Ultraudion Circuit

Since this oscillator is designed for extremely high-frequency operation, assume that the tank inductor L is merely a single wire loop of small diameter connected between the grid and plate, so that the inductor includes the leads to the tube as part of the tank. For the moment neglect C_1; since the inductor is connected between the plate and grid, it is evident that the grid-plate tube capacitance is in shunt with the inductor and forms a part of the tuned circuit, as shown in A. The grid-cathode and plate-cathode tube capacitances form a voltage divider between grid and plate, with the cathode at ground potential. Likewise, the distributed wiring capacitances C_{d_1} and C_{d_2} are in parallel with the voltage divider and, since the tube-element capacitances are small, they form a major portion of the capacitance in the voltage divider. Referring to the Colpitts theory, it is seen that C_{gk} and C_{pk} in series form the capacitance across the tank inductor. The tube-element (interelectrode) capacitance is usually small, with the grid-plate capacitance being larger than either C_{gk} or C_{pk}. Therefore, the grid-plate capacitance acts as a swamping capacitor across the tank, being equal to, and in most instances greater than, the total series grid-cathode and plate-cathode capacitances. Thus, when C_1 is added across the tank inductor, the tank circuit is relatively independent of the feedback capacitors and is the primary frequency-determining component. Where the stray wiring capacitance is large, it assumes more control over frequency than the tube capacitance does; therefore, disturbing the wiring may cause extreme detuning of the circuit.

To eliminate this stray capacitance effect and allow the tube capacitance alone to control feedback, the arrangement of B is used. In this case the cathode is above ground, as the RFC is chosen to resonate with its self-capacitance somewhere within the tuning range. Wiring and stray capacitances to ground effectively form a balanced capacitive divider across the tank circuit, but have no effect on the feedback circuit. Thus the stray wiring capacitance affects the frequency of operation to some extent, but it does not affect feedback; consequently, the tube that is most effective for the frequency of operation desired can be used.

FAILURE ANALYSIS.

No Output. Loss of, or improper, feedback will result in non-oscillation, as evidenced by a lack of grid voltage across grid leak R_g and by a high plate current because of operation near zero bias. Since the capacitance to ground of the measuring probe will change the feedback ratio at the frequencies used, a grid voltage measurement to detect non-oscillation is not as effective as at lower frequencies and in other oscillator circuits. High plate current is usually a more positive indication. At extremely critical frequencies, change of lead dress can produce stray-distributed-capacitance swamping in the unbalanced circuit. Loss of tube gain will also reduce output and, if sufficient, will cause a lack of oscillation. Tank circuit losses are more serious at the very high frequencies because the resistance introduced will prevent operation. Thus poor soldering or shorted turns will have a greater effect than at lower frequencies. [illegible] grid-leak resistance or grid blocking capacitor will also affect operation and small changes will easily stop oscillation at the higher frequencies. An open or high-resistance connection in the cathode RFC (when used) or the plate RFC will also result in a lack of output.

Reduced or Unstable Output. Low plate voltage or too high a value of grid-leak resistance will reduce the output. Poor soldered connections or high-resistance joints will also reduce the output. Unstable operation will occur if the grid-leak time constant changes because of a change in the component values of C_g or R_g. If present in a sufficient amount, stray capacitance which affects the feedback voltage will also produce instability. A reduction of filament emission will affect both the output and stability. Large changes in ambient temperature may affect output, as well as operating frequency. Tube substitutions may be critical, particularly at the higher frequencies, because of minor variations in interelectrode capacitance from one tube to another. More than one replacement tube should be tried if the first substitution does not achieve the desired results in output frequency and stability.

Incorrect Output Frequency. Any change in wiring-to-ground capacitance or lead length will affect the frequency. Changes in the tank circuit will have the greatest effect, and changes in the grid-plate capacitance and the grid- or plate-to-ground stray capacitance will have less effect, with the grid-cathode and plate-cathode variations having the least effect. Changes in the plate voltage will produce a greater frequency change at the higher frequencies than at the lower frequencies. The effects of tube substitution and ambient temperatures on output frequency were discussed above.

R-C OSCILLATORS.

The R-C oscillator uses a circuit consisting of resistance and capacitance to provide the feedback necessary for oscillation. This type of oscillator is used in the audio- and low radio-frequency range, where tuned L-C circuits are difficult to construct, are economically unfeasible, or are relatively unstable. The R-C type circuit is cheap and easy to construct, reliable, and relatively stable. Generally speaking there are two classes of R-C oscillators that produce a sine-wave output — the phase-shift and the bridge type. Nonsinusoidal oscillators are considered as relaxation oscillators and are discussed in Sections 8 and 9. There are a number of circuit variations in each class of sinusoidal oscillator, but the basic principles of operation are the same. The phase-shift type usually employs a single electron tube and a series of phase-shifting networks composed of resistance and reactance elements to produce a 180-degree phase shift, which, together with the phase shift in the tube, produces an output signal that is shifted in phase 360 degrees from the input. A portion of this signal is applied to the input as positive feedback to sustain oscillation. On the other hand, the bridge type usually uses two electron tubes to shift the phase 360 degrees, and employs some type of bridge circuit to control the positive feedback at the desired frequency of operation; it also uses inverse feedback to control the amplitude and linearity of the output signal and produce a stable signal of good waveform.

[illegible] the L-C type for a specific capacitance range, so that fewer parts are needed to cover a given range of frequencies. For example, the capacitance of a convenient tuning capacitor for the broadcast range averages about 350 picofarads maximum and 30 to 40 picofarads (including stray circuit capacitance) minimum, thus covering a range of 10 to 1 in capacitance; however, the frequency of the tuned circuit varies inversely as the square root of L x C, so with a fixed value of L the frequency will vary slightly more than 3 to 1, as confirmed by the fact that the range usually covered is 550 to 1600 kc. Since the R-C circuit frequency varies inversely as the capacitance ratio, it is possible for an R-C oscillator to cover a range of from 10 to 100,000 cycles per second in only four steps (or bands) using the conventional tuning capacitor, as compared to 12 bands for the L-C oscillator.

To provide a sinusoidal output signal, the R-C oscillator necessarily must operate Class A as a linear amplifier with positive feedback. Thus the over-all efficiency is low; as a result this type of oscillator is generally used for laboratory and test instruments, rather than as power oscillators.

The stability of the R-C oscillator in the audio range is generally much better than that of a comparable L-C circuit because the L-C circuit requires a huge inductor which is susceptible to disturbance from stray fields and it is difficult to shield adequately for maximum stability. The use of inverse feedback (when possible) aids stability as well as improves the waveform.

R-C PHASE-SHIFT OSCILLATOR.

APPLICATION.

The R-C phase-shift oscillator is used to produce a constant-amplitude, constant-frequency, sine-wave output.

CHARACTERISTICS.

Utilizes a single-stage amplifier with resistance-capacitance network to provide in-phase feedback.

Output frequency in audio range; usually fixed-frequency, but may be variable for certain applications.

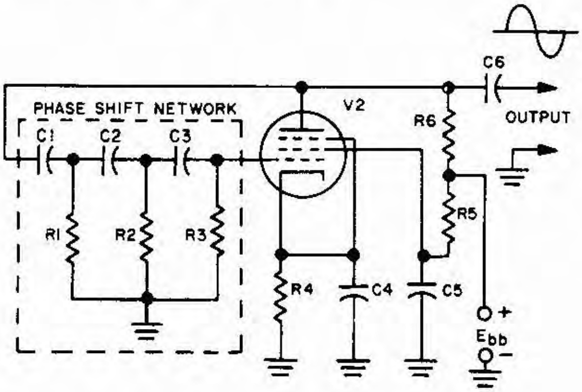
Frequency stability good.

Operated Class A to obtain a sinusoidal output.

CIRCUIT ANALYSIS.

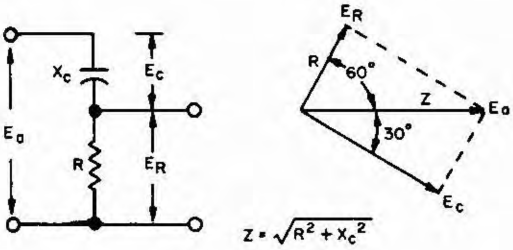
General. In the basic circuit shown in the accompanying illustration, a sharp cutoff, pentode-type tube is used as the amplifier tube; however, a triode tube can be employed in a similar circuit. Bias voltage is developed across cathode resistor R4. Cathode bypass capacitor C4, by virtue of its filtering action, keeps the bias voltage relatively constant and places the cathode at signal-ground potential. The sine-wave voltage is developed across plate-load resistor R6; capacitor C6 is the output coupling capacitor. Any variation in plate current will cause a corresponding change in plate voltage. These plate voltage variations will also be present at the grid of the tube, since the plate is coupled to the grid through the phase-shift network, Z1.

The operating condition for oscillation is a function of the amount of bias established by the cathode bias resistor, R4. The use of degenerative feedback (cancellation) and regenerative feedback (reinforcement) in the circuit simultaneously for undesired and desired frequencies is made possible by the action of the phase-shift network, Z1. The phase-shifting network is comprised of three separate R-C sections; each section is effectively a series R-C circuit. The three R-C sections are designated as C1, R1; C2, R2; and C3, R3. The discussion given in the following paragraphs describes the action of only one series R-C circuit, but applies to all three sections.



R-C Oscillator Circuit

Phase-Shift Network. It is the property of a capacitor that an a-c voltage applied across the capacitor lags the current through the capacitor by 90 degrees. In a series circuit containing both resistance and capacitance, however, the voltage lags the current by some angle less than 90 degrees. A series resistance-capacitance circuit is shown in the accompanying illustration, together with its vector diagram.



Vector Analysis of R-C Circuit

The values of capacitive reactance (X_C) and resistance (R), chosen for each section of the phase-shift network, are such as to cause a total impedance (Z). Assuming that this impedance represents the first section of the phase-shift network, it is across this section that plate-voltage variations are applied. The applied voltage is represented in the vector diagram as E_a. The circuit current passes through resistor R and, since this current leads the applied voltage E_a by 60 degrees, the voltage drop E_R across resistor R leads the applied voltage E_a by 60 degrees. The voltage, E_R, developed across resistor R is applied to the second section and is shifted another 60 degrees in phase, so that the output voltage of the second series R-C section leads E_a by 120 degrees. The output voltage of the second R-C section is applied to a third section, and is again shifted an additional 60 degrees to lead the applied voltage E_a by a total of 180 degrees. The output of the third R-C section is applied to the grid of the tube.

Referring to the vector diagram, it is apparent that, since the capacitive reactance (X_C) varies with frequency, the frequencies above or below the frequency for which the circuit is designed will be shifted more or less than 60 degrees by each section of the network, so that the total phase shift contributed by all three sections will be something more or less than exactly 180 degrees. In this manner, the circuit is caused to oscillate at only one frequency; that is, the frequency which is shifted exactly 180 degrees by the phase-shift network, Z1.

By increasing the number of phase-shift sections comprising the network, the losses of the total network can be decreased; this means that the additional sections will each be required to have a lesser degree of phase shift per section so that the over-all phase shift of the network remains at 180 degrees for the desired frequency of oscillation. Assuming that the values of R and C are equal in all sections, networks consisting of four, five, and six sections are designed to produce phase shifts per section of 45, 36, and 30 degrees, respectively.

Circuit Operation. Oscillations are initially started in this circuit by small changes in the B-supply voltage or by random noise. If it were not for the action of the phase-shift network, Z1, the voltage variations fed from the plate back to the grid of the tube would cancel the plate-current variations, since the tube introduces a polarity inversion between the grid and plate signals. For example, if the plate-voltage variation at any instant of time was positive, the positive variation would be present on the grid. This positive-going grid voltage would then cause the plate current to increase, in turn causing the plate-voltage variation to go negative and, thus, cancelling out the original grid-voltage variation.

Assuming that the plate-voltage variations are applied to the grid 180 degrees out-of-phase with respect to the initial grid-signal voltage, maximum degeneration (or cancellation) will occur. However, if the plate-voltage variations fed back to the grid approach zero-degree phase difference, minimum degeneration will occur. Therefore, if the phase difference between the plate-voltage variations and the initial grid-signal voltage is exactly zero (in phase), the plate-voltage variations will reinforce the grid-signal voltage at any instant of time, causing regeneration; furthermore, these variations will be amplified by the tube and reapplied to the grid, amplified again, and so on, until a point of stage equilibrium is reached and no further amplification takes place. The phase-shift network provides the required phase shift of 180 degrees to bring the voltage fed back to the grid in phase with the initial grid-signal voltage and cause regeneration. The circuit then oscillates under these conditions with relatively constant amplitude.

The phase-shift oscillator is designed primarily for fixed-frequency operation; however, the operating frequency can be made variable by using variable resistors or capacitors in the phase-shift network. An increase in the value of resistance or capacitance will decrease the operating frequency; a decrease in the value of resistance or capacitance will increase the operating frequency. In several practical applications of this circuit, three or more fixed R-C sections are employed together with a variable section to provide a limited range of output frequencies which are determined by the setting of a variable capacitor. In this circuit variation, the fixed R-C sections use values of R and C which will provide a phase shift somewhat less than 180 degrees at the operating frequency desired, and the last (variable) R-C section completes the required phase shift to exactly 180 degrees. The operating frequency is then determined by the setting of the variable capacitor.

FAILURE ANALYSIS.

No Output. Assuming that the applied voltages are correct, the lack of output results from two possible conditions; either the gain of the tube has decreased to a point where gain is insufficient to overcome the losses inherent in the phase-shift network, or one or more sections of the phase-shift network is possibly defective and does not provide proper phase shift of the plate-to-grid feedback signal.

In some cases, the phase-shift network must be replaced as an assembly if found defective. In cases where the phase-shift network is composed of individual resistors and capacitors, the individual components may be checked and replaced if found defective.

Reduced Output. Reduced output is generally caused by decreased stage gain; however, a small reduction in gain may cause oscillations to cease before any appreciable decrease in output can be detected.

Nonsinusoidal Output. Nonsinusoidal output results when the tube is operating on the nonlinear portion of its characteristic curve. Such operation results from a change in B-supply voltage or bias voltage which causes partial or complete clipping of the output waveform.

Output Frequency Incorrect. Since the values of resistance and capacitance that form the phase-shift network determine the operating frequency of the oscillator, any change in component values will be reflected as a change in the frequency of oscillation.

WIEN-BRIDGE OSCILLATOR.

APPLICATION.

The Wien-bridge oscillator is used as a variable-frequency oscillator for test equipment and laboratory equipment to supply a sinusoidal output of practically constant amplitude and exceptional stability over the audio-frequency and low-radio-frequency ranges.

CHARACTERISTICS.

It uses a bridge circuit to supply positive feedback voltage at the R-C frequency to produce oscillation.

It operates as a Class A linear amplifier and employs negative feedback to produce an almost perfect sine-wave output.

It also uses negative feedback to provide a practically constant output amplitude.

Frequency stability is excellent (2 to 3 parts per million).

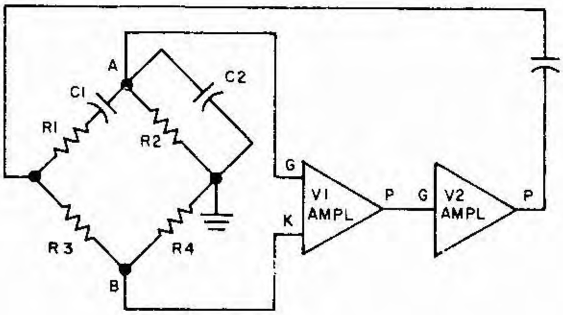
Operates over a wide frequency range (10 cps to 200 kc or higher).

CIRCUIT ANALYSIS.

General. When the output of a linear amplifier is applied to its input, a feedback loop is produced. If the feedback is out-of-phase with the input, or negative, the amplifier output will be reduced. If the feedback is in-phase, or positive, the amplifier will oscillate. The frequency of oscillation for positive feedback can be controlled by using a frequency-selective network in the feedback loop, such as the Wien bridge. When negative feedback is applied to the cathode circuit of an amplifier, it produces a degenerative effect which reduces the output and improves the amplifier response (this is called inverse feedback). By use of the impedance bridge circuit a differential input can be used to provide oscillation at the desired frequency, with amplitude and waveform control.

Circuit Operation. The basic bridge circuit and feedback loop are shown in the accompanying simplified diagram. In the actual circuit, R4 is a small incandescent lamp with a tungsten filament, and is normally operated at a temperature that produces a dull red or orange glow to give automatic control of amplitude (thermistors are also used). Resistors R1 and R2 are of equal value, as are capacitors C1 and C2, with R3 having twice the resistance of lamp R4 at the operating temperature. The bridge is balanced and the circuit oscillates at a frequency given by:

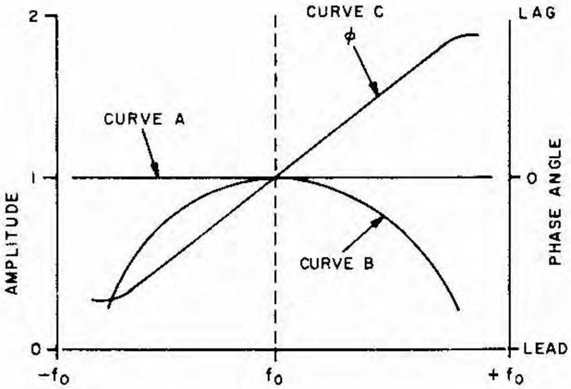
$$f_0 = \frac{1}{2\pi \ R1C1}$$



Simplified Wien Bridge Oscillator

It can be seen by inspection that resistors R3 and R4 form a resistive voltage divider across which the output voltage of V_2 is applied. Since these resistors are not frequency-responsive, the voltage at any instant from point B (and the cathode of V1) of the bridge with respect to ground is dependent upon the ratio of R3 to R4 for any frequency which the amplifier produces at its output. Components R1, C1 and R2, C2 form a reactive voltage divider, between the output of V2 and ground, which is frequency-responsive, with the grid of V1 connected at point A. Thus the voltage across R2 is applied to the input of the amplifier, between grid and ground. When the voltage between point A and ground is in phase with the output voltage of V2, maximum voltage will appear between the grid and ground; therefore, maximum amplification occurs and a large output voltage is produced by V2. Two amplifier stages, V1 and V2, are used to produce a total phase shift of 180 degrees x 2, or 360 degrees, to insure that the voltage at the output is in phase with the input. Thus reactive networks R1, C1 and R2, C2 are not required to shift the phase to produce oscillation, but are used to control the frequency at which oscillation takes place.

The manner in which these various feedback voltages vary in amplitude and phase are best shown by the graphic representation below. The center (dotted) vertical line, (ordinate) represents the frequency at which the oscillator operates. The left and right vertical lines represent a frequency much lower than the operating frequency, and a frequency much higher than the operating frequency, respectively.

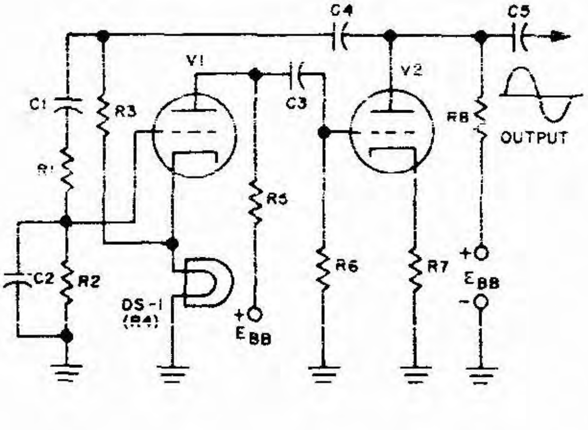


Phasing Diagram

Curve A represents the negative feedback between point B of the simplified schematic and ground. Since it is the same at all frequencies, it is represented by the horizontal line covering the middle of the graph. Curve B represents the positive feedback voltage existing between the grid (point A) of V1 and ground, or the voltage across R2. At frequencies below the operating frequency (f_o), the series reactance of C1 is large, and the voltage across R2 is reduced. As the operating frequency is approached, the reactance diminishes, and the voltage across R2 reaches a maximum at f_o. As the frequency is increased above f_o, the parallel reactance of C2 shunts R2, effectively reducing the voltage across R2. Thus, both above and below f_o the voltage across R2 is reduced, and only at the operating frequency is it a maximum. At this frequency, the positive *feedback voltage (at the grid)* is exactly equal to (or very slightly greater than) the negative feedback voltage (at the cathode), amplification is at a maximum for V1 and V2. Now consider the phase of the output voltage which is fed back to the input of V1; this is shown by curve C. Because of the phase shift produced by R1, C1, a phase shift occurs above or below the operating frequency; at the operating frequency, *however, the phase change is zero*, and the output of V2 is exactly 360 degrees from the input voltage, because of the phase inversion through two stages of amplification. Thus, below f_o the phase angle leads and above f_o it lags. The out-of-phase voltage above and below f_o, together with the decrease in the regenerative feedback voltage applied to the grid as compared with the degenerative feedback voltage applied to the cathode of V1 *effectively* stops oscillation at all frequencies except the operating frequency, where R1C1 equals R2C2.

The schematic of the Wien bridge oscillator is shown in the accompanying illustration. Operation is the same as previously discussed. Amplitude regulation is provided by the use of resistor R4, which is an incandescent lamp (DS1) with a tungsten filament. The current through this lamp consists of the cathode current of V1 plus the a-c current at the oscillating frequency through R3 and R4. The design is such that the lamp is operated at a temperature-sensitive point (where the resistance of the lamp changes rapidly with temperature). When the amplitude of oscillation tends to increase, the a-c component of the current through the cathode and through the lamp increases. The resistance of R4 (DS1) increases in value because of its higher temperature, and, being in the inverse feedback circuit causes an *increase of degenerative feedback. Thus, the amplitude* of oscillation is automatically reduced back toward the original level.

In the schematic, resistors R1, R2, R3, and DS1 and capacitors C1 and C2 form the arms of the Wien bridge.



Wien Bridge Oscillator

Tube V1 is R-C-coupled through C3 to the grid of V2. R5 is the plate resistor of V1, which produces a 180-degree phase inversion. *Resistor R6 is the grid resistor for V2* across which the output of V1 is applied. The circuit design is such that the phase shift through the coupling network consisting of R5, C3, and R6 is kept to a minimum. The cathode of V2 is biased by R7, which is left unbypassed to provide degeneration and help keep the output waveform linear. The sinusoidal output waveform is developed across R8 and applied through C4 *from the plate of V2 to the input* of the Wien bridge as a 360-degree phase-shifted signal, which is now in-phase with the original signal. An output is also taken from the plate of V2 through capacitor C5 for external use. The values R8, C4, and C5 are also chosen to provide an absolute minimum of phase shift, so that the bridge circuit alone determines the feedback frequency. The operation of this *circuit is similar to that of the basic* circuit described above, with the oscillation frequency being at the frequency where R1 C1 equals R2 C2 and with waveform linearity retained by inverse feedback through R3 and R4. Biasing is a combination of cathode and contact bias, with a large amount of degeneration (inverse feedback) being provided by the unbypassed cathode bias circuits; the output waveform is extremely linear. The output amplitude is small because of the large amount of degeneration employed, and circuit stability is excellent with a minimum of phase shift or frequency variation.

FAILURE ANALYSIS.

No Output. Since the feedback loop involves two tubes and a bridge network, it is apparent that an open circuit in the coupling capacitors or bias resistors will stop oscillation immediately. An excessive phase shift caused by *the change of coupling network* values due to aging may also cause stopping of oscillation at the lower frequencies. It is rather improbable that changes due to the aging of tubes would result in the stoppage of oscillation, although failure of one tube due to lack of emission or loss of gain could prevent operation. A defective lamp would produce an open cathode circuit in V1 and stop oscillation. Usually a resistance check *will quickly isolate the trouble in this circuit.*

Reduced or Unstable Output. The principal components to suspect in the case of reduced output are the electron tubes and the degenerative feedback components. An increase of cathode bias resistance with age or leaky capacitors which place improper bias on the grids not only will reduce the output, but will probably distort the waveform. Poor connections and soldered joints will also cause either condition. Following the signal path from grid to plate with an oscilloscope will quickly show lack of amplitude and any waveform distortion. Motorboating at low frequencies may occur through common impedance coupling in the power supply, and should be suspected if oscillations are produced at more than one frequency simultaneously.

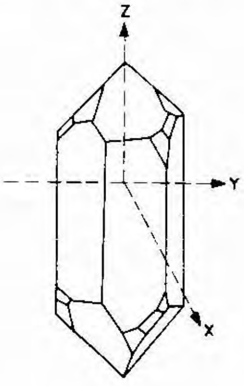
Incorrect Frequency. Since the frequency is primarily under control of the reactive portion of the bridge network, these components should be suspected when the frequency is incorrect. Where band switching and tuning arrangements are included in the design, faulty switches, poor contacts, and bad connections would be the primary cause of frequency shift.

ELECTROMECHANICAL OSCILLATORS.

The electromechanical type of oscillator combines the extreme stability of the high-quality mechanical oscillator with electrical control of excitation to attain a frequency stability on the order of 0.0015 percent (for quartz) without temperature compensation. Generally speaking, there are two types of electromechanical oscillators: the crystal type and the magnetostriction type. The crystal type of oscillator uses natural or synthetic nonconducting crystals excited by the piezoelectric effect and vibrating at or near their natural frequency to control the frequency of oscillation; the magnetostriction type uses a magnetic field to excite a metal bar, rod, or tuning fork at its mechanically resonant frequency.

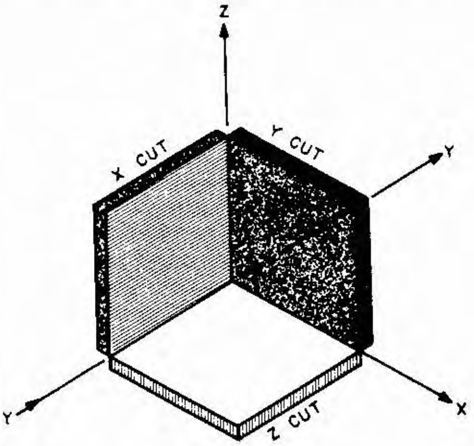
The electrical excitation of the mechanical device at or near its fundamental, harmonic, or subharmonic frequency produces stable mechanical oscillations; these are converted into electrical impulses of the same frequency and are fed back into the oscillator circuit to sustain highly stable oscillations at the desired frequency of operation.

The magnetostriction oscillator is usually used only at audio frequencies, and the crystal oscillator is used at both audio and radio frequencies. For audio frequencies, the crystals usually consist of Rochelle salt (sodium potassium tartrate), which breaks down and decomposes at temperatures above 135 degrees Fahrenheit. For radio frequencies, other kinds of crystals are used. The most popular, economical, and plentiful kind is the quartz crystal (shown below), which in its natural (alpha) state only requires cutting, grinding, and polishing to size. The frequency of oscillation is determined mainly by the thickness (or length for very low frequencies) of the crystal slab. The crystal cannot be made to vibrate too strongly or it will shatter. Tourmaline crystals were once popular for the higher frequencies since they are more rugged and thicker for a given frequency. Because of the expense and scarcity of large-sized crystal prisms, and since tourmaline has a negative temperature coefficient which prevents a zero-temperature-coefficient cut from being obtained, tourmaline crystals are not in common use today, although they may occasionally be encountered.

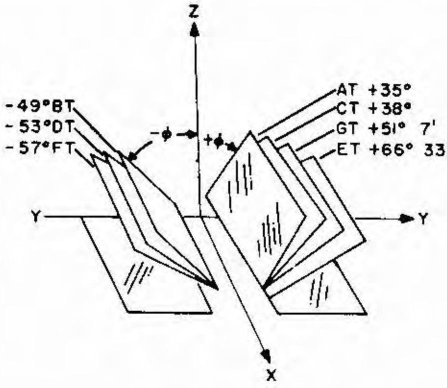


Natural Quartz Crystal, Showing the X, Y, and Z Axes

Originally there were only two quartz crystal cuts, X and Y, with axes at right angles as shown in the illustration. However, today there are many cuts at slightly different angles, each having a certain temperature coefficient over a limited range of temperature and frequencies. The most stable is the GT cut, which has a zero temperature coefficient over a range of 100 degrees centigrade, within the r-f range of 100 to 500 kc. As might be expected, this cut is expensive; therefore, it is used only in primary standards and clocks where the greatest accuracy is necessary. The X-cut family includes the X, V, MT, NT, 5° X, and 180°X, covering a range of 5 to 20,000 kc; the Y-cut family (shown below) includes the Y, AC, AT, BC, BT, CT, DT, ET, EF, and GT, covering a range of 60 to 20,000 kc, of which the AT and BT are the most popular.



Relationship of Axes to Cuts

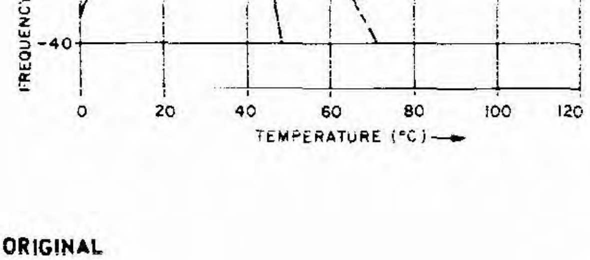


Typical Y Cuts

Since the high-frequency crystals are thinner, it is evident that there is a frequency at which the thinness and fragility of the crystal determine the maximum frequency of operation. Therefore, there is a definite high-frequency limit beyond which the use of crystals is impracticable. The low-frequency limit is mostly defined by the bulk of the crystal and its mounting problem. Actually, for low audio frequencies, the Rochelle salt type of crystal is used (for laboratory and experimental work) in preference to the quartz crystal, mostly because of the difficulty in securing basic quartz prisms of the proper size and their accompanying high cost.

While the natural frequency is the one most used, it is also possible to grind crystals to operate on harmonics (called **overtones**) which are **not** integral multiples of the fundamental frequency. Overtone operation is also aided by special circuits to ensure or enhance this type of oscillation. Thus, an extremely high-frequency output can be obtained by the use of second, third, fourth, or fifth overtone operation (overtones usually utilize the odd rather than the even values) with a stability equal to that of the fundamental frequency. Therefore, crystal control is economically feasible and practical in the very-high and ultra-high-frequency regions, where frequency stability becomes a problem, with a minimum number of doubler and tripler stages.

Generally speaking, the X-cut crystal is slightly thicker than the Y-cut crystal; therefore, for a given application the X-cut crystal can produce a greater output. Originally, temperature compensation was a requirement for frequency stability, but with the various low-temperature-coefficient cuts now available, it is usually not necessary to use temperature control except for the most rigorous use, as in frequency standards and frequency synthesizers, or where the ambient temperature varies greatly, as in aeronautical or mobile operation. The following chart illustrates several crystal cuts and their temperature-frequency variations. It is seen that the GT cut varies only slightly over a large range of temperatures, while the CT cut varies rapidly first in a positive direction and then in a negative direction over a relatively small range of temperatures. The BT cut is an expanded version of the CT cut, covering a greater range of temperatures. Although the AT cut also varies considerably, it reaches zero variation over a small temperature range around 50 degrees centigrade, and varies only 5 parts per million for a + or − change of 15 degrees.



Synthetic crystals simulating the structure of quartz are available, but are not in mass production at the present state of the art; hence, in the following circuit discussions, the term **crystal**, unless otherwise indicated, will mean a natural quartz crystal. Since the designing and producing of crystals is a field and science of its own, they will hereafter be discussed only when their properties are pertinent to circuit operation. For further information on crystallography, see the Handbook of Piezo-electric Crystals for Radio Equipment Designers (WADC Technical Report #56-156, dated October 1956), which is available through the Department of Commerce.

There are two types of operation possible with crystal oscillators, namely, **crystal-controlled** operation and **crystal-stabilized** operation. The crystal-controlled oscillator is defined as an oscillator which will not oscillate without the crystal, and whose operation is at all times under complete control of the crystal. On the other hand, the crystal-stabilized oscillator is inherently a free-running oscillator without the crystal in place, but when the frequency of resonance of the crystal is approached, the free-running oscillator locks in and is kept operating in a stabilized state over a small range around the crystal frequency. Thus, the crystal-stabilized oscillator provides most of the benefits of the crystal-controlled oscillator, but is slightly more susceptible to frequency instability because of the inherent free-running design. The following circuit discussions are limited to the crystal-controlled type of oscillator since it is the only type used in the Navy.

GRID-CATHODE (MILLER) CRYSTAL OSCILLATOR

APPLICATION.

The Miller crystal oscillator circuit is used to supply a constant-frequency sine-wave output at a relatively constant amplitude, usually within the r-f range. This circuit is used wherever a highly stable specific frequency is needed, such as the basic oscillator in a transmitter, receiver, frequency standard, or test equipment.

CHARACTERISTICS.

Utilizes piezoelectric effect of a natural or synthetic crystal to control frequency of oscillation.

Crystal is connected between grid and cathode of an electron tube.

R-F feedback occurs only through grid-to-plate interelectrode tube capacitance.

Operates normally with class B or C automatic self-bias, but may be operated class A or with combination fixed and self-bias for special designs.

Frequency stability is excellent, with or without temperature compensation.

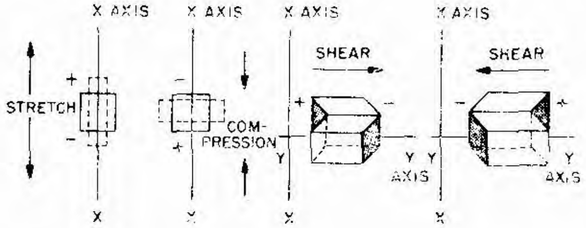
Output amplitude is relatively constant.

CIRCUIT ANALYSIS.

General. Before circuit operation is considered, a brief review of basic crystal principles is given for background.

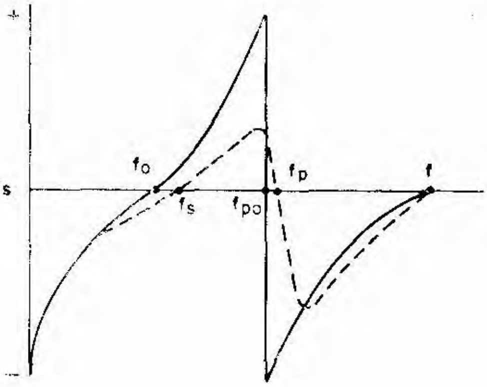
A quartz prism has three basic axes, X, Y, and Z. The Z axis is the optical axis, the Y axis is considered the mechanical axis, and the X axis is considered the electrical axis (see quartz crystal illustrated above). No piezoelectric effects are directly associated with the Z axis; an electric field applied in this direction produces no piezoelectric effect on the crystal, nor will a mechanical stress along the Z axis produce a difference of potential. A simple compressional or tensional mechanical stress applied along the Y axes will cause a change of polarization of the X axis, but not the Y axis; however, if a shearing or flexural strain is applied along the Y axis a change of polarization will occur. When the crystal is stretched along the X axis, a positive charge will appear on one end of the crystal, and when the crystal is compressed along the X axis, a negative charge will appear. Thus, piezoelectric effects are produced for either X- or Y-cut crystals, as shown in the accompanying illustration.

The piezoelectric effect is defined as that effect which produces a potential across the parallel faces of a crystalline dielectric substance when pressure or torsional forces are applied between the faces, or, conversely, that effect which causes the crystal to distort itself when a voltage is applied between the faces. Thus, when alternating voltages are applied between the crystal faces, it will oscillate (vibrate mechanically) at a specific frequency, which is determined mainly by the thickness of the crystal.



Piezoelectric Action

When loosely coupled to a suitable oscillator circuit and excited at the proper frequency, the crystal will stabilize the frequency of oscillation. If the circuit is arranged to provide self-oscillation at the natural frequency of vibration of the crystal and will not oscillate without the crystal, it is a crystal-controlled oscillator. Normally, a crystal has two frequencies or modes of operation: the **resonant** (fundamental) frequency, or **series** mode, and the **antiresonant** frequency, or **parallel** mode. The series and parallel modes are similar to the equivalent types of resonance. In the series mode, the crystal presents a low impedance and provides a maximum of stability. In the parallel mode, it presents a high impedance (usually considered infinite), since the crystal is used as a high-Q inductor which is resonated with the crystal circuit shunt capacitance (including crystal and holder capacitances), to form a highly stable **parallel-resonant circuit** operating at the antiresonant frequency of the crystal. The antiresonant crystal frequency is always slightly higher than the natural, or series-resonant, frequency.



Variation of Series Reactance of Crystal with Frequency

The variation with frequency of the series reactance (X_s) of a typical quartz crystal is shown qualitatively in the accompanying figure. The solid line represents the condition where the resistance R is equal to zero (which is only theoretically possible); the dotted line represents the true conditions where R has some finite value. Thus, where R is equal to zero, the series reactance is equal to

zero at $f_o = \frac{1}{2\pi\sqrt{LC}}$ and changes

from + infinity to − infinity at the frequency f_{po} (the solid line on the graph). When R is greater than zero, the dotted line indicates that the series crystal reactance has a finite maximum and minimum, and that it actually has a zero value at both f_s and f_p, the series- and parallel-resonance frequencies. For a reasonably small R, the frequency difference between f_s and f_p is approximately the same as that between f_o and f_{po} (they are quite close). In practice, the frequency difference between series and parallel resonance varies with the type of crystal and its cut. For example, a GT-cut quartz crystal can have a difference as low as 0.08 percent of the resonant frequency, and an AT-cut crystal can be as great as 2 percent.

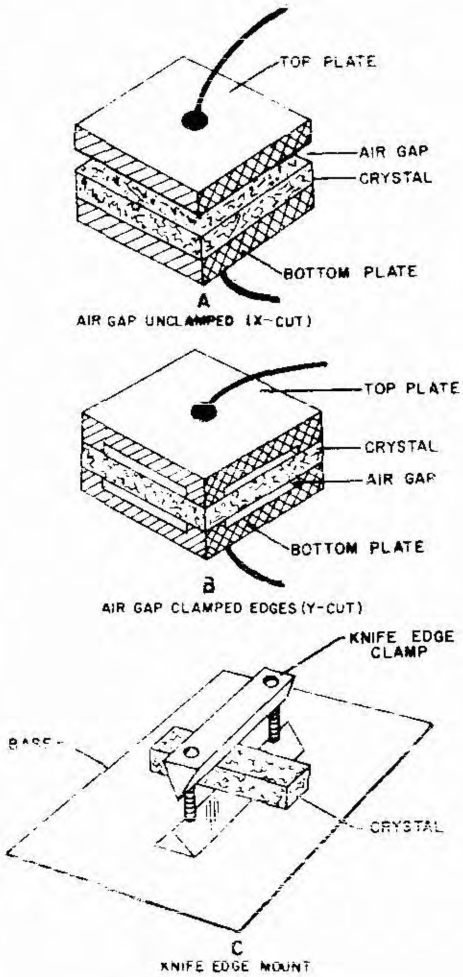
The series mode of operation is usually used for wave-filter circuits where a specific frequency is to be absorbed, or for overtone oscillators operating at high frequencies. The parallel mode is usually used in oscillator circuits where its extremely high Q produces stable operation not normally possible with the ordinary inductor or LC tank circuit. As issued, the antiresonant (parallel-resonant) frequency is marked on the holder unless otherwise specified on the nameplate (overtone crystals are stamped at the overtone frequency). Crystal calibration and rating are for a specified shunt capacitance and holder, and for operation in a **standard** circuit. For MIL STD crystals the circuit is that specified in the Standard. For commercial crystals the schematic of the circuit used for calibration is generally supplied with the unit, or is otherwise specified. When used in a **nonstandard** circuit, the crystal will operate at a slightly different frequency from the calibration obtained in the standard circuit (±3 kc maximum), depending upon the tolerance to which it is ground, the holder capacitance, and stray inductance and capacitance effects of wiring.

Generally speaking, the series-resonant crystal oscillator has greater frequency stability and can generate higher frequencies, *whereas the parallel-resonant type oscillator* is more economical to construct, can operate over a wider frequency range (by substitution of different crystals), and can generate greater output. However, there are a number of exceptions to this general rule. The **parallel-resonant oscillator** is primarily used with fundamental-mode crystals *at frequencies below 20 mc. In conventional circuits of* this type, the crystal must operate between its resonant (series-resonant) and antiresonant (parallel-resonant) frequencies, thereby behaving as an inductor. Under these conditions, the circuit will not oscillate if the crystal becomes defective and the oscillator is a true crystal-controlled type. *Maximum stability is achieved with low cry*stal drive and with operation in the class A to class B range. For maximum power output, the oscillator is operated class C. With normal voltages the electromechanical coupling in the parallel mode of operation tends to become too weak to sustain oscillation at the higher frequencies. This *reduction in coupling, plus the shunting effects of tube and* crystal capacitances, makes increased drive and plate voltage necessary to produce oscillation, thus leading to crystal fracture or instability; hence, it is impractical to use the parallel mode at the higher frequencies. It is possible though, by frequency multiplication in a number of subsequent stages, to obtain high-frequency operation with a parallel mode basic crystal.

The **series-resonant oscillator** is almost always used with overtone crystals. Because the output is lower than that of the parallel-resonant type, the operating range is restricted, and more parts are required. The series-resonant crystal oscillator is usually used only for high frequencies, or for low and medium frequencies where special design considerations make its use justifiable (mostly for frequency standards and laboratory and test equipment).

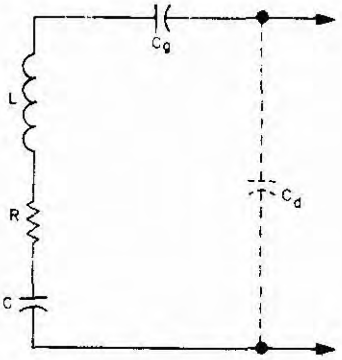
The inertia of the mechanical equivalent of the crystal oscillator provides a stable oscillatory action that is little affected by the varying parameters of the electron tube circuit (and for which crystal controlled oscillators are noted) so that changes of tube capacitance or line voltage have little effect on the frequency of operation. In fact, the change of crystal dimensions with temperature usually has a greater effect. In this respect, the X-cut crystal has a **negative** temperature coefficient of 20 to 25 parts per million per degree centigrade (a 10° C rise in temperature of a 5000-kc crystal produces a lowering in frequency of 1000 to 1250 cps), and the Y-cut crystal has a **positive** temperature coefficient of 75 to 125 parts per million per degree centigrade. Thus, it can be understood that various crystal cuts provide different temperature coefficients, each suitable for different ranges of operation, with each different cut designed for zero temperature coefficient (see previous illustrations for typical cuts and typical temperature-frequency variations) or as near thereto as possible. (The GT cut is the only one which covers a large range of temperatures.) For exact frequency operation, as needed in *frequency standards or for special uses, temperature com*pensation is utilized, with the crystal ground and cut for a zero temperature coefficient over a temperature range easily sustained by the thermostatically controlled oven.

The effect of the crystal holder and the shape of the crystal have a slight effect on the resonant frequency, which varies with the cut. For example, a Y-cut crystal may be clamped at the edges without affecting operation (see accompanying illustration), whereas an X-cut crystal will oscillate only if all edges are free. Since the crystal is mounted between two metal plates and is a dielectric, there is an equivalent capacitance for the crystal determined by its dimensions, plus a capacitive effect due to



Typical Mountings

the plates of the holder. Thus air gap holders, provided with a variable top plate adjustment, are sometimes used. Changing the effective capacitance by adjusting the gap changes the frequency of operation slightly (from 500 cps to 3000 cps maximum).

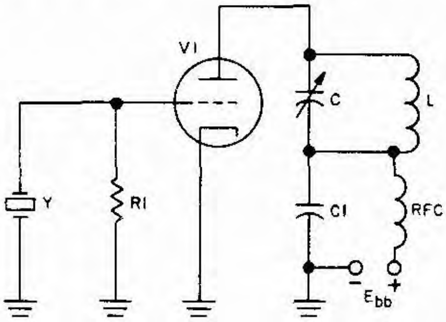


Crystal Equivalent Circuit

The electrical equivalent circuit of the crystal and holder is illustrated in the figure above, to show the parameters and components needed to simulate a single quartz crystal. The inductance, L, is on the order of henries (for low-frequency crystals) with a Q of 100,000 or better. The series resistance, R, varies from unit to unit but is usually less than 500 ohms (the lower the better since it represents a loss of power). The capacitance of the crystal without a holder is represented by C and is on the order of a few picofarads. Where an air gap holder is used, the capacitance of the holder air gap is in series with the crystal, as indicated by C_g. The holder capacitance (with no air gap) appears in shunt with the crystal and also includes any wiring, stray, and distributed capacitance plus the grid interelectrode capacitance of the tube, all of which are lumped together as C_d. For the parallel-resonant mode of crystal operation, this capacitance is fixed at 32 picofarads for Military Standard crystals.

The Miller-type crystal oscillator uses the crystal connected between the grid and cathode tube elements. Because of its popular usage, it is sometimes considered the basic crystal oscillator. However, the Pierce-type crystal oscillator which uses the crystal connected between the grid and anode tube elements, and is discussed later in this section, is also a basic type of crystal oscillator. In some other texts the Miller oscillator may be called the Pierce-Miller oscillator. However, to avoid confusion in this Handbook, the grid-cathode-connected crystal is called the Miller oscillator, while the grid-plate-connected crystal is called the Pierce oscillator. The Miller circuit is popularly used because, for a given amount of crystal excitation, it provides a greater output than any other circuit arrangement; the output is greater because the basic feedback occurs between the grid and plate of the electron tube, and not through the crystal. This also prevents the crystal from being subjected to sufficient strain to cause fracture of the crystal, and the tube may be driven harder.

Circuit Operation. The basic Miller oscillator is shown in the accompanying illustration. The crystal is located between the grid and cathode, and grid-leak bias is obtained through R1, with the shunt capacitance of the crystal, together with that of the holder, acting as the grid-leak capacitor. The tuned tank circuit, LC, is located in the plate-to-cathode circuit. As shown, the rfc and C1 form a conventional series plate-feed decoupling circuit, but the tank may be shunt-fed, if desired.



Basic Crystal (Miller) Oscillator

Crystal action in controlling oscillation can be explained as follows: Assume that the tank circuit in the basic oscillator is tuned to a higher frequency than the antiresonant (parallel-resonant) crystal frequency, so that the plate circuit appears inductive. Assume also that filament and plate potentials are applied and that the crystal is not vibrating. A positive voltage is present between plate and ground, and a negative voltage is present between grid and ground (due to contact potential). By piezolectric action, the negative grid voltage will cause the crystal to be deformed slightly. Assume that a noise pulse occurs and causes the grid to go more negative, thus further deforming the crystal. The deforming of the crystal produces a piezoelectric action, increasing the charge on the grid in the same direction, and drives it further negative. When plate current cutoff is reached, the feedback becomes zero, and the accumulated grid voltage discharges through grid leak resistor R1. As the grid voltage is reduced, the deformation of the crystal is reduced, and the negative piezoelectric charge on the grid is also reduced by a corresponding positive induced piezoelectric voltage until plate current again flows. This cumulative action causes the crystal to vibrate mechanically near its parallel-resonant frequency. Once started the vibrations continue and induce in the grid circuit an a-c voltage of a frequency almost equal to the vibration frequency of the crystal. As long as the plate tank is tuned to present an inductive reactance, the proper phase for feedback is maintained. When the tank is tuned on the capacitive side of the frequency of oscillation (to a lower frequency), the phase of the crystal oscillation opposes the plate-to-grid feedback, and oscillation is reduced and eventually stopped. Tuning the tank circuit allows the feedback to be controlled from minimum to maximum with a corresponding output. To produce the proper phase relationship, tuning is approached from the high capacitance side of resonance. Plate current varies in a similar manner from a high value to a low value at the optimum point, then suddenly increases and abruptly reaches its normal static (non-oscillating) value as the series-resonant frequency is approached. The action described, although slightly exaggerated for ease of understanding, happens very quickly. That is, the tube reaches its class B or C operating condition in one or two cycles of operation.

Since the crystal is essentially the equivalent of a high-Q circuit, it resonates only over a very narrow range of frequencies *(tuning is very sharp)*. Therefore, slight changes in tube parameters and supply voltages have a minimal effect, about 100 to 200 times less than in the conventional LC oscillator.

Biasing Considerations. In the basic Miller oscillator shown above, the bias is supplied by means of grid-leak action, as in the conventional LC feedback oscillator. Since the crystal represents a very high-Q circuit (a Q of 100 times or more than that of the conventional LC tank), it is evident that grid leak resistor R1 effectively acts as a shunt for the voltage generated by the vibrating crystal. Therefore, an r-f choke is sometimes placed in series with the grid leak to reduce the load on the crystal and help it start oscillating more easily. When a bias battery replaces the grid leak and the series-connected r-f choke is also used, the grid operating point is fixed by the battery bias, and the circuit can be adjusted for maximum power output, with minimum crystal excitation and good output waveform. The combination of battery bias and r-f choke, however, does not make for easy starting. The use of cathode bias, together with the r-f choke and with or without the grid *resistor, normally provides the most effective starting,* and is used where keyed oscillator operation is required (maximum stability dictates that keyed operation be avoided).

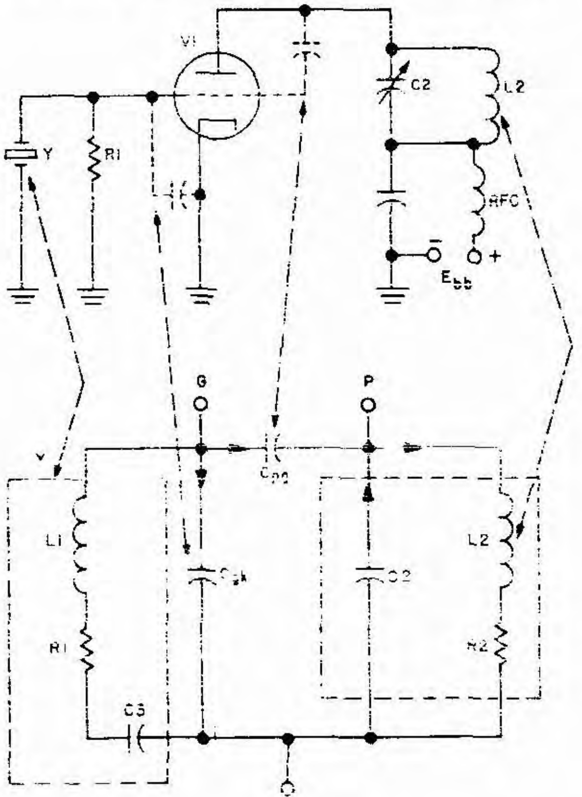
As the bias is increased, the crystal current increases, because more excitation is needed to swing the operation into the cutoff region and overcome the bias. The increased bias also increases the mechanical distortion of the crystal and causes it to vibrate harder. If driven excessively, the crystal will shatter.

Other Considerations. The plate voltage applied to the crystal oscillator is limited to a value lower than that applied to the standard LC oscillator, because as the power increases with an increase of plate voltage, so does the feedback voltage, which in turn increases the current through the crystal. The increase of crystal current has two effects: (1) it may exceed the value where it causes the crystal to vibrate so strongly that it shatters; (2) since the temperature of the crystal depends upon the current flow through it among other things, unless the crystal has a zero temperature coefficient over a wide enough range, the frequency of operation will vary, either increasing or decreasing, depending upon whether the temperature coefficient is positive or negative.

Temperature changes external to the crystal will change the grid-to-plate interelectrode capacitance of the tube, and supply voltage changes will change the plate impedance *and affect the frequency of operation. This frequency* change occurs in parallel-resonant crystal operation because either a change in the feedback capacitance or the plate load impedance will affect the phase shift in the feedback loop, and cause the crystal to operate at a frequency somewhat nearer to or farther from the antiresonant frequency, to satisfy the conditions for sustaining oscillation.

The Miller oscillator provides an average frequency deviation of approximately 1.5 times that of the Pierce oscillator (to be discussed later) and is therefore less stable than the latter circuit. On the other hand, it will give the same output (or slightly more) with only half the grid excitation and crystal current. Thus, with the same *excitation, the Miller oscillator can supply twice the power* of the Pierce oscillator and effectively obviate the need for an additional stage of amplification to bring its output up to the value needed to drive a following power amplifier. (The high output power largely accounts for the popularity of the Miller circuit and its almost universal used.) When used with a pentode, the Miller circuit provides maximum output with minimum crystal strain and excitation, and also greater stability (see the Electron-Coupled Crystal Oscillator circuit discussion given later in this section).

Detailed Analysis. The basic Miller oscillator is considered to be a variation of the tuned-grid, tuned-plate oscillator, in which the feedback occurs solely through the grid-plate interelectrode capacitance. The equivalent circuit of the Miller oscillator is shown below with bias and plate voltages omitted for simplicity. The crystal tank (tuned-grid) circuit is represented by L_1, R_1, C_3, tuned by interelectrode capacitance C_{gk}, and the plate tank by L_2,

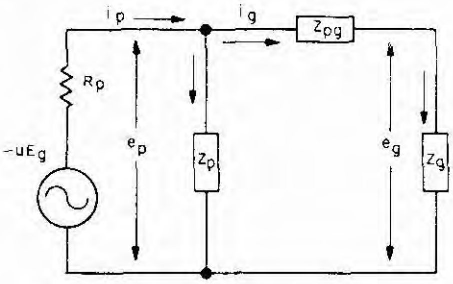


Basic Miller Equivalent Circuit

R_2, tuned by variable capacitor C_2. The two circuits are coupled by the internal plate-grid capacitance, C_{pg}, for feedback purposes.

The plate circuit must appear inductive so that the correct phase shift will be produced in the developed r-f plate voltage to compensate for the effect of the resistance in the feedback loop; this resistance prevents the necessary 180-degree phase rotation of the equivalent generator voltage of the amplifier from occurring entirely in the feedback circuit. Since the load capacitance is a function of frequency, the Miller oscillator cannot be operated at more than one frequency and still present the same load capacitance to each crystal unit, unless provision is made for adjustment of the circuit parameters. Hence, the tuned tank circuit is required so that the plate circuit will appear inductive when the tank is tuned to the high-frequency side of crystal resonance.

Let us examine the means by which the proper phase relationships between the grid and plate voltages are maintained to produce oscillation. In the conventional electron tube, the grid and plate voltages are always 180 degrees out of phase. When the grid voltage is positive, it causes the plate current to increase. Consequently, the voltage drop across the plate load impedance produces a negative-going output voltage. If this output were fed back to the grid, it would oppose the grid voltage and reduce or prevent any possible oscillation. To produce oscillation it is necessary to shift this phase another 180 degrees. Thus, a positive-going grid voltage must be reinforced and enhanced by a positive-going (feedback) voltage from the plate circuit. If the feedback voltage is sufficient to replace any losses in the feedback circuit, continuous oscillation will occur. Now consider the crystal oscillator equivalent circuit which follows.



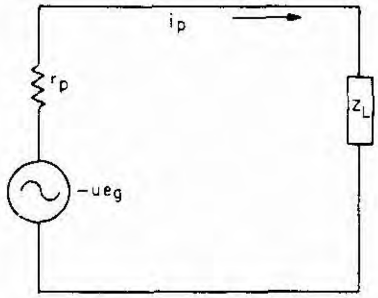
Crystal Oscillator Equivalent Circuit

The equivalent generator voltage is $-\mu E_g$, where μ is the amplificator factor of the tube and E_g is the excitation voltage on the grid. R_p is the plate resistance of the tube, and Z_p is the plate impedance from plate to cathode, with Z_g as the grid impedance from grid to cathode. These impedances are reactive, and must always have the same sign for oscillation to be produced. Considering an ideal circuit with no feedback losses, the plate-to-grid impedance, Z_{pg}, is the dominant impedance in the feedback circuit, and is always opposite in sign to Z_p and Z_g. If Z_p and Z_g are positive, Z_{pg} is negative; thus the current, i_g, leads e_p and $-\mu E_g$ by 90 degrees. If Z_p and Z_g are negative, Z_{pg} is positive; thus i_g lags e_p 90 degrees. The voltage across Z_{pg}, of course, is in phase with e_p in both instances. Since Z_g is opposite in sign to Z_{pg}, e_g is thus opposite in sign to e_p, and the required phase reversal takes place. Note that i_g is first rotated in phase with respect to e_p; next, e_g is rotated in the same direction with respect to i_g.

In a practical circuit, the feedback losses cannot be zero; thus an exact 180-degree reversal cannot be obtained in the feedback circuit alone. This means that e_p must first be rotated by an amount exactly sufficient to make up the losses in the feedback circuit. To do this, the plate tank is tuned to a higher frequency than the antiresonant crystal frequency. Therefore, Z_p appears as an inductive reactance, and e_p is rotated in a leading direction. The smaller the value of R_p, the more nearly will Z_p control the phase of i_p, and the more detuned must the tank circuit become in order to produce the necessary rotation of e_p. If practically all the resistance in the feedback arm is between the grid and the cathode, as is normally the case when e_g is developed directly across the crystal unit, e_p must be rotated through a larger angle than otherwise, thereby requiring the tank circuit to be detuned to a greater degree.

In a conventional parallel-resonant crystal oscillator having an ideal feedback arm, the frequency would be entirely determined by the resonance of the tank circuit; thus fluctuations in R_p, although effective in changing the activity, would not affect the frequency. In practical circuits, changes in both R_p and Z_p will slightly shift the phase of E_p and, consequently, the frequency. The basic amount of frequency shift is fixed by the crystal used, varying directly with the Q and the shunt capacitance of the crystal. This is the reason for using a standard value of 32 picofarads for crystal capacitance; the Q depends upon crystal processing and composition, and thus varies somewhat.

In the Miller circuit, the maximum permissible voltage across the crystal unit is (k + 1) times the maximum voltage, where k is the gain of the stage and is equal to e_p/e_g, as shown in the crystal equivalent circuit. Theoretically, this gain can approach the mu of the tube as a limit when the load impedance, Z_L, is large as compared with the plate resistance, r_p (as shown by the simple electron tube amplifier equivalent circuit below); this explains the large output obtainable from this circuit when used with hi-mu tubes.



Electron Tube Amplifier Equivalent Circuit

When a pentode, instead of a triode, is used as the oscillator tube, it is usually necessary to insert a small feedback capacitance between plate and grid, because of the small value of interelectrode capacitance present in the pentode. The output waveform is also improved by using a tuned tank circuit with a low L/C ratio. Since the tuning must be such that the tank impedance appears inductive, the tank circuit provides an effectively high-Q plate load when the tank capacitor is set for the proper load capacitance.

FAILURE ANALYSIS.

No Output. Since the crystal controls oscillation, the crystal will not oscillate and no output will be obtained if the crystal is removed, if poor or loose holder connections cause an open or high-resistance circuit, if the plate circuit is detuned sufficiently, or if no plate voltage is present because of open- or short-circuit conditions. When sustained arcing (caused by too high a crystal r-f excitation current) produces burnt spots on the holder or crystal, it will not oscillate until cleaned (this condition normally does not occur in pressure type holders, but may occur in unloaded or air gap holders). Navy policy is to return defective crystals to the crystal laboratory for repair. Do not attempt to clean crystals. An open r-f choke or a short-circuited plate bypass capacitor will remove plate voltage from the tube, and the crystal will not oscillate. Poor soldered connections on the tank coil in a series-fed circuit will produce a similar result. An open-circuited grid RFC in a circuit using no grid or cathode bias resistor will open the grid circuit and prevent oscillation unless the crystal is defective and has a low resistance. Insufficient feedback capacitance between tube elements (most likely to be associated with pentodes) will cause the crystal to stop oscillating (this condition will not occur in an oscillator which has previously oscillated unless the tube becomes defective). Substitution of a known good crystal will quickly determine whether the crystal or circuit is defective.

Reduced Output. Low plate voltage, a detuned plate tank circuit, or a crystal of low activity will result in reduced output. An open-circuited tank capacitor will allow the circuit to act as an untuned plate oscillator and, if the feedback is not too greatly out-of-phase, may permit weak oscillation; this trouble may be easily located because the tuning of the tank will not affect the plate current, and the plate current will be high, near its normal non-oscillating value. Increased resistance in the feedback arm due to poorly soldered connections will cause less phase rotation and, if excessive, will result in weak oscillation or entirely prevent operation.

Unstable Output. Any instability as far as oscillation is concerned would be associated with the feedback circuit and the crystal. A defective crystal, due to a partial fracture, may cause instability of amplitude and frequency. A defect causing the output to change from one mode of crystal operation to another could also cause instability, but in most instances it would be easily discovered because it would also change the operating frequency. An intermittent open, short-circuited, or partially open bypass capacitor may also cause a similar condition, although it is more likely to result in either no output or reduced output.

Incorrect Frequency. Since frequency is primarily determined by the crystal and tank circuit tuning, either a defective crystal or tank circuit may cause a change of frequency. The most probable trouble would be a defective, burnt, dirty, or fractured crystal. Changes of frequency on the order of only a few cycles per second may be due to tank detuning or temperature effects; changes greater than a few cycles per second indicate a change of crystal parameters. Temperature variations are generally indicated by a slow change of frequency in one direction with an increase of temperature; such variations may occur if the ambient temperature is above the range of thermal compensation provided. A slight change in frequency, due to aging or a change in drive level, can normally be compensated for by a slight change of tank tuning; otherwise, the crystal must be replaced.

GRID-PLATE (PIERCE) CRYSTAL OSCILLATOR.

APPLICATION.

The Pierce crystal oscillator circuit is used to supply approximately a sine-wave output of relatively constant frequency, usually within (although not restricted to) the r-f range. This circuit is used wherever a specific frequency of extreme stability and of moderate power output is needed, such as the basic oscillator in multistage transmitters, test equipment, receiver-converters, etc. It is usually interchangeable with the Miller oscillator in low- and medium-frequency applications, but it is not often used in high-frequency applications, mostly because of its low output.

CHARACTERISTICS.

Utilizes piezoelectric effect of a natural or synthetic crystal to control frequency of oscillation.

Crystal is connected between grid and plate (or any other element acting as an anode) of an electron tube.

Does not require an LC tank circuit for fundamental mode operation.

R-F feedback occurs only through crystal.

Operates normally with class B or C automatic self-bias, but may be operated class A or with combination fixed and self-bias for special design.

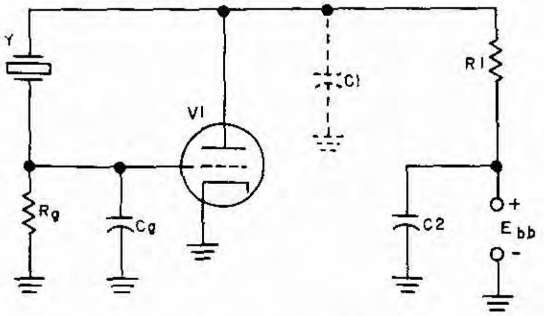
Frequency stability is excellent, with or without temperature compensation.

Output amplitude is relatively constant.

CIRCUIT ANALYSIS.

General. The generalities applicable to the basic crystal oscillator in the discussion of the Miller circuit are also applicable to the Pierce circuit. The simplicity of the Pierce oscillator, with its lack of tuned plate tank and its ability to oscillate easily over a broad range of frequencies with different crystals, makes it popular for use in crystal calibrators, receivers, and test equipment, and in transmitters not requiring much drive. The Pierce circuit is sometimes considered as the inverse of the Miller circuit since it exhibits opposite effects. Thus, instead of operating as an inductive reactance as the Miller circuit does, the Pierce circuit operates as a capacitive reactance (when a tank circuit is employed, it is always tuned for a lower frequency). The crystal excitation voltage for the Pierce is approximately half that permissible with the Miller circuit. The plate load of the Pierce oscillator is resistive and is usually large enough in value that minor fluctuations in the tube plate resistance have much less effect on the frequency of operation than in the Miller circuit. This is used to best advantage when a pentode is employed, since its inherently high plate resistance and low grid-plate capacitance permit a greater range of plate load with the use of an external capacitor to fix the amount of excitation.

Circuit Operation. The basic Pierce oscillator circuit is shown in the accompanying illustration. Conventional grid-leak bias is obtained through C_g and R_g, which operate as described previously in Section 2 and in the LC Tickler Coil Oscillator Circuit discussion given previously in this Section. The crystal, which is connected between grid and plate, offers a high Q. The inductive reactance of the crystal, together with the capacitive reactance of C1 (which consists of tube and stray wiring capacitance), provides the final phase rotation required to produce the 180-degree shift in the feedback voltage in order to sustain oscillation. The plate load is resistor R1. C2 is the conventional plate bypass capacitor used in series plate feed arrangements.



Pierce Crystal Oscillator Circuit

The use of resistor R1 in the plate circuit provides a relatively flat response over a wide range of frequencies, so that various crystals may be substituted for operation on other frequencies without any tuning being required. In some instances, however, when it is desired to operate on a single frequency or over a narrow range of frequencies, with increased output, an r-f choke is substituted for R1. This choke eliminates the d-c power loss in the resistor and provides a high r-f impedance for proper operation; since the plate voltage is increased, the (resistor voltage drop is eliminated) output is also increased.

Now consider one cycle of operation. Assume that crystal Y is at rest and that the circuit as illustrated above is inoperative, with no plate voltage applied. At rest, the crystal is unstressed and there is no charge on either plate. When the plate voltage is applied, since no bias exists initially, heavy plate and grid current flows. Simultaneously, the crystal is stressed by this plate potential, and a peizoelectric charge appears across the crystal. The sudden shock of applied plate voltage causes the crystal to start oscillating at its parallel-resonant frequency. Assume also that the plate voltage stress induces a positive piezoelectric charge on the grid, which tends to increase plate current and grid current flow. The plate current quickly reaches saturation at some low plate voltage, caused by the drop through plate resistor R1. Meanwhile, grid current flow is producing a negative voltage drop across R_g, thus charging C_g. As the crystal vibrates in the opposite direction, it induces a negative charge which adds to the negative grid voltage produced by the charging of C_g. As a result, plate current is now reduced by the increasing grid bias, and the plate voltage rises. The rising plate voltage again induces a positive charge on the grid. The crystal now flexes in the opposite direction, and the plate voltage again induces a positive charge on the grid by piezoelectric effect. Grid current flow again tends to charge C_g, and the cycle is repeated.

For oscillations to occur, the crystal must be effectively synchronized in its vibration, so that the piezoelectric effect does not oppose oscillation by reducing the feedback between grid and plate. The proper phasing is accomplished by connection of the crystal between grid and plate. The inherently high Q of the crystal makes it act as a large inductor to shift the phase of the feedback voltage in the proper direction to cause oscillation. Capacitance C1 provides additional phase shift to complete the 180-degree rotation needed.

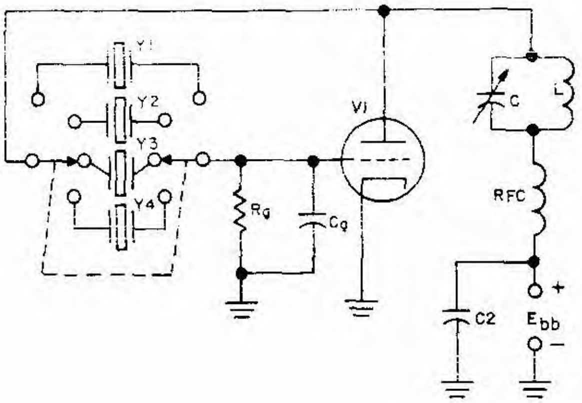
Bias Considerations. As in the conventional LC oscillator, grid-leak bias may be employed for self-bias and amplitude stabilization, but unlike the grid-leak circuit in the Miller oscillator previously discussed, it usually employs a grid capacitor (C_g) because the crystal is connected between grid and plate and cannot provide the necessary grid-leak capacitance.

During operation, grid bias is produced by the grid leak and capacitor combination of R_g, C_g. As grid current is drawn the capacitor charges, and in the absence of grid current it discharges. After a few cycles of operation an equilibrium state is reached where the slight amount that leaks off during the negative cycle just equals the amount of charge during the positive cycle; thus a steady bias is maintained. This action is similar in all respects to that of the conventional grid leak in other forms of oscillator circuits.

Since the excitation in a Pierce oscillator is low, it is common to use a higher value of grid-leak resistance than in the Miller oscillator (grid bias is equal to I_gR_g). Fixed bias can be used in place of grid-leak bias to stabilize the operating point; however, fixed-bias operation normally requires that starting provisions be made, particularly if the bias voltage is at or below cutoff. Where a power-type oscillator is required, a combination of cathode bias and grid-leak bias is sometimes employed. Use of the cathode bias provides a protective bias voltage in the absence of excitation and allows the use of a lower value of grid-leak resistance. However, the use of the combination bias also reduces the starting sensitivity and may be objectionable for keyed oscillators.

Other Considerations. Although the Pierce oscillator is normally used without a plate tank circuit, this is not always so. Where the output waveform is important, use of a selective tuned circuit in the plate circuit minimizes the harmonic content in the output and thus provides a purer waveform than is produced by a resistive plate load, which is not frequency responsive and provides a high harmonic content. Selection of the circuit with a resistor plate load for use *in a crystal calibrator* to supply harmonics of 200 to 300 times that of the fundamental proves particularly advantangeous. On the other hand, when overtone operation is desired, the Pierce circuit **must** use a tuned tank circuit to select the desired overtone if a useful and practical output is to be obtained.

Since this circuit is a vigorous oscillator, it lends itself to use as a multifrequency oscillator which permits numerous crystals to be switched into the circuit to obtain operation over a wide range of frequencies, as shown in the following illustration. A particular advantage of the Pierce oscillator is that, since crystal activity varies considerably *from crystal to crystal*, it will operate with a weak crystal as well as a strong one. Since the Pierce oscillator is normally operated at a lower output than that of the Miller oscillator, an *additional amplifier stage can bring the output* up to the same level. Such operation can be accomplished conveniently by using a single dual-triode tube as oscillator and amplifier.



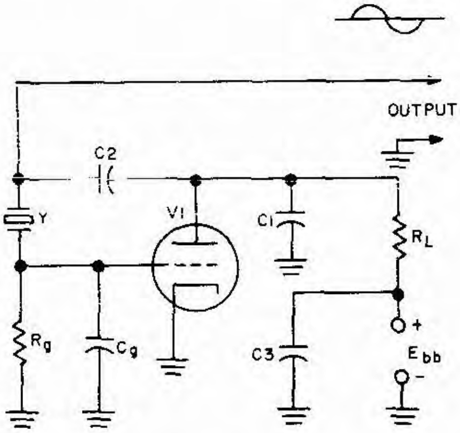
Multifrequency Crystal Oscillator with Plate Tank

Lack of a tuned output circuit sometimes causes difficulty when a crystal is used which has a strong overtone activity as compared with the fundamental, because the Pierce circuit tends to respond at the frequency of *strongest activity*. However, this is a fault of the crystal rather than the circuit, as a fundamental-ground crystal has its greatest activity at the fundamental frequency.

Because the plate impedance is *resistive and of a high order*, fluctuations in the plate resistance of the tube (which are only a small percentage of the total plate resistance) because of varying supply voltages or loads have less effect on the output frequency, so that this circuit is basically more stable than the Miller type oscillator.

Because the crystal is in series with the feedback from plate to grid and has full plate voltage across it, caution must always be observed to keep the fixed plate voltage below that which could cause excessive feedback and produce shattering of the crystal, or a frequency change due to heating of the crystal.

Circuit Modifications. Some typical circuit modifications made to improve the operation of the Pierce circuit or to overcome an inherent defect are shown in the following illustrations and are accompanied by a brief explanation. There are many variations of the basic Pierce circuit, because as long as the crystal is connected between the grid and any element other than the cathode, the resulting oscillator is basically a Pierce circuit.

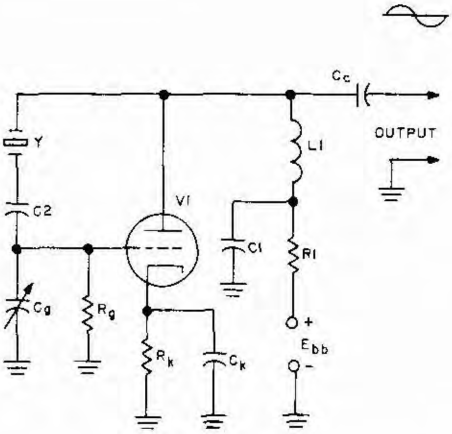


Grounded-Plate Pierce Circuit

The grounded-plate version of the Pierce circuit uses a capacitor, C2, to block the plate supply from the crystal and thus minimize the electrostatic strain on the crystal. Sometimes an r-f choke is placed in series with the cathode to reduce the shunting effect of C1; however, this choke is unnecessary if the other components are properly chosen. The plate load resistor, R_L, may or may *not be used* (when it is not used, C3 is also eliminated). It might appear that, with no cathode choke and no plate load, the shunting effects of C1 and the power supply capacitor would *effectively short-circuit the crystal output*; however, since the output is taken directly between the crystal and ground, the shunting has little effect, and maximum crystal output is obtained.

The operation of this circuit is practically identical with that of the basic Pierce oscillator. Even though the schematic of the grounded-plate Pierce circuit shows that C2 prevents the d-c plate voltage from straining the crystal, *it does not prevent* the plate voltage changes from appearing on the crystal. Furthermore, C2 is charged and discharged through the crystal capacitance. Therefore, the crystal is initially shocked into *oscillation by the a-c or r-f* voltage changes occurring in the plate and grid circuits. Once oscillations are started, the operation is identical with that previously described for the basic circuit.

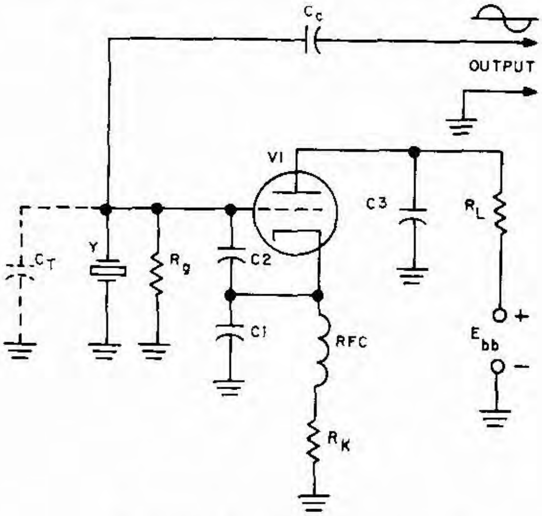
Another variation, using combination cathode and grid-leak bias, is shown in the following figure.



Combination Bias Arrangement

In the circuit above, R_k is a low-value resistor (say 200 ohms) and furnishes cathode bias, being bypassed by C_k. Grid-leak bias is supplied by R_g (resistance on the order of 100,000 ohms) and C_g. The grid capacitor is made variable to provide a slight amount of tuning for the crystal, in order to permit operation with crystals of different frequencies. Actually, it has the same effect as C_1 in the basic Pierce circuit, shown previously; that is, it provides the proper phasing for the predominantly inductive crystal to ensure oscillation. Capacitor C2 effectively reduces the strain on the crystal though it does not isolate it from the plate supply. In this respect, both this circuit and the preceding circuit show two variations of using a blocking capacitor in series with the crystal to reduce the crystal strain. This is done to protect the crystal; with a constant d-c potential applied to the crystal, it would be permanently strained in one direction, and could be shattered by the excessive strain produced when the oscillations are in the same direction as the applied plate voltage, causing it to vibrate greater in one direction than the other. In the circuit above, the plate load resistor is replaced by inductor L1 to avoid the d-c losses in a resistive load. The inductor also makes it desirable to have C_g variable to compensate for the phase-shifting of L1 (it is assumed that the distributed capacitance of L1 in this case does not tune the inductor to the frequency of oscillation). Resistor R1 is a voltage-dropping resistor which is used to reduce the plate supply voltage to the desired plate voltage level; it is not required if the correct voltage is provided by the power supply. Capacitor C1 is the conventional series-feed decoupling capacitor.

Another method of connecting the crystal to avoid the strain produced by the plate voltage is to ground the crystal directly and to ground the plate through a capacitor, as shown below. With this arrangement, the cathode must operate above ground, and an r-f choke is used to provide the necessary isolation. Capacitor C3 effectively grounds the plate so that the crystal is connected between grid and plate, but is unstrained by the d-c supply potential. Resistor R_g, and capacitor C2, together with RFC and R_k, provide combination grid-leak and cathode bias, and C1 and C2 form the typical Colpitts type capacitive feedback voltage divider. Capacitor Ct represents the total grid tuning capacitance (both the interelectrode and stray wiring) which is the effective tuning capacitance across the crystal (32 picofarads for MIL-STD types). In this case, it is clearly seen that the crystal acts as the tank circuit (see Ultraudion Oscillator equivalent circuit shown below), but that it is shunted by the grid leak, which effectively reduces its Q. The output is taken from across the crystal through coupling capacitor C_c.

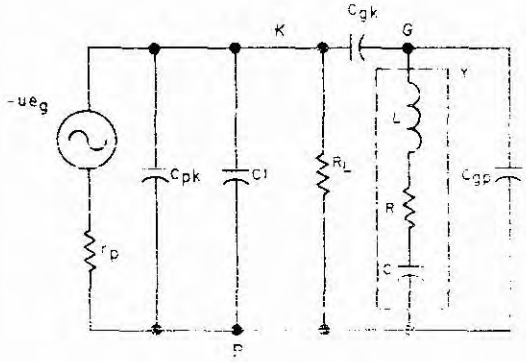


Grounded-Crystal Circuit Variation

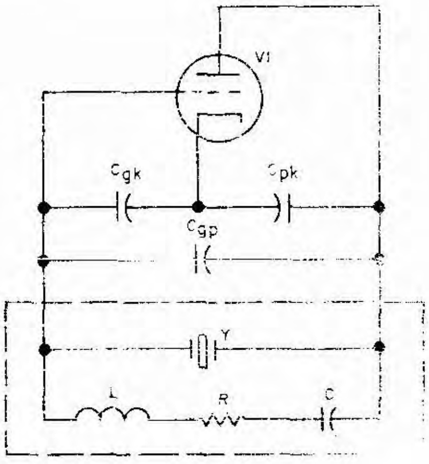
Again, the circuit operation of the grounded-crystal stage illustrated above is practically identical with that of the basic Pierce oscillator previously described. The crystal is shocked-excited into vibration by the a-c plate and grid voltage changes. In addition, the capacitive voltage divider formed by C1 and C2 provides additional feedback to overcome the shunting effect on the crystal caused by grid leak R_g. Their value is such that the circuit will not oscillate with the crystal removed. Their use makes the circuit easier to start, and permits the use of crystals with much weaker activity than normal.

Detailed Analysis. The Pierce oscillator is considered to be the ultraudion version of the Colpitts type of L-C oscillator circuit, with the crystal taking the place of the plate tank as illustrated in the accompanying illustrations.

The Pierce circuit operates at a frequency which places it on the inductive side of parallel resonance in the crystal. When a plate tank circuit is used, it is always tuned to a lower frequency to make it appear as a capacitive reactance. Thus, the crystal operates somewhere between its series- and parallel-resonant frequencies. The tube grid-plate interelectrode capacitance, C_{gp}, is in shunt with the crystal, and the effective tank tuning capacitance of the inductive crystal is the electrostatic crystal capacitance (represented by C in the Ultraudion equivalent illustration) in parallel



Pierce Equivalent Circuit



Ultraudion Equivalent Circuit

Ultraudion as Compared with Pierce Crystal Equivalent Circuit

with grid-plate tube capacitance C_{gk}, together with the series-parallel combination of grid-cathode capacitance, C_{gk}, and plate-cathode capacitance, C_{pk} (which includes the distributed wiring capacitances). For Military Standard crystals, this capacitance is always held to 32 picofarads total. Since the plate circuit is predominantly resistive, consisting of R_L only, as shown in the Pierce equivalent circuit above, any small fluctuation in any of these capacitances is minimized; as a result, the circuit has a more stable frequency of operation than the Miller oscillator. Capacitor C_1, previously illustrated in the basic Pierce oscillator circuit, is usually inserted to ensure that the circuit will oscillate with many different types of crystals. Although the crystal (tank circuit L, R, C in the illustration) is connected between plate and grid, and feedback occurs through the crystal, [illegible] tric charge applied to the grid-cathode interelectrode capacitance, C_{gk}, that couples the crystal into the circuit electrically, as is evident from examination of the Pierce equivalent circuit shown previously. Because the plate circuit is predominantly resistive, small fluctuations in tube plate resistance due to changes in operating voltages are a smaller percentage of the over-all *total plate resistance;* therefore, greater frequency stability is obtained than in the tuned plate oscillator, in which plate resistance changes are a much greater percentage of the total load resistance. The higher plate resistance and lower grid-plate capacitance of the screen grid tube are particularly advantageous in the Pierce oscillator. Since the crystal is effectively the tank circuit and represents the highest impedance in the circuit, it is evident that the largest voltage is developed across the crystal, but it is limited by the maximum voltage and power dissipation that the crystal can withstand without shattering. Thus, the maximum output from this type of circuit is limited by the crystal power-handling capability (area), rather than by circuit components. (Modern 1/2-inch square, crystals have only 1/4 the power-handling ability of the old 1-inch-square type.)

FAILURE ANALYSIS.

No Output. If the crystal is removed or if poor or defective holder connections cause an open (or high-resistance) circuit, the crystal will not oscillate, and no output will be obtained. Also, if the plate load resistor is open or if a short circuit lowers the plate voltage sufficiently, the crystal will not oscillate. In the case of over-excitation when unloaded or air gap holders are used, the crystal may be burnt because of r-f arcs between the crystal and mounting plates, *and it will not operate until cleaned.* (Return crystal to repair center; do not attempt to clean it yourself.) In a poorly sealed holder, dust accumulation or moisture from condensation may also make crystal cleaning necessary. Normally, with the sealed, pressure-type holder, cleaning is unnecessary. An open series blocking capacitor will disconnect the crystal and stop operation.

Insufficient feedback capacitance between electron tube elements (most likely with pentodes) will prevent the crystal from oscillating, but this condition will not occur with a tube which has previously oscillated unless the tube becomes defective. An open grid resistor or capacitor will probably prevent operation, but may result in reduced output. *Usually, only open-circuited or short-circuited conditions will prevent the circuit from operation.* In the case of overtone operation, excessive detuning of the plate tank [illegible] of oscillation, which will resume after the circuit is properly tuned. Substitution of a known good crystal will quickly determine whether the crystal or circuit is defective.

Reduced Output. Since the Pierce crystal oscillator operates vigorously when excited, any reduction in output will result from lack of excitation or low plate voltage, rather than from high resistance or poorly soldered contacts. An open or shorted grid capacitor or grid-leak resistor will change the bias conditions and result in either reduced output or no output. When the grid-leak bias is combined with cathode bias, failure of the grid-leak bias [illegible] dirty crystal may not oscillate at all or only weakly, and could be the cause of reduced output. With unsealed crystal holders a reduction in output, hard starting, or stoppage of oscillation was a signal for possible cleaning; however, with modern sealed holders the possibility of crystal contamination is not very likely, but should be kept in mind. (Return crystal to repair center; do not attempt to clean it yourself.)

Unstable Output. Instability may be due to an intermittent or poor (high-resistance) connection in the feedback circuit, but it is more likely to be due to a defective crystal which has been partially fractured by over-excitation. A crystal which normally operates satisfactorily in a tuned Miller oscillator may be defective and have a spurious frequency which is produced alternately with the desired frequency, when the crystal is used in a Pierce circuit, and thus cause an unstable output. Such a condition is evidenced by changes in frequency, due to erratic jumping from one frequency to the other.

Incorrect Frequency. Since the crystal frequency is primarily determined by its own constants, an incorrect frequency is probably the result of a change in the crystal itself or in the holder and associated wiring capacitances. Normally these changes are very small. If the crystal is not temperature-controlled, over-excitation can cause sufficient heating of the crystal to change the frequency; this condition is normally indicated by a continuous drift in one direction as the crystal is heated. A zero-temperature-coefficient crystal operating within its range of compensation will not be affected by minor temperature changes. Since a tuning adjustment is usually not provided, a noticeable change in crystal frequency indicates a circuit or crystal parameter change which should be checked. With the few parts concerned in this type of oscillator, it should not be too difficult to determine the defective component. Crystal or tube aging effects may also cause a change in frequency, which would be indicated by a slow change over a long time. Any decrease in grid circuit resistance may cause an increase in frequency, and an increase in the grid resistance due to high-resistance contacts may decrease the frequency. Cleaning the crystal sometimes restores it to its normal frequency of operation. However, do not attempt this yourself. Return it to the repair center. Actual aging of the crystal may cause a change of frequency, which is not correctable except by grinding or plating (at the repair center) to restore the proper thickness. Such aging usually does not occur quickly, but is cumulative over a long period of time. It should be noted that frequency is based upon time and that time is controlled astronomically and does vary in very minute parts. Thus, primary frequency standards are only accurate to 2 or 3 parts per 100 million for short time operation, but this accuracy decreases as the time interval is lengthened. Therefore, crystal frequencies should not be expected to be absolutely accurate. However, they should be as accurate as their rated tolerance, and should normally require a stable secondary frequency standard to determine their error. Where crystal-controlled receiving and transmitting frequencies are involved, it may sometimes be suspected that either one or the other is in error when, in fact, both could be in error.

ELECTRON-COUPLED CRYSTAL OSCILLATOR.

APPLICATION.

The electron-coupled crystal oscillator is used almost universally to provide an approximate sine wave r-f output over the low-, medium-, and high-frequency r-f ranges. It utilizes a screen grid or pentode tube to provide extreme stability and greater output than is possible with a basic triode crystal oscillator, and is widely used in transmitters, receivers, test equipment, and other equipments which require crystal frequency control. Its widest application is for frequency multiplication in the plate circuit.

CHARACTERISTICS.

Utilizes piezoelectric effect of a natural or synthetic crystal to control frequency of oscillation.

Uses electron coupling to the load to reduce strain on crystal, to minimize load variations, and to provide extra stability.

Normally operates with automatic self-bias and class C, but may be operated with combination fixed and self-bias and class A or B for special design purposes.

Frequency stability is better than frequency stability of triode crystal oscillator, and power output is also greater.

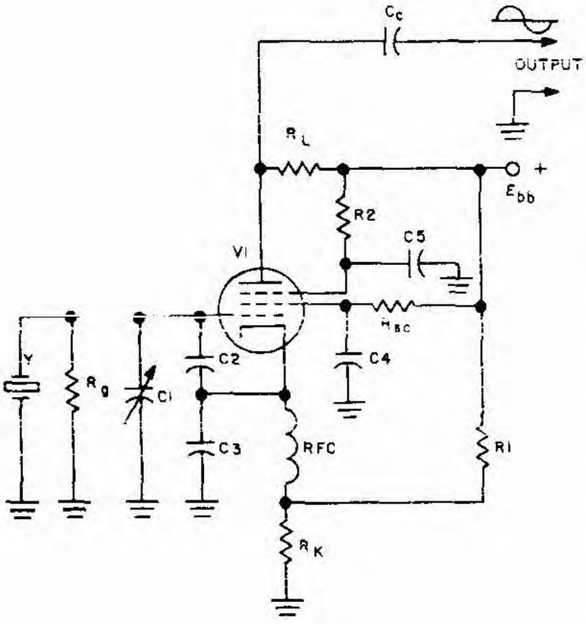
Output waveform is a relatively constant amplitude sine wave, but if output [illegible] primary consideration it may be a distorted sine wave.

Uses a tuned plate tank for harmonic operation.

CIRCUIT ANALYSIS.

General. The discussion on the Electron-Coupled LC Oscillator given earlier in this Section is generally applicable to this circuit. The basic crystal-controlled circuit employs either a Miller or Pierce oscillator which utilizes the screen grid of a tetrode or pentode tube as the anode. Either grounded-cathode or grounded-plate circuits may be used, with the grounded cathode being used mostly with a basic Miller oscillator, and the grounded plate being used mostly with the basic Pierce oscillator. The basic Miller oscillator is usually used for single-frequency operation, and always incorporates a tuned tank circuit. The Pierce oscillator is used where a number of frequencies are to be covered by changing of crystals, with no tuning adjustment being provided; however, plate tuning is required if harmonic operation (frequency multiplication) is desired.

Circuit Operation. A typical electron-coupled Pierce type oscillator is shown schematically in the following illustration. The grounded-plate version of the basic circuit is used to minimize the electrostatic strain on the crystal. The illustration shows a pentode tube rather than a tetrode because better electron coupling, or looser coupling, between load and crystal oscillator is possible because of the effect of the suppressor element. The looser coupling results from the fact that the screen grid completely surrounds the control grid and effectively isolates it from the plate circuit, and from the fact that the suppressor, if grounded or properly biased, minimizes capacitance coupling between screen and plate. Thus, the coupling between oscillator and load circuit is provided by the electron stream alone, and any reflected load changes have negligible effects. Although the circuit shown may at first glance



Grounded-Plate Pierce Electron-Coupled Oscillator

appear to be a Miller oscillator, it can be seen that the cathode is effectively above ground and that the oscillator plate (the screen grid) is grounded for ac by capacitor C4; hence, the crystal is connected (as in the typical Pierce circuit) between grid and plate (screen). This type of connection prevents the supply voltage from placing permanent electrostatic strain on the crystal, and is preferred for that reason.

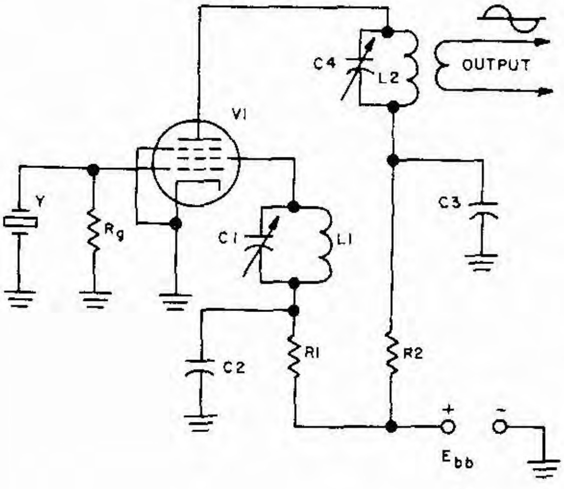
In the schematic, the suppressor is shown grounded through C5, and it is held effectively at zero bias with respect to the plate by its connection to B+ through R2 (an internally connected suppressor type tube should **not** be *used in this circuit*). Thus, by construction, the grid is effectively shielded from the plate, and the coupling effects of plate-cathode capacitance are therefore reduced. Since the oscillator plate (the screen) is grounded, the RFC is used to keep the cathode above ground for rf. The output is taken from across plate load resistor R_L through capacitive coupling. Actually, the plate load can be an r-f choke or a tuned LC circuit when the circuit is operating on the fundamental frequency. When it is desired to double or triple the frequency, it is necessary to tune the plate circuit to the desired harmonic, or overtone, for maximum output. Combination fixed-bias (from voltage divider R_1 and R_k) and self-bias (from R_k) is used to stabilize the circuit against frequency changes caused by bias variations because the *excitation changes for various crystals and frequencies* of operation. Therefore, with a fixed oscillator anode (screen) voltage which is relatively unaffected by load variations caused by supply changes or tuning, plus a stable operating point established by the fixed bias, usually only temperature effects need be considered when evaluating the short-time frequency *stability of the circuit*. In a typical circuit of this type, changes in resistor values of 20% result in a frequency change of only 1 part per million (ppm), and capacitance changes of up to 10% produce frequency changes of less than 8 ppm, whereas changes in temperature of the crystal and other circuit parts produce frequency changes as high as 35 ppm per degree centigrade above ambient room temperature. Use of a crystal with a better temperature coefficient and with temperature control can reduce this to a short-time frequency variation of only 2 to 3 ppm.

Electron *coupling also* affords greater output because the circuit employs the equivalent of two tubes, the triode section operating as a low-voltage oscillator with low grid excitation and low crystal strain, and the pentode section operating as an amplifier loosely coupled to the oscillator by the electron stream between screen and plate. Thus, the amplifier portion may be operated at high voltages, which if used in the basic oscillator would normally shatter the crystal: consequently, the power output from the amplifier plate is greater than that from the basic unit. The over-all result is a stable crystal oscillator operating with crystal *excitation on the order of a few milliwatts and providing* a power output on the order of watts. In most cases, the output is equal to or greater than the output available from the basic Miller type power oscillator, *and has a* greater frequency stability.

Now consider one cycle of operation. When B+ voltage is applied, the fixed cathode bias produced by voltage divider R1 and R_k permits a heavy flow of screen and plate current. Since the plate is isolated from the oscillator portion of the circuit by the zero-biased suppressor grid, and is coupled only through the electron stream in the tube *plate current flow has no effect on* oscillator operation. Since the grid is located between cathode and screen, electrons will be intercepted from the space current, causing a small grid current to flow. Grid current *flow through* R_g develops a negative bias on the grid, which tends to charge C1. Thus R_g and C1 act as a grid leak and grid capacitor, respectively. Simultaneously, the crystal is shock-excited into oscillation by the changing grid and screen voltages. The crystal vibrations produce a piezoelectric voltage across the crystal, and between grid and ground (the screen is bypassed by C4, and acts as the oscillator anode). The crystal oscillates in synchronism with the grid and plate voltage changes. On the negative swing, the crystal generated voltage adds to increase the bias and reduce the anode (screen) current. On the positive half-cycle, the total bias is decreased. Consequently, the screen current (and thus the electron stream through the tube from cathode to plate) is caused to alternately decrease and increase at the oscillator frequency. The capacitive voltage divider (C2 and C3), connected between grid and cathode, and plate and cathode, fixes the minimum amount of feedback. Thus it helps stabilize the circuit *and overcome* any tendency toward hard starting because of the initial fixed cathode bias. The cathode is kept above ground potential by the rfc; otherwise, oscillation would not occur (screen and cathode would be short-circuited for rf).

The electron stream between screen and plate varies in accordance with the crystal oscillation frequency. Since the plate voltage and current are greater than the screen voltage and current, the r-f output voltage developed across load resistor R_L is larger than the voltage developed across the crystal. Since the plate is isolated from the screen and oscillator section of the tube by the zero suppressor bias, any load variations or supply voltage changes have little or no effect on the oscillator. Thus, a more stable and higher-powered output is taken from the plate circuit of the electron-coupled crystal oscillator. The d-c power dissipated in R_L, of course, appears as a loss of efficiency, since it is wasted in heating the resistor.

The accompanying circuit schematic shows the Miller version of the electron-coupled crystal oscillator. Although this circuit requires two tank circuits, it has the advantage that doubling (or tripling) can be accomplished in the final tank, while the basic stability of the fundamental frequency is retained.



Miller Electron-Coupled Oscillator

Note that in this circuit the cathode is grounded; hence, even though the suppressor is shown externally connected, an internally connected suppressor type of tube could be used without impairing the electron coupling. Actually the second tank circuit (C4, L2) need not be used; a resistor or RFC could be used in its place, but tuning the plate circuit ensures that the proper output frequency is selected and reduces the harmonic content to a minimum. From the illustration it is evident that the basic oscillator circuit is connected between the cathode, grid, and screen (anode) tube elements, just as in the Pierce electron-coupled oscillator. However, the crystal is connected between grid and cathode, and the operation of the oscillator is as described previously (see Grid-Cathode (Miller) Crystal Oscillator discussion at the beginning of this section of the Handbook). Electrostatic isolation of the plate by means of the grounded suppressor limits the coupling to the electron stream alone, thus providing increased stability because of freedom from the effects of load variations on the oscillator.

FAILURE ANALYSIS.

No Output. Lack of output from this type of oscillator may be due to a fault in either the oscillator portion or the amplifier portion of the circuit. Thus, it should first be determined whether the crystal oscillator is oscillating, using the failure analysis discussion of the basic oscillator as a guide. If the oscillator is operating, then lack of output is caused by lack of plate voltage due to an open or short-circuited condition. An open suppressor bypass capacitor may cause a virtual cathode to be formed between screen and plate and reduce the output almost completely. A defective electron tube may oscillate, but have insufficient emission to supply any appreciable output in the plate circuit. Usually, the cause of a no output condition can be quickly localized to a particular part by a resistance check of the few components involved.

Reduced Output. This condition is more likely than no output and may be caused by low plate voltage, by the presence of a high resistance in the plate load circuit due to poor connections, particularly in tuned tank circuits, and by excessive bias. Short-circuiting of the cathode bias voltage-dropping resistor connected to the supply source (R_1 in Pierce circuit) would produce cutoff-bias conditions and the tube would not operate; an increase in this resistance would minimize the fixed bias and allow the cathode bias alone to prevail, causing class A operation of the plate section, so that reduced output and a reduction of harmonic content would occur.

Incorrect Frequency. Since the frequency is determined by crystal operation, any basic frequency changes will occur solely in the oscillator section, except when the circuit employs a plate output tank. If this tank becomes tuned (either accidentally or by component failure) to the wrong harmonic of the crystal frequency, the circuit will produce an output of incorrect frequency. Any changes caused by load fluctuations or supply voltage fluctuations will be so small that they may go unnoticed unless precision measuring equipment is available.

OVERTONE CATHODE-COUPLED (BUTLER) CRYSTAL OSCILLATOR.

APPLICATION.

The cathode-coupled (Butler) crystal oscillator is used primarily for overtone crystal operation on high or very high radio frequencies. It is used in receivers, transmitters, test equipment, and other equipment which requires the use of a stable crystal-controlled high-frequency oscillator.

CHARACTERISTICS.

Uses an overtone crystal to provide operation on frequencies which are not integral harmonics of the fundamental crystal frequency.

Employs two triodes coupled by the crystal operating at series resonance.

Normally operates class A, but may be operated class C for greater power output.

Provides an approximate sine-wave output of relatively constant amplitude.

CIRCUIT ANALYSIS.

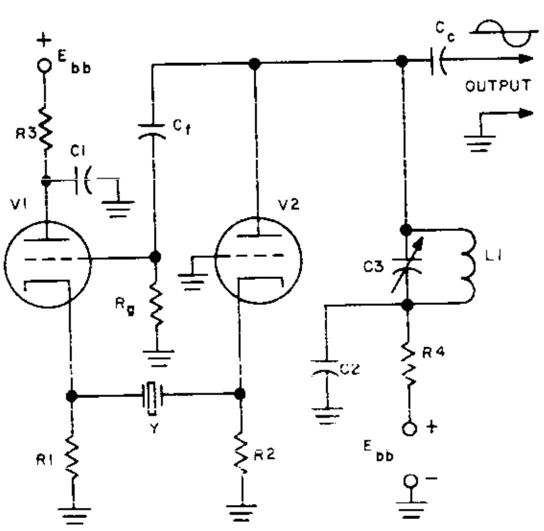
General. At the present time, the Butler cathode-coupled two-stage oscillator is probably the most widely used of the **series mode** oscillators because of its simplicity, versatility, frequency stability, and comparatively great reliability. This circuit seems to be the least critical to design and adjust for operation at a given harmonic with any type crystal. The balanced circuit, plus the fact that twin triodes within a single envelope can be used, contributes to a saving in space and cost and provides for short leads. The cathode-coupled circuit can also be used for operation on the lower radio frequencies, provided that the resistance of the crystal unit is not greater than a few hundred ohms. However, the power output is less than that of the Miller circuit for the same crystal power, and the broad bandwidth of operation without tuning as provided by the Pierce circuit is not possible.

At series resonance, the crystal element appears as a resistance, so that in the normal circuit it can be short-circuited or replaced with a comparable resistor without stopping oscillations. Although circuit operation of the series-mode oscillator is less complicated than that of the parallel-mode oscillator, the circuit design becomes increasingly critical at the higher frequencies and higher overtones. It is vitally important to keep stray capacitance at a minimum, and all leads must be as short as possible to eliminate unwanted resonances. It is sometimes necessary to nullify the shunt crystal capacitance by paralleling the crystal with an inductor which is antiresonant with the shunt crystal capacitance at the operating frequency. It may also be desirable to connect a capacitor in series with the crystal to tune out the stray inductance of the crystal leads, and tuned output circuits must be provided to select the proper overtone. For maximum frequency stability, the effective resistance of the circuit facing the crystal unit should be as small as possible. At the higher frequencies, stray capacitances limit the impedances obtainable with tuned circuits, making them more selective, and more effective in influencing the frequency and increasing instability.

Usually, the output is taken from the plate or cathode of either tube. Sometimes the cathode follower is a pentode tube utilizing the cathode, screen, and grid elements as the basic oscillator, which is electron-coupled to the plate load. This provides greater stability and affords the possibility of tuning the plate circuit to a higher harmonic.

Circuit Operation. The accompanying illustration shows the basic cathode-coupled circuit using triodes.

Tube V2 is a grounded-grid amplifier whose output is fed back to the cathode (input circuit) through cathode follower V1 and the series-connected crystal. Cathode bias is supplied through R1 and R2, and V1 normally conducts more heavily than V2 (both tubes are identical triodes). The feedback voltage is coupled capacitively through C_f to the grid of V1, and grid resistor R_g provides conventional grid-drive bias which varies with the excitation supplied. When operated class A, no grid current is drawn, and there is no grid-drive bias produced across R_g. In this instance R_g acts solely as the grid-return resistor in a conventional R-C coupling network, and the bias is produced by R1 alone. In class C operation, grid current is drawn, and grid drive bias is produced exactly as in the conventional r-f driven amplifier. In this case, the total bias consists of the self-bias produced through cathode resistor R1, plus the drive bias in the grid circuit. The tuned tank circuit (L_1 and C_3) in the plate of V2 offers maximum impedance at the frequency to which it is tuned. The maximum output voltage (and feedback) occurs at this point, neglecting crystal operation. The crystal is normally an overtone type, and is ground for maximum activity at the overtone frequency (fundamental frequency crystals are occasionally used with this circuit, but this fact does not materially affect the theory of operation of the circuit). Usually the circuit will oscillate when the crystal is short-circuited or replaced with an equivalent resistance, operating at the frequency of the tank circuit. Resistor R4 and capacitor C2 are a conventional plate voltage dropping and decoupling network provided for series plate feed of V2. Resistor R3 and C1 perform a similar function for V1 with sufficient capacitance to effectively ground the plate of V1 for rf at the frequency of operation. The output is taken from the plate of V2 through coupling capacitor C_c, but it could also be taken from V1 or from the cathode without materially changing operation.



Basic Cathode-Coupled Crystal Oscillator

Off resonance, the crystal exhibits a high resistance, which effectively reduces the feedback and prevents oscillation. At the series resonant frequency, the crystal exhibits a low resistance and the circuit oscillates vigorously. Since the gain of the cathode follower tube cannot exceed unity, there is partial control of excitation because V1 cannot amplify the feedback from V2; as a result, greater feedback is provided for a weak crystal than for a strong crystal. This action enhances overtone operation, since the strongest oscillations are at the fundamental frequency, with successively weaker oscillations being obtained as the numerical value of the overtone increases.

Now consider one cycle of operation. When plate voltage is applied to V1 and V2, since no initial bias exists, there is a heavy flow of plate current. The flow of plate current through R1 and R2 produces a cathode bias on each tube which reduces the plate current flow. At the same time, the flow of plate current in V1 through plate resistor R3 drops the supply voltage to the proper value. Any a-c variations in voltage produced by changing plate current through R3 are bypassed to ground by C1, and tube V1 operates as a cathode follower. The initial flow of current shock-excites the crystal so that it vibrates at its series-resonant frequency. At resonance the crystal appears as a low value of resistance, while on either side of resonance it appears as a large resistance. In the off-resonance, high-resistance state, the crystal attenuates any feedback from the plate of V2 through V1 and thus prevents oscillation. In the series-resonant state, the low crystal resistance permits practically all the feedback to be applied across R2. (The crystal resistance, R, and the cathode bias resistor, R2, form a voltage divider connected in parallel with R1.)

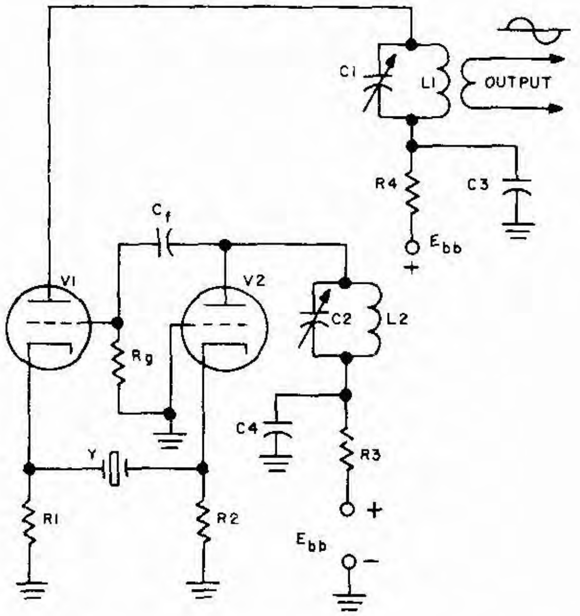
With the crystal oscillating on the positive half-cycle, assume that a positive voltage produced by piezoelectric effect is applied to R2, and increases the bias. The plate current of V2, therefore, is reduced. Since the output voltage is developed across the impedance of the plate tank circuit, a reduction in plate current produces less drop across the tank, and the plate voltage approaches the source (goes positive). Thus, a positive-going voltage is fed through coupling capacitor C_f to the grid of V1. The positive-swinging grid voltage produces an increase of plate current in V1 and a positive increase across cathode bias resistor R1. Since the gain through cathode follower V1 is less than unity, no amplification of the signal occurs through V1. Sufficient feedback occurs, however, to replace the small circuit losses; thus oscillation is sustained.

On the negative half-cycle of operation the crystal develops a negative voltage which is applied to R2. The bias on V2 is thus reduced, and the plate current increases. The output voltage produced across the tank circuit is now negative-going, and is fed back to the grid of V1 to reduce plate current flow. Consequently, the voltage drop across cathode resistor R1 is decreased, and a negative-going voltage is applied through the crystal to maintain oscillation.

Although it might appear that the feedback voltage is such as to oppose crystal oscillation, it must be realized that this circuit will operate with the crystal removed if the equivalent resistance (or an ohmic connection) is placed across the crystal terminals. Operation without the crystal, however, is never as stable as with the crystal.

Circuit Modifications. As with all other oscillator circuits, there are numerous variations of the basic circuit. A typical variation is shown in the accompanying illustration.

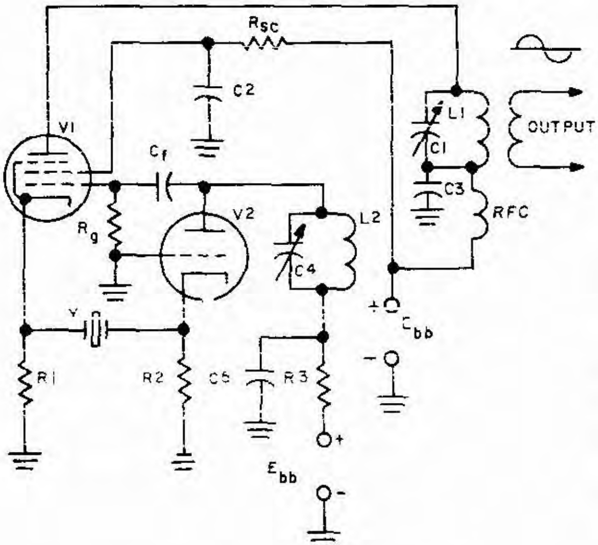
This circuit is essentially identical with the basic Butler overtone oscillator, except for the insertion of a tuned tank in the plate circuit of the cathode follower. Thus, the cathode follower stage becomes a cathode-coupled stage. The effect on over-all operation is to make available an output which can be tuned to a harmonic of the overtone frequency (instead of being bypassed to ground as in the basic circuit) and provide effective frequency multiplication.



Frequency Multiplying Overtone Oscillator

As far as the basic oscillator is concerned, the operation is the same as described for the basic circuit. Although amplification occurs in the plate circuit, since the plate load of V1 is tuned to a different frequency, any coupling effects through the plate-grid capacitance do not affect the basic frequency.

An electron-coupled version is formed by connecting V1 as a conventional pentode amplifier which is resistance-capacitance coupled to V2, with the frequency multiplying tank in the plate circuit of V1, as illustrated below. This version is identical with the basic Butler circuit except that the screen of V1 acts as the anode of the cathode-follower stage. With the screen a-c-grounded through C2 and the suppressor tied back to the cathode, the plate is coupled solely through the electron stream between screen and plate. The rfc and C3 form a conventional series plate feed decoupling network, and R_{sc} is the screen resistor. All other components function as in the basic oscillator. In this circuit V1 is usually operated class C, and has a high applied plate voltage. Thus, the plate output is considerably higher than in the previous triode type of frequency-multiplying circuit, and the tank L_1 and C_1 may be tuned to either the second or third harmonic of the oscillator frequency. The basic tank C_4 L_2 is tuned to the fundamental frequency.



Electron-Coupled Overtone Oscillator

Although other versions of the Butler circuit exist, they are similar to the versions described above. The identifying feature of the Butler oscillator is the connection of the crystal as a series feedback arm between two cathode-coupled stages. Overtone oscillators with grid-cathode or grid-plate connected crystals are special versions of the Miller and Pierce circuits.

FAILURE ANALYSIS.

No Output. A primary cause of inoperation is a defective crystal or poor holder connections; the crystal and holder resistance should not exceed 500 ohms for proper operation. Since two tubes are involved, a defective tube is also a possible cause of no output. An open circuit in the feedback path, either in the coupling capacitor or crystal holder, will also stop operation. In addition, short-circuited components will cause the affected tube to draw greater than normal current and stop oscillation. A short circuit across the crystal will not stop oscillation; depending on the design, it is possible for oscillation to continue at the tank frequency. Lack of supply voltage will also stop operation, but low supply voltage will primarily affect only the output amplitude. Because of the few components involved, a quick voltage and resistance check should isolate the defective part. If all parts and voltages appear normal, the cause of trouble is in the crystal, or the tank tuning capacitor is shorted or tuned to the wrong frequency. If other crystals oscillate in the circuit, cleaning the defective crystal may restore activity. (Return crystal to repair activity for cleaning.)

Low or Unstable Output. Excessive bias on one or both tubes will reduce the output. Such bias could be caused by heavy current through the cathode bias resistors due to defective tubes or short-circuited components in the plate circuits. A change in the grid-leak resistor and in the coupling capacitor constants may cause blocking and motorboating or intermittent operation. A weak or dirty crystal may also produce low output. (Replace the crystal.) Too low or too high a plate voltage can cause instability.

Incorrect Frequency. The series-resonant crystal oscillator is the most stable kind. Therefore, a change in frequency will probably be due to crystal caused effects. Cleaning the crystal should restore proper operation (cleaning to be done only at repair activity); if not, there is a possibility that changes in stray capacitance between cathode and ground (perhaps from a change of lead dress) have caused a slight detuning. Though operation at a frequency above the series frequency can occur, it is rather unlikely because the limits of series resonance do not permit as much detuning as those of parallel resonance.

MAGNETOSTRICTION OSCILLATORS.

APPLICATION.

The magnetostriction type oscillator is usually used at audio, supersonic, or low radio frequencies to provide an extremely stable sine-wave output. This circuit is employed in preference to the crystal type of oscillator at the vey low frequencies because of its simplicity, ease of construction, and economy due to the lack of suitable quartz crystals. It finds particular application in laboratory test equipment and low-frequency standards.

CHARACTERISTICS.

Uses a nickel-steel alloy rod to control the frequency of oscillation.

Feedback is through magnetostriction effects and not through externally coupled inductors.

Provides frequency stability of less than one cycle per second at audio frequencies.

Produces an approximate sine wave of relatively constant amplitude.

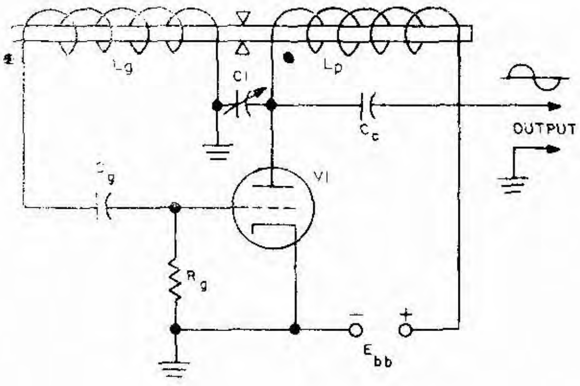
CIRCUIT ANALYSIS.

General. The magnetostriction effect is similar to the piezoelectric effect found in crystal oscillators. Instead of using electric charges, however, it operates by the effect of a changing magnetic field. When an iron-alloy rod is placed within a magnetic field, there is a change in length due to the strain placed on the rod by the magnetic field. This compressional strain, in effect, squeezes the rod and makes it longer; when the field is removed, the rod returns to nearly its former length. Similarly, when a rod located within a magnetic field changes its length, it also induces a change in the magnetic field, increasing or decreasing the field. The induced change is dependent upon the original direction of the magnetic field and the polarization of the metal rod and its composition. When the change in length of the bar is performed at the resonant (mechanical) frequency of the bar, and the induced change is properly phased to enhance the field that produces the strain, mechanical oscillations are set up at the fundamental frequency of the bar. When clamped in a fixed position at the middle, the bar will vibrate with a flexural motion similar to a tuning fork. The metal composition of the bar determines its efficiency and effectiveness as a resonator. A pure iron rod will oscillate very feebly if at all, and a nickel rod will vibrate strongly, but has poor stability. A combination of nickel and iron, such as Invar or Stoic metal, oscillates strongly but has a poor temperature coefficient. With the addition of a small amount of chromium to the nickel alloy, one of the strongest vibrators and most readily available metals (Nichrome) is produced. A copper-nickel alloy (Monel) has too little residual magnetism to operate without an external field, but when a permanent magnet is held nearby it oscillates strongly. Temperature effects will cause changes in the bar length and thus affect the frequency of operation; hence, for extreme stability, the alloy must have a small temperature coefficient or temperature control must be used. Operation in this respect is similar to the operation of crystal oscillators.

The change in length at fundamental longitudinal (mechanical) vibrations is on the order of one part in one million (of an inch) for a field of one gauss, using a nickel rod as an example, but when the rod is resonant, the change in length is multiplied one hundred times or more. Thus, at the resonant frequency the mechanical change in length is sufficient to produce a substantial change of field, and control the operation of the oscillator. At the lower audio frequencies, it is desirable to use an oscillator phased to oscillate very feebly, if at all, without the rod. At supersonic and low r-f frequencies of from 25 to 300 kc, the oscillator is not very greatly affected if the basic electronic circuit oscillates strongly without the bar. The stability of the bar prevails in either case. By utilizing nickel tubing with a negative temperature coefficient and filling the tubing with Stoic metal which has a positive temperature coefficient, temperature compensation may be achieved to produce a nearly zero-temperature-coefficient bar.

Although operation is possible at 2 megacycles and higher, the oscillation is usually feeble and not nearly so strong as that of the conventional quartz crystal; therefore, operation of this type of oscillator is usually restricted to the lower frequencies.

Circuit Operation. The basic circuit of the magnetostriction oscillator is shown in the accompanying illustration. Grid bias is obtained conventionally through grid-leak operation (C_g R_g), and series plate feed is used. The coils are wound so as to produce the same flux at the plate end of the bar for an increasing plate current or an increasing grid current (they are in-phase). This condition, which is opposite to that of the normal feedback oscillator, produces degenerative feedback, rather than regenerative feedback. In addition, these plate and grid coils have no coupling or only very loose coupling. Thus, the oscillator will normally not oscillate at all, or oscillate only feebly, as a result of feedback between the interelectrode capacitances. Capacitor C1 is the tuning capacitor, and is connected so as to tune both the plate and grid coils (either one alone may be tuned if desired). For a single frequency or frequencies within a narrow range of operation, C1 may be fixed and different lengths of rod may be inserted in the coils (similar to crystal plug-in operation) for the different frequencies.



Magnetostriction Oscillator

Assume that plate voltage is applied and that the plate current is producing a steady strain on the rod. If a noise pulse occurs and produces an increase of flux in the plate coil, a compressional wave will be started at the plate end of the bar and will travel to the left toward the grid end. This compressional wave due to magnetostriction will travel through the bar in a manner similar to the propagation of sound waves through a metal bar. When the compressional wave reaches the grid coil, L_g, the lengthening of the bar induces a positive voltage in the grid coil, which is applied to the grid and causes the plate current to increase. The increased plate current induces a stronger field around the plate coil, inducing another compressional wave into the bar. The compressional waves in the bar are reflected from the grid end and travel back to the plate end, where they again are reflected back toward the grid end. When the compressional wave which is reflected from the grid or left end of the bar reaches the right or plate end, a voltage is induced in plate coil L_p by the lengthening of the bar. This voltage, by induction, creates a stronger field around the plate coil. Consequently, the motion of the plate end of the bar is further reinforced, causing it to vibrate more strongly. As a result, another compressional wave is started and the cycle repeats. When the induced and reflected waves are in phase, the grid-reflected wave arriving at the plate end will always reinforce the induced wave at the plate end, producing a stronger oscillation. Therefore, the length of time it takes for the wave to travel from one end of the bar to the other and return will determine the phasing of the reflected and induced waves. For each length of bar, there will be a specific time taken for a wave to travel to the end and return; if the length is made equivalent to an electrical half-wave-length, each wave will reinforce the other. When the frequency of the tuned circuit (as adjusted by C1) is approximately the same as the resonant frequency of the bar, maximum reinforcement will occur and maximum mechanical vibration will be produced. With the bar initially unpolarized, operation will occur at the second harmonic. Therefore, the bar is usually permanently magnetized and inserted into the coils so that the field of the plate coil increases the polarization. Operation then takes place at the fundamental frequency ($f = v/2l$ where v is the velocity of sound and l is the length of the bar). Adjusting tuning capacitor C1 for *maximum plate* current tunes the oscillator to the bar frequency, and feedback is provided mainly through magnetostriction action. Even though there may be some coupling to produce oscillation without the bar, with the bar in place oscillation is strengthened and maintained, being controlled by the mechanical vibration of the bar.

When the bar vibrates at an audio frequency, the sound is audible close to the bar. The operation is similar to the operation of an a-c driven tuning fork. The difference is that the tuning fork is actually driven by an a-c signal (audio) from an oscillator operating at the frequency of the tuning fork. The tuning fork vibrations induce a magnetic change in a pickup coil around one leg of the fork, thus inducing a stable mechanically controlled signal back into the driving oscillator. The output of the magnetostriction oscillator is usually capacitively coupled from the plate circuit into an amplifier, operating as a buffer on either the fundamental or the desired harmonic frequency.

FAILURE ANALYSIS.

No Output. If the bar (or tube) is mechanically defective or the tuned circuit is not adjusted to the bar frequency, no output will result. A plate milliammeter connected in the plate circuit will abruptly indicate a two or three times increase of current when tuning capacitor C1 is adjusted to the bar frequency. Otherwise, the circuit is probably open and should be checked with an ohmmeter.

Low Output. A low supply voltage or poor soldered connections which introduce high resistance into the circuit can cause a reduction of developed signal. Excessive bias developed by an RC grid-leak combination which has too large a time constant can cause blocking of the grid and motorboating. Normal resistance and voltage checks will quickly isolate the defective portion of the circuit.

Incorrect Frequency. Since feedback occurs at the bar frequency and is practically independent of the tuned circuit, only a free-running oscillator operating considerably away from the fundamental bar frequency can produce an incorrect frequency. Actually, once the bar starts oscillating the tuned circuit can be varied over quite a noticeable tuning range before oscillations cease. Thus, small changes in the LC circuit will affect only the output amplitude. The usefulness of this circuit as a frequency stabilizer stems from the fact that only the mechanical vibration of the bar determines the frequency of oscillation. Therefore, at low audio frequencies it will be practically impossible to obtain a different frequency. At r-f frequencies, however, it is possible for spurious oscillations to occur at a frequency not related to the bar frequency because of operation of the electron tube circuit as another form of self-excited oscillator. The frequency of operation should indicate the relative values of components involved, so that the circuit can be examined for lumped capacitance and inductance which could resonate at the undesired oscillating frequency.

NEGATIVE RESISTANCE OSCILLATORS.

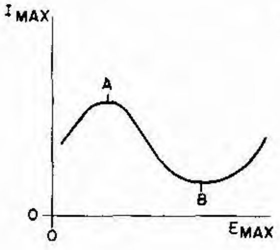
The negative resistance type of oscillator includes the dynatron, which operates by virtue of secondary emission effects in a screen grid tube, the negative transconductance pentode (or transitron) circuit, and the push-pull (or kallitron) circuit. There is also a possible fourth class, that is, the negative grid resistance type (better known as the tuned grid oscillator with capacitive feedback inherent within the tube); however, this oscillator is not used very much at present. Since it is sometimes included in the negative resistance group, however, it is mentioned here; the interested reader is referred to standard texts for this data.

Negative resistance is a somewhat vague term, which is not very well understood by the layman, or even by many engineers. Actually, it is a term used to describe an imaginary property dealt with in the mathematical analysis of oscillators (and also in amplifiers to a limited extent). It is often erroneously defined as the opposite of positive resistance, which is considered as conventional, or real, resistance. This definition is based on the fact that positive resistance manifests itself by an increasing voltage drop as the current is increased. Negative resistance, on the other hand, manifests itself by a decreasing current as the voltage applied to the device exhibiting the negative resistance is increased, or by a decrease in voltage as the current is increased. While these physical effects are real, the derivation and meaning of the term is purely artificial.

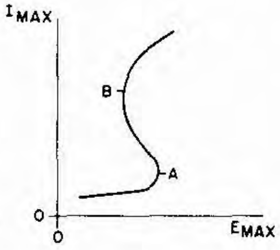
In the mathematical analysis of oscillators, a series of terms have been developed to describe the properties of the circuit; they are then added and equated to zero. One of these terms is always positive resistance, which is real; it exists in the d-c and a-c resistance of the coils and leads, and is always assigned a positive value. Therefore, to be equated to zero, the series must contain certain other terms that are of equal, but negative, value. It is this negative resistance which, when it equals the positive resistance mathematically, permits oscillation. With any type of oscillator, both the positive and negative resistance concepts apply. In the oscillators considered previously, the negative resistance is created by an external circuit, such as an inductive or capacitive feedback arrangement. In the true negative resistance type of oscillator, however, the negative resistance is an inherent property within the tube or device which exhibits it. There is no circuitry involved other than the requirements to supply a tank circuit or inductor in parallel (or sometimes in series) with the negative resistance. The basic simplicity of this type of circuit makes it useful if its inherent defects do not nullify the advantage of its simplicity.

A more effective way to understand **negative resistance** is to visualize it as a generator of energy. In contrast to positive resistance, which **dissipates** energy at a rate proportional to the square of the impressed voltage or current, negative resistance **generates** energy at a rate proportional to the square of the impressed voltage or current.

Negative resistance may be either voltage-controlled or current-controlled; the accompanying figure illustrates the volt-ampere characteristics of these two types of control. As can be seen, each type is the exact inverse of the other. In the voltage-controlled device, as the voltage is increased the current rises to a peak, and then drops to a low value from A to B (this is the negative resistance region) and then increases to a new peak value thus the voltage is a single-valued function of the current. In the current-controlled type, the voltage varies similarly as the current is increased, and the current is a single-valued function of the voltage. Note the characteristic "lazy S" pattern of these curves, which makes them easily identifiable. The oscillators described in the following discussions are all of the voltage-controlled type.

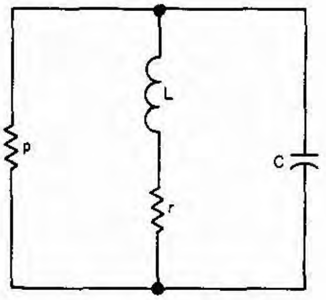


Voltage-Controlled



Current-Controlled

When either a parallel resonant or a series resonant tank circuit is connected across a negative resistance device, it can be mathematically demonstrated that oscillation will occur if certain conditions are satisfied. The basic equivalent circuit of a negative resistance oscillator is shown in the accompanying illustration. L, C and r in the figure represent the tank inductor, capacitor, and tank resistance respectively, and p represents the negative resistance.



Basic Negative Resistance Oscillator Equivalent Circuit

It can be shown mathematically that when p is smaller than the ratio L/rC the amplitude of oscillations will build up. On the other hand, when p is greater than the ratio of L/rC, the oscillations will diminish in amplitude and eventually cease. The criterion for constant oscillation with no change in amplitude is that p be just equal to L/rC. Thus for oscillation to occur, p must be less than, or equal to, L/rC.

If a generator is substituted for p in the basic figure, it can be understood how the basic concept of negative resistance applies. The region where the device exhibits a negative resistance normally covers a limited range, and is never associated with postive resistance. That is to say, when the device is operated as a conventional feedback oscillator, the operating region is beyond that portion associated with the negative resistance properties. Thus, devices which exhibit negative resistance can also be employed in circuits involving the positive resistance region of operation without any conflict with their negative resistance characteristics. For example, the same type of tube which is particularly useful in the dynatron oscillator (because of its inherent secondary emission at plate voltages lower than the screen voltage) may also be used in conventional LC feedback oscillator circuits operating at higher plate and screen voltages in the so-called positive region. For good waveform, it is important that large capacitance values be used in the tank circuit of the negative resistance oscillator, as small capacitance will cause distorted output waveform.

DYNATRON OSCILLATOR.

APPLICATION.

The dynatron oscillator is used to produce a stable sinusoidal output over the low, medium, and high-frequency r-f ranges (and sometimes the audio-frequency ranges). It is used mostly as a signal generator for laboratory or test equipment purposes or as a beat-frequency oscillator in receivers.

CHARACTERISTICS.

Uses the negative resistance of a screen-grid tetrode to produce oscillation.

Provides very good stability, but at a low output amplitude.

Uses a two-terminal tuned circuit to determine the frequency of operation.

CIRCUIT ANALYSIS.

General. The dynatron circuit was originally based upon the use of the type 24 screen-grid tube, which exhibited considerable negative resistance at low plate voltages. The negative resistance was due to secondary emission from the tube plate. Present day tube manufacturing and design methods have minimized the undesired secondary emission, but it still exists at very low plate voltages in most tetrodes. Secondary emission occurs when the plate is much lower than the screen voltage, because of bombardment of the plate by electrons which have passed the screen grid. With high or normal plate voltage these electrons are attracted back to the plate and have no effect. With low plate voltage, however, the field of the grid extends into the plate region and attracts the secondary emitted electrons knocked out of the plate. Thus, the plate current is reduced by the amount of secondary electrons captured by the screen grid, and the screen current is increased. The accompanying figure illustrates typical plate and screen currents for a type 24 tube. These curves have the distorted "lazy S" shape characteristics of negative resistance as explained previously in the general discussion. When the tube is operated in the region of negative slope with a tank circuit connected to either the screen or the plate, oscillation will occur. Maximum screen current flows when the plate current is minimum (point B on the curve). Useful oscillation is possible between points A and B, with the oscillator adjusted to work at the midpoint of this negative resistance region. From points B to C and beyond is the positive resistance region, which cannot be used for dynatron operation. It can be clearly seen that the plate of the dynatron must be operated at extremely low voltages; therefore, the amplitude of oscillation is limited and the circuit is capable of only a small output. The output amplitude is controlled by adjusting the grid voltage, which varies the slope of the negative resistance region.

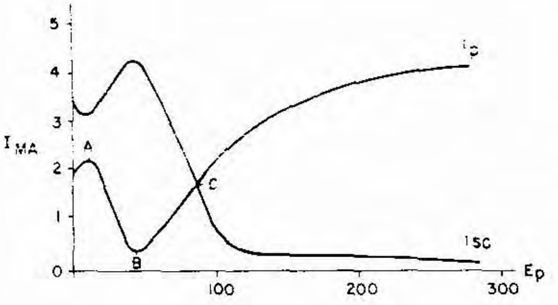
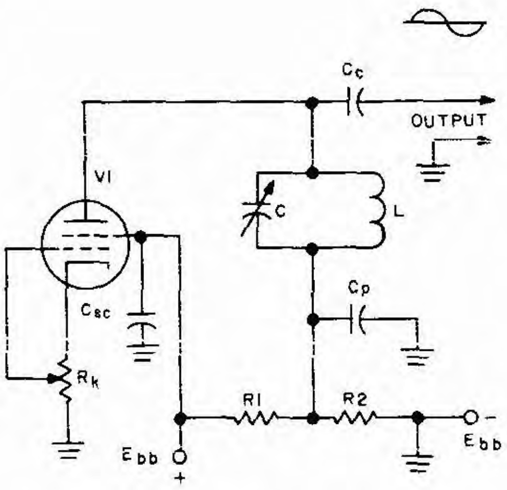


Plate and Screen Current Relationships

One of the advantages of this type of oscillator is that it requires only a single coil with tuning capacitor, instead of a tapped coil or an additional tickler winding. Thus its extreme simplicity made it popular. On the other hand, since secondary emission varies with the age and emission of the tube, and since tubes of the same type and manufacture have widely different secondary emissions, it is necessary to have a plate voltage control to permit adjustment for stability with tube aging and the use of different tubes. Because of the low output and the variation of secondary emission from tube to tube, this circuit is not very widely used today.

Circuit Operation. A typical dynatron oscillator circuit is shown schematically in the accompanying figure. The grid is biased by means of potentiometer R_k when cathode current flows. Adjustment of the grid arm of the potentiometer effectively places the grid at a more negative potential with respect to the cathode in one direction of rotation, and at a less negative potential in the other direction of rotation. The screen is connected to the high side of the plate supply and bypassed by C_{sc}, and the plate is connected to a voltage divider consisting of R1 and R2. Thus, the plate voltage is reduced below the screen voltage. Capacitor C_p is the conventional series-feed bypass. The tuned tank, consisting of L and C, is placed in the plate circuit, although it could also be placed in the screen circuit. The output is taken capacitively from the plate by C_c.



Dynatron Oscillator

The inherent stability in this type of oscillator is based upon the action of the tank circuit primarily, as in other types of the LC oscillator. Although operation at a low plate voltage limits the output to a low value, it also contributes some stability, because load changes are a smaller percentage variation than in other self-excited power type oscillators. Since the feedback is inherent in the tube, rather than being provided by an external circuit, changes in tube element capacitances are not as effective in causing frequency changes, thus contributing to the stability of this type of oscillator. Therefore, a dynatron which is properly adjusted for the correct operating point and plate voltage is practically equivalent to the electron-coupled LC oscillator, as far as frequency stability is concerned.

Operation at a low amplitude insures better linearity and less harmonic content in the output, accounting for the relatively pure output waveform of this type of oscillator. Variation of the grid voltage changes the slope of the negative resistance characteristic and thus governs the operating amplitude.

Detailed Analysis. Mathematically it can be demonstrated that when an LC tank circuit is connected to a negative resistance element oscillations will start and continue, with the negative resistance supplying the losses caused by the positive resistance of the tank. In the conventional external feedback oscillator, this same action is obtained by the feeding back of output voltage in-phase with the input voltage. In the dynatron it is inherent within the electron tube. Thus, in the conventional feedback oscillator, as the plate voltage is increased, the plate current is also increased and the amplitude of oscillation is primarily limited by the power supply voltage. In the dynatron, with the plate operating at a lower voltage than the screen, as the plate voltage increases the plate current decreases. As the plate current decreases, since the supply voltage remains substantially the same (considering a regulated supply), there is more voltage available for the load. Thus, as the tube current becomes smaller, the voltage across the load builds up. In effect, the tube is releasing energy from the power supply instead of absorbing it. Therefore, the tube can be considered as a generator which supplies power to the tank circuit. This generated energy is used to overcome the losses in the tank circuit, and the oscillation builds up until an amplitude is reached where a state of equilibrium is obtained, and continuous oscillations are produced without any external feedback circuitry. All that is required is to shock excite the tank circuit into oscillation, and once started the action continues. Starting is produced by turning the circuit on. The initial rush of current to the plate produces a transient oscillation in the tank circuit, at the approximate frequency to which it is tuned. In the absence of negative resistance, this oscillation would quickly die out, being damped by the positive resistance of the tank. The inherent negative resistance of the tube, however, provides an effective in-phase feedback. Consider the tank circuit and its operation. In an oscillatory condition, the coil and capacitor are interchanging energy. First the capacitor tends to charge as the transient increases, and the charging current flows through the inductor in a direction which increases its magnetic field. As the transient reaches its peak and drops, the magnetic field about the coil collapses and induces a reverse voltage in the coil, which is in the direction of capacitor discharge. Consider now the instantaneous a-c component of plate voltage. As the transient increases in amplitude, the total effective plate voltage is increased and the instantaneous plate current is reduced. With a lowered current the plate voltage tends to rise, and this constitutes a higher effective plate voltage. Thus, the action within the tube is such as to aid the transient, and the tube is quickly driven to its saturation region (point B on the plate and screen curves shown previously). At saturation the plate current does not change, so the inductor field collapses and the reverse cycle occurs. Since the voltage is decreasing, the plate current increases; this in turn, reduces the available plate voltage, and the tube absorbs the power. The transient is now falling and effectively subtracts from the total applied plate voltage. Thus the plate voltage is driven in a negative direction (a peculiarity of the dynatron region), whereupon the plate current change reverses itself. At this time the capacitor, which is discharged, proceeds to charge again and the cycle is repeated. The limits of operation are set by the applied grid bias, which determines the operating point, and the static plate voltage.

Unfortunately, the effects of secondary emission are not completely controllable, and the setting for optimum amplitude and efficiency for each tube of the same type varies. The negative resistance oscillator circuits which follow are considered to be better from the standpoint of stability and criticalness of adjustment than the dynatron circuit. When the tank tuning capacitance is reduced to that of the tube elements and leads, the output waveform is considerably distorted, and operation approaches that of the relaxation oscillator with the frequency of operation being set by the time constant of the resistance and capacitance in the circuit. With the tuned tank, however, the angular frequency of oscillation is approximately $\omega = \sqrt{\frac{r+p}{p} \quad \frac{1}{LC}}$

Since r, which represents the a-c resistance of the coil and leads, is usually only a few ohms, whereas the negative resistance p is seldom less than two or three thousand ohms, the frequency of oscillation is practically equal to

$$f_o = \frac{1}{2\pi\sqrt{LC}}$$

As a result, small changes in p which result from changes in the supply voltage have negligible effect on the frequency of oscillation at the threshold value, where p is equal to or less than L/rC.

FAILURE ANALYSIS.

No Output. A no output indication will be caused by lack of supply voltage, or by a plate voltage which exceeds the screen voltage and places operation in the positive resistance region, producing a non-oscillatory condition. An increase in coil resistance due to poor contacts or soldered joints can place operation in the non-starting region; such resistance will be so high that it will be revealed by a resistance analysis. With normal voltages applied and no oscillation, either the tank circuit is short circuited, or the secondary emission has changed and requires an adjustment of plate, screen, and grid voltages or a change of tubes. A change of load can change the negative resistance values and place the circuit in the non-operative region. In this case, removing the load will restore normal operation and indicate the source of trouble.

Reduced Output. A primary cause of reduced output, which is common in this circuit, is for a change to occur in secondary emission, requiring a readjustment of operating voltages or the selection of another tube. A change in grid voltage to an operating region of small slope will also cause an amplitude change and reduced output. Such a condition will be evident by a grid voltage check. The reduction of applied plate voltage through a defective voltage divider can also cause the same condition. Thus, voltage and resistance checks should quickly reveal any defective components. If the trouble still persists, either replacement of the tube or readjustment of the circuit voltages is in order.

Incorrect Frequency. Changes in load or changes in applied screen and plate voltages will change the frequency slightly, but the effect is usually negligible. Since the tank circuit is the primary frequency-determining portion of the circuit, any large frequency change will be due to a change in tank circuit parameters. Usually the tuning range is sufficient to adjust the circuit to the desired frequency. Once properly set, any noticeable frequency change indicates either ambient temperature effects or poor contact resistances (soldered joints) in the tank circuit. Otherwise, the tube parameters have changed and selection of a new tube is necessary.

TRANSITRON (NEGATIVE GM) OSCILLATOR.

APPLICATION.

The transitron, or negative transconductance (g_m), oscillator is used to supply a stable sinusoidal waveform at audio and low or medium radio frequencies. It is used mainly in test equipment, receivers, and laboratory instruments that require a simple bandswitching oscillator.

CHARACTERISTICS.

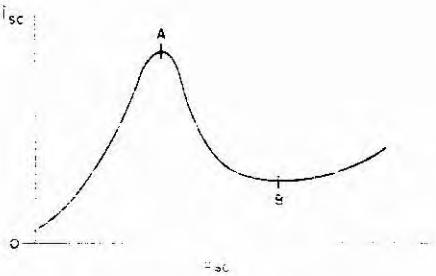
Uses the negative transconductance effects of a pentode to provide negative resistance type of oscillation.

Uses an external capacitor coupled between the suppressor and screen to obtain negative transconductance.

Utilizes a two-terminal tank circuit to determine the frequency of operation.

CIRCUIT ANALYSIS.

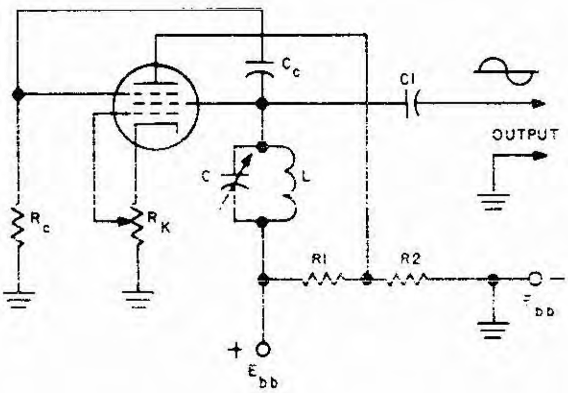
General. When a negative voltage is applied to the suppressor grid of a pentode, it will cause electrons that have passed through the screen grid to return to the screen grid. If the negative suppressor voltage is decreased (made more positive), more electrons will be attracted to the plate, and the screen-grid current will be reduced. Thus, the screen-to-suppressor transconductance is negative. With proper voltages and circuit arrangements, the screen current will decrease with a small positive voltage increase on the suppressor, even when the screen voltage is also increased an equal amount. The accompanying figure shows a typical screen current versus screen voltage characteristic curve of a pentode which has its suppressor coupled to the screen through a capacitor. The typical distorted "lazy S" pattern indicates that there is a negative slope. Thus, oscillation will occur if an LC tank circuit is connected in the screen circuit.



Negative Transconductance Characteristic

If the control grid is biased negatively, the bias may be adjusted to control the amount of negative resistance developed. With the negative transconductance arrangement, the control and development of the negative resistance effect is by electrode voltages and circuit parameters. Thus, the transitron oscillator does not depend upon secondary emission for its operation; therefore, it does not have the undesirable features of the dynatron oscillator, although the circuit is somewhat more complicated.

Circuit Operation. The schematic of the basic transitron oscillator is shown in the accompanying figure. In this circuit, the LC tank is inserted in the screen grid circuit, and the screen is capacitively coupled to the suppressor through capacitor C_c. The output is taken capacitively from the screen circuit through C1.



Basic Transitron Oscillator

Cathode bias is employed, and the grid is returned to potentiometer R_k. Variation of the negative grid bias permits the slope of the negative transconductance region to be controlled. Thus, both output and linearity control are effected. Note that the plate is placed at a reduced potential with respect to the screen grid by means of the voltage divider consisting of R1 and R2. The basic arrangement is the same as in the dynatron oscillator, except that the pentode has an additional element, the suppressor. Since the suppressor is located between the screen and plate, it will control the current between these elements when properly biased. To produce the negative transconductance, the screen is capacitively coupled through C_c to the suppressor, and the suppressor is returned to ground through R_c. As a result of these connections, instantaneous a-c variations of the screen voltages are effectively applied to the suppressor, and d-c variations are effected through the RC network in accordance with the time constant. For proper operation, it is imperative that the reactance of C_c at the operating frequency be very small as compared with the resistance of R_c. This is necessary to ensure that practically all of the feedback voltage appears across R_c and that very little voltage divider action occurs, as when C_c has a large value of reactance. The effect of the voltage divider action is to reduce the feedback and produce a higher negative resistance, which is not desired.

In a pentode, the movement of electrons from the cathode to the screen and plate constitutes the screen (i_{sc}) and plate currents (i_p), respectively. Variations in suppressor voltage (e_{su}) have negligible effect on the total number of electrons leaving the cathode because of the shielding effect of the screen and control grids. The suppressor grid voltage, however, does control the division of the space current between the screen and plate. Making the suppressor voltage less negative results in a greater number of electrons passing through to the plate; consequently, the plate current, i_p, increases while the screen current, i_{sc}, decreases. On the other hand, making the suppressor voltage more negative results in fewer electrons being passed through to the plate, and a decrease of i_p, with an increase in i_{sc}. Typical variations of the screen and plate currents with changes in the suppressor voltage are shown in the accompanying graph. A decrease of i_{sc} with an increase of e_{su} indicates the existence of a negative transconductance between the screen suppressor grids. Since the reactance of C_c is negligible at the frequency of oscillation, the alternating components of the screen voltage and the suppressor voltage are of the same polarity. Therefore, an increase in screen voltage instantaneously increases the suppressor voltage and, because of the negative transconductance, decreases the screen current. Thus, the negative transconductance of the tube produces, in effect, a negative resistance between the screen grid and cathode.

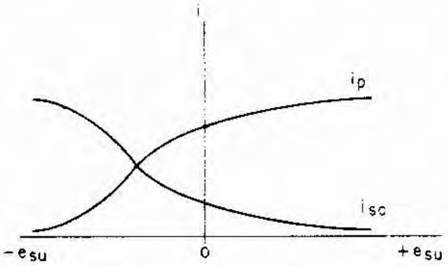
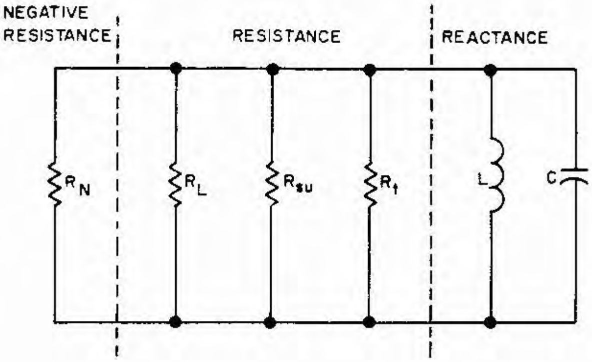


Plate and Screen Currents vs. Suppressor Voltage

When the transitron oscillator is adjusted so that the negative resistance is smaller than the value needed to produce continuous oscillations, any brief oscillation or transient caused by closing of the plate switch is amplified. As a result, the operating range on the screen current versus suppressor voltage characteristic curve is increased, and, because of the curvature of the characteristic, the average slope of the part used is decreased. Since this is the same as increasing the value of the negative resistance, the amplitude of oscillation increases until the value of the negative resistance is such that it maintains a constant amplitude of oscillation.

Detailed Analysis. For oscillations to be sustained, the losses in the tuned circuit must be replaced by energy supplied from the electron tube. The losses produced by the circuit resistances are best illustrated in the accompanying transitron equivalent circuit.

The negative resistance presented by the tube to the tuned circuit is represented by R_N, and the tank circuit losses by R_t in parallel with the LC tank. The shunt resistance of suppressor return resistor R_{su} and load resistor R_L are effectively in parallel with the negative resistance and the tank loss resistance. The sum of R_L, R_{su}, and R_t is the effective positive resistance. The current in R_N must be equal and opposite to the total current through this positive resistance. If R_N is larger than the positive resistance, the current through R_N is too small and the oscillations die out. If R_N is smaller, the current is too large and the oscillations increase in amplitude. When the current through R_N is just sufficient to sustain oscillations, the circuit is the equivalent of a simple LC combination,



Transitron Equivalent Circuit

and the frequency of operation is: $f = \dfrac{1}{2\pi\sqrt{LC}}$

FAILURE ANALYSIS.

No Output. The loss of plate voltage due to defective divider resistors, the lack of screen voltage due to an open tank coil or a defective supply source, or a defective tube will cause loss of output. A change in the value of the feedback capacitor can reduce the feedback below the amount required for oscillation, depending upon the frequency of operation. High resistance coil contacts (poor solder joints) will also cause circuit losses high enough to stop operation. Since there are relatively few components, trouble should easily be isolated by a voltage check to determine proper operating conditions, and by a resistance analysis if the voltages are apparently correct. It should not be necessary to select tubes to produce oscillation, because, unlike the dynatron, the circuit is operable regardless of secondary emission. Restoring oscillation by the selection of tubes indicates insufficient feedback between the screen and suppressor due to incorrect or changed values of R_c or C_c.

Reduced Output. Excessive reactance in the suppressor-screen feedback circuit can change the negative resistance value and reduce the amplitude of oscillation. However, reduction of output is more likely to be caused by excessive bias on the control grid, which will restrict operation to a very limited range of negative slope. Also, excessively low screen and plate voltages will cause a reduction in over-all amplitude, even though the tank circuit at resonance will provide an increase of output. In oscillators covering a wide frequency range where the feedback capacitor value is changed by a switching arrangement to produce optimum feedback, difficulties with switch contacts may cause loss of amplitude on some of the ranges.

Incorrect Frequency or Instability. Since the tank circuit is the primary frequency-determining element, normal variations of frequency due to aging of components should be easily compensated for by adjustment of the tuning capacitor. After the capacitor is adjusted, if the frequency varies it is probably due to the effect of ambient temperature changes or r-f heating on the tank inductance and distributed capacitance.

KALLITRON (PUSH-PULL) OSCILLATOR.

APPLICATION.

The push-pull negative resistance type of oscillator, known as the **Kallitron**, is used to produce pure audio-frequency waveforms, with low harmonic content. Its use is mostly confined to laboratory type audio generators and test equipment.

CHARACTERISTICS.

Uses two tubes in a push-pull feedback arrangement.

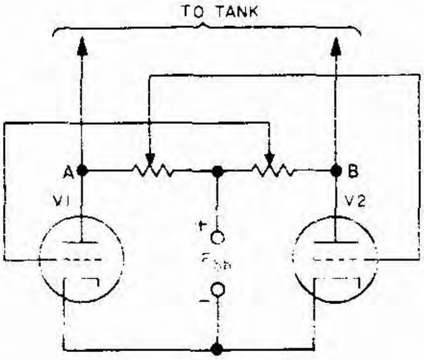
Uses a tuned LC tank to determine frequency of operation.

Produces a sinusoidal output waveform, with low harmonic content.

CIRCUIT ANALYSIS.

General. In a balanced push-pull circuit with no input voltage applied, the quiescent plate currents and voltages are equal. When an input is applied, first one tube conducts, and then the other conducts. Assuming a sine wave input, as tube 1 goes through a positive grid excursion, it develops an inverted polarity output across its plate load resistor. If this inverted output is applied to the grid of tube 2, a positive output will be developed in the plate load of tube 2. If the plate output of tube 2 is fed back to the grid of tube 1, the positive input excursion will be enhanced, and the tubes will be driven in opposite directions equally. As the input waveform changes polarity the opposite action occurs, with grid 2 now being driven positive and grid 1 negative. If a tank circuit is connected between the plates of these tubes, oscillation will occur because of current flow in the external circuit, and the frequency will be determined mainly by the tank circuit resonant frequency. The accompanying figure shows an elementary oscillator circuit of this type, with the tank connected between points A and B (bias voltage is not shown for simplicity).

As can be seen, the circuit is basically a simple multivibrator. However, in a multivibrator the current (and voltage) changes abruptly from one value to another and is determined mainly by the values of R and C in the circuit. In the Kallitron oscillator, however, the oscillation is controlled by the tuned tank circuit, and there are no abrupt changes, the transition from one state to another of conduction being smoothly sinusoidal. Because the plate voltage of each tube increases when the plate current decreases, there is in effect a negative resistance between the two plates. The second harmonic output is effectively reduced by the push-pull action, and the third harmonic content is reduced by the tuned circuit. Therefore, the output waveform is relatively pure, having a minimal amount of harmonic distortion.

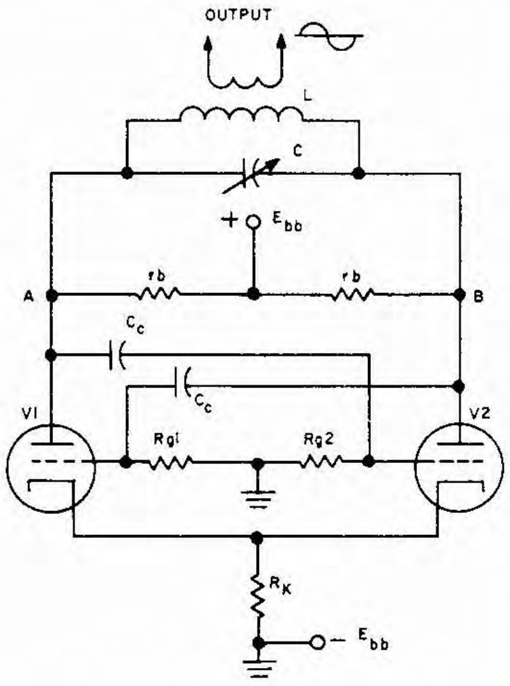


Elementary Push-Pull Oscillator

Circuit Operation. The schematic of a typical Kallitron oscillator is shown in the accompanying illustration. Usually a dual triode in one envelope with its accompanying circuitry is used to provide, in effect, a single tube oscillator. To keep the push-pull relationships in balance, the output is generally taken inductively, but it may be taken capacitively.

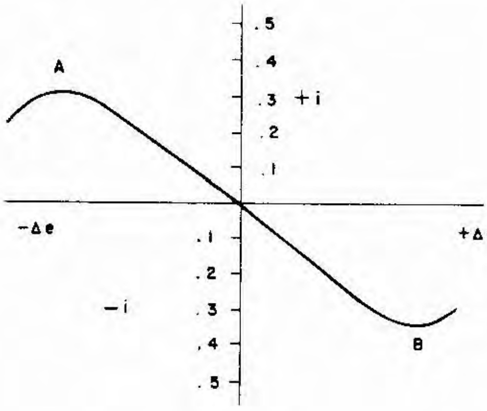
Cathode bias is provided by R_k. Since the tubes operate in push-pull through a common cathode bias resistor, it can be seen that as the plate current of tube 1 increases the bias also increases, and, being applied to the V2 cathode, it reduces the plate current of tube 2. On the other half cycle, the operation is reversed, with the V1 current decreasing and the V2 current increasing. The net result is a negligible change in cathode current. Feedback is obtained by cross-connecting the grids and plates through C_c. Thus as the grid of V1 rises, the plate current increases, causing the voltage on V2 grid to fall, which increases the plate voltage of V2 and feeds back a rising grid voltage to V1 grid. Likewise, on the opposite cycle the conditions reverse. The output amplitude is controlled by proportioning the grid resistors, R_g, and the grid coupling capacitors, C_c. The amplitude is also affected to some extent by the *applied plate voltage and the values of the plate load resistors*. However, the most effective method is to adjust the bias by means of R_k to obtain the desired amplitude. Actually, C_c and R_g operate essentially as grid leaks. When the reactance of the grid coupling capacitor is small in comparison with the grid leak resistance at the lowest operating frequency, the feedback is at a maximum, and the tank circuit can be connected in either the grid or plate circuits.

A typical curve showing plate voltage change versus external current flow between points A and B exhibits a continuous negative slope over most of its range, indicating



Kallitron (Push-Pull) Oscillator

typical negative resistance characteristics, as illustrated in the accompanying figure.



Typical Current-Voltage Characteristics

With the feedback action now understood, it can be clearly seen that when the LC tank is connected between points A and B it is alternately charged and discharged at its natural resonant frequency. Since the voltage on one plate is increasing when the voltage on the other tube plate is decreasing, points A and B are always of opposite potential. With a low-resistance tank circuit in place, the negative resistance action, produced by the tube operating at reduced conduction, effectively supplies energy to the tank circuit to overcome its positive resistance losses, so that continuous oscillation is maintained.

FAILURE ANALYSIS.

No Output. Lack of plate voltage due to an increase in external load resistance or short-circuiting of the supply will cause lack of output. Since the negative resistance primarily depends on the amplifying action of the tube, insufficient amplification may also result in no output. Any change in the feedback circuit which reduces the feedback below the critical point can also stop oscillation. Since these conditions are generally produced only by an open- or short-circuited component, resistance and voltage checks should quickly isolate the defective component. Tank circuit losses resulting from shorted turns or from increased resistance due to poor contacts (poor solder joints) can also be a contributing cause. Shorted turns will show up as a change in frequency if the circuit oscillates at all, and excessive resistance will cause reduced amplitude if it does not entirely stop oscillation.

Reduced Output. Excessive bias resistance will cause a reduction of amplitude. A reduction of applied plate voltage will also reduce the amplitude, but it can easily be detected by a voltage check. Changes in the feedback capacitors or the grid-leak resistors will also reduce the amplitude. Checking the capacitor with an in-circuit capacitor analyzer will quickly determine whether the capacitance is correct, and a resistance analysis will determine whether a grid-leak resistor has changed value. A decrease in the amplification factor of the tube with aging can also reduce the output. Substitute a known good tube to determine whether the tube is at fault.

Incorrect Frequency or Instability. Since the tank circuit is the primary frequency-determining element, major frequency change would indicate the possibility of shorted turns or a reduction of capacitance. The nature of the trouble is indicated by the direction of the frequency change. That is, an increase in frequency indicates shorted turns or a reduction of capacitance, and a decrease in frequency indicates an increase of capacitance, since the number of turns cannot increase.

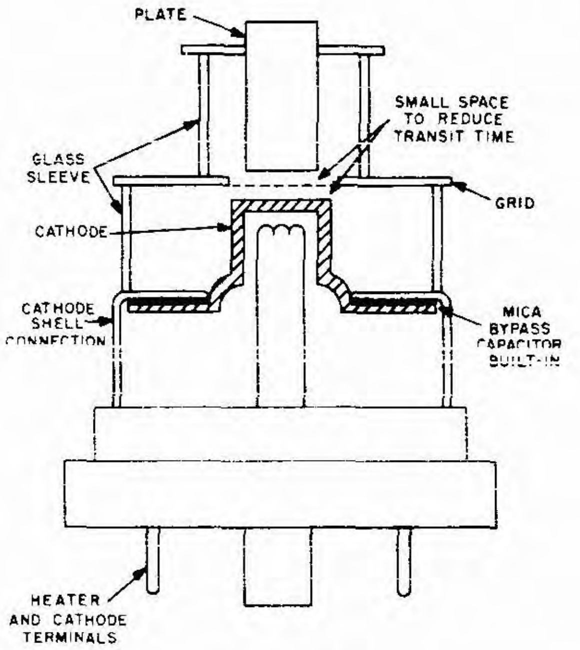
Usually minor frequency changes, which may be produced by slight changes in plate voltage with changes in load or line voltage, can be compensated for by retuning the tank circuit. Since the stability of this circuit is normally better than that of either the dynatron or transitron, small frequency changes will require the use of a reliable secondary frequency standard to determine them. At the frequencies used, changes in tube element capacitances with temperature is rather unlikely to affect the frequency. Unstable operation might possibly be caused by a reduction of the tank capacitance to a minimal value, due to such trouble as defective bearing contacts in the tuning capacitor. This could produce a distorted waveshape and possibly result in the relaxation type of oscillation. Such operation would be evidenced by abrupt changes in current and voltage from one value to another, and the frequency would, no doubt, *be out of the frequency range for which the circuit was designed.*

TUNED-LINE OSCILLATORS.

As the frequency of operation extends into the VHF and UHF regions and into the microwaves, it becomes more and more difficult to produce oscillations using conventional electron tubes. At the extremely high frequencies even the best oscillators are not very efficient. The difficulties of high-frequency operation involve the construction of the electron tube. As the frequency increases, the transit time between electrodes must be considered. Also, the tube electrodes have capacitance between each other and ground, and their leads have inductance. At the lower frequencies these capacitances and inductances are negligible as compared with the other lumped circuit components, but at the very high frequencies they become the major part of the circuit, and often must be minimized to extend the upper frequency limit. To minimize lead inductance, electron tubes are debased (no base is used), they use large leads to minimize skin effect, and sometimes have their grids or plates brought out through the envelopes. To reduce interelectrode capacitance, tubes are miniaturized to make their elements smaller (this also reduces their power-handling capability), and special construction in the form of a planar triode or tetrode is used. (The planar type of construction uses a single flat grid (or plate) through which the electron stream passes, instead of grids or plates made up of wires or screens, which are "wrapped" around the emitter as in conventional tube construction.) The original derivation of the planar tube was the well known lighthouse tube (also called **disc seal** tube), which is so named because of its physical resemblance (three or more stepped cylinders) to a lighthouse. These tubes utilize coaxial and planar elements, or rings, with direct physical connection to the electrodes themselves. There are two forms of oscillator used. One form, which operates in the VHF region, uses a special socket and its operation is similar to that of a conventional LC oscillator. The other, which is used in the UHF region, incorporates a series of coaxial cylinders into which the lighthouse tube fits as an integral part, forming a tuned *line coaxial oscillator. Tubes used for low power and* receiving purpose are usually provided with conventional pin type sockets, and those used for transmitting are either provided with a special socket and plate cooling fins or are inserted into the cavities or lines to form a compact unit. *The construction of a typical tube is illustrated in the* accompanying figure.

In addition to the coaxial line oscillators, tuned transmission line, or Lecher line, oscillators are also used. The tuned lines in these oscillators are arranged parallel to each other, instead of being arranged coaxially. At the lower frequencies the lines are used as inductances and are tuned with a shorting capacitor. At the higher frequencies they are tuned with a shorting bar and operate essentially as a quarter wave transmission line.

The tuned line can be substituted for an LC tank circuit because it possesses the same properties as the tuned tank. When the line is exactly a quarter wavelength long electrically, and is shorted at the far end with the input open, it presents a high impedance at the input and a low impedance at the far end. When it is coupled to a source of energy, a heavy current will flow in the line at the shorted end, *but only a small current (or no current) will flow at* the open or input end, because of the high input impedance. This effect is exactly the same as that produced by the conventional LC tank; therefore, the quarter-wave line can be substituted in its place.



Lighthouse Tube

Use of the transmission line tuned circuit provides a higher Q and lower losses than is possible with conventional lumped inductance and capacitance. The higher Q is obtained because the resistance of the line is low for a given value of reactance, since Q is equal to X_L/R. The low resistance is obtained by using relatively large diameter tubing, since at radio frequencies current flows on the outside of the conductor because of **skin effect.** For UHF applications this loss is made even less by silver-plating the outside of the conductor, so that the r-f current flows through a highly conductive path of silver. For single-tube oscillators the concentric type line is frequently used, and for push-pull circuits a balanced two-wire line offers a convenient arrangement (two concentric lines may also be used). The concentric line has the additional advantage that the outer conductor shields the inner conductor and thus reduces unwanted radiation from the tank to a minimum.

An incidental feature of the quarter-wave transmission line tank results from the use of the high-impedance property at the open (input) end and the low-impedance property at the output end to insulate the line as far as rf is concerned. Thus the shorted end of the line may actually be attached to the chassis without affecting the operation. This helps to reduce dielectric losses, which otherwise would be introduced if an actual insulator were used. Unfortunately, this feature cannot be used where dc is applied to the line as in series plate feed arrangements, but it can be used in shunt-feed arrangements.

The tuned lines and circuits discussed in this section are confined to negative grid oscillators; that is, to oscillators where the average grid voltage is always negative, since there are other special oscillators (such as the Barkhausen-Kurz and Gill-Morrell oscillators) which use positive grid operation to obtain UHF oscillations. This classification is necessary to avoid confusion, as both groups appear to be identical schematically at first glance, since both employ tuned lines. The positive grid voltage is the major identifying feature of the postive grid oscillator, and the circuit operation is entirely different from the operation described below.

Because the reactance of the tube interelectrode capacitance and distributed circuit capacitance is small at ultra high frequencies, the circulating (or charging) current in these capacitances is large. It is on the order of many amperes for large power tubes. This high current adds nothing to performance, and may cause damage. Because of skin effect, the current follows the surface of the metal electrodes of the electron tube, and causes localized heating of the seals, sometimes causing cracks and tube failure. Thus, in UHF oscillators the tuned circuit is designed to have a high inductance and the minimum capacitance that will resonate the tank to the operating frequency. Tuned-line tanks provide the required high inductance with a minimum of capacitance. The trend in present day tube manufacturing is to employ ceramics instead of glass as dielectrics, because of their better heat resistance and easy machining properties, in addition to the reduction of interelectrode capacitances. The push-pull circuit effectively reduces these capacitances to half their normal value since they are in series in push-pull operation. Although an open transmission line has some eddy current and radiation losses, close spacing to less than one hundredth of a wavelength (a few inches) causes the field around one conductor to neutralize the field around the other. Radiation and eddy current losses are thereby minimized, but not as completely as with the shielded coaxial line.

The Q of the quarter-wave short-circuited section of line is much higher than that of the conventional tank circuit because larger diameter conductors can be used than in the conventional coil, making the skin effect less. Specially constructed (planar) tubes extend the transmission line as a part of the tube leads. Thus, the interelectrode capacitances and lead inductances of the tube are all incorporated as a part of the tuned circuit.

Transit time produces two different effects at UHF. (1) It causes the plate current to lag the grid voltage by a small angle, so that the phase difference between the plate current and plate voltage is greater than 180 degrees. As a result, the power output is decreased and the plate dissipation is increased. (2) The transit time permits an accumulation of electrons on the grid and causes grid current flow, even when the grid is negative. This produces a grid loss which is similar to the loss incurred by shunting the grid with a resistor. At extremely high frequencies this loss is so great that the effect is as though the shunting resistor produced a short circuit between grid and cathode and prevented proper excitation of the tube. The grid loss also results in the development of heat, which can exceed the tube ratings.

Therefore, while tuned lines, together with special tube construction, offer a partial solution to the transit time problem, a different kind of generator other than the simple ultraudion feedback arrangement is required to operate at UHF with reasonable power output. The lighthouse tube provides efficiencies on the order of 48% at 500 mc to 10% at 2100 mc for CW operation, and 52% to 35%, respectively, for pulsed emissions. The present day trend is to use klystron generators for UHF, planar tubes for VHF, and either klystron or magnetron generators for microwaves and beyond.

LIGHTHOUSE-TUBE OSCILLATOR.

APPLICATION.

The lighthouse tube oscillator is used as an r-f source in the UHF range for receivers, test equipment, and low-power oscillators or transmitters. The planar type triode or tetrode is used for transmitters where more than a few watts are needed.

CHARACTERISTICS.

Uses special tube construction to overcome high-frequency limitations.

At frequencies of 300 to 1500 mc uses external lines, and at frequencies of 1500 to 2500 mc uses coaxial cylinders, into which the tube is inserted as an integral part.

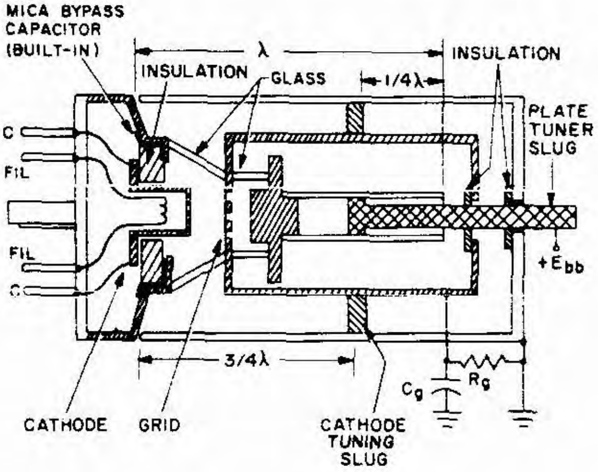
Tuning is accomplished by means of shorting bars or plungers.

Has low output and low efficiency (10-30%).

CIRCUIT ANALYSIS.

General. The so-called lighthouse tube oscillator is operable over a large range of frequencies, and the frequency of operation basically determines the final form of the oscillator. At frequencies up to about 1500 mc, the size of the coaxial elements that would be required is so great that external open-wire line or tubing must be used. When the frequency approaches 2500 mc, however, coaxial elements become small enough for practical use, and the tube itself can be inserted into them to form part of the line. Since the design of the lighthouse tube provided the necessary means of overcoming the difficulty of obtaining oscillations at the high frequencies above 300 mc, there have been a number of similar designs. Thus, the basic lighthouse tube evolved into the co-planar type of triode and pentode. In this tube the elements are coaxial cylinders, with the outside of the ring forming the electrode contact. Planar tubes using plane rings instead of coaxial cylinders can be used in coaxial lines, or separately with a special socket. The receiving type (or low-power type) has a conventional octal socket using only cathode and heater pins. The transmitting type requires the special socket and is usually equipped with radiation type cooling fins connected to the plate and normally requires forced air cooling. Where coaxial construction is used, the coaxial line itself acts as the heat radiator. Since the basic lighthouse coaxial unit is representative of this type of design, all discussion will be confined to the original type of lighthouse tube. Although now replaced by tubes of planar design, the original lighthouse tube may still be encountered.

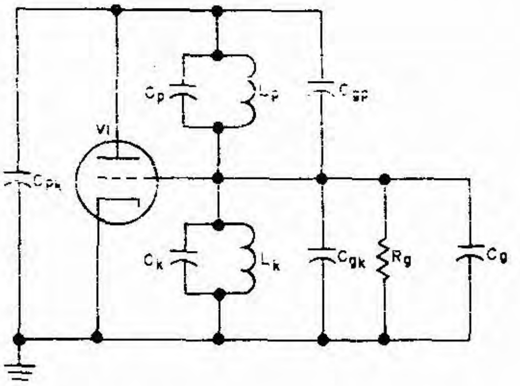
Circuit Operation. The construction of a typical self-contained lighthouse tube oscillator is shown in the accompanying illustration. The tuner assembly consists of three concentric tubes, or coaxial lines. The inner tubing is connected to the plate, the center tubing to the control grid, and the outer tubing to the shell or base envelope of the tube. The outer tube is effectively shorted to the cathode for rf by a built-in mica capacitor connected between the metal envelope and the cathode.



Coaxial Cavity Tuned Oscillator

The cathode (outer) and control grid cylinders form a coaxial cathode line which is effectively short-circuited by a capacitive non-conducting plunger at a point approximately 3/4 of a wavelength from the point of connection to the tube elements. The position of this plunger is adjusted for the proper amount of feedback. The capacitance between the plunger dielectric and the grid conductor of the coaxial line effectively shunts the rf to the cathode, but does not short-circuit it for dc. The d-c path between the cathode and control grid is provided by grid-leak resistor R_g, bypassed by grid capacitor C_g, which produces grid-leak operating bias. A shorting plunger is inserted into the plate line 1/4 wavelength from the open end (3/4 wave from plate end) to tune the plate circuit. Plate voltage is supplied by connecting B+ to the plunger. The short circuit provided by the shorting plunger offers a high impedance to r-f energy a quarter wavelength away, so that no rfc is needed to isolate the plate supply. Since the grid is located approximately one wavelength from the open end of the line and a high impedance is reflected there by the plate tuning plunger, the grid is also placed at a point of high impedance with respect to plate. Thus the open wavelength-long plate conductor and the shorted three-quarter-wavelength cathode conductor both act as parallel resonant tank circuits. The tuning of the plate circuit determines the operating frequency of the oscillator, and the tuning of the cathode circuit determines the proper amount of feed-back for stable oscillation. Since there is a certain amount of interaction between the plate and cathode circuits, it is necessary when changing frequency to adjust both plungers for optimum operation.

Detailed Analysis. The r-f equivalent circuit of the lighthouse tube oscillator is shown in the accompanying illustration.



Lighthouse Equivalent Circuit

The interelectrode capacitance of the lighthouse tube, plus the capacitive effect of the open ends of the grid conductor, is represented in the diagram as C_{pk}. The net reactance of the parallel tuned circuit containing C_k and L_k, shunted by C_{gk}, must be capacitive to ensure that the voltage divider which they form with C_{gp} supplies alternating voltage of the proper polarity to the grid. This means that the frequency of the cathode tank circuit must be lower than the output frequency of the oscillator. The operating frequency of the oscillator is determined primarily by the resonant tank in the plate circuit (C_p, L_p), which is in parallel with C_{gp}, and the effective input capacitance of the voltage divider network; consequently, it is lower than the resonant frequency of the plate tank alone, and slightly higher than the frequency of the cathode tank. To provide the proper feedback to sustain oscillation, it is necessary that the resonant frequency of the cathode tank circuit be less than the resonant frequency of the plate tank circuit. This is accomplished by careful tuning of the lines. Particular care is necessary in adjusting the cathode line, if the line is too short, it appears inductive and oscillation stops. On the other hand, if the line is too long, the effective feedback divider capacitance is increased, and the amplitude of the feedback voltage becomes too low to sustain oscillation. Consider now one cycle of operation. When the plate voltage is applied, heavy current tends to flow in the plate circuit since the tube is self-biased and the initial bias is zero. The initial rush of current shock-excites both plate-grid and grid-cathode tanks into oscillation. Since the grid-cathode tank (C_k L_k) is tuned to a lower frequency than the oscillator output, it appears as a capacitive reactance shunting the grid-cathode interelectrode capacity, C_{gk}. Neglecting the plate tank for the moment, it is seen that C_{gp} will charge due to momentary grid current flow, since C_{gp} and C_{gk} form a capacitive voltage divider between plate and cathode, or ground. Assuming that the charge is in such a direction as to make the grid more positive a momentary and amplified increase in plate current will occur. This action is regenerative. Since the plate tank is tuned to a higher frequency than the r-f output, it appears as an inductive reactance shunting C_{gp}. The result is to produce a negative grid input resistance which overcomes grid circuit losses and permits oscillation to occur. This negative resistance occurs primarily from the tank circuit which, in effect, returns energy to the circuit through its flywheel effect. When the grid pulse reaches its maximum, the plate tank appears as a high inductive impedance across which the plate voltage is dropped. During this time the tank absorbs energy from the circuit. As the grid swings negative plate current is reduced and eventually cut off. During this time the tank is returning energy to the circuit. The feedback is now in an opposite direction to the initial charging current (C_{gp} is discharging), is likewise regenerative, and quickly drives the tube to cutoff. Once oscillatory action is started it continues until the plate voltage is removed, or until the grid tank is detuned too far from resonance to retain the proper phasing. If tuned too high in frequency it appears inductive and the feedback is opposed and oscillation stops. Conversely, if tuned too low in frequency it acts as a heavy capacitive shunt from grid to cathode and also stops oscillation.

Grid bias is provided by grid-leak resistor R_g and capacitor C_g, which are connected between the open (high-impedance) end of the grid line and ground. After a few oscillations are built up, a small charge is put on C_g each time the lower end of the tank circuit swings positive. During the time the grid is not positive with respect to the cathode part of the charge leaks off through grid leak R_g. The voltage to which the grid capacitor is charged ultimately makes the grid sufficiently negative so that only a small amount of charge is added to the capacitor at the peak of each cycle, and all of this small increase of charge leaks off through R_g during the remaining time of the cycle. Thus the grid is maintained at the proper bias for good operation. If the high negative bias required for proper operation were applied at the time the oscillator was turned on, the tube would be completely cut off and oscillations could not start. It can be seen from the schematic that this circuit is essentially a simple tuned-plate, tuned-grid oscillator with the basic feedback being supplied through the plate-to-grid capacitance.

FAILURE ANALYSIS.

No Output. Since the unit is of integral construction, loss of output may be caused by failure of the cavity to tune properly, a defective tube, or an open or shorted supply. Where contact fingers are used for the shorting plunger, as in the plate line, poor contact will cause improper tuning and lack of oscillation. Also, poor contact will cause a reduction or complete lack of plate voltage, and produce loss of oscillation. The presence of voltage may be determined by a voltmeter. Poor contacts will be indicated by fluctuations of the plate current as the plunger is tuned, and sometimes by burnt spots on the lines. A defective tube is usually indicated by lack of normal plate current when due to lack of emission, or by abnormal plate current when short-circuited. Because of the inherent solid construction of the coaxial tuner, poor contacts or tube failure are the most common troubles. At radio frequencies any additional resistance in contacts produces losses which are serious in the UHF range. Therefore, effects which are not very noticeable at the lower frequencies can produce complete lack of oscillation at UHF. Since the inner cavities are inaccessible until disassembled, the only practical check is a test for voltage on the heaters and plate, and between grid leak and ground, if accessible. Observation of the plate current while tuning and a check of the voltages should be made first. The unit should then be disassembled and the tube and coaxial tuner checked. If the trouble still persists, substitution of a tube known to be good will isolate the trouble to the tuner.

Reduced Output. Reduced output is usually due to low plate voltage or improper tuning. Low plate voltage can be the result of poor contact resistance in the tuner or a defective supply, which can be easily located by making a voltage test. Improper tuning can be quickly verified by slight readjustment of the controls to see whether the output improves. With normal plate voltage and correct tuning, if the output remains low, either the tube or the grid leak is probably defective. The tube can be tested by substitution of a tube known to be good, and the grid leak can be checked by a resistance analysis.

Incorrect Frequency. Since the frequency is determined by the adjustment of the plate tank, small frequency changes can be corrected by tuning. Plate voltage and load changes will also affect the frequency to a small extent; these can be checked by changing the load and measuring the supply voltage. Normally the high Q tank afforded by the coaxial cavity results in a highly stable frequency. In cases of high ambient temperature, however, the line and cavity dimensions may change and produce a drift in frequency, depending upon the metal used. For temperature-caused changes, adequate ventilation by means of forced-air cooling is necessary. If the cavities and lines are made from temperature-compensated alloys, the cause of frequency changes will be limited to supply or tube defects.

Instability. Unstable oscillations may be caused by erratic plate supply voltage, lack of regulation, or improper tuning.

LECHER-WIRE OSCILLATOR.

APPLICATIONS.

Lecher-wire oscillators are used in the VHF and UHF regions to generate rf for the receiver oscillators, test equipment, and transmitters.

CHARACTERISTICS.

Uses a pair of lecher wires, or tuned lines, in place of conventional LC tanks.

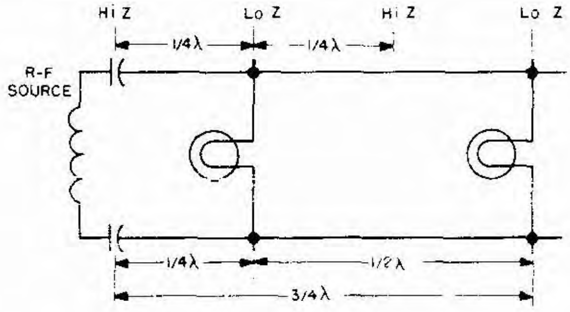
Frequency of operation is such that use of quarter-wave or half-wave lines are practical.

Has better stability and efficiency than a conventional LC circuit.

Usually used with the planar type of high-frequency tube, but not restricted to any type (can be used with any tube that will oscillate).

CIRCUIT ANALYSIS.

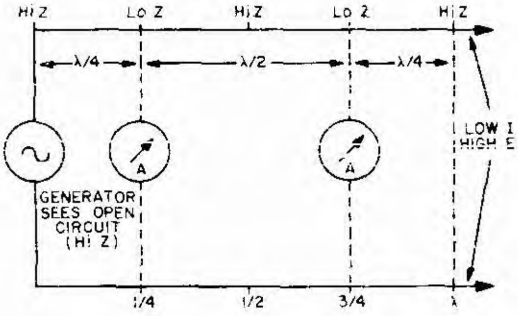
General. The lecher-wire, or transmission-line, oscillator is derived from the lecher wire wavelength measuring principle and the application of transmission line theory. The lecher-wire principle is shown in the accompanying illustration, in which two parallel wires a few inches apart are capacitively coupled to an r-f source. Assuming that the coupling is loose, the wires are in effect open-circuited. The length of the wires should be at least one full wavelength at frequency of the r-f source. When a shorting bar in series with a current indicator, such as a lamp or r-f ammeter, is placed across the lines, it will be observed that at a point 1/4 wavelength from the source maximum current is obtained. If the shorting bar is left at that spot and another one is moved along the line, an identical maximum indication (but not the same value) will be obtained at a point 1/2 wavelength from the first indication (3/4 wavelength from the source). This demonstrates that standing waves exist on the line. Such a device can be used to measure the frequency of operation in wavelengths. When the lecher wire is coupled through a single-turn loop to the r-f source, the line is considered closed at both ends; in this case, the first indication will be obtained at the half wavelength point.



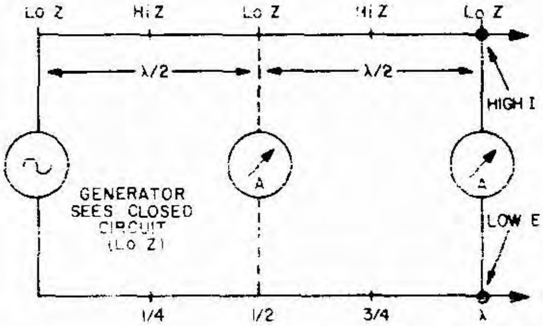
Lecher Line

Transmission line theory predicts that a half-wave line repeats, or reflects, the input conditions at the output.

If a transmission line is open-circuited, it will have *maximum impedance at the half-wave points*, as shown in the above figure. If the transmission line is shorted, it will have the lowest impedance at the half wave points as shown in the following figure. Conversely, a quarter-wave line (if open) will see a high imput impedance (at its source) when shorted at a point a quarter wave *from the input end, and if shorted at the* input, will have a maximum impedance one quarter wave from the short as shown in the above illustrations of open and closed lines.

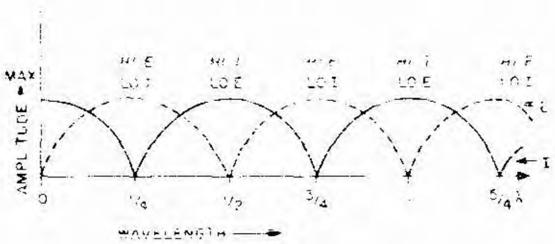


Open-End Line



Closed-End Line

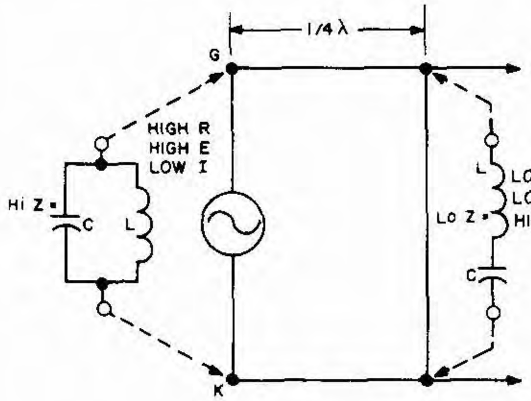
When standing waves exist on the transmission line, the current and voltage are out of phase. That is, at a point of maximum current, the voltage is at a minimum and, conversely, at the point of maximum voltage, the current is at a minimum as shown in the accompanying illustration.



Relationships of Standing Waves

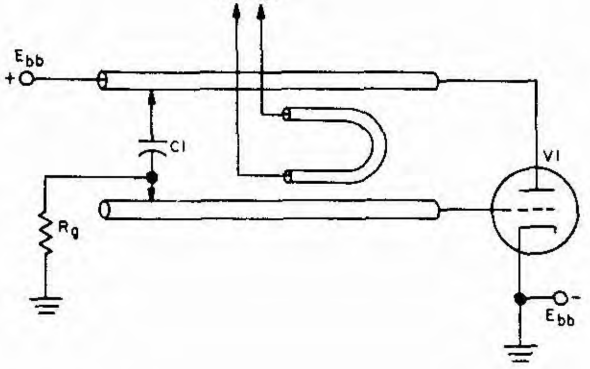
Thus, either voltage or current indications may be used in the lecher wire.

If the lecher line is attached to the grid and cathode of an electron tube and ground, and is tuned to a quarter wavelength, the current through the line will be heavy since it is limited only by the resistance in the line at the short; this is the equivalent of a series resonant circuit formed by an LC tank. At the grid and cathode (one quarter wavelength away), the impedance will be high and only a minimum current will flow between cathode and grid. Thus the line simulates a parallel resonant circuit, with a heavy circulating line current and minimum external current as shown in the following illustration.



Shorted Line Equivalents

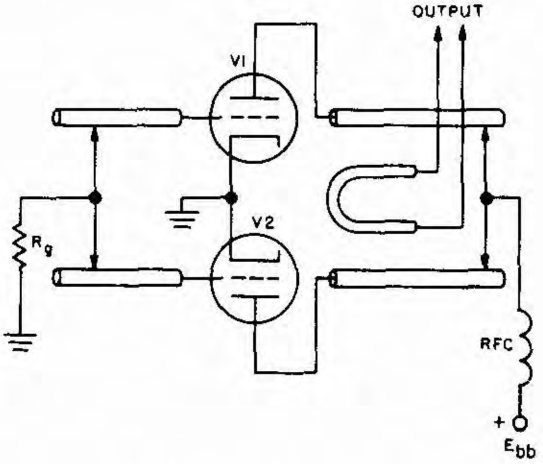
Circuit Operation. When the lecher line is connected between the grid and plate of an electron tube, a simple ultraudion oscillator results, with the line forming the tank connected between grid and plate of the tube, as shown below.



Simple Lecher Line Oscillator

In the illustration a capacitive shorting bar is employed; since plate voltage is present on the plate bar, it would be applied to the grid if a direct shorting bar were used. At the frequencies used, the capacitor has such a low reactance that it is effectively a short circuit for rf, but it will block dc. Grid-leak bias is obtained through the action of R_g, and the total effective grid-cathode circuit capacitance acts as the grid-leak capacitor. The r-f output can be taken from the circuit with a hairpin coupling loop or capacitively from the grid or plate bar. Tuning is accomplished by moving the shorting bar along the lecher line. The amplitude is controlled by the grid-leak value and the applied plate voltage, by the spacing between the bars, and by the tube electrode capacitance. See the ultraudion oscillator circuit discussion in another part of this section for an explanation of the feedback operation of this type of circuit.

Although the simple oscillator just discussed is operable, it has been found advantageous at UHF to utilize circuits which minimize the circuit capacitance. This allows the lecher lines to act more like lumped components, and thereby serve as the controlling factor in the circuit, permitting tube replacement with minimum effect on circuit operation.

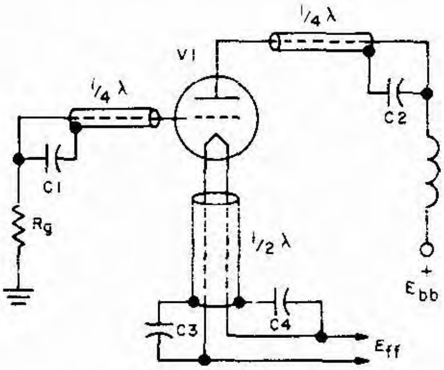


Push-Pull Lecher Line Oscillator

The tubes may be any type that will operate at the desired frequency of operation. In this circuit all elements are balanced. Since the interelectrode capacitances are in series in a push-pull oscillator, the effective capacitance shunting the circuit is half that for a single tube. Thus, the charging current for this amount of capacitance is reduced with a consequent reduction of capacitive circulating currents. As a result, tube seal heating effects and circuit losses are also reduced. Since the tubes operate alternately and the currents are opposite, losses resulting from eddy currents and radiation from the lecher lines are reduced. Such reduction is due to the complete balance in the circuit and the close line spacing which causes the electromagnetic field around one line to almost completely cancel that around the other. Since the same voltages are present on both grid bars and on both plate bars, shorting bars can be used.

For best efficiency and stability at ultra high frequencies, not only the tube losses but also the losses in associated circuits must be kept as low as possible. On the other hand, both the loaded Q and the unloaded Q must be kept high as possible. For this reason, the tuned circuits associated with UHF oscillators use resonant sections of transmission line, rather than coil and capacitor tank combinations.

Since the coaxial line is a form of transmission line, it has properties similar to the open-wire type. At high frequencies it has the further advantage of shielding the line, because the center conductor is entirely surrounded by the shield. As a result, coaxial lines reduce radiation and eddy current losses to an absolute minimum, and for this reason are used extensively. A typical coaxial type of lecher line oscillator is shown in the following illustration.



Coaxial Line Oscillator

In this type of oscillator, the grid and plate coaxial lines are shorted by small capacitors, C1 and C2, and have an effective length of one quarter wave each. This oscillator corresponds to a tuned-plate, tuned-grid LC oscillator with series plate feed and grid-leak bias. The filament type of tube shown utilizes the transforming action of a half-wave line section to bypass the filament to ground. At low frequencies the filament would be directly bypassed to ground with a capacitor. At the UHF region, however, this method of bypassing proves ineffective because the filament leads are long enough to offer a large inductive reactance. As a result of the transformer action in the half-wave line, connecting C3 and C4 to the far end of the line provides an effective shunt at the filament **inside the tube**, which ordinarily is inaccessible. Since the length of the line includes the filament leads, the physical length of the external line is slightly shorter than a half-wavelength.

FAILURE ANALYSIS.

No Output. Lack of supply voltage, a defective tube, an open circuit, or improper tuning can cause loss of output. Resistance and voltage checks will quickly reveal lack of circuit continuity or incorrect voltage conditions. The trouble then may be either in the tube or tuning. If the circuit will not tune and the plate current is excessively high or low, the tube is defective. Substitution of a tube known to be good will further localize the trouble. Lack of contact in the shorting bar is then most probable, since it is possible to have a low d-c resistance or continuity indication and a high r-f resistance which will not show on an ohmmeter. The usual troubles in this type of unit are open or high-resistance circuits due to poor solder joints or defective components. Most line sections are mechanically and electrically of excellent construction. It is possible, however, for silver-plated components to develop a heavy oxide film which effectively open-circuits them at UHF, particularly in areas where corrosive vapors react with the silver. In this case, frequent cleaning is necessary, or gold plating may be required.

Low Output. Low plate supply voltage, together with reduced tube emission, is the primary cause of low output. Substitution of a good tube and a check of voltages will detect this type of trouble. Improper tuning can also result in reduced output; it can be eliminated by a slight readjustment of the shorting bars for maximum output. Defective contacts in the shorting bars are usually obvious, causing erratic indications as the bars are moved slightly back and forth. A high-resistance grid leak can also reduce the amplitude of oscillations, but it is easily located by a resistance check. In the open-wire unshielded line, it is also possible for nearby objects to produce capacitive unbalance and mistuning. If this effect is present, the plate meter will show a change in current as the hands or other objects are moved near the tuning controls.

Incorrect Frequency. This type of oscillator is adjustable over a sufficiently broad range that normal plate voltage changes or slight emission changes may be compensated for by tuning. Since the stability is determined by the tuned lines, any large frequency change indicates a defect in the tuning of the lines. This can be caused by poor contact resistance of the shorting bar and by defective shorting capacitors. Reflected load reactance can also affect the circuit operation; this condition is normally indicated by a return of the frequency to original value as the load is adjusted. A lecher line circuit is usually so stable that calibration markings ruled on the line itself can be used to accurately determine the line frequency. Normally, a resistance analysis and voltage checks should quickly reveal the component at fault. If all resistance and voltage indications are normal, substitute a tube known to be good to determine whether the internal plate resistance has changed sufficiently to be at fault.

MAGNETRON OSCILLATOR.

APPLICATIONS.

The magnetron oscillator is used in the region of 100 mc to 30 gc and beyond, to develop r-f energy. It is used in test equipment, in low-power CW transmitters, in beacons, and particularly in radar equipment, as a source of high-power pulsed r-f energy.

CHARACTERISTICS.

Utilizes a specially constructed tube with a resonator surrounded by a permanent magnetic field to produce the r-f energy.

Operates with grounded anode.

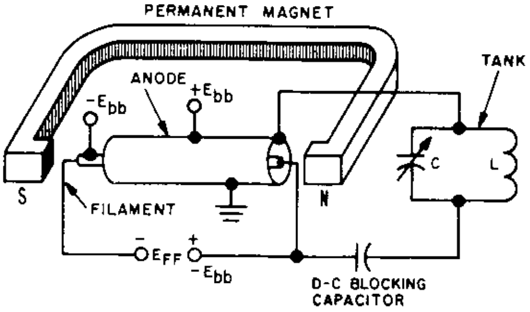
Is usually operated by a negative pulse applied to the cathode.

Has either coaxial or waveguide output, depending upon the frequency of operation.

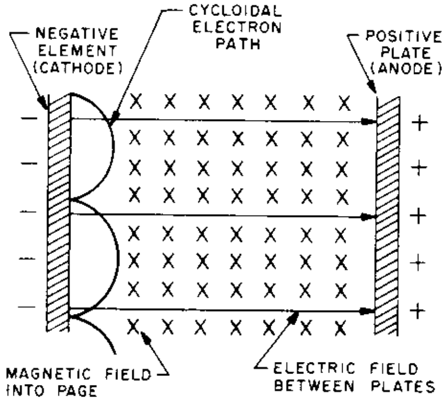
CIRCUIT ANALYSIS.

General. There are, generally speaking, two types of magnetrons: the split-anode **negative resistance** (or **dynatron**) type, and the **transit-time** (or **electronic**) type. The negative resistance type uses the principle of negative resistance between the two anodes to produce oscillation, and operates only at frequencies which are low with respect to the transit-time frequency (on the order of 100 mc to 1000 mc). The efficiency is low in comparison with the efficiency obtainable with transit-time operation; therefore, it is not very popular, being more or less supplanted by the power type klystron at these frequencies. The frequency of oscillation in this type of magnetron is controlled entirely by the resonator with which it is used, as in conventional LC oscillators. On the other hand, the **transit-time** type of magnetron depends entirely upon the transit time to determine the frequency, with the resonator(s) providing greater efficiency and proper phasing for maximum output. A short treatment of the negative resistance type of magnetron is given below for the sake of completeness, with the remainder of the discussion devoted to transit-time magnetrons, which are in greater use.

Circuit Operation. Before discussing the two types of circuits, it is necessary to establish the fundamentals of operation. The accompanying figure shows a simple magnetron. As can be seen, the tube is a diode with a cylindrical plate surrounding a coaxial cathode or filament. A negative voltage is applied to the cathode, in addition to the heater voltage needed for filament emission or heating of the cathode, depending upon whether direct or indirect heating (filament) is used. Because the plate is positive with respect to the cathode, an electrical field exists between cathode and plate (anode); an external d-c magnetic field is placed perpendicular to the electric field, and is produced by a strong permanent magnet. (While an electromagnet could be used and the magnetic field could be alternating, as well, this is done only on the low frequencies for special effects, and will not be discussed further.) In these discussions it is assumed that the magnetic field is produced by a permanent magnet. The tuned tank circuit in which the oscillations take place is connected between the plate and the cathode. This can be a tuned LC circuit, a coaxial cavity, or a special cavity resonator built into the tube.

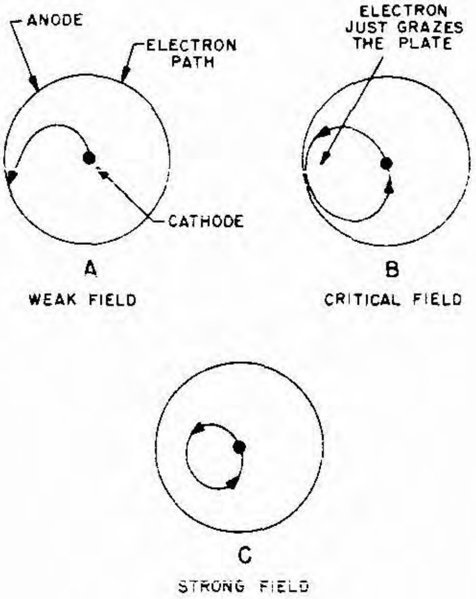


Elementary Magnetron



Motion of Electron in Electric and Magnetic Fields

Consider now the effect of the electric field on the electrons emitted from the cathode. In the absence of the permanent magnet field there would be a continuous electron flow in all directions, radially, direct from the cathode to the plate. But with the magnetic field applied, as the electrons are attracted toward the plate they encounter a force (due to the magnetic field) that tends to push them in a direction perpendicular to the forces applied. Since two fields are involved, the plate-to-cathode-voltage induced electric field and the permanent magnet field, and since they are at right angles with respect to each other, the electrons are affected by the vector sum of these forces; with a strong enough field the electrons are deflected in a cycloidal path as shown in the above illustration. Thus they are effectively bent back toward the cathode. The following illustration shows the path followed by a single electron as the external magnetic field is increased. At some low value of field (A in the figure), the electron travels in a slightly curved path, but reaches the anode. At the critical value of field (B in the figure), the electron just grazes the plate and returns to the cathode. When the field exceeds the critical value (C in the figure), the electron follows a smaller-diameter circular path and returns to the cathode without getting near the plate.



Electron Path with Increasing Magnetic Field

The current flow of the magnetron for the previous conditions is shown, perhaps more clearly, by the following graph. With the low value field a constant flow of current occurs between anode and cathode until the critical field value is reached, whereupon the current abruptly ceases and drops off to zero, since the electron can no longer reach the plate. The useful point of operation is where the electron is just prevented from reaching the plate by the critical field value. Oscillation is then produced by the current induced in the cavity or resonator by the electron movement.

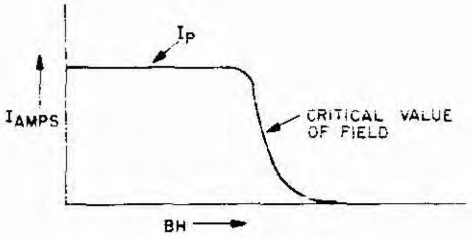
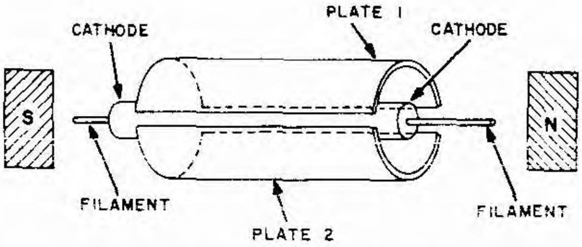


Plate Current vs Field Strength

While the actual electron flow in a magnetron is complicated, it is evident that since an electron is basically a negative charge of electricity, as it approaches an electrode it will change the field distribution around the electrode, inducing a positive charge and causing current flow within or on the electrode by electrostatic induction.. As it recedes, a negative charge will be induced. If the electron reaches the electrode it will be absorbed, and current will cease. When positive and negative charges are induced in a resonator, current flows alternately back and forth within the resonator, at the frequency to which it is tuned (resonant), and r-f oscillations are thereby produced. This is the simple basic principle by virtue of which the magnetron operates.

Negative Resistance Magnetron. The negative resistance magnetron is a variation of the basic magnetron using a split anode. It is capable of operating at a higher frequency (than the single plate magnetron) and with higher output. Its general construction is similar to the basic magnetron, except that it has a split plate, as shown in the accompanying figure. These half-plates are operated at different potentials by connecting them to opposite ends of a tuned tank circuit (or cavity). When the tank circuit is oscillating, the voltage on one half-plate is increased, while that on the other half-plate is decreased by an equal amount. This results in a different electron trajectory.



Split-Anode Magnetron

A graph of the plate current versus plate voltage characteristics of one segment of a two-segment magnetron, showing four different values of voltage applied to the other segment, is shown in the accompanying figure. Note that for each voltage there is a negative slope to the curve where the current is reducing as the voltage applied to the segment is increasing. Likewise, a curve of the difference current to the two segments of a split-anode magnetron as a function of the difference in the potential of the two segments when the voltage on one segment is raised as the other segment potential is lowered a like amount shows the same effect, that is, a negative slope. From the earlier discussion on negative resistance oscillators (see contents list under NEGATIVE RESISTANCE OSCILLATORS for location) it can be seen that this curve bears a resemblance to the typical lazy "S" type curve that indicates negative resistance. Therefore this tube will produce oscillations

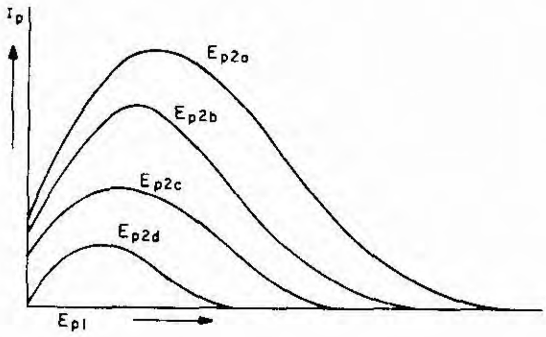
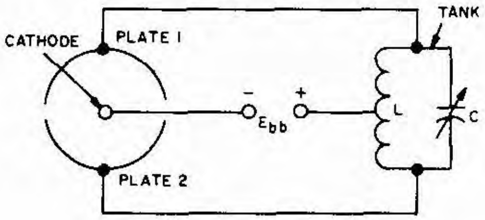


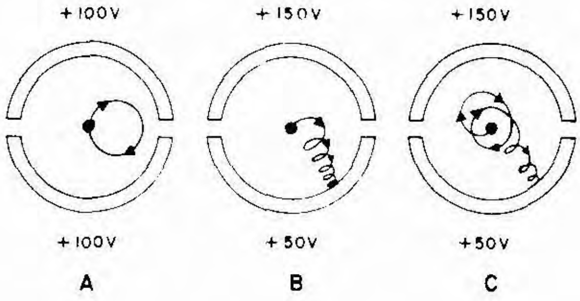
Plate Current vs Plate Voltage Characteristic

of the negative resistance type if a parallel-tuned tank is series connected, either from one segment to the cathode or between the two segments. A schematic showing the tank connected between the two segments is shown in the following figure; this is a typical so-called **push-pull magnetron** circuit (from its resemblance to the push-pull type electron tube circuit.)

Consider now the effect of the different potential fields between the segments and the cathode. In the quiescent or static condition, since the plate potential is applied equally through the tank coil, the d-c field between the cathode and either segment is of equal strength. Once shock-excited (by application of B+), a transient oscillation is produced to increase the potential on one segment and decrease the potential on the other segment by a like amount. Thus the field is stronger in one half of the area around the cathode than in the other half. By applying the external permanent magnet field so that it is perpendicular to the cathode, a cycloidal motion is imparted to the single electron in a manner similar to that described in the basic magnetron discussion. The effect of the distorted field, however, is to cause the electron to make a number of revolutions before eventually being attracted to the segment with the lower potential as explained below. This action occurs because after the initial deflection by the field in a particular path of motion, the electron passes the split between the two plates and enters the electrostatic field set up by the lower-potential plate. Here the magnetic field has a stronger effect on the electron (since the electric field is weaker), and causes it to be deflected with a smaller radius of curvature. As the split is passed again (on the opposite side of the cathode) and the electron once again enters the higher-potential field area, it is again caused to deflect with a change in the radius of curvature. Thus the electron continues to make a series of loops through the magnetic and electric fields until it finally hits the low-potential plate and is absorbed. The accompanying figure shows the effects of different potentials on the motion. In part A the fields are equal, with the permanent magnetic field below the critical value. In B and C the field is above the critical value and current flows because of the action just discussed. Two different electron paths are shown for clarity. Actually, it has been found that optimum efficiency is obtained when the electron makes approximately 10 revolutions before contacting the anode. Since oscillation is produced by the negative resistance effect, the tank frequency governs the path of the electron and transit time is maximized. Naturally, this can happen only at the lower frequencies. As the frequency of operation is increased, the transit time eventually becomes the important limiting parameter, and the negative resistance oscillation is ineffective. Since a very concentrated field is required for the negative-resistance magnetron oscillator, the length of the tube plate is limited to a few centimeters for a magnet of reasonable dimensions.. In addition, a small-size tube is required to make the magnetron operate efficiently at UHF. Therefore, the plate size (area) is limited, and produces a serious limitation on the permissible plate heat dissipation. For this reason, heavy-walled plates are necessary to increase the heat radiating properties, and artificial air or water cooling is necessary for high-power operation. These parameters, in effect, are the limitations which restrict its use to the low-frequency end of the UHF spectrum and cause the transit-time magnetron to be in greater demand.



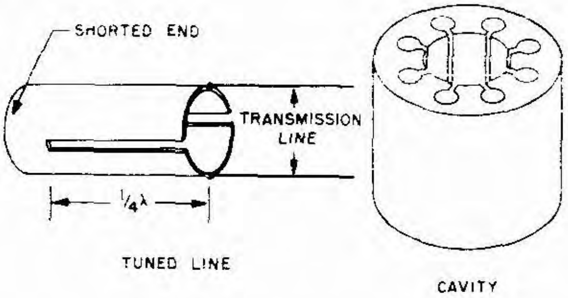
Push-Pull Magnetron Circuit



Electron Transit Paths

With the electrons traveling in numerous loops, there are bound to be collisions between electrons and bombarding of the filament (or cathode), producing secondary emission and in some cases even destruction of the filament or cathode. This action is cumulative, and sometimes results in filament burnout before the current can be reduced to a safe value. To minimize this effect, and to prevent unstable operation, the tubes are operated with reduced plate and filament voltage. In some tubes it is possible to use the electron bombardment of the cathode element to provide the heat for emission, once oscillation is started.

Transit Time Magnetron. In this type of magnetron the plate or anode block is usually constructed so that it functions as a tank circuit resonant to a particular frequency. The construction may be that of a simple shorted quarter-wave line resonator, as shown in the accompanying illustration, or as a multicavity resonator also illustrated.



TUNED LINE

CAVITY

Magnetron Tank Circuits

In either case there are no external tank circuits to be tuned, and the output of the magnetron is picked up by a transmission line with coupling loop (or aperture for waveguide) built into the tube. Usually, the anode is composed of more than two segments; as many as eight or more are often used (while as many as 64 cavities have been used). While this type of magnetron has a reasonably high efficiency (30 to 60 percent) and large output, it is limited in that the frequency of oscillation is fixed by the resonator. Thus it tends to be supplied as a single-frequency unit which usually has provisions for tuning over a limited range (on the order of 1% at 9 gc), and is operated at a fixed frequency. The average power is limited by the filament emission, and the peak power is limited by the maximum voltage it can safely withstand without damage. Actually, during initial operation the high-power magnetron arcs from plate to cathode, and must be properly adjusted by a process known as **seasoning**, after which it can handle the high voltage properly without damage (within limitations).

New magnetrons require an initial break-in period or seasoning because violent internal arcing occurs when they are first put into operation. Actually, arcing or sparking in small magnetrons, and in high power magnetrons is very common. It occurs with a new tube or after long periods of idleness once a tube has been seasoned. One of the prime causes is the liberation of gas from the tube elements during idle periods. Arcs are also caused by the presence of sharp surfaces in the tube, mode shifting, and by overworking the cathode (drawing excessive current). While the cathode can withstand considerable arcing for short periods of time, if continued excessively it will shorten the useful life of the magnetron and can quickly destroy it. Hence each time the excessive arcing occurs, the tube must be seasoned again until the arcing ceases and the tube is stabilized.

The seasoning procedure is relatively simple. The magnetron voltage is raised from a low value until arcing occurs several times a second. The voltage is left at that value until the arcing dies out. Then the voltage is raised further until arcing again occurs, and is left at that value until the arcing again dies out. Whenever the arcing becomes very violent and resembles a continuous arc the applied voltage is excessive and is reduced to permit the magnetron to recover. Once recovered the procedure is again continued. When normal rated voltage is reached and the magnetron remains stable at the rated current value, the seasoning is completed. It is good maintenance practice to season magnetrons left idle either in the equipment, or held as spares, when long periods of non-operating time have accumulated. Follow the recommended procedures and times for seasoning specified in the equipment technical manuals. The preceding information is general and of an informational nature only.

The outputs of pulsed magnetrons are on the order of megawatts, with an average power of not much more than 1000 to 2000 watts being usable for CW operation (a typical 3-megawatt pulsed radar has a 6-kw average rating). However, as the state of the art changes, these limitations also change; thus where 50 kw was once high power, 5 to 10 megawatts now represents high power.

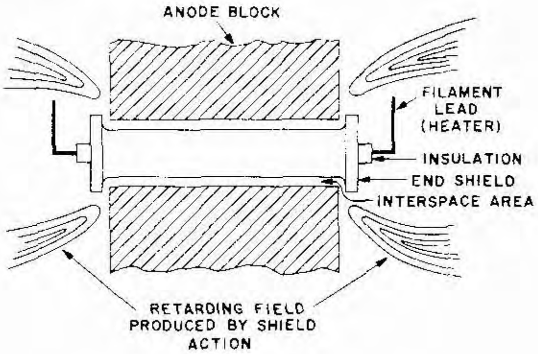
The construction of transit-time magnetrons is varied; they operate in the VHF, UHF, and SHF regions. Some are not tunable, while others are voltage tunable (anode potential is varied), mechanically tunable by hand or by motor, or are fixed-tuned. They provide power outputs of 50 to 100 milliwatts for receiver operation, and in the megawatt region for high-power radars, with all ranges of in-between powers. They are provided with integral built-in permanent magnets or with external magnets. They are supplied with transmission line outputs or waveguide outputs, or with transition type coaxial-to-waveguide outputs. They are of glass-metal or ceramic-metal construction, with advantages claimed for each. Cooling is achieved directly by natural air draft for low powers, by forced air or liquid air-convection, or by heat exchangers for the high-powered types. It is evident, therefore, that the subject of magnetrons covers a large field, with a complexity far beyond the scope of this technical manual. Thus, in the following discussion sufficient detail is provided to insure a basic understanding of the general principles of operation, with the important principles emphasized or expanded as needed. For details on a specific type of magnetron, consult the manufacturer's specifications, and refer to a more comprehensive text for further information.

Detailed Analysis. The magnetron, while capable of generating continuous-wave oscillations, is particularly suited for pulsed power applications, as in radar. That is, the magnetron is capable of producing pulsed powers of more than 1000 times greater than the best c-w output at the same frequency. Basically, there are three factors which produce the favorable conditions for pulsed powers; the magnetron is more efficient at very high levels of power and voltage; an oxide cathode under pulsed operation produces currents over 100 times greater than that obtainable under d-c (non-pulsed or CW) conditions; and finally, by pulsing with small duty cycles, anode heat dissipation is less of a problem, so that greater powers can be handled. On the other hand, a new problem is posed, where the build-up of oscillations from noise to full power must occur reliably for every pulse in a time that may be as short as one-hundredth of a microsecond. Failure of this build-up produces misfiring or mode changing, and often occurs under the proper conditions.

From the preceding discussion it is clearly seen that the understanding of pulsed operation involves new concepts, some entirely different from those in CW operation. Since the magnetron consists basically of an emission system involving electron flow, plus resonators (or cavities) which modify the electron flow, and a means of extracting the r-f output, a discussion of the functioning of each of these items logically leads to a better understanding of the magnetron oscillator.

First consider the emission system, which may be a straight filament, a coiled filament, or an oxide-coated cathode cylinder. Magnetrons using thoriated tungsten or pure tungsten filaments are generally operated at high temperature; because of their ruggedness, these filaments are suitable for c-w type tubes, but consume considerable filament power. The low-temperature, oxide-coated filaments operate best for pulsed-type tubes, producing much larger emissions than the high-temperature type (for a given filament power). However, since they are not as rugged, they are more susceptible to damage from electron bombardment and deterioration effects. The oxide-coated cathode cylinder provides the most practical construction for low-temperature operation; keeping the heater filament independent of the operating circuit avoids any filament inductance effects which might adversely affect the frequency of operation. Another type of operation is also possible with the cathode sleeve, namely, cold-cathode operation. Because of the extremely high secondary emission produced by electron bombardment of the cathode by electrons out of the useful orbit, once started by heated-cathode operation, cold-cathode operation may be obtained by lowering the heater voltage or by removing it entirely. Such operation is commonly used in high-powered magnetrons, operating with extremely high plate voltages and heavy electron bombardment of the cathode.

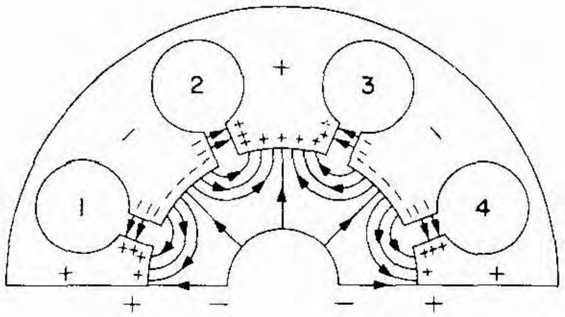
Since it is desired that the electrons travel in the interspace area between the anode and cathode of the cavity block and thus contribute to the excitation of the various cavities, end shields are placed at the ends of the cathode. These shields, which are of various designs (some may be only small protuberences at the ends of the cathode), minimize the electron leakage paths at the ends of the cathode. These cathode end shields are considered to operate by producing a retarding electrostatic field at the ends of the interspacial area. By distorting the equipotential lines at this point in such a way as to produce an inwardly directed force upon the electrons attempting to leak out of the area, they simply urge the electrons toward the center plane of the anode block. While in some cases secondary electrons may also be emitted from the end shields, through bombardment by partially controlled electrons in orbit, the useful electron emission is usually restricted to the cathode alone. An exaggerated illustration of end shields and the retarding field they produce is shown in the accompanying illustration.



Cathode End Shields

With the cathode emitting a stream of electrons into the interaction space, let us examine the method by which the electrons produce oscillation. A half-section of a typical eight-cavity anode is shown in the following illustration, with the fields and current flow as indicated.

Assume for the initial operation that the cavities have been excited by an r-f field so that each cavity is oscillating. In the capacitive space between the walls of the entrance to the cavity (slot) a charge exists, with one wall negative and the other wall positive. By construction, the segments are placed 180 degrees apart electrically (pi



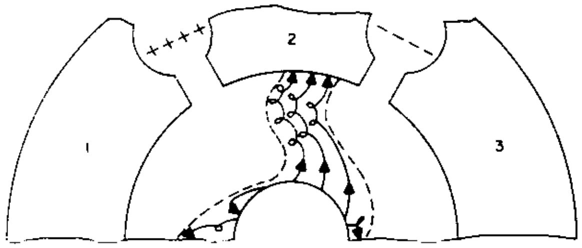
Development of Internal Fields

mode), so that when traveling from one cavity to the other in the interaction space, each cavity is oppositely polarized. Thus the original negative-to-positive charge in cavity 1 is now a positive-to-negative charge in cavity 2, and likewise for the other cavities around the interaction space. A complete cycle of rotation around the anode block is produced in 360 degrees of rotation or some multiple thereof. In the case illustrated, since there are eight cavities (only half are shown) and the phase shift between the cavities is 180 degrees, there is a total of 8 pi radians shift which, when divided by 2 pi (for one full 360° of rotation), gives a number of 4. This arbitrary number is called a **mode** number. As might be surmised, magnetrons can be constructed so that they will operate at a different number of modes for the same frequency.

Examine the illustration and observe the effect of the fields produced. First the r-f field at the entrance to the cavity is strong at the lip but weaker as it extends into the interaction space, as shown by the widely separated lines. Arrows indicate field direction. The straight lines between the anode and cathode represent the d-c field produced electrostatically by the anode-to-cathode potential. The d-c field is steady except where reinforced or reduced by the changing r-f field. The permanent magnet field is at right angles to it (into the page), and is not shown. Thus two fields are always present in the cavity, and the resulting field affecting the electron is the vector sum of the two.

Recalling from basic magnetron theory that when an electron approaches an anode it induces a positive charge, and as it recedes from the anode it induces a negative charge. It is evident that as an electron approaches an anode which is going positive (because of the r-f cavity field), that segment is made more positive, aiding cavity oscillations. If the electron recedes from the anode as it is going negative, oscillations also will be aided. On the other hand, if the electron approaches the anode as it is swinging negative, or recedes as it swings positive, the electron tends to oppose oscillations. If sufficient electrons were so phased, oscillation would stop. Therefore, to sustain oscillation the phasing must be such as to produce more aiding than opposing electrons, or to remove those that oppose the oscillation, retaining only those that aid.

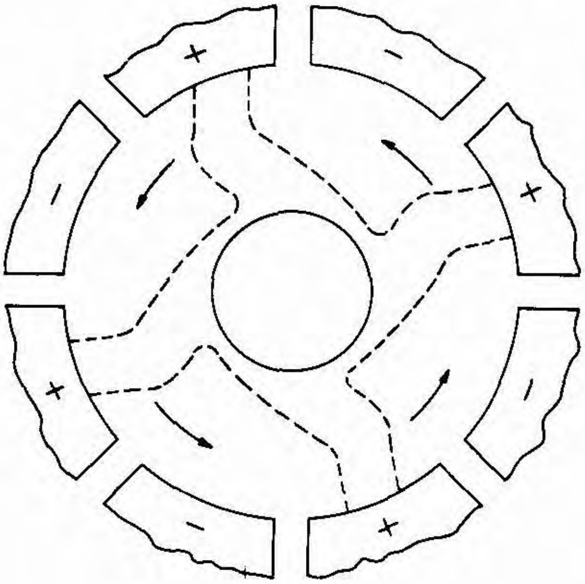
In addition to the r-f fields existing because of cavity resonance, assume that the magnetic field is just slightly greater than the cutoff value. Therefore, if the r-f oscillating field did not exist, or were zero at a point in the interaction space, the electron emitted at the cathode would be returned by the effect of the d-c magnetic field. On the other hand, when the r-f field is going positive, the electric field is enhanced, and an electron emitted at a point affected by this field would be attracted toward the anode. Because of the effects of the two fields, the electron is forced to travel in a cycloidal path instead of straight, and around the interaction space in a clockwise or counterclockwise direction (depending on the polarity of the magnet). If the distance between the cavity segments is such that the electron traverses the space between adjacent slots in a time equal to one-half cycle of r-f oscillation, when the second slot is reached the electric field will be reversed (the next half-cycle of r-f oscillation is now starting) and will still be in an aiding direction. Because of the curved path, however, the **working** electron is traveling in a long path and through a decreasing potential (since the potential through which it falls is less as it approaches the anode). The result is a change in phase of such a nature that by the time the electron approaches the third slot the polarity is opposing and repels the electron. Thus the electron is forced to curve back upon itself, and, by the time it is traveling towards the direction from whence it started, the field in segment 2 is again attracting it, and it again curves toward the anode. Likewise, because of the curved path it enters the number 1 segment field when the field is in a direction that pushes it back toward the number 2 and 3 segments. In this way the working electron follows a series of looped paths between two segments, as shown in the figure until it reaches the anode. During the time it is being attracted by the field, it effectively aids oscillation in that cavity just as if an additional charge were induced into it. Because of the curved path it is in an aiding condition longer than it is in a position where it removes energy from the cavity; therefore, the net result is to enhance the oscillations. Since the distance traversed between segments is effectively 180 degrees, the electron is operating in the pi mode. Thus in an eight-cavity magnetron, four pairs of segments are operating simultaneously, and the effect is the same as that existing in a polyphase motor; that is, an effective traveling field is produced which rotates around the circumference of the interaction space, and oscillation is successively enhanced in each cavity as the field rotates past the slot. The effect is as though a wheel of four spokes were being rotated, as shown in the figure.



Electron Path

Conversely, the **non-working** electron is emitted at a time during which the r-f field opposes it and is quickly directed back to the cathode. This is a harmful electron in that it strikes the cathode with considerable force and tends to destroy it. Since this **back radiation** cannot be eliminated, it is used to produce secondary electrons and economize on filament heating.

Since there are electrons emitted from all points on the cathode, there are electrons which start at intermediate points of changing field, and are not attracted or repelled as strongly as the working electron; therefore, their paths are of different orbits. However, since the r-f field varies sinusoidally with time, the result is that the electron emitted before the working electron is retarded until the elec-

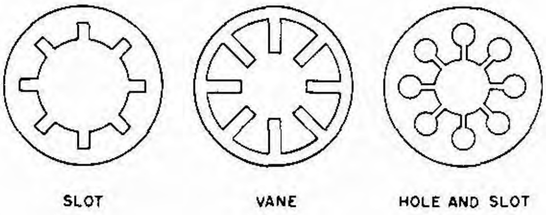


Rotating Electron Field

tron emitted after the working electron catches up. For this reason there is an effective electron density grouping (or bunching) about the working electron, or a **velocity modulation** effect similar to that in the klystron. Thus standing waves similar to those on traveling wave tubes are caused to exist in the inter-action space.

While the r-f field was initially assumed, it is produced by application of the anode voltage or negative cathode driving pulse, which is sufficient to shock-excite the cavities, and with the proper phasing oscillations are built up. This proper phasing is produced through construction and by the proper selection of anode voltages and field strength. Since the phasing of magnetrons is a highly technical subject and of concern only to the designer, it is beyond the scope of this technical manual and will not be discussed.

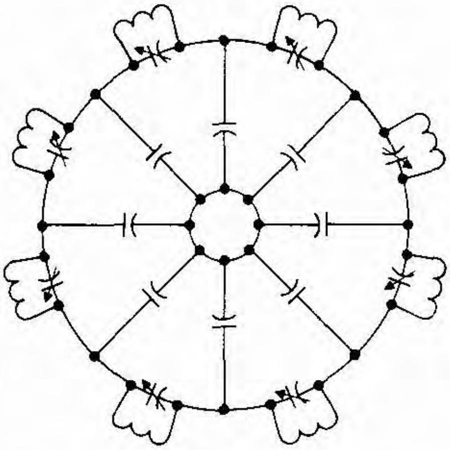
Types of Cavities and Modes. There are basically, three different types of cavities used in unstraped resonant systems; these are the slot, the vane, and the hole-and-slot types of side resonators shown in the figure.


SLOT VANE HOLE AND SLOT

Types of Resonators

Regardless of the type of resonator used, it is primarily the simple equivalent of a parallel LC tuned circuit, which can be represented schematically by a series of tanks, as shown in the following illustration, the interaction space is represented by capacitance between the anode and cathode; inductive effects are neglected for simplicity.

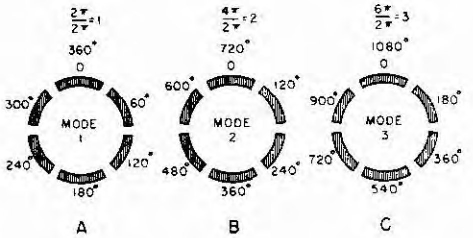
While the resonators are shown connected in series, actually each one is independent and is dimensioned and shaped so that all are resonant to the same frequency (identically shaped resonators are used). They are coupled together by the interaction space between the cathode and anode. The spacing of the cavity entrances is approximately a half-wave at the desired frequency of operation (assuming the pi mode of operation). Therefore, the smallest number of cavities that are operable is two (2 x 180 equals 360 degrees), corresponding to split-plate usage.



Resonator Equivalent Schematic

The maximum number of cavities is limited only by construction since multiplication by two produces the same result (2, 4, 8, 16, 24, and up to 64 as a practical limit).

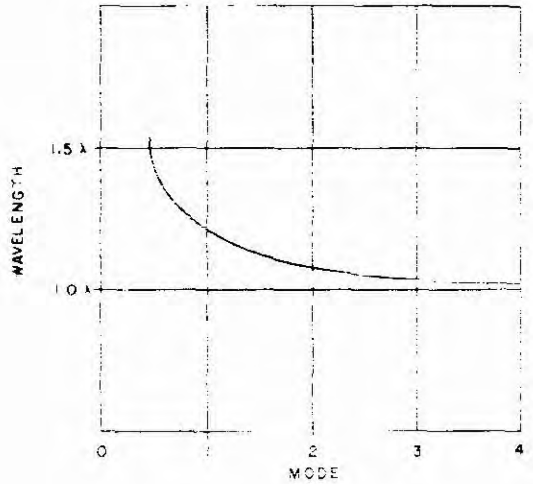
Consider now the mode of operation. Assume a basic six-cavity magnetron, as shown in the following illustration; operation is possible in three types of modes, as shown.



Examples of Various Modes

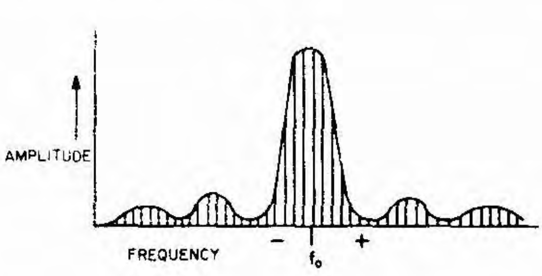
In part A of the figure there is a phasing of 60 degrees between adjacent segments. Therefore, six segments must be traversed before a total phase rotation of 360 degrees (one cycle) is obtained. Since there are 2 pi radians in 360 degrees by angular measure, this represents a rotation of 2 pi radians divided by 2 pi, or mode 1. In part B of the figure the segments are separated 120 degrees, and only one-half as many segments (three segments) need be traversed to produce a complete cycle of operation. When the complete cycle around the magnetron is traversed, a total of 720 degrees of rotation is completed (two complete cycles of operation), or 4 pi radians divided by 2 pi, giving mode 2. In part C of the figure adjacent segments are oppositely polarized, so that only two segments need be traversed to complete a cycle. Therefore, in a complete rotation of the magnetron cavity, 1080 degrees of rotation is produced, or 6 pi radians divided by 2 pi, giving mode 3.

Since a six-cavity magnetron can operate in at least three modes (with either leading or lagging phase, this represents 2 x 3 modes, or a total of 1 mode for each cavity), there is a frequency for each of these modes at which the output is a maximum. Thus the magnetron generates a series of discrete frequencies arranged symmetrically (in the ideal case) around a center frequency of maximum amplitude for each mode. A typical plot of wavelength variation with mode for typical magnetron is shown in the following graph.



Wavelength vs Mode Variations

The c-w magnetron provides a different output from that of the pulsed magnetron, in that a steady anode voltage is supplied, and the output is mainly concentrated at the mode chosen by the plate voltage and current applied. It still does not consist of a single frequency, however, since the cavity at microwave frequencies can support a number of different types of oscillation. This concept is diametrically opposed to the normal concept of a tuned tank being responsive to only one frequency. It is true, however, because the magnetron consists not of a single cavity, but of a number of cavities, each coupled to the other. As in coupled circuits at the lower frequencies, it is possible to achieve a response curve having a main lobe with numerous side lobes, depending upon the interaction and amount of coupling between the cavities. This condition is further complicated by the possibility of phased bunching of electrons in the interaction space; thus it can be clearly seen that a single pure frequency output is rather unlikely. In the tunable types of magnetrons, the main spectrum can be shifted to the desired frequency by tuning. In the fixed-tuned magnetron, operation consists mainly of operating at the proper current, which for a pulse of a particular shape produces the desired main lobe at the proper frequency with a minimum of side lobes (other modes). A typical output spectrum for a pulsed magnetron is shown in the accompanying figure.

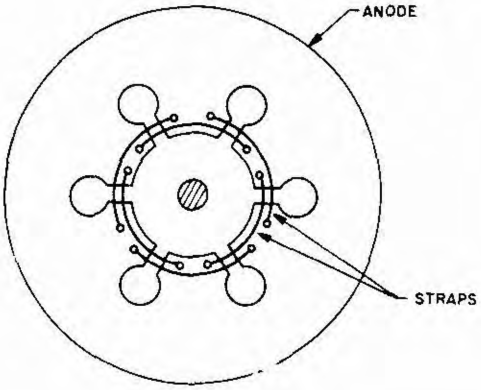


Typical Magnetron Spectrum

The broad spectrum shown is caused mainly by pulsing. Because the pulse is a rectangle with steeply sloping sides, it approximates a square wave with a similar harmonic content. Thus, in effect, many frequencies are induced into the cavities, and all those to which it responds will be present. The shape of the anode pulse is important, since it can cause a distorted output and place the main output energy in an unwanted portion of the spectrum. It should also be understood that this discussion is necessarily general since it concerns actions mostly of interest to the designer. The technician is concerned with making the magnetron perform as designed. He can control only the voltages applied and the currents at which it is operated, plus any cavity tuning which may be possible. Therefore, the preceding discussion of modes and spectrum effects is intended to indicate, in a very limited manner, internal operation effects which are highly complex and beyond the scope of this circuit analysis. The interested reader is referred to standard texts such as the Radiation Laboratory volume on ***Microwave Magnetrons***, from which much of this material was selected.

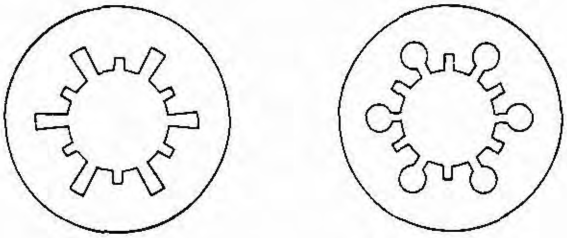
Since the unstrapped magnetron presents a number of modes of nearly equal outputs, it has been discarded for the **strapped** type, and for a special type known as the **rising sun** magnetron because of the design of the cavity. Strapping consists of connecting together alternate segments with short, heavy conductors, as shown in the accompanying figure. Thus strapping favors mode 3, the pi mode, and places alternate segments at the same potential (which corresponds to a shift of 2 pi radians). Operation at mode

2 is impossible, since it would require a shift of 4/3 pi radians between alternate segments, and cannot occur with the segments short-circuited. While the straps are essentially simple short circuits, at the frequencies used they have inductance; moreover, since the straps pass near the segments which they connect, they also have capacitance. As a result, the frequency of the mode of operation is slightly altered. At the pi mode the straps are at the same potentials at the ends, and carry no current (except for a slight capacitive current between them); therefore, the inductance is negligible and the capacitive effect predominates, lowering the basic frequency of the pi mode. When the magnetron is excited in a different mode, there is a difference in potential between the segments, causing the straps to carry more current between them because of the difference in potentials. Thus both inductive and capacitive effects operate on the other modes, changing their operating frequency. The result is to further separate the modes and eliminate the possibility of simultaneous operation on two closely spaced modes. Suppression of the unwanted modes increases the over-all efficiency of the magnetron. While it might appear that the symmetry of strapping is essential, this is not so in practice. Actually, by omitting certain straps (usually the ones at the output resonator and adjacent to the input cathode), even greater discrimination is obtained.



Double Ring Strapping

The rising sun magnetron design evolved from the fact that symmetry is not required for best results in strapping. The typical design of alternate cavities of the same shape, with adjacent cavities of dissimilar shape, produced the so-called "rising sun" design. Since the sizes of the cavities in the two groups are different, the mode frequencies of this type of magnetron tends to form into two groups as though there were only two resonators. Thus the respective mode frequencies are well separated from the pi mode, and this unit is suitable for pi mode operation without the use of strapping. The rising sun design is used at the higher frequencies (above 10 gc), while strapping with the conventional design is used at the lower frequencies to provide a smaller assembly. A typical rising sun design is shown in the following illustration.

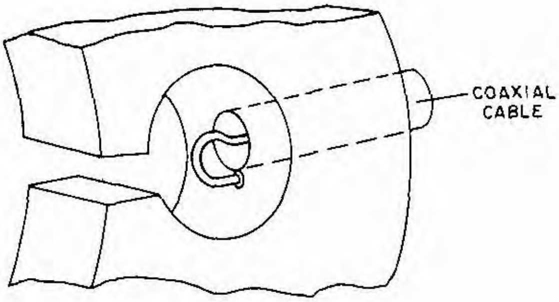


SLOT TYPE

MODIFIED SLOT AND HOLE

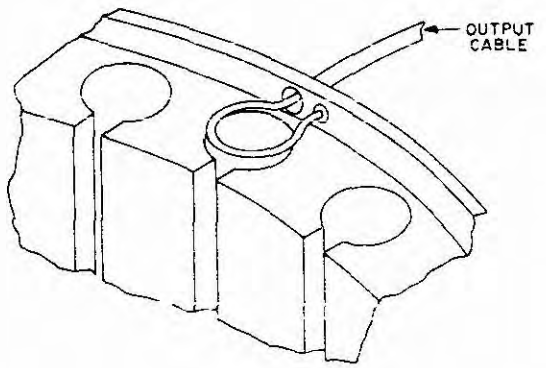
Rising Sun Magnetron

Coupling Methods. R-F energy is usually removed from the magnetron by means of a coupling loop. At frequencies lower than 3 cm the coupling loop is made by bending the inner conductor of a coaxial line into a loop (center-fed coupling) and soldering the end to the outer conductor, so that the loop projects into the cavity, as shown in the following figure.



Coaxial (center-fed) Coupling Loop

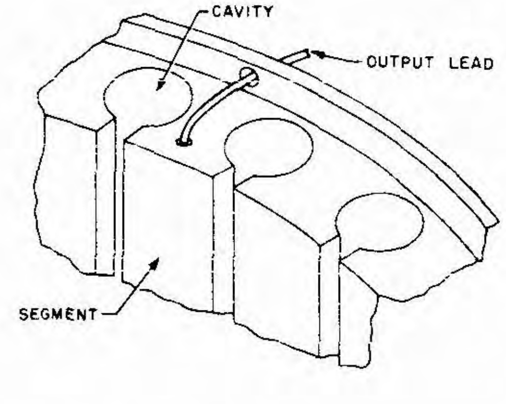
At the higher frequencies to obtain sufficient pickup the loop is located at the end of the cavity (halo loop), as shown in the accompanying illustration.

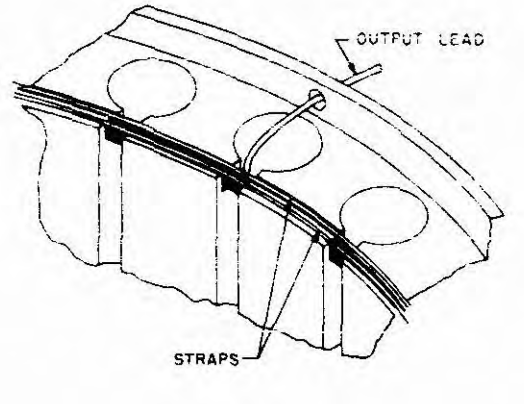


External (halo) Coupling Loop

Other forms of inductive couplings are shown in the following illustration.

In the segment-fed loop it is presumed to intercept the flux passing between cavities, while the strap-fed loop intercepts the energy picked up between the strap and the segment. On the output side, the coaxial line feeds another coax line directly, or it feeds a waveguide through a choke joint, with the vacuum seal at the inner conductor helping to support the line. Direct waveguide connection is usually through a slot in the back of the cavity, with an iris feeding into the waveguide connector through a window.





Segment-Fed Coupling **Strap-Fed Coupling**

Tuning. The magnetron is basically fixed-tuned. It is pretuned by adjusting the straps, pressing them in or out to resonate with a test voltage inserted into the cavity from a klystron at the desired operating frequency; the adjustment is made for maximum response on a detector-indicator. Some magnetrons have a flexible plate arranged to move in or out by means of a screw adjustment. Still other magnetrons have pins or rods that screw in or out of the cavities (as in the klystron), and some low-powered types are voltage-tuned. Usually, pretuning is necessary before the magnetron is placed in operation; therefore, some form of mechanical tuning which can be externally performed over a small range is used to adjust it to the desired operating frequency. (Of course, this frequency must be within a specified band of frequencies over which the magnetron is designed to be operable.) Thus in most cases the magnetron output frequency is essentially fixed, with the receiver having its bandpass and frequency automatically centered and maintained in synchronism with the transmitting magnetron.

FAILURE ANALYSIS.

No Output. Lack of output can be caused by nonoscillation of the magnetron, or by oscillation on an undesired mode which will not couple to the output circuit; it can also be caused by a short circuit or an open circuit. Use of the ammeters and voltmeters supplied with the equipment will usually pinpoint the trouble. A steady high current with low applied anode voltage usually indicates a loss of magnetism which allows the electrons to pass directly from cathode to anode. In this case, remagnetization or replacement of the magnets will generally restore operation. (Sometimes insertion and reinsertion of the small soft iron bar placed between the magnet poles during storage, known as the keeper, a few times will restore the magnet.) An anode-to-cathode short will produce heavy plate current and blow fuses or operate protective circuits immediately after the plate voltage is applied. Such a condition will be indicated by a simple ohmmeter check between the anode and cathode, **with the voltages removed.**

An erratic heavy plate current, usually accompanied by noise and internal flashes within the magnetron (seen through the coupling ports or at visible portions of the glass envelope), particularly in high-power magnetrons, indicates arcing. This is a common occurrence after periods of long idleness or after exceeding the permissible ratings; it can also be caused by load changes or discontinuities in choke or rotating joints, producing excessive r-f reflections. Immediate reduction of plate voltage is imperative to prevent damage to the magnetron or modulator equipment. Then, by following the normal **seasoning** process, the arcing should occur less frequently until the magnetron stabilizes and resumes normal operation.

If there is no output until a number of starting attempts have been made and the output then builds up slowly, this is a possible indication of an open filament. Particularly with extremely high-powered tubes using very high voltages, the phenomenon of cold cathode operation can occur through the **back bombardment** effect. Checking the filament for continuity **with the plate voltage removed** will quickly determine whether this condition exists.

Since magnetrons are expensive and usually do not plug in as conveniently as common receiving tubes, replacement of the magnetron should be resorted to only after all other checks have been made. Where the current meter indicates zero, it is most probably an open circuit caused by cathode burnout, an open anode or cathode lead, or failure of the modulator or power supply. Checking with the voltmeters provided on the equipment will quickly determine whether the power supply and modulator are normal; if they are, the open must be between these units or within the magnetron. A resistance check for continuity of connections will indicate whether the condition is external to, or within, the magnetron. Do not overlook resetting any overload relays or replacing open fuses in the search.

Reduced Output. Reduction of output below normal is usually more difficult to analyze than lack of output, since the magnetron is very susceptible to variations in the strength of its magnetic field, anode voltage, and load impedance. Such variations cause a loss of output power and efficiency to a large extent, and usually affect the frequency of operation. A shift in the mode of operation can usually be caused by any of the previously mentioned items, and, since the magnetron is normally designed to operate at a particular frequency with maximum output, reduced output may indicate such a condition. Perhaps the best method of trouble shooting is to use a spectrum analyzer such as the echo box, detector, and meter, or by direct observation of the r-f envelope on an oscilloscope. Since the shape of the high-voltage modulator pulse is important, using a portable spectrum analyzer connected via a directional coupler to the magnetron output will save time. Double moding will be indicated by the presence of two or more maximum lobes. A jittering pulse which changes in amplitude or wiggles back and forth is immediately apparent. Changes in load can be made and the effect observed and evaluated. Likewise, the anode voltage can be varied and its effects observed; any frequency instability will be evident. The effect of reduced output will be obvious from local meter indications in the case of c-w magnetron type of operation, but they are not as accurate and are sometimes actually misleading in pulsed operation. A change in current or voltage will show immediately in the steady voltage type of c-w operation. However, in pulsed operation, where the pulse width and duty cycle govern the average value of the current and voltage, a change in pulse width may compensate for a change in duty cycle (or vice versa); thus the pulsed indications may appear normal, when actually there is a reduction in efficiency and output power. Low power output usually results from a weak magnetron or or low modulator output. If the modulator pulse is normal, the trouble lies in the magnetron. A weak magnet will cause a loss of power, by reducing the efficiency of operation, and also a change in the spectrum, which is usually obvious on the oscilloscope. For further information, tests, and typical waveforms, refer to **Test Methods and Practices,** NAVSHIPS 91828, latest edition.

Incorrect Frequency. While magnetron troubles may be divided into three general classifications, namely, wrong frequency, poor spectrum, and low output, they are usually interlinked. For example, a magnetron operating off frequency will most probably show a poor spectrum and produce a lower output, as compared with previously recorded data obtained when the magnetron was known to be operating correctly. In the case of wrong frequency operation for fixed-tuned magnetrons, there are three possible causes. The magnetron may be defective, or frequency pulling or pushing may be present. Frequency pulling may be present because of some fault in the r-f system, such as varying impedance, faulty rotating joints, or be caused by a strong reflection from a nearby object. A change in magnetron frequency due to a change in **load impedance** is known as "pulling". The effect of pulling is greatest at high output powers. The operating point of a magnetron is usually a compromise between high output power and good frequency stability, and is usually chosen for a matched load condition. Magnetron performance is often summed up in what is called the **pulling figure.** This figure is the total change in frequency (usually in megacycles) which occurs when the load is adjusted to produce a voltage-standing-wave ratio of 1.5:1, and the phase of the reflection is varied through 360 degrees

When off-frequency operation occurs and another magnetron is substituted, satisfactory operation of the replacement does not necessarily indicate that the original magnetron is defective. In some cases a magnetron may be in good condition, but because of individual differences it may be more easily pulled outside the operating band by external conditions (such as a change in load impedance) than another magnetron of the same type number. Blind replacement of the magnetron when off-frequency operation occurs, therefore may result in the discarding of a perfectly good tube. The VSWR of the r-f system should first be checked to determine whether it is high or low. With a low VSWR, normal operation of the r-f system is indicated, and the fault is most likely the magnetron. Sometimes the effects of pulling are not noticed if the frequency is within the operating band, so that occasional off-frequency operation is possible without any visible external indications. Frequency pushing (indicated by waveform distortion) may be present because of improper anode or filament voltage. Magnetron **pushing,** caused by a change in d-c anode voltage, is frequently indicated by a poor spectrum shape; this condition results from improper modulator pulse amplitude or shape. The frequency of operation may be slightly altered, or may change from pulse to pulse. Although such operation may be indicated by a changing anode current, a more definite check can be made by use of an oscilloscope.

Magnetron pushing is usually produced by a change of input conditions. The pushing figure is usually expressed in terms of megacycles per second per ampere. In most cases pushing can be neglected for the longer wavelengths where it is slight. It cannot, however, be neglected at the shorter wavelengths. Regardless of the cause of the frequency change, in the case of the tunable magnetron, only a slight adjustment of the tuning control to establish the desired frequency may be all that is required.

When frequencies appear and disappear in the spectrum, the cause is usually arcing, which produces temporary transients. If this condition occurs frequently, seasoning is necessary; there is also the possibility that the magnetron is becoming unstable and approaching the end of its useful life. If it occurs infrequently, operation can be considered normal, but there is the possibility of incipient magnetron failure.

REFLEX KLYSTRON OSCILLATOR.

APPLICATIONS.

The reflex klystron is used as a low-power r-f oscillator *in the microwave region (from 1000 mc to 10,000 mc) in* receivers, test equipment, and low-power transmitters.

CHARACTERISTICS.

Uses special tube construction to produce r-f feedback *and oscillation.*

Operates as a positive grid oscillator.

Uses a tuned cavity, either integral (built-in) or external, to determine the basic range of operation.

Uses negative anode (repeller-plate) voltage.

CIRCUIT ANALYSIS.

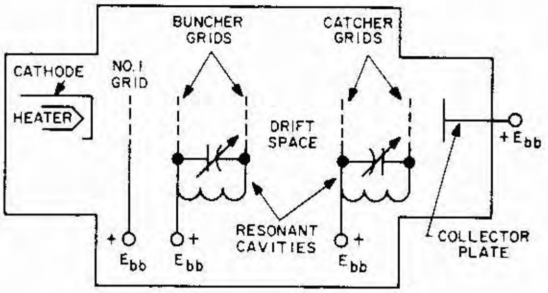
General. A klystron tube is a specially constructed electron tube using the properties of **transit time** and **velocity modulation** of the electron beam to produce microwave frequency operation. It can be used as an oscillator or an amplifier. The amplifier employs two or more cavities to produce the proper bunching of electrons, upon which its function and amplifying properties are based. The amplifier type of klystron can produce a large amount of power (up to megawatts) and can be used as an oscillator if proper feedback arrangements are made. However, the reflex klystron offers a simpler type of feedback arrangement and performs specifically as a special tube designed for oscillator operation alone. Although the power output of the reflex klystron is limited, it is adequate for receiving and test equipment functions and for low-power transmitters. Where high power is required, it can be achieved by using the reflex klystron as a master oscillator and the conventional amplifier type klystron as a power amplifier. Since microwave radiation is limited to line-of-sight distances, the reflex klystron usually furnishes sufficient power for these relatively short rf transmission paths.

Generally speaking, although the efficiency of the klystron is low as compared with efficiencies obtainable with conventional tubes at the lower frequencies (on the order of 30% as compared with 60%), *it is more efficient than the* other types of high-frequency generators in the microwave region. The negative grid tetrode provides approximately the same efficiency at 500 mc, but its output drops to zero around 1500 mc; similarly, the lighthouse tube covers a *range of from* 800 *mc* to 2500 or 3000 mc with comparable efficiencies and then its output drops off; the multicavity klystron, however, is operable up to 10,000 mc and beyond with efficiencies not less than 10%. In this respect, the reflex klystron offers the lowest efficiency (on the order of 2 or 3 percent) mostly because of its simplicity of construction. For example, the use of more cavities to provide better bunching would give higher efficiency. Actually, the klystron is the only device other than the magnetron (and perhaps the travelling wave tube) which offers practical operation on the microwave frequencies; *it is simpler* and cheaper than the magnetron (or TWT) and more flexible in its applications, which is the reason for its popular use. Present trends indicate that the reflex klystron will be replaced for high-power operation by the two- or three-cavity klystron, but for *simplicity and economy for low-power* applications the reflex klystron is more practical.

The klystron has a larger power gain than the negative grid tube at the higher frequencies because the tetrode primarily has a smaller cathode area, is limited in the *amount of* plate voltage that can be applied, and has greater r-f losses. The advantages of the klystron accrue because the cathode is not limited in size but can be made as large as necessary, and, being outside the r-f field in the tube, it is unaffected by radio-frequency bombardment or other deleterious effects. Although the negative grid tube has a closely spaced grid and plate (to reduce transit time effects), the distance between the anode and the cathode in the klystron is large (on the order of one inch), permitting larger applied plate voltage before breakdown occurs. Since there is no grid structure in the klystron to heat and cause losses (actually, grids are sometimes used, but are very rugged) and the collector is located outside the r-f field and designed solely to dissipate heat, better efficiency results. The major loss in the klystron is dielectric loss (such as the loss produced by windows in cavities for waveguide couplings), as well as wall absorption. Thus, the r-f gain is limited only by the small r-f input cavity loss and by beam loading of the output cavity. Normally there is no negative feedback to be overcome by virtue of interelectrode couplings, as in the negative grid tube, since the input and output cavities are isolated. In the case of the reflex klystron, positive feedback is obtained by the use of a repeller electrode so that only one cavity is required.

In the preceding discussion, a number of generalities were made to bring out the inherent differences between negative grid tubes and the klystron. Since the subject of klystrons and their design considerations cover a large field, which is beyond the scope of this text, and since there are so many variations between different products, it is possible that exceptions to some of the generalities can be made. In fact, considering reflex klystrons alone as a small branch of a large family of klystron tubes, there are a number of variations in design from type to type. Therefore, the interested reader is referred to other texts for specific data on a particular type or design, and the generalities made herein should be viewed broadly. The discussion that follows will be restricted to basic principles which can be applied to any type of tube.

The operation of the klystron is predicated upon the development of **velocity modulation** of the electron beam, that is, the velocity of the electron beam is controlled to produce a grouping or bunching of electrons. These bunches of electrons are then passed through grids or cavities to produce oscillations at the desired frequency by direct excitation of the cavities. A basic **klystron** (not reflex type) is shown in the accompanying illustration to establish the fundamental principle of operation. As shown in the figure, a heater is used to produce electron emission from a cathode. The electrons from the cathode are attracted to the accelerator grid (No. 1), which is at a positive potential with respect to the cathode. The accelerator grid may be a flat grid structure or an annular ring (cylinder or sleeve) through which the electrons pass unhindered. Assume that this attraction produces a constant-velocity electron beam, which is further attracted to the next electrode, the buncher grids (of cavity), and then to the next electrode, the catcher grids (or cavity), also at a higher positive potential. If the output from the catcher is fed back to the buncher, and if the proper phase and energy relations are maintained between the buncher and the catcher, the tube will operate as an oscillator. The collector plate, which is also at a positive potential, serves only to collect the electrons which pass the catcher. Successful operation requires that the energy needed for bunching be less than that delivered to the catcher. Amplifying action is obtained because the electrons pass through the buncher in a continuous stream and are effectively grouped so that they pass through the catcher in definite bunches or groups as explained in the following paragraphs.



Basic Klystron

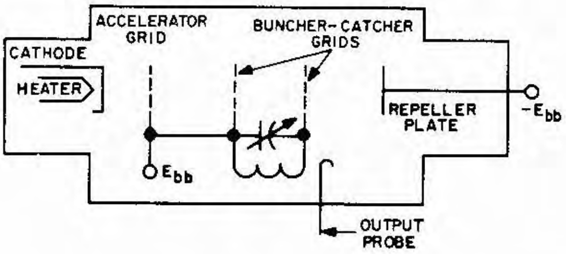
Bunching is produced by applying an alternating voltage to the buncher grids (produced by excitation of the buncher resonator by the passing electron beam). Assuming that a sine-wave voltage is produced and applied between the buncher grids, it is evident that on the positive alternation the buncher grid nearest the catcher effectively has its positive potential increased, and therefore further accelerates the electron flow. On the negative alternation, the same buncher grid voltage is made less positive and the electron stream is slowed down. Since a continuous stream of electrons enters the bunching grids, the number of electrons accelerated by the alternating field between the buncher grids on one half-cycle of operation is equalled almost exactly by the number of electrons decelerated on the negative half-cycle. Therefore, the net energy exchange between the electron stream and the buncher is zero over a complete cycle of alternation, except for the losses that occur in the tuned circuit (cavity) of the buncher.

After passing through the buncher grids, the electrons move through the **drift space** in the tube with velocities which have been determined by their transit through the buncher grids. Since in a conventional klystron the drift space is free of any fields, at some point in this drift space the electrons which were accelerated will catch up with these which were previously decelerated (in a prior passage) to form a bunch. The catcher grids are placed at this point of bunching (determined by frequency and transit time), to extract r-f energy from the bunched electrons.

At the catcher a different situation exists. Since the electrons are traveling in bunches, spaced so that they enter the catcher field only when the oscillating circuit is in its decelerating half cycle, more energy is delivered to the catcher than is taken from it. The remaining electrons in the beam pass through the grid and travel to the collector plate, where they are absorbed.

In the **reflex klystron,** the catcher grids are replaced by a repeller plate, to which a negative potential is applied, as illustrated in the accompanying figure.

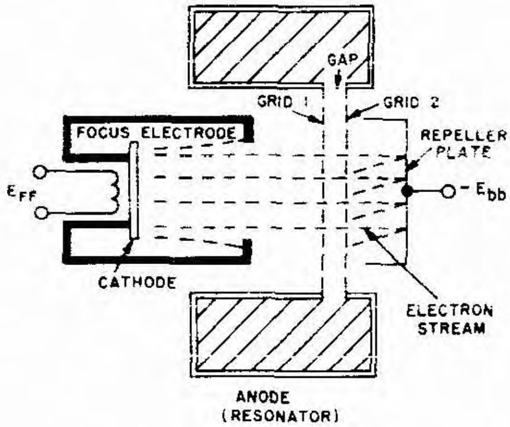
In this type of klystron, the electron beam is also velocity-modulated, and, by proper adjustment of the negative voltage on the repeller plate, the electrons which have passed the bunching field may be made to pass through the resonator again (in the reverse direction) at the proper time to deliver energy to this circuit. Thus, the feedback necessary to produce oscillation is obtained and the tube construction is simplified. Spent electrons are removed from the tube by the positive accelerator grid (when used) or by the grids of the positive buncher cavity. Energy is coupled out of the cavity by means of a one-turn hairpin coupling loop. The operating frequency can be varied over a small range by changing the negative potential applied to the repeller, because this potential determines the transit time of the electrons between their first and second passages through the resonator. Since maximum output depends upon the fact that the electrons must return through the resonator at just the time when they are bunched and at exactly the decelerating half-cycle of oscillating resonator grid voltage, the output is more dependent than the frequency upon the repeller potential; therefore, the amount of tuning provided by varying the repeller voltage is limited. Usually the volume of the resonator cavity is changed (by mechanical tuning) to make a coarse adjustment of the oscillator frequency, and the repeller voltage is varied over a narrow range to make a fine adjustment of the frequency



Reflex Klystron

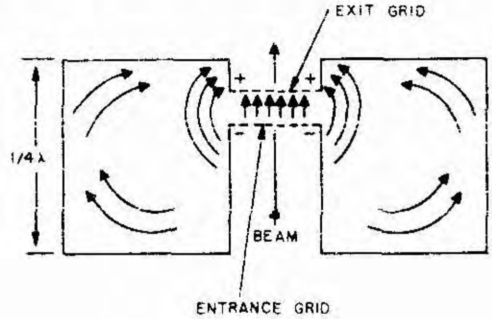
(electronic tuning) consistent with good output. Since the same grids perform the dual function of bunching and catching in the reflex klystron, they are frequently referred to as the **buncher-catcher grids.** Because of the variation of frequency with accelerating voltage, it is difficult to achieve linear amplitude modulation with a klystron. Frequency modulation may be readily accomplished, however, by introducing a small modulating voltage at the cathode or repeller. The tuned circuit used in the reflex klystron is a cavity resonator, which has a very high Q. Depending upon the tube type, the cavity may be an integral cavity (built into the tube) or an external cavity (clamped around the tube). Several methods are used to tune cavity resonators. Capacitive tuning is provided by mechanically varying the grid gap spacing; inductive tuning is provided by moving screw plugs in or out of the cavity (this changes the volume, making it either smaller and tuned to a higher frequency, or larger and tuned to a lower frequency). In some instances thermal tuning is used by applying heat to grid gap to produce capacitive variations. Several types of output couplings are used, but the coupling loop is the most popular type. Capacitive probe coupling is often used with the external type of cavity because construction difficulties do not readily permit the use of coupling loops with this type of cavity. At frequencies above 10,000 mc waveguides are employed, and the output is coupled to the waveguide through a window or aperture.

Detailed Analysis. In the practical klystron, the function of the accelerating grid is provided by the cavity, which is maintained at a positive potential sufficiently strong to produce the initial effect of accelerating the electrons to a constant velocity. A focus electrode, in the form of a cylinder connected to the cathode, is also provided to confine and effectively focus the electrons into a narrow beam. Focusing is achieved electrostatically without any external control. Any electrons which travel outside the beam are intercepted and removed, while those within the beam are attracted by the strong positive cavity field and accelerated uniformly. A typical reflex klystron, showing the focusing electrode and the cavity structure, is illustrated in the accompanying figure.



Practical Reflex Klystron

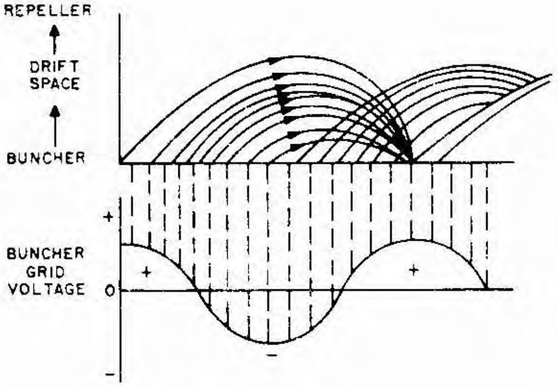
Note the particular shape of the cavity, which has a post-shaped center hole. As a result of this construction, the cavity is very narrow at the point (the gap) where the electrons pass through it. The narrow gap is necessary for proper operation since the transit time through the cavity must be much less than the time for a complete cycle at the frequency of operation. Beyond the center hole the cavity is much larger. The portion of the cavity at the gap where the ends are close together may be considered capacitive in effect, and the remaining portions, where the capacitance is small, may be considered inductive in effect. Consider now the operation of velocity modulation. Since the cavity is developed as a quarter wave coaxial resonator, the input and output ends are at opposite polarities. Also, the current distrubution is approximately uniform at the center, where the beam passage takes place. Hence, in the gap a uniform electric field is produced. The passage of the electron beam through this field will distort the field and cause energy to be absorbed from the beam. Thus, the cavity is excited, and it oscillates at a frequency determined by its dimensions. These oscillations produce opposite polarities at the entrance (grid 1) and exit (grid 2) grids, because the sides of the cavity are exactly one quarter wavelength apart at the operating frequency. By virtue of resonance and the use of a high-Q cavity, the r-f oscillations develop a large instantaneous voltage, which on the positive alternation places the exit grid at a more positive potential than the entrance grid. As a result, the exit grid is polarized in the proper direction to attract the electron beam and increase the electron beam velocity. See the following illustration for a representation of the cavity action.



Cavity Action

On the negative alternation the beam is opposed and effectively slowed down. At and near the changeover points, the a-c oscillation voltage is practically zero so that the beam is not affected and it passes through with the initial velocity. The alternate acceleration and deceleration of the beam, together with the ineffective period of no change produces a bunching of the electrons. (In effect, the bunches of electrons occur at a period equal to the frequency of oscillation. Thus, actual density modulation is produced, resulting in an alternating current varying in strength at the frequency of operation, which when absorbed by a resonant cavity will cause r-f oscillations.)

Before the electrons with different accelerations are completely bunched, they enter into the repeller-plate field, which is negative and repels the electrons. An electron which was accelerated by the field at the cavity grids will penetrate the electric field at the repeller plate to a greater depth than one which was accelerated less or not at all, and will require a longer time to return to the cavity. Thus, bunching can be achieved by adjustment of the repeller plate voltage to the optimum value. When the voltage is optimized, bunches are formed at the cavity by those electrons which were accelerated meeting those which were not accelerated, but which passed through the gap at a later time, and also by those decelerated electrons which passed through at a still later time. A typical Applegate diagram illustrating the bunching effect is shown in the accompanying figure.

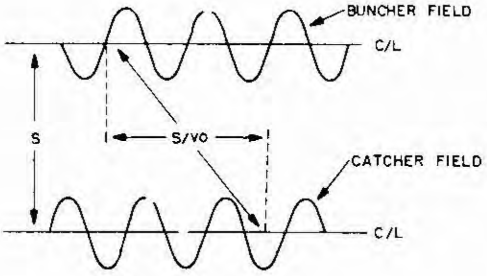


Applegate Diagram

To more clearly understand buncher and catcher operation, we shall review the operation of the two-cavity type of tube. Action is based upon the fact that electrons will give up energy when slowed down, and absorb energy when accelerated. In order for an electron to give up the greatest amount of energy to the catcher, it is necessary that the electron arrive at the center of the catcher at the instant when the electric field at the center of the catcher has its maximum negative (retarding) value. Similarly, in order for a symmetrical group of electrons to deliver as much energy as possible, the center of the group must arrive at the center of the catcher when the catcher field has its maximum negative value. Since the electron at the center of the group is the one that passed the center of the buncher at the instant when the buncher field was changing from negative to positive, the time s/v_o required by this electron to move through the distance s from the center of the buncher to the center of the catcher, must be equal to the time interval between the zero value of the buncher field and a negative maximum of the catcher field, as shown in the following figure. It is evident from examination of the illustration that for maximum energy transfer, the catcher field must lag the buncher field by the angle

$$\frac{s}{v_o} \times \frac{2\pi}{T} + 2\pi(\tfrac{1}{4}-n),$$

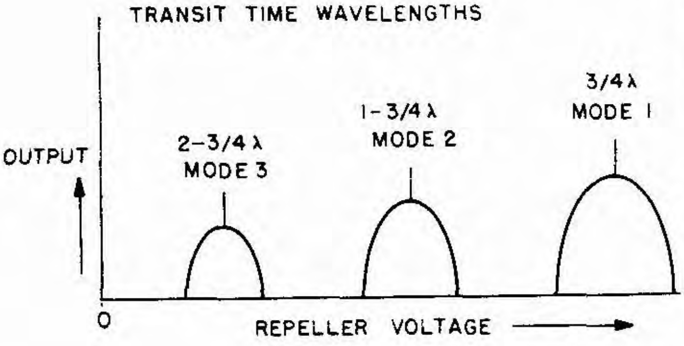
where T is the period of the field and n is any integer.



Buncher-Catcher Phase Relationships

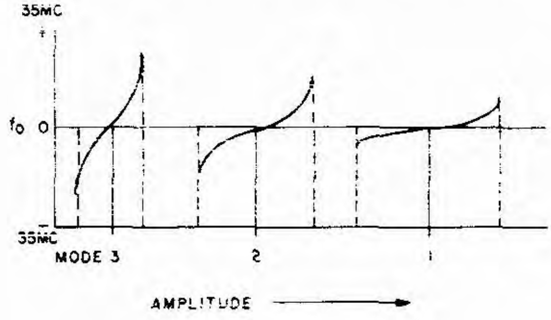
Up to this point nothing has been said regarding the means by which the catcher is kept in oscillation. The motion of an electron through a cavity resonator sets up an electromagnetic field within the resonator. In a klystron the electrons pass through the catcher in bunches; therefore, the fields resulting from individual electrons will, for the most part, reinforce each other and thus produce a resultant field of appreciable magnitude. Because the bunches pass through the catcher at time intervals equal to the natural period of oscillation of the catcher, the catcher is set into oscillation. Since the amplitude of oscillation can build up only if the catcher gains energy, the oscillation automatically tends to assume the proper phase relative to the cycle of arrival of electron bunches to result in maximum transfer of energy from the electrons to the catcher. Since the cavity of the reflex klystron acts both as a buncher and a catcher, if an output is to be obtained, the returning electrons must be phased so as to impart energy to the cavity and be absorbed. It is necesary that they approach the cavity when the buncher voltage originally induced is opposing them, or producing deceleration. Therefore, the time taken for a bunch to return to the cavity must be 3/4 of a cycle of the operating frequency to supply energy by feedback and satisfy the requirements for oscillation. The phasing must be such that the electrons add energy to the cavity. Therefore, during the first quarter cycle they have not yet returned, and during the second quarter cycle they are in phase opposition (180° apart), but at the 3/4 cycle they are in phase and will add energy to the cavity. A bunch of electrons which returns to the cavity at a time equal to 3/4 of a cycle, or any whole number of cycles plus 3/4 cycle, will supply energy of the proper phase for sustaining oscillations. Thus, oscillations may be obtained at a number of repeller plate voltages for a given frequency setting of the resonator cavity.

Oscillations of maximum amplitude are obtained when the frequency of operation, as determined by the return time of the reflected electrons forming a bunch, coincides with the frequency to which the resonator is tuned. Since only one resonator is used, the tuning of the reflex klystron is relatively simple. Although the frequency of operation for fixed cavity tuning may be varied by changing the repeller voltage, the power output drops off on either side of the cavity frequency because the field of the gap does not provide optimum retardation. The various values of repeller voltage which produce oscillation result in what is known as different **modes** of operation. The most negative repeller voltage for which oscillation results is known as mode 1. Lower values of repeller voltage successively produce the higher modes (2, 3, 4, etc) of operation. A typical output response with repeller voltage variation is illustrated in the following figure.



Power Output vs Repeller Voltage

Since the bunching of the electrons for the higher-numbered modes is not so well defined, the net energy given up by the beam to the resonator field is less, and the output power is smaller, as illustrated. On the other hand, because the bunching is not so well defined, the modes of higher number are tunable over a greater range of frequencies (by adjustment of the repeller voltage). The accompanying illustration of electronic tuning ranges versus modes indicates that for the lower repeller voltages (mode 3) the range of electronic tuning increases but the output decreases.



Tuning Ranges vs Modes of Operation

The variation of frequency with changes in the repeller voltage permits the reflex klystron to be used with an automatic-frequency-control circuit, which controls the klystron frequency by lowering (or by increasing) the repeller voltage in the proper direction to compensate for any frequency change. Thus, the circuit can be made self-tuning and provide reasonably good frequency stability, particularly in pulsed operation where voltages and pulse amplitudes change drastically. (See Section 21 for a discussion of various types of AFC circuits.)

Tuning Methods. The method used for tuning the resonator has an important bearing on the performance of a reflex klystron. Tuning is commonly accomplished by varying the length of the r-f gap, to adjust the capacitive portion of the resonator, although in some tubes the inductive portion is altered. Capacitive tuning requires small motions for large frequency shifts, particularly near the low-frequency end of the tuning range. This extra sensitivity can be either an advantage or a disadvantage depending upon the application. Generally speaking, it creates a problem when temperature compensation is attempted because there must be considerable reduction of motion by a mechanical linkage between the control knob and the gap itself.

The use of capacitive tuning reduces the range over which reasonable efficiency is obtained. As the frequency is raised by lengthening the gap, the transit angle through the gap increases rapidly because the electrons have farther to go and less time to make the trip. The beam coupling coefficient also drops rapidly at the high frequencies so that the output drops quickly. On the low-frequency side of resonance, a similar drop-off occurs, but it is not so rapid. Since the resonator must incorporate a flexible diaphragm to permit capacitive tuning, problems arise in providing the proper vacuum seal; also, the tube is susceptible to changes caused by strong sound waves impinging on the diaphragm, and to changes in barometric pressure, which cause problems in aeronautical applications.

On the other hand, inductive tuning is usually less sensitive because larger mechanical motions are required to produce the same effect. In radial cavities, screw plugs are used (as many as four to six) for tuning. This method of tuning usually results in a fixed-tuned arrangement because of the mechanical difficulties in providing remote control of a number of plugs. However, since the transit time varies directly with the phase angle, rather than the 3/2 power as in capacitive tuning, much larger tuning ranges are available with inductive tuning. The largest tuning range (approximately 2 to 1) is provided by a coaxial cavity, but at greatly reduced efficiency (capacitive tuning range is about 0.7 to 1).

Mechanical tuning is usually employed in preference to thermal tuning because of the complexity of the frequency control circuit. Since the thermal motion is usually small, capacitive tuning is practically always used for thermal control. The main drawback of thermal control is thermal inertia, which prevents a rapid response to sudden frequency changes; as a result, overshoot becomes a major problem. In general, thermal tuning is used only for special applications where the simpler types of tuning are inadequate.

Output Coupling. Tubes with integral resonators usually have built-in output circuits that consist basically of a coupling device and an output transmission line. The most common pickup device is an inductive loop formed on the end of a coaxial line and inserted in a region of the cavity where the magnetic field is high. Aperture coupling, sometimes called **iris** coupling, is also used, but to a lesser extent than the pickup loop. In waveguide applications, the aperture is usually used for simplicity and convenience. For external cavity tubes employing coaxial-line tuners, a capacitive probe is sometimes used.

FAILURE ANALYSIS.

No Output. Incorrect or no plate voltage can prevent oscillation. An incorrect repeller voltage can usually be re-adjusted (within range of the control) to the proper value, or output frequency may be adjusted by tuning the cavity until the tube operates on some other frequency. Lack of oscillation for all values of repeller voltage and cavity tuning indicates an open circuit, loss of accelerator anode voltage, or a defective tube. With an external cavity klystron, poor electrode contacts can also cause lack of output. A voltage check will quickly indicate whether the potentials are normal. Note: **Although low voltages are used, the cavity is positive while the repeller is negative so both supplies in series provide a possibility of dangerous shock. Observe safety precautions when testing.** A tube with decreasing emission indicates incipient failure by a gradual reduction of plate current, and failure to oscillate at the usual repeller control settings. Such a condition becomes progressively worse over a period of time, and complete failure can be anticipated. Loss of output when automatic frequency control is used can result from failure of the AFC circuits; this type of trouble can be determined by switching to manual control and noting whether normal tuning occurs. Since the reflex klystron is an integral unit with only output and supply connections, complete loss of oscillation is usually due to mistuning, loss of supply voltage, or a defective unit.

Reduced Output. In the majority of cases, reduced output is caused by mistuning or lack of proper electrode voltages. Mistuning can usually be corrected by a slight readjustment of the repeller voltage and the cavity tuning unless the tube or supply is defective. There is also a possibility that the output load has changed, requiring a readjustment of the controls. Where stub tuners are employed in the output circuit, reduced output may be caused by improper stub tuning. In either case, a slight readjustment of each of the tuning controls should quickly indicate which is at fault. Operation on a lower mode due to incorrect supply voltage can be detected by a voltage check; this condition is usually indicated when the controls must be set to a position other than normal for maximum output, or when reduced output is obtained at the optimum adjustment point. If the supply voltages and load are normal, reduced output usually indicates incipient tube failure.

Incorrect Frequency. Slight changes in frequency can usually be corrected by making slight repeller voltage changes and by tuning the cavity. Normally a rough frequency setting is obtained by adjusting the cavity tuning, and a fine frequency setting with optimum output is obtained by adjusting the repeller control. A simple voltage check should indicate whether the repeller and cavity voltages are correct. If the cavity tuning is operable and the repeller voltage is correct, incorrect frequency operation can be caused only by load changes or by a change in the tube cavity mechanism with age. It should be possible to restore the frequency by proper load adjustment. Changes in the mode of operation can be detected by noting whether the tuning range is greater and the output is less. Where AFC circuits are used to maintain the frequency, a shift to manual control will quickly determine whether they are at fault.

Changes in frequency resulting from changes in temperature are usually compensated for by adjustment of the tuning controls; such changes may be caused by localized heating due to improper operation when power type klystrons are used, or by greater than normal ambient temperature changes. When proper operation and normal temperature are restored, the unit should again stabilize at the proper frequency. Unless thermal compensation circuits or devices are provided, it will be necessary to compensate by the use of manual tuning. If continued drift is observed, the tube ratings are probably being exceeded. Where a stable frequency is important, an AFC circuit is usually incorporated. Improper operation of the AFC can be checked by switching to manual operation and observing whether operation is normal.

PART B. SEMICONDUCTOR CIRCUITS

L-C OSCILLATORS.

The L-C type of transistor oscillator uses a tuned tank circuit consisting of either a parallel- or series-connected capacitor and inductor similar to the electron tube type L-C oscillator. Choice of parallel or series resonant tank is dependent on the circuit configuration used and the characteristics desired. The parallel tank offers a high impedance at the resonant frequency with high circulating current and minimum line current, while the series resonant tank offers a low impedance at resonance with high line current and no circulating current. In most applications the parallel resonant tank is used.

Although operation is usually in the radio-frequency range, it is also possible for a tuned L-C tank to operate at audio frequencies. Oscillation is achieved by positive (regenerative) feedback (usually from the collector to the base in a CE circuit but fixed by the circuit used) through inductive or capacitive coupling, or through the internal transistor parameters themselves.

Operation is usually Class C, but it can be Class A for waveform (test equipment) applications. Bias is obtained as specified for the basic transistor in Section 3 of this technical manual. A combined voltage divider and feedback type biasing arrangement is often used because it helps produce oscillation, and at the same time establishes a stable d-c bias point. Emitter biasing with a bypass capacitor is also used, the operation being similar to that of the grid-leak-capacitor biasing combination used for electron tubes. Usually, the amplitude is regulated by driving the transistor into the saturation and cutoff regions of its characteristic or by using special diode arrangements where needed. Either shunt or series type collector feed may be employed, but the shunt type is preferred for greater output efficiency. Actually, for design purposes the oscillator is considered to be a Class C amplifier with a feedback loop, operating at the same voltages and currents as an amplifier but with a lower over-all output because of feedback and circuit losses. If proper design considerations are taken into account, the loss of power in the feedback loop is negligible, as the well designed transistor amplifier is normally operated with a power reserve of at least 10 percent.

Frequency stability is equivalent to, and sometimes better than, that of the electron tube counterpart. The use of lower voltages, currents, and power permits construction of better tank circuits both electrically and mechanically. In particular, the low power employed with transistors proves advantageous from a stability standpoint, because it minimizes thermal changes. However, the transistor operating point is somewhat more critical, as slight bias changes can cause large frequency changes. Unfortunately, voltage and current changes on the transistor elements are not equal and, therefore, do not entirely cancel out to provide voltage or current stabilization. Actually, the transistor oscillator produces a current waveform which, when passed through the load, produces a sine-wave output voltage. Therefore, it is more important to stabilize current changes than voltage changes; however, supply voltage variations cannot be neglected if amplitude variations are to be minimized. It should be noted that the transistor is particularly susceptible to instant damage by transient voltages.

In the following discussion the three basic circuit configurations for each oscillator are shown to aid recognition, and to point out any salient differences that exist. Normally, the common-emitter circuit is the one most encountered for a number of reasons, as follows: The power, current, and voltage gains in this configuration are all better than 1, and the highest possible power gain can be achieved. There is a phase (polarity) reversal between input and output so that additional phase shifting in the positive feedback direction is easily achieved by addition of the tank circuit. Also, the common-emitter circuit is the counterpart of the electron tube grounded-cathode circuit, and moderate input and output impedances make less power necessary for feedback. Whereas with the common-base configuration, the low-input and high-output impedances inherent in the circuit cause mismatch in the feedback circuit, producing greater losses and requiring more feedback. The current gain in the CB circuit is less than 1, even though voltage and power gains are higher than unity, and the input and output currents are in phase (this condition is advantageous for oscillators not having a tank circuit). A somewhat similar condition exists in the common-collector circuit; that is, high input and moderate output impedances provide mismatching and require additional feedback. Low voltage gain negates the current and power gain possible, and the in-phase output condition tends to prevent, rather than enhance, oscillation.

Transistor parameters generally limit the maximum usable frequency of oscillation for any particular oscillator circuit which is defined as the alpha cutoff frequency (f_{ab}) for the common base configuration and the beta cutoff frequency (f_{ae}) for the common emitter. This is the frequency at which the forward current gain drops 3 db, or to 70.7 percent of the 1000-cps value of current gain. It should be noted that this value is not f_{max}, which is the maximum theoretical frequency at which the transistor could oscillate, or as sometimes stated, equal to the frequency at which the power gain is unity. The cutoff frequency actually defines the highest frequency at which the most useful power gain is obtained. Transistors are usable and will oscillate in the region between the cutoff frequency and f_{max}; their output, however, will be lower than that between 1000 cps and cutoff. At exactly f_{max}, theoretically no feedback can occur and there will be no oscillation at that frequency.

Since transistors have interelectrode capacitance similar to electron tubes, it should be kept in mind that a change in these values can affect oscillation. Since Class C operation is normally used with reverse base-emitter bias (self-bias), C_{be} is small and can be neglected. The collector-to-base capacitance, C_{cb}, varies on the average from 2 to 4 picofarads for high-frequency transistors to as high as 50 picofarads or more for audio transistors. Increased collector voltage will reduce the collector-base capacitance, and increased emitter current will increase the collector-base capacitance, but these effects are not equal and therefore do not compensate each other. The collector-to-emitter capacitance, C_{ce}, is 5 to 10 times greater than C_{cb} and varies similarly with changes of voltage and current.

TICKLER COIL (ARMSTRONG) OSCILLATOR.

APPLICATION.

The tickler coil (Armstrong) oscillator is used to produce a sine-wave output of constant amplitude and fairly constant frequency within the r-f range. The circuit is generally used as a local oscillator in receivers, as a signal source in signal generators, and as a variable-frequency oscillator over the medium- and high-frequency ranges.

CHARACTERISTICS.

Uses an L-C parallel tuned circuit to establish the frequency of oscillation, with feedback being provided by a separate tickler coil of proper polarity to sustain oscillation.

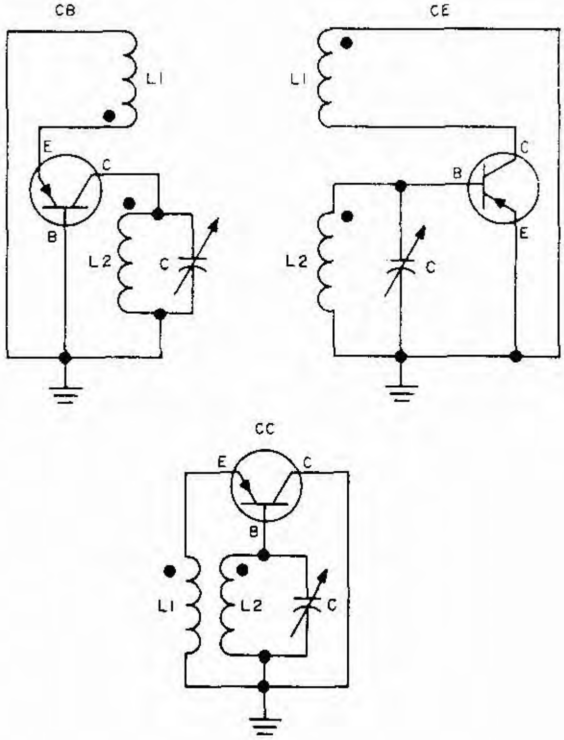
Operates Class C with stabilized bias for applications where linearity of waveform is not important, and Class A where linearity of waveform is important.

Frequency stability is fair (generally comparable to that of the Armstrong vacuum-tube oscillator).

CIRCUIT ANALYSIS.

General. A sine-wave output may be obtained from an oscillator utilizing a tuned L-C circuit, especially when the transistor is operating over the linear portion of its transfer characteristic curve. The L-C circuit (commonly called a tank circuit) determines the frequency of oscillation. The tank circuit can be located in either the base or the collector circuits to produce two versions of this circuit known as the tuned-base and tuned-collector circuits, respectively; these are similar to the tuned-grid and tuned-plate electron tube oscillators. Although three basic transistor configurations (common base, common emitter, and common collector) can be used, generally, only two, the common emitter and common base, are used in practice. A trend is developing towards the use of the common-emitter arrangement in preference to the others, since it so nearly parallels the electron tube and has input and output impedances that are more easily matched. In the CE circuit, since the input and output are 180 degrees out-of-phase (opposite polarity), it is necessary to provide a 180-degree phase shift (reverse polarity) to bring the output in-phase (of proper polarity) so that oscillation may be sustained. However, in the common-base and common-collector arrangements, the input and output are already in-phase (identically polarized); therefore, no phase shift (polarity reversal) is required (at extremely low frequencies excessive phase shift may prove troublesome). The basic advantage of the Armstrong oscillator, however, is that since the feedback is developed by a separate (tickler) coil, the amount and polarity of the feedback are easily adjusted at the time of manufacture by changing the number of turns or direction of the winding.

Circuit Operation. The three basic transistor configurations of the Armstrong oscillator circuit are shown below. Bias and plate feed arrangements are omitted for the sake of simplicity, but will be discussed later. It is assumed that forward bias is applied to the emitter-base junction and that reverse bias is applied to the collector-base junction. Only junction transistors are discussed, since point-contact transistors require slightly different considerations and their use is constantly diminishing, except for special applications which will be discussed elsewhere in this technical manual when applicable.



Basic Armstrong Configurations

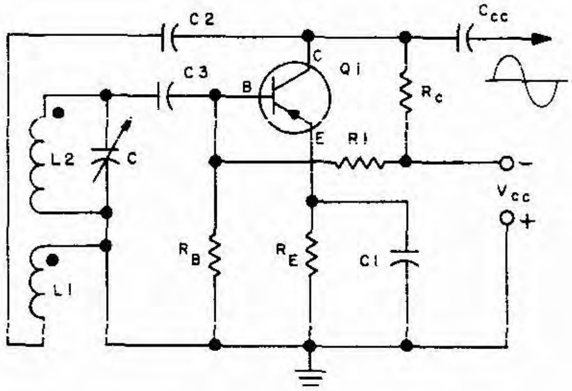
The common-base circuit is usually preferred at the higher frequencies because the collector-emitter capacitance, C_{ce}, helps feed back an in-phase (properly polarized) voltage independently of tickler coil L1, and oscillation is more easily obtained. In the common-emitter circuit this capacitance feeds back an out-of-phase (oppositely polarized) voltage which requires additional feedback from the tickler coil to overcome it. In both the CB and CE circuits, since feeedback is primarily provided by voltage induced through the mutual induction between L1 and L2, and since the voltage gain of these circuits is greater than unity, oscillation is easily sustained. In the common-collector circuit, the voltage gain is always less than unity; therefore, feedback tends to be insufficient for stable oscillation at the lower frequencies, while at the higher frequencies it is assisted by C_{ce}. In some instances, an external capacitor is added between the collector and emitter to provide additional feedback, but when this is done the oscillator can no longer be considered an Armstrong circuit; consequently, the CC circuit is not often employed for this type of oscillator.

The CB circuit with the tuned collector permits convenient matching of input and output impedances, since the low input resistance is easily matched with the tickler coil, and the high output impedance is matched by the tuned parallel-resonant tank circuit. Moreover, the collector-base internal capacitance is swamped by the high-C tank circuit.

In the common-emitter circuit, the moderate input and output impedances are more easily matched, and the tank may be placed in either the base or collector circuits without noticeably affecting the performance.

The operation of the L-C circuit is identical to that of the L-C circuit for the Armstrong electron tube oscillator circuit described in the beginning of this section. The transistor action is as follows: As the oscillator is switched on, current flows through the transistor as determined by the biasing circuit. Internal noise or thermal variations (initial current) produce a feedback voltage between the collector and the emitter which is in-phase with the input circuit. Thus, as the emitter current increases, the collector current also increases, and additional feedback between L1 and L2 further increases the emitter current until it reaches the saturation region, where the emitter current no longer increases. When the current stops changing, the induced feedback voltage is reduced until there is no longer any voltage fed back into the emitter circuit. At this time the collapsing field around the tank and tickler coils induces a reverse voltage into the emitter circuit which causes a decrease in the emitter current, and hence a decrease in the collector current. The decreasing current then induces a greater reverse voltage in the feedback loop, driving the emitter current to zero or cutoff. Although the emitter current is cut off, a small reverse saturation current (I_{CEO}) flows; this current has essentially no effect on the operation of the circuit, but it does represent a loss which lowers the overall efficiency. In this repect, the transistor differs from the electron tube, which has zero current flow at cutoff.

The discharge of the tank capacitor through L2 will cause the voltage applied to the emitter to rise from a reverse-bias value through zero to a forward-bias value. Emitter and collector current will flow, and the previous described action will repeat itself, resulting in sustained oscillations. Actually, the shunting action of the transistor parameters provides both a resistive and capacitive effect, which causes the frequency of operation to be slightly lower than the tank circuit resonant frequency, but the frequency decrease is so small that the basic frequency of operation is considered, for all practical purposes, to be the tank frequency that is, $F_r = \dfrac{1}{2\pi\sqrt{LC}}$, where L and C are the values of L2 and C at resonance.



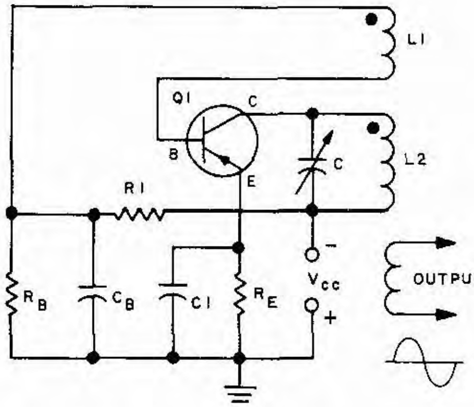
Tuned-Base Armstrong Oscillator

Tuned-Base Oscillator. The tuned-base (tuned-grid) Armstrong oscillator using the common-emitter configuration is shown in the accompanying illustration. One voltage supply is used, with fixed bias being supplied by voltage-dividing resistors R1 and R_B (see Section 3, paragraph 3.4.1, for bias explanation). Emitter swamping resistor R_E bypassed by C1, is used for temperature stabilization.

The collector is shunt-fed through R_C, with C2 serving as the coupling (and blocking) capacitor for the tickler coil, to prevent shunting of the d-c collector voltage to ground. The tuned tank consists of L2 and tuning capacitor C, coupled to the base of transistor Q1 by capacitor C3, which prevents short-circuiting of the base bias to ground through the tank inductor.

When the circuit is energized, the initial bias is determined by R1 and R_B, and oscillation is built up by feedback from L1 to L2. Besides acting as a thermal stabilizer and swamping resistor, the combination of R_E and C1 acts similarly to a grid leak in an electron tube circuit and builds up a degenerative bias which places operation in the Class C region. That is, while R_B and R1 produce a forward bias, R_E produces a reverse bias, with the algebraic sum of the two biases providing the operating bias. Circuit constants can be adjusted by changing the values of parts to produce practically any value of bias between Class A and C. The r-f output is taken from the collector through C_{cc}. The output frequency is determined by the resonant frequency of the tank.

Tuned-Collector Oscillator. The tuned-collector (tuned-plate) Armstrong oscillator using the common-emitter configuration is shown schematically in the accompanying illustration. One voltage supply is used, with fixed base bias being supplied by voltage-dividing resistors R1 and R_B as in the tuned-base oscillator shown previously. The arrangement below uses series base feed, together with series collector feed through the tank inductor, although parallel feed may be used equally well.



Tuned-Collector Armstrong Oscillator

Since the collector is series fed through L2, tuning capacitor C is above ground and will be subject to hand-capacitance effects. In some circuit variations a radio-frequency choke may be used in series with the tank and bypassed to chassis to shunt any remaining rf around the power supply. Base bias resistor R_B is shunted by C_B, to prevent signal variations from affecting the fixed base bias. Emitter-swamping and base-biasing arrangements operate exactly the same as in the tuned-base oscillator previously discussed. The r-f output, however, is taken through inductive coupling to the tank circuit. Use of series collector and base bias feeds eliminates the need for coupling and blocking capacitors, and thus eliminates any dead spots caused by unwanted resonances of these parts with stray circuit or internal transistor capacitance. The feedback polarity is arranged to provide a 180-degree phase shift, in order to produce positive (regenerative) feedback similar to that obtained in the tuned-base oscillator. Placing the tank in the collector circuit provides an effective swamping capacitance across the collector and emitter, to minimize effects due to the variations of C_{CE}. Although this circuit appears to be more stable from a frequency standpoint than the tuned-base oscillator, it is not so stable thermally. Since the series feed arrangement is used in both the collector and base, there is a d-c path of relatively low resistance for reverse saturation current I_{CBO}, which flows during cutoff. The path is from the negative collector supply through the low resistance of L2, through the collector to the base of Q1, and through the low d-c resistance of L1, then through the high base bias resistance R_B to the positive supply terminal. Thus the relatively high resistance of collector resistor R_C of the tuned-base oscillator circuit is replaced by the very low d-c resistance of the windings of L1 and L2. As a result, the individual transistor I_{CBO} current determines how large a current will flow through the tank and feedback inductances to decrease the effective circuit Q and reduce the over-all efficiency of the oscillator. Where battery power supplies are used, such leakage current will provide a small but constant drain on the battery, an effect not possible with electron tubes.

FAILURE ANALYSIS.

No Output As in a vacuum-tube counterpart, loss of gain in the transistor can result in lack of oscillation through loss of feedback. It should be kept in mind that, unlike the electron tube, the transistor cannot lose gain through loss of emission. Failures of the transistor mostly result in short- or open-circuit conditions rather than deteriorated operation. An excessive time constant in the emitter bias circuit, produced by an increase in the resistance of R_E, could cause blocking effects. A change in the value of emitter bias capacitor C1 will affect the operating bias, but will be rather unlikely to completely stop oscillation unless the change is large. Once oscillations have started, loss of forward bias through an open in the base circuit will not necessarily stop oscillations because the feedback signal swinging both positive and negative (on a reference of zero or the established self-bias) will apply on the negative or positive half cycle, depending on the circuit configuration and the type of transistor used, a forward bias and cause emitter collector current to flow (while possible, this condition is not very common). Particular care should be taken not to aggravate troubles by applying potentials greater than the rated voltages (or of the wrong polarity) to the transistor elements when checking the resistance of bias elements and circuit continuity. Failure of the tank and tickler blocking capacitors in the parallel-fed circuit will cause the shorting of bias or supply potentials and stop oscillation; however, at the low voltages used such failure is not very likely. Shorted tickler or tank inductor turns or poorly soldered connections may produce sufficient shunting (or high resistance) to stop feedback, although the tank inductor change would probably be indicated by a frequency change rather than loss of oscillation. A short in the tuning capacitor can cause loss of oscillation, and it may not be detected by a continuity check unless the tank coil is disconnected.

Reduced or Unstable Output. Instability should be resolved into one of two types – frequency or amplitude. If temperature variations are the cause of frequency instability, the trouble is most likely in the biasing circuit or the emitter swamping circuit. Opening of the bias voltage divider or shorting of one of its resistors will provide less stability, but such a condition is easily found by checking for proper bias with a high-resistance voltmeter, preferably of the electronic type. It is important, in the case of the electronic voltmeter, to make certain that its chassis does not have an above-ground voltage which could be accidentally applied to the transistor under test. Frequency instability can also result from poor connections or changes of L and C values. Mechanical, electrical, and thermal considerations affecting the tank circuit should be considered. Lack of regulated supply voltage for bias and operation is important. In general, the percentage of regulation in the supply voltage must be better for transistor oscillators than for vacuum tube oscillators. If external to the equipment, power supply regulation effects can sometimes be easily corrected by appropriate use of Zener diodes at the points affected.

Instability in the amplitude can be traced in most cases to variations in the supply voltage or to component failure in limiting diodes placed in the circuit for the sole purpose of maintaining amplitude stability.

While reduced output can result from loss of gain in the transistor, this condition is not as common as it is with electron tubes; *therefore, it is more logical to investigate* supply and bias voltages first before changing transistors. Excessive bias, rather than lack of bias, is more likely to reduce output.

Incorrect Output Frequency. Normally, a small change in output frequency can be compensated for by realigning or adjusting the variable component of the L-C resonant tank circuit, assuming that all component parts of the circuit are shown to be satisfactory. Changes in distributed capacitance or reflected load reactance will also affect the frequency of operation. Additional capacitance will lower the frequency and less capacitance will increase the frequency; corresponding changes in inductance will produce the same effect. A change in transistor parameters will also affect the frequency; for example, an increase in the collector voltage will reduce the collector-base capacitance, while an increase in the emitter current will increase the collector-base capacitance. Power supply regulation effects can, therefore, be suspected when temporary frequency changes occur. Comparison of actual indications with those of the operational standard will generally indicate the area at fault. It may normally be assumed that major frequency changes will involve the transistor elements and components associated with the tank circuit, since they constitute the major frequency-determining portion of the circuit.

HARTLEY OSCILLATOR.

APPLICATION.

The Hartley oscillator is used to produce a sine-wave output of constant amplitude and fairly constant frequency within the medium- and high-frequency rf ranges. The circuit is generally used as a local oscillator in receivers, as a signal source in signal generators, and as a variable-*frequency* oscillator for general use.

CHARACTERISTICS.

Uses an L-C parallel tuned circuit to establish the frequency of oscillation.

Feedback is obtained through a common, tapped coil.

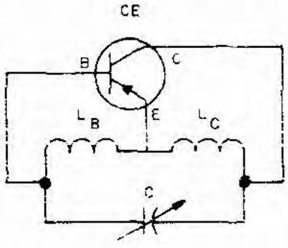
Operates Class C with stabilized bias for applications *where waveform is not important, and Class A where linearity* of waveform is important.

Frequency stability is fair (better than that of the Armstrong oscillator).

CIRCUIT ANALYSIS.

General. A sine-wave output may be obtained from an oscillator utilizing a tuned L-C *circuit, especially* when the transistor is operating over the linear portion of its transfer characteristic curve. The L-C circuit (commonly called a tank circuit) determines the frequency of oscillation. By using a tapped inductor for the tank inductance, a portion of the tank voltage can be fed back to provide positive feedback and sustain oscillation. The tapped inductor tank circuit may be used as either an autotransformer or a phase shifter, depending on the type of feedback needed for the specific circuit configuration. Unlike the Armstrong oscillator where feedback can be shifted in phase 180° by reversing the tickler coil, the Hartley oscillator will operate only in a common-emitter arrangement since the feedback is *always shifted in phase* 180°.

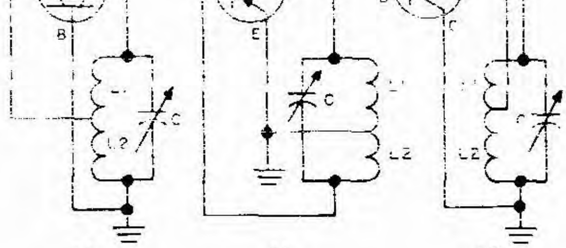
Circuit Operation. The basic transistor configuration of the Hartley oscillator circuit is shown in the following illustration. Bias and collector feed arrangements are not shown, but will be discussed later. It is assumed that forward bias is initially applied to the emitter-base junction and that reverse bias is applied to the collector junction. This discussion concerns junction transistors only; however, point-contact transistors operate in a somewhat similar manner.



Basic Hartley Configuration

The common-emitter circuit is similar to an electron tube oscillator in that it requires a 180-degree phase shift from collector to base to produce positive (regenerative) feedback. Grounding the emitter tap (see illustration below for grounding points) produces the effect of inverting the windings and thus provides the desired 180-degree phase shift. The resonant frequency is determined by the tuning of the tank capacitor, *C, and is given by the formula:*

$$f = \frac{1}{2\pi \sqrt{(L_1 + L_2 + {}_2M)C}}$$



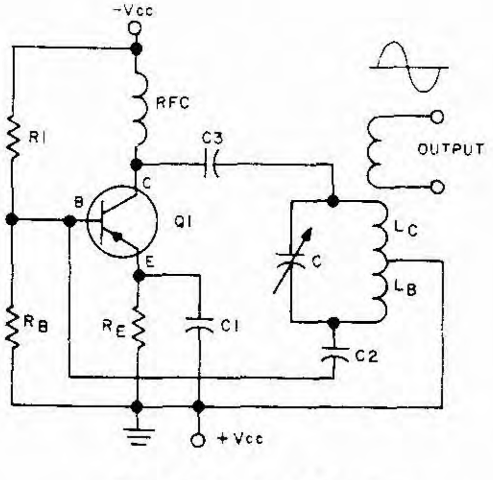
C E Hartley Oscillator Grounding Points

The figure shows three different arrangements of the common-emitter configuration for grounding the transistor elements. These circuits provide a convenient method for grounding the rotor of the tuning capacitor to eliminate hand-capacitance tuning effects and to obtain proper feedback phasing. Note that the three configurations in the illustration are all **common-emitter** arrangements and that the only difference from the basic schematic is the grounding point. In some texts, these configurations are referred to as **common base, common emitter,** and **common collector,** respectively. In all three grounding arrangements of the figure, the feedback is fed from collector to base, and the emitter is the common element.

The discussion under the Armstrong circuit concerning the relative merits of the various configurations and the transistor action are applicable to this oscillator. Operation of the L-C circuit is similar to that of the tickler coil electron tube oscillator circuit discussed at the beginning of this Section. In fact, the operation of the Hartley circuit can be considered exactly the same as that of the Armstrong circuit, with the tickler coil being an integral portion of the tuned tank circuit. The frequency stability of the Hartley oscillator is slightly better than that of the Armstrong oscillator because the tank tuning capacitor tunes the entire coil and feedback loop, and a high C-to-L ratio provides effective capacitance swamping.

Shunt-Fed Hartley. The shunt-fed Hartley oscillator using the common-emitter configuration is shown in the following figure. One voltage supply is used, with fixed base bias being supplied by voltage-dividing resistors R1 and R_B (see Section 3, paragraph 3.4.1, for explanation of biasing). Emitter swamping resistor R_E, bypassed by C1, is used for temperature stabilization.

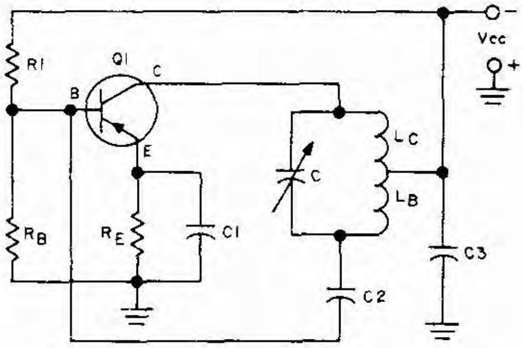
The collector is shunt fed through radio-frequency choke RFC, with C3 serving as the d-c blocking and r-f coupling capacitor to keep the tank coil from shorting the collector. Similarly, C2 serves as the base blocking and coupling capacitor to prevent shorting of the base to ground through the tank inductor.



Shunt-Fed Hartley CE Oscillator

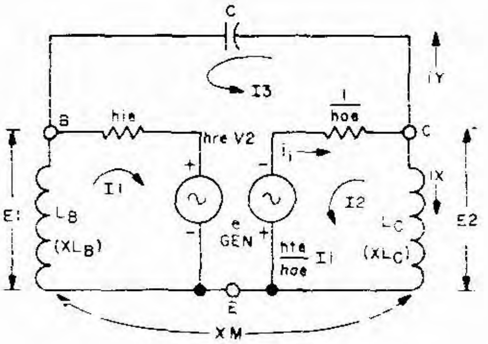
When the shunt-fed circuit is energized, the initial bias is determined by R1 and R_B, and oscillation is built up by feedback supplied from the collector to the base through sections L_C and L_B of the tank inductor. Note that an a-c path exists from the emitter through the L_C portion of the tank and coupling capacitor C3 to the collector, and that a similar path exists through L_B and C2 to the base. As oscillation occurs, a degenerative bias is developed across R_E (if C1 is of the correct value) similar to that of the grid-leak-capacitor combination used in electron tube oscillators, and this bias places operation somewhere between Class A and Class C depending on the parts values. Usually the values of voltage divider R1 and R_B are chosen to provide Class A bias for easy starting, and the values of R_E and C1 are chosen to provide Class B or C bias for the desired efficiency of operation, with thermal stabilization. The output may be taken from a capacitor connected to the collector or from an inductor coupled to the tank.

Series-Fed Hartley. The series-fed Hartley oscillator is shown below. The base circuit is voltage-divider biased and emitter stabilized as in the shunt-fed version. The collector voltage is applied through the tap on the tank inductor, the voltage source being shunted for rf by C3. Operation of the series-fed circuit is identical to that of the shunt-fed circuit discussed previously. Since a d-c current flows through a portion of the tank circuit, the Q is lowered and the frequency stability is not as great as that of the shunt-fed circuit.



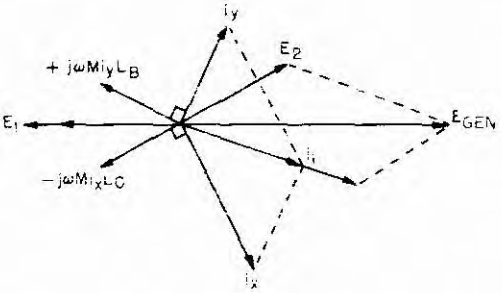
Series-Fed Hartley CE Oscillator

Detailed Analysis. Like the vacuum tube oscillator, the transistor oscillator can be converted to an equivalent circuit and analyzed mathematically to determine the conditions required for oscillation and the frequency of operation, using the h-parameters of the transistor. A typical common-emitter equivalent circuit for the Hartley oscillator is illustrated below. Since the mathematical analysis is complex and beyond the scope of this text, and exact only for low audio frequencies, the interested reader is referred to standard text books for this data.



Hartley Semiconductor Equivalent Circuit

The accompanying vector diagram may be more helpful to a better understanding of circuit operation, since it shows the voltage and current relationships. The common-emitter circuit is illustrated.



Hartley Vector Diagram

The voltage e_{gen} is used as a reference vector. Since the Hartley circuit operates slightly below resonance, the tank circuit appears resistive and inductive, causing i_1 to lag e_{gen}, and the voltage across the tank E_2 to lead by a small angle. Current i_y leads E_2 by some angle less than 90 degrees since that branch is largely capacitive. Current i_x lags E_2 by some angle less than 90 degrees, depending upon the Q of that branch. The voltage induced in the base coil $-j\omega M i_x L_C$ lags i_x by 90 degrees as indicated by its -j coefficient, while the positive component $+j\omega M i_y L_B$ leads i_y by 90 degrees. The base voltage, E_1, is the vector sum of the voltages induced in base coil L_B. Note that with higher values of circuit Q the voltages developed across the grid coil more closely approach in-phase quantities, and the angle between i_1 and E_2 also diminishes, thereby improving the oscillator stability.

FAILURE ANALYSIS.

No Output. Lack of oscillation may be due to a shorted or open-circuited transistor. Deterioration with age causing lack of gain may result under high-temperature conditions. Unlike vacuum tubes, however, transistors have operated for years without noticeable deterioration under proper operating conditions. Failure of the collector and base blocking capacitors will short-circuit the biasing arrangement through the tank coil and prevent operation. Open-circuit conditions of the biasing resistors may stop oscillation, though it is more likely that reduced output will result rather than no output. Where radio frequency chokes are used to keep rf out of the supply or bias circuits, failure of these components may shunt the rf to ground through power supply capacitors. A more likely condition is an open circuit in the RFC caused by poorly soldered connections. A shorted condition of the tuning capacitor will stop oscillation, and it cannot be detected by a continuity check unless the tank coil is disconnected. When trouble-shooting with test equipment containing line filter capacitors, care should be exercised to prevent application of excessive voltage to the transistor by using a common ground on both the transistor and test chassis. Use high-impedance meters to avoid placing a d-c shunt or return path in the circuit and causing improper current flow or voltage distribution.

Reduced or Unstable Output. Instability should be resolved into one of two types — frequency or amplitude. Frequency instability will most likely result from poor tank circuit connections, poor insulation between turns, or changes in L and C values. Also, changes in the supply voltage will produce changes in frequency because of changes in the operating point and changes in the internal capacitance of the transistor with different applied voltages. Excessive bias will probably cause a reduction in output and will most likely be produced by an increase in value of the bias resistor or opening of the bias bypass capacitors with the consequent production of degeneration. Temperature changes are usually evidenced by increased current in the collector circuit and can be caused by a shorted emitter swamping resistor.

Incorrect Output Frequency. Normally, a small change in output frequency can be compensated for by realigning or readjusting the variable component of the L-C resonant tank circuit, assuming that all parts of the circuit are known to be satisfactory. A change of transistor parameters will also affect frequency; for example, increased collector voltages will reduce the collector-base capacitance, and increased emitter current will increase the collector-base capacitance, but these effects are not equal and therefore do not compensate each other. Reflected load reactance can cause a change of frequency depending on the tightness of coupling between the oscillator and the load. Change in circuit [illegible] of the tank inductor will also cause frequency changes. A comparison of operational [illegible] against operational standards will generally indicate the area of fault. For example, frequency changes that vary with power supply voltage fluctuations indicate that supply regulation is necessary and trouble is not in the equipment. Major frequency changes [illegible] involve the transistor element [illegible] with the tank circuit, since they constitute the major frequency-determining portion of the circuit.

COLPITTS OSCILLATOR.

APPLICATION.

The Colpitts oscillator is used to produce a sine-wave output of constant amplitude and fairly constant frequency within the r-f range and sometimes within the audio range. The circuit is generally used as a local oscillator in receivers, as a signal source in signal generators, as a variable-frequency oscillator for general use over the low-, medium-, and high-frequency ranges.

CHARACTERISTICS.

Uses an L-C parallel tuned circuit to establish frequency of operation

Features inductive tuning rather than capacitive.

Feedback is obtained through a capacitance-type voltage divider.

Operates Class C where waveform linearity is not important, and Class A where linearity of waveform is important.

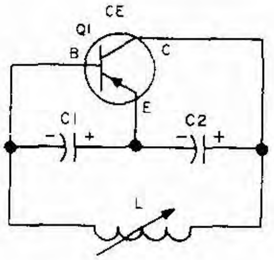
Frequency stability is good (considered better than that of the Hartley at the lower and medium frequencies).

Oscillates easily at high frequencies, where inductive feedback types have difficulty securing sufficient feedback.

CIRCUIT ANALYSIS.

General. A sine-wave output may be obtained from a transistor oscillator using a tuned L-C circuit, particularly when the transistor is operating in the linear region of its transfer characteristics. The L-C (tank) circuit determines the frequency of oscillation. The tank circuit consists of two series-connected capacitors in parallel with the inductor. The two series capacitors will act as a capacitance voltage divider across the inductor (in addition to tuning the coil to resonance) with the larger voltage appearing across the smaller capacitor. The capacitance feedback voltage divider may be connected so as to provide either an in-phase voltage or an out-of-phase voltage, to suit the various transistor configurations used. The reactance ratio of the two series capacitors is usually chosen to match the input-output resistances of the transistor used. Mathematical analysis predicts a larger ratio between them than is employed in electron tube practice. The large ratio between capacitor values makes it practical to employ fixed capacitors and tune the inductance over the desired frequency range. The use of capacitance (separate or ganged) tuning over small ranges is occasionally encountered. The frequency of operation is the same as the resonant frequency of the tank circuit, which is given by: $f = \dfrac{1}{2\pi\sqrt{L\dfrac{C_1C_2}{C_1+C_2}}}$

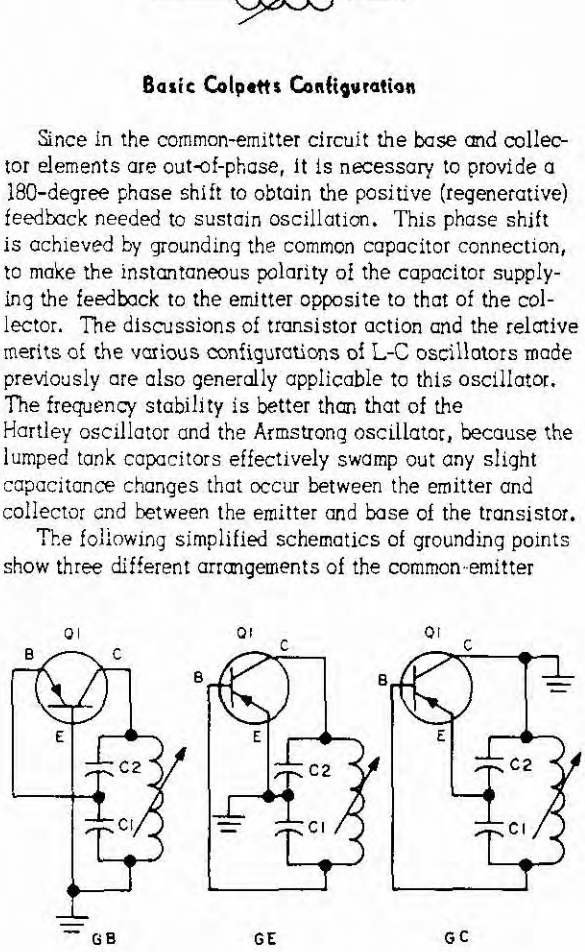
Circuit Operation. The basic configuration of the Colpitts transistor oscillator is shown in the figure below. For simplicity, bias and collector feed arrangements are not shown, but are discussed later. It is assumed that forward bias is initially applied to the emitter-base junction and that reverse bias is applied to the collector-base junction. Only junction transistors are considered since point-contact transistors operate somewhat differently.



Basic Colpetts Configuration

Since in the common-emitter circuit the base and collector elements are out-of-phase, it is necessary to provide a 180-degree phase shift to obtain the positive (regenerative) feedback needed to sustain oscillation. This phase shift is achieved by grounding the common capacitor connection, to make the instantaneous polarity of the capacitor supplying the feedback to the emitter opposite to that of the collector. The discussions of transistor action and the relative merits of the various configurations of L-C oscillators made previously are also generally applicable to this oscillator. The frequency stability is better than that of the Hartley oscillator and the Armstrong oscillator, because the lumped tank capacitors effectively swamp out any slight capacitance changes that occur between the emitter and collector and between the emitter and base of the transistor.

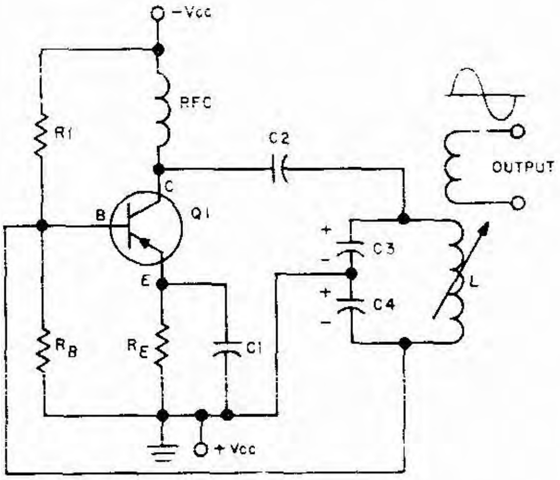
The following simplified schematics of grounding points show three different arrangements of the common-emitter configuration for grounding the transistor elements. These circuits provide a convenient method of grounding the tuning-capacitor rotor to eliminate hand-capacitance tuning effects



CE Colpitts Oscillator Grounding Points

and to achieve the proper phasing for the feedback. Note that the three grounding point configurations are all **common-emitter** arrangements and that the only difference from the basic oscillator is the grounding point. In some texts these *configurations are referred to as* **common base, common emitter,** and **common collector,** respectively.

Shunt-Fed Colpitts. The shunt-fed Colpitts oscillator arranged in the common-emitter transistor configuration is shown schematically in the accompanying illustration. One voltage supply is used, with fixed bias being supplied by voltage-dividing resistors R1 and R_B (see Section 3, paragraph 3.4.1, for an explanation of biasing). Emitter swamping resistor R_E, bypassed by C1, is used for temperature stabilization.

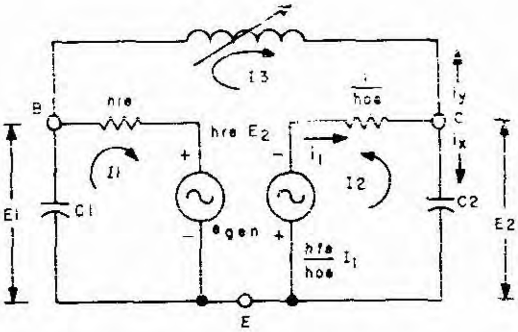


Shunt-Fed Colpitts GE Oscillator

The collector is shunt-fed through radio-frequency choke *RFC to keep the rf out of the supply circuit,* with capacitor C2 acting as a coupling capacitor for the tank circuit. Capacitor C2 also serves as a blocking capacitor, preventing the d-c supply from entering the tank circuit and shunting (actually shorting) R1 through the tank inductance.

When the circuit is energized, the initial bias is determined by R1 and R_H, and oscillation is built up by feedback from the tank circuit through divider capacitor C4. Since the divider is grounded at the common connection, opposite polarities exist across capacitors C3 and C4 in respect to ground, with the voltages across these capacitors being determined by *the capacitive reactance ratio.* Thus a voltage that is out-of-phase with the collector is applied between the emitter and base to supply a positive feedback and sustain oscillation. The combination of R_E and C1 provides an emitter swamping resistor for thermal stabilization, with sufficient capacitance as a bypass to permit degenerative voltage buildup to occur and bias the transistor into the Class B or C operating region after a few initial oscillations. The values of R1 and R_H are usually chosen to provide Class A bias for easy starting. The amplitude of oscillation is essentially regulated by driving the transistor to saturation on one portion of the cycle and to cutoff on the other portion. Although such action normally would cause abrupt changes and distort the waveform, the tank circuit effectively smoothes out the pulsations in Class C operation to provide oscillations that are essentially sine waves. In the linear Class A region, the circuit provides satisfactory sine wave output for test equipment use. The oscillator output is normally taken inductively by a coil coupled to the tank inductor, although a capacitive tap may be used if necessary.

Detailed Analysis. A typical common-emitter equivalent circuit for the Colpitts oscillator is illustrated below.



Colpitts Semiconductor Equivalent Circuit

As in the Hartley circuit, the mathematical analysis of the *equivalent circuit is too involved* for this text, but can be found in standard texts. With both the Hartley and Colpitts equivalent circuits it is possible, with slight modifications, to represent most of the other oscillator circuits now in use. Thus, the interested reader will find these two circuits most useful.

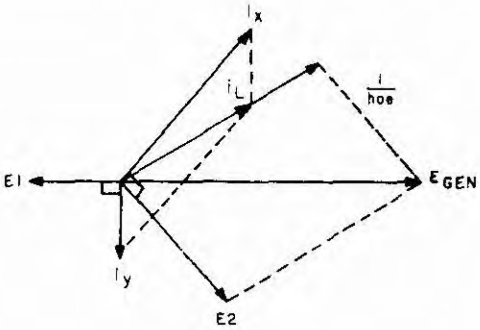
One interesting fact develops from the Colpitts analysis; that is, the starting conditions are found to be:

$$\frac{h_{fe}}{\Delta h_e} = \frac{C_1}{C_2}$$

Where $\Delta h_e = h_{ie} h_{oe} - h_{re} h_{fe}$.

Thus, when h_{fe} is large and Δh_e is small, capacitors C_1 and C_2 will have large differences of values (from 10 to 100 times), which is not the case with the electron tube counterpart.

The accompanying vector diagram shows the current and voltage relationships for the Colpitts oscillator equivalent circuit above.



Colpitts Vector Diagram

Note that the Colpitts is exactly the inverse of the Hartley. The reference vector is e_{gen}, with the induced base voltage, E1, directed 180 degrees out of phase. Since the Colpitts oscillator operates above the tank frequency, the tank circuit appears slightly capacitive. Thus i_1 leads e_{gen} by a small angle, while E_2 lags. Current i_x through capacitor C_2 leads E_2 by 90 degrees. Current i_y through the branch containing the tank inductance and C_1 is primarily inductive and lags E_2 by an angle less than 90 degrees depending largely upon the Q of the tank inductance. Since the induced base voltage, E_1, appears across capacitor C_1, it lags i_y by 90 degrees, thereby satisfying the conditions for oscillation. It can be seen that with higher values of circuit Q the phase difference between i_1 and E_2 will diminish.

FAILURE ANALYSIS.

No Output. Although oscillation may fail because of a shorted or open-circuited transistor, deterioration with age similar to the decrease of emission in electron tubes does not normally occur. High-temperature operation may cause premature failure or drop-off in performance of the transistor; however, this can normally be obviated by proper ventilation of the equipment. Reflected reactance from heavy loading due to tight coupling may occur and prevent oscillation, but it should not occur with proper design. Failure of collector blocking capacitor C2 will place a d-c short circuit across the collector and base of transistor Q1 through the tank inductance and stop oscillation; it may also ruin the emitter-base junction. Changes in value of the bias resistors will probably reduce the output rather than prevent oscillation completely. Shorting of either of the tuning capacitors will prevent oscillation. In making continuity checks of these tuning capacitors with an ohmmeter, it is important to connect the ohmmeter with the correct polarity because, since the emitter-base junction is in parallel, use of the incorrect polarity would apply a forward bias and possibly damage the transistor.

Reduced or Unstable Output. As in the oscillators discussed previously, it is important to determine whether the instability is associated with frequency or amplitude. If amplitude instability is caused by temperature effects, the bias divider and emitter stabilizing resistors are probably at fault. Reduced output will most likely be due to excessive biasing caused by changes in value of the bias resistors, or to excessive degeneration caused by an open capacitor (or a reduced value of capacitance) in the emitter bypass circuit. A leaky collector coupling capacitor will cause a change in bias by reflecting, through the tank inductance, a parallel resistance between the base and collector elements of the transistor. Frequency instability will indicate that the tank circuit or supply voltage is at fault. Although this circuit provides capacitance swamping of the elements to minimize transistor capacitance changes with supply voltage changes, it should be noted that a varying supply voltage also changes the transistor operating point and may therefore affect the frequency to some extent. As in the other oscillators, poor mechanical connections and shorted turns or deteriorated insulation in the tank circuit may cause unstable operation.

Incorrect Output Frequency. As in the other oscillators discussed previously, small changes in frequency can be corrected by adjusting the tuning capacitor, assuming that all parts are in good condition. Variations of frequency with supply voltage changes indicate the need for external supply regulation. Major frequency changes will most likely indicate trouble in the tank circuit since it is the primary frequency-determining circuit. Although a change in transistor parameters may change the frequency to some extent, a major parameter change will most likely result in reduced output or unstable operation. Too tight coupling of the load is indicated if the frequency changes noticeably with changes in loading (a slight change is normal).

CLAPP OSCILLATOR.

APPLICATION.

The Clapp oscillator is used to produce a sine-wave output of constant amplitude and frequency within the r-f range. The circuit is generally used as a signal source in signal generators and as a variable-frequency oscillator for general use over the high- and very-high-frequency ranges.

CHARACTERISTICS.

Uses a series-resonant L-C circuit to determine the frequency of oscillation.

Feedback is obtained through a capacitance-type voltage divider.

Frequency of operation is relatively independent of transistor parameters.

Operates Class C where waveform linearity is not important, and Class A where a linear waveform is required.

Frequency stability is good (better than that of the Colpitts oscillator).

CIRCUIT ANALYSIS.

General. The Clapp circuit is considered to be a variation of the Colpitts circuit discussed previously. It uses the stabilizing effect of a series-resonant tuned tank

The collector is shunt-fed through radio-frequency choke RFC to keep rf out of the power supply and avoid power supply shunting effects. Note that series feed cannot be used with the Clapp circuit because tuning capacitor C is in series with tank inductance. Thus a blocking capacitor in either the base or the collector lead is not required for this circuit. When the circuit is energized, Class A bias is supplied for starting by the bias voltage divider consisting of R1 and R_B, and feedback to the base is applied through feedback divider capacitor C3. Grounding the common connection between the feedback divider capacitors provides the 180-degree phase reversal necessary to provide positive feedback from collector to base. The emitter resistor and capacitor combination acts in the same manner as an electron-tube grid-leak to provide essentially Class C bias after a few oscillations. R_E also acts as a d-c thermal stabilizer for collector-current temperature variations. In a properly designed circuit, the proper feedback voltage divider capacitor ratio for stable feedback with the transistor used may be selected, independently of tank circuit design considerations, to provide oscillation over the desired range of operation. The output may be taken capacitively or by inductance coupling to the tuned tank circuit. With loose inductive coupling, the output obtained is very stable and relatively free of the detuning effects of loading, since the tank circuit is loosely coupled to the feedback loop and relatively independent of any change in transistor parameters.

FAILURE ANALYSIS.

No Output. Since no blocking capacitors are employed and since the tank circuit is essentially unaffected by changes in transistor parameters, lack of output is usually limited to lack of feedback or improper bias voltages. An open or shorted transistor or an open or shorted feedback capacitor will stop oscillation. A shorted tuning capacitor C will also stop oscillation because it will permit the collector voltage on tank coil L to be shorted to the base. Poorly soldered connections may produce circuit losses sufficient to prevent oscillation, while changes in value or open bias resistors will probably reduce rather than stop oscillation completely.

Reduced or Unstable Output. Reduced output would most likely indicate a change in bias resistor values or a defective emitter bypass capacitor. An open or partially open emitter bypass would produce excessive degeneration and perhaps complete cutoff, though the latter is very unlikely, whereas a shorted emitter bypass would probably be indicated by thermal instability. Frequency instability would be directly traceable to the tank circuit components and connections. An unstable output amplitude could be caused by an intermittent open or short in the bias circuitry or by a poor connection to the transistor or supply voltage. Lack of supply voltage regulation would normally be indicated by amplitude changes rather than by frequency changes.

Incorrect Output Frequency. Changes in distributed circuit capacitance or reflected load reactance will affect the frequency of operation to some extent, but can normally be corrected by resetting or adjusting the tuning capacitor. Large frequency changes will be produced by changes of tank circuit inductance caused by shorted turns or poorly soldered connections. At first glance it might appear that a shorted tuning capacitor would cause the frequency of oscillation to be determined by the inductance of the tank circuit alone (plus some distributed capacitance); however, for this condition oscillation could not occur because the shorted capacitor would short the collector voltage through the tank coil L to the base.

R-C OSCILLATORS

Since semiconductor R-C oscillators are directly analogous to electron tube R-C oscillators, all of the information in the discussion of electron tube R-C oscillators is generally applicable. The phase-shift oscillator is normally used in the common-emitter configuration, but with the proper phase-shifting networks it can be used in other configurations. The Wien bridge oscillator is shown and discussed in the common-emitter configuration, but with proper circuit arrangements it can also be used in other configurations.

Non-sinusoidal semiconductor R-C oscillators are considered as relaxation oscillators and are discussed later in Sections 8 and 9 of this technical manual.

R-C PHASE-SHIFT OSCILLATOR.

APPLICATION.

The R-C phase-shift oscillator is used to produce a sine-wave output of relatively constant amplitude and frequency.

CHARACTERISTICS.

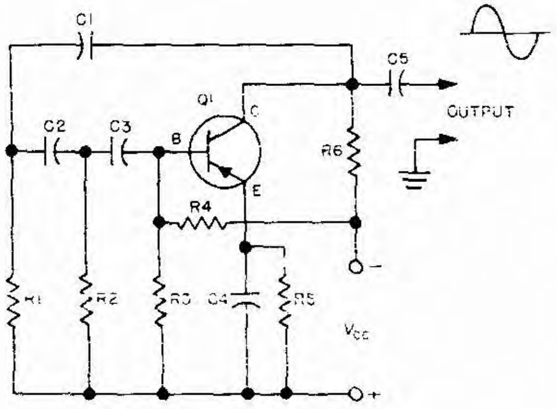
Utilizes R-C network to provide feedback.

Eliminates need for inductors in resonant circuit.

Output frequency is usually fixed within the range of 15 cycles per second to 200 kilocycles per second, although the circuit can be arranged to provide an output which can be varied over a wide range of frequencies by changing R or C.

CIRCUIT ANALYSIS.

General. A sine-wave output may be obtained from an oscillator using an R-C network in lieu of an L-C network. The R-C network determines the frequency of oscillation and provides regenerative feedback from the output circuit to the input. In the common-emitter circuit configuration for transistors, the signal between the base and collector is shifted in phase by 180 degrees; therefore, an additional 180-degree phase shift is necessary to provide the correct feedback signal when returned from the output circuit to the input in order to sustain oscillations. The feedback signal of proper phase relationship is obtained using a network consisting of three equal R-C sections; each section produces a 60-degree phase shift at the desired frequency of operation. In the accompanying circuit schematic, the three R-C sections are designated as C1, R1; C2, R2; and C3, R3.



R-C Phase-Shift Oscillator Using PNP Transistor

Phase-Shift Network. The current in a series circuit comprised of resistance and capacitance is determined by the applied voltage divided by the series impedance of the components $(I = \frac{E}{Z})$. Since a series R-C circuit exhibits capacitive reactance, the current leads the applied voltage by a specific phase angle. The phase angle is determined by the relationship of resistance and capacitance. The voltage drop produced across the resistance is determined by the current through the resistance and therefore leads the applied voltage by a given phase angle.

For a vector analysis of the phase-shift network, refer to the discussion given for the electron tube R-C phase-shift oscillator.

At least three R-C sections are required to provide the 180-degree phase shift needed to produce a positive (in-phase) feedback voltage. The values of resistance and capacitance for a three-section network are chosen so that each section of the network will provide a 60-degree phase shift at the desired frequency.

The R-C phase-shift oscillator is normally fixed in frequency, but the output frequency can be made variable over a range of frequencies by providing ganged variable capacitors or resistors in the phase-shift network. An increase in the value of either R or C will produce a decrease in the output frequency; conversely, a decrease in the value of either R or C will produce an increase in the output frequency.

By increasing the number of phase-shift sections comprising the network, the losses of the total network can be decreased; this means that the additional sections will each be required to have a lesser degree of phase shift per section so that the over-all phase shift of the network remains at 180 degrees for the desired frequency of oscillation. Since the loss per section is decreased as the amount of phase shift (per section) is reduced, many oscillators employ networks consisting of four, five, and six sections; assuming that the values of R and C are equal for each section, the individual sections are designed to produce phase shifts per section of 45, 36, and 30 degrees, respectively.

Circuit Operation. The accompanying circuit schematic illustrates a PNP transistor in a common-emitter configuration. Resistors R1, R2, and R3 and capacitors C1, C2, and C3 comprise the feedback and phase-shift network. Resistors R3 and R4 establish base bias for the PNP transistor. Resistor R5 is the emitter swamping resistor, which prevents large increases in emitter current and causes the variation of emitter-base junction resistance to be a small percentage of the total emitter circuit resistance. Capacitor C4 bypasses the emitter swamping resistor, R5, and effectively places the emitter at signal ground potential. Resistor R6 is the collector load resistance across which the output signal is developed. Capacitor C5 is the output coupling capacitor.

Oscillations are started by any random noise in the power source or the transistor when input power is first applied to the circuit. A change in the base current results in an amplified change in collector current which is shifted in phase 180 degrees. The output signal developed across the the collector load resistance, R6, is returned to the transistor base as an input signal inverted 180 degrees by the action of the feedback and phase-shift network, making the circuit regenerative.

The output waveform is essentially a sine wave; the output frequency is a fixed frequency. When fixed values of resistance and capacitance are used for the feedback network, the 180-degree phase shift occurs at only one frequency. At all other frequencies, the capacitive reactance either increases or decreases, causing a variation in phase relationship; thus, the feedback is no longer in phase and is therefore degenerative. Note, however, that if the components comprising the phase-shift network should change value, the frequency of oscillation will change to the frequency at which a phase shift of 180 degrees will occur to sustain oscillations.

FAILURE ANALYSIS.

No Output. All input voltages should be measured with an electronic voltmeter to determine whether the input voltage is present and whether the biasing voltages applied to the transistor are within correct operating limits. If it has been established that all voltages are correct, it is likely that circuit losses are present in the phase-shift network or that degeneration in the emitter circuit is preventing oscillation.

Reduced or Distorted Output. All voltages should be measured with an electronic voltmeter to determine whether the input voltage is present and whether the biasing voltages applied to the transistor are within correct operating limits. A change in base bias or load impedance or degeneration in the emitter circuit will cause reduced output and possible distortion; however, the output frequency will remain substantially correct.

Incorrect Output Frequency. The correct operating frequency of the R-C oscillator is determined by the circuit constants comprising the phase-shift network; therefore, if the output frequency is incorrect, it is likely that the phase-shift network components have changed value in such a manner as to permit a 180-degree phase shift to occur and sustain oscillations at the incorrect output frequency.

WIEN-BRIDGE OSCILLATOR.

APPLICATION.

The Wien-bridge oscillator is used as a variable-frequency oscillator in test and laboratory equipment to supply a sinusoidal output waveform, with practically constant amplitude and exceptional stability, over the audio-frequency and low-radio frequency ranges.

CHARACTERISTICS.

Uses a bridge circuit to control positive feedback and produce oscillation at the R-C frequency.

Operates as a Class A linear amplifier.

Employs negative feedback to control the output amplitude and to provide improved linearity.

Frequency stability is excellent.

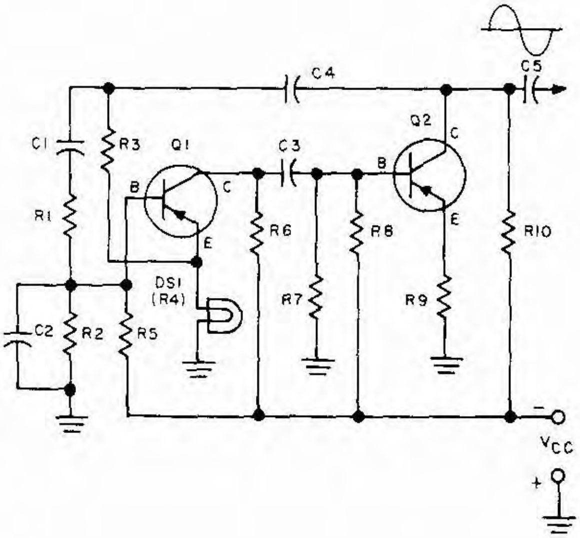
Operates over a wide frequency range (10 cps to 200 kc).

CIRCUIT ANALYSIS.

General. The Wien-bridge circuit consists of a resistive element and a reactive element arranged in a bridge. The resistive element supplies an inverse (negative) feedback voltage to the emitter, and the reactive network supplies a regenerative (positive) feedback voltage to the base of the same transistor. When the bridge is balanced (at the operating frequency), the positive feedback is slightly greater than the negative feedback and oscillation occurs. The operating frequency is determined by the R-C networks employed in the reactive bridge arm. To obtain the feedback, two transistor amplifiers are used, each producing a 180-degree phase shift, or the total 360-degree phase shift necessary for positive feedback to the base circuit. The negative feedback is obtained by inserting a portion of the feedback into the emitter circuit of the input transistor to produce an out-of-phase or negative feedback. The operation of the bridge circuit and the development of the positive and negative feedback voltages are the same as described for the electron tube counterpart.

Circuit Operation. The semiconductor Wien-bridge oscillator is shown schematically in the figure below. Except for bias arrangement, it is practically identical to the electron-tube Wien-bridge oscillator.

Voltage divider base bias is used, with R2 and R5 biasing Q1, and R7 and R8 biasing Q2. Temperature stabilization is provided by series emitter (swamping) resistors R4 and R9 (see Section 3, paragraph 3.4, for an explanation of this action).



Wien Bridge Oscillator Using PNP Transistor

Resistors R3 and R4 form the resistive arm of the bridge across which the output of Q2 is applied; a portion of this voltage appears across R4 (DS-1) as a negative feedback, being in-phase with the emitter voltage. Resistor R4 (or DS-1 or RT-1) is either an incandescent lamp or a thermistor with a positive temperature coefficient. When a lamp is used, it is operated at a current which produces a temperature-sensitive point (where resistance varies rapidly with temperature); when a thermistor is used, it is selected to have the desired temperature-current characteristic. In either case, the bias developed across this resistor is in opposition to the normal (forward) bias, and produces a degenerative effect. The feedback voltage is of the same polarity as the degenerative bias and increases the degeneration. However, since the output of the voltage divider is not frequency-sensitive, the feedback voltage is always constant regardless of the frequency of operation. At frequencies other than the frequency of operation the degenerative feedback predominates and prevents oscillation.
At the frequency of operation, which is controlled by the bridge reactive arms consisting of R1, C1, and R2, C2 the positive feedback is a maximum. This in-phase feedback signal is applied to the base and is slightly greater than the negative feedback at the balance point or frequency of operation which is given by: $f_o = \frac{1}{2\pi R_1 C_1}$ where R1 is equal to R2, C2 is equal to C1, and R3 is slightly greater than twice R4.

The amplified output of Q1 is developed across collector resistor R6, and it is applied by capacitor C3 and base resistor R7 which form a conventional resistance-coupling network (designed for minimum phase shift), to the input (base) of transistor Q2. The signal is further amplified by Q2, and the voltage developed across collector resistor R10 is supplied as an output through capacitor C5, and, as a positive feedback through C4 to the bridge network. Note that the Q2 emitter resistor, R9, is not bypassed and that the circuit of Q2 is therefore degenerative. Note also that R10, C4, and C5 are designed to provide a minimum amount of phase shift. Thus, with a highly degenerative two-stage amplifier and Class A bias, the output signal is essentially a pure sine wave. Since the coupling networks are arranged for minimum phase shift, the phase shift required for regeneration is obtained from the inverting action of the common-emitter configuration, with each amplifier stage providing a 180-degree shift. The feedback input signal is thus shifted 360 degrees in phase to produce a regenerative (positive) feedback independent of circuit parameters. The reactive portion of the bridge (C1, C2 and R1, R2) determines the frequency at which maximum amplification (and feedback) occurs. Resistor R4 (DS-1) controls the degenerative feedback and also the output amplitude; that is, when the input signal to Q1 increases, more emitter current flows through R4 (DS-1), and the lamp or thermistor resistance increases, producing a degenerative voltage which opposes the input signal, and tends to restore it to the original operating value by reducing the amount of amplification through the feedback loop. This oscillator then, with amplitude stability, temperature stabilization, and degenerative feedback to control the waveform, and with an R-C frequency-selective circuit to determine the frequency of operation provides a signal of excellent stability and pure waveshape for test applications. In order to control the frequency, either resistors R1 and R2 or capacitors C1 and C2 are changed in value or made variable. With a two-gang variable capacitor and a selector switch (or fixed and variable resistors), a continuous range of frequencies over a number of bands may be obtained.

FAILURE ANALYSIS.

No Output. If the feedback loop or the coupling network between stages is open because of a defective (open) component or if the supply voltage is too low the circuit will not oscillate. Also, if the coupling capacitors are short circuited, the circuit will not oscillate because the bias circuits will apply an abnormal bias to Q1 and Q2. For example, with C4 shorted the emitter of Q1 will be negatively biased and stop oscillation; with C3 shorted the bias will be provided by the parallel combination of R6 and R8 in series with R7 and most likely will be too large to permit operation. If the R4 bridge arm opens, the emitter will be disconnected from the circuit and the transistor will not operate. A resistance analysis and continuity check of the circuit with a high-impedance voltohmmeter should quickly determine the defective component.

Reduced or Unstable Output. An intermittent open or short in any of the bridge reactive network parts will change the frequency of operation and cause instability. Poor contacts in band switches will also cause instability. When the output is reduced, it is logical to suspect that a defective component in the positive feedback loop is permitting the degenerative action to predominate. Since some positive feedback is required to maintain even a weak oscillation, the reduced output would most likely be caused by increased series resistance in the positive feedback loop, because an open in this loop would stop oscillation. Failure of the transistors with age or reduced output because of lack of emission as in an electron tube would be the least likely cause of reduced output. Normal aging of the transistor will have little effect on oscillation since operation is over only a small range of amplitude and only small currents are involved. In the event of damage to the transistor, by the application of improper bias or by the application of ohmmeter voltages and polarities that exceed the transistor rating (through poor testing techniques) reduced or no output will occur, but this type of trouble is due to factors external to the circuit and normally should not happen. The supply voltage should be checked for the rated output voltage because a low supply voltage could readily affect the oscillator output.

Incorrect Frequency. Where the frequency of operation differs from the original calibration, the cause might be the aging of circuit parts such as changes in value of R and C in the reactive arm of the bridge or possibly poor switch contacts. Any large change of frequency which cannot be compensated for by retrimming or recalibration is most likely due to defective parts in the frequency arm of the bridge (C1, C2, R1, R2). If the frequency change is linear, the resistive parts should be suspected; if it is nonlinear, the capacitive parts should be suspected. The circuits of Q1 and Q2 would not effect any frequency changes.

ELECTROMECHANICAL OSCILLATORS.

The discussion of electron-tube electromechanical oscillators is also generally applicable to semiconductor electromechanical oscillators. While the magnetostriction type of electromechanical oscillator can be used with semiconductors, at the present state of the art it has not found much application; therefore, the discussion in this section is limited to quartz crystal-controlled semiconductor oscillators. Although the quartz crystal and the semiconductor (transistor) are both solid-state devices, there is no direct relationship so far as frequency stability or piezoelectric effects are concerned. The frequency stability of the quartz crystal is derived from its basic mechanical vibration, and due to the piezoelectric effect, we have a means for controlling the vibration, and hence for controlling the electronic circuit. The quartz crystal is cut to enhance the mechanical vibrating properties at a specific frequency; the transistor is cut to a convenient, economical size, and has electrodes attached so that it cannot easily oscillate mechanically. Because the semiconductor is a partial conductor, it exhibits very little, if any, piezoelectric effect. Thus, it has no inherent frequency stability even though it is a solid-state device. Actually, the basic semiconductor is less frequency stable than an electron tube, mostly because of its inherent ability to act as a variable capacitor with a change of collector voltage. In an LC oscillator the **tank circuit** is the frequency-determining and stabilizing element, but in the crystal oscillator, it is the **crystal** itself, because the crystal operates essentially as a parallel tuned tank or series tuned tank depending on the mode of operation. Therefore, whether semiconductors or electron tubes are used, the basic principles of operation of the resulting electromechanical oscillators are identical.

The chief differences in operation are the effects on feedback and the circuitry used for the effective feedback control.

Like the self-excited semiconductor oscillator, the crystal-controlled semiconductor oscillator also has circuit configurations similar to those in the electron-tube field, but none so well known by name as the Miller and Pierce circuits. Therefore, the circuit discussions are identified primarily from a functional standpoint rather than by name. By the principle of **duality**, most of the electron-tube circuit configurations have duals in the semiconductor field. Since there are numerous circuit variations now in use and the state of the art is such that changes occur constantly, the circuits have been classified into three arbitrary groups and a circuit typical of each group will be discussed.

The first group, known as the **transformer-coupled group,** includes those oscillators using mutually coupled separate coils to provide feedback. The oscillators in this group have the advantage of extreme flexibility. They can be used in either CB, CE, or CC configurations, since polarities and impedances can be completely controlled by the number of turns and directions of the windings. The second group uses a capacitive voltage divider and is called the **Colpitts-type crystal oscillator.** The third group is the **overtone group,** which generally uses a tuned tank with a tapped coil in a Hartley type feedback arrangement operating at a desired harmonic or overtone. In any of these circuits, series or parallel resonance of the crystal may be employed. However, since the transistor is a low-impedance device, operating with relatively low voltage and high current, it conveniently lends itself to the use of series mode crystal operation, using only one stage instead of two stages as is necessary in the electron-tube circuit.

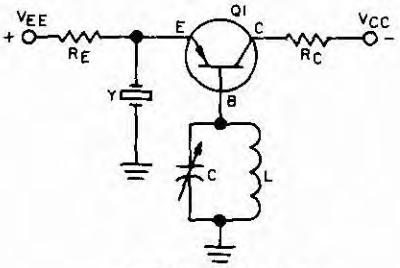
Because the transistor is basically a low-power device, it minimizes problems of heating and over excitation, which often cause crystal shattering in the power-tube oscillator. Thus, frequency changes due to thermal effects within the crystal are usually negligible, and ambient temperature changes are more important. For extreme stability, temperature compensation is necessary, particularly since the transistor itself is temperature sensitive and generally requires compensation. At normal room temperatures (or lower), and with average low-temperature or zero-temperature coefficient crystals, the transistor crystal oscillator is stable enough for average use without compensation. At higher temperatures, compensation of the transistor, if not the crystal, is necessary in most cases.

D-C stabilization (biasing) methods as discussed in Section 3 of this handbook are used in crystal oscillators, as well as self-excited oscillators, to insure that variations of emitter and collector voltages and currents do not cause parameter changes. The use of this form of stabilization generally results in more power being consumed in the biasing circuits than in the basic oscillator.

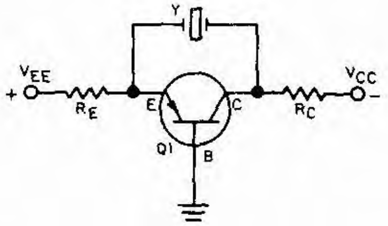
In considering output requirements, we find that the load is generally in shunt with the crystal or the tuned tank circuit; as a result, increased power output usually affects the frequency stability by degrading the Q of the resonator or increasing the effective coupling impedance between crystal and feedback circuit. Or, as in self-excited oscillators, the less the output required, the more stable the frequency, and the less load changes affect the circuit. For all ordinary purposes, the good mechanical stability of the crystal resonator makes it almost free from the effects of load changes, particularly if the collector voltage is regulated.

Good crystal oscillator design requires the use of low-impedance coupling between the oscillator and resonator, the use of either resistance stabilization (in the form of series resistance in the emitter and collector circuits) or reactance stabilization, regulation of supply and bias voltages through the use of Zener diodes, and temperature control of both the transistor and the crystal.

In the following circuit discussions, the external feedback type of oscillator is discussed. However, it is possible to use the inherent negative resistance of a transistor to provide oscillation. In this case, a tuned or high-impedance circuit is employed in the base-emitter circuit, and the crystal provides a low-impedance (series) feedback connection resembling the Miller and Pierce electron-tube circuits, as shown in the accompanying illustration. These types of oscillators (primarily used with point-contact transistors), however, are dependent entirely upon the transistor parameters since the feedback is entirely within the transistor and varies with each one. Such circuits are considered undersirable, except for special applications; they have been mentioned only for general information and will not be discussed further.



EMITTER-BASE CRYSTAL



EMITTER-COLLECTOR CRYSTAL

Basic Negative-Resistance Type Oscillators

TICKER COIL FEEDBACK CRYSTAL OSCILLATOR.

APPLICATION.

This oscillator is used to provide an approximate sine-wave r-f output that is extremely stable under crystal control, and operable over the low-, medium-, and high-frequency r-f ranges. It is universally used where a transistor oscillator is required; typical applications are local oscillators in receivers and heterodyne converters and oscillators in test equipment.

CHARACTERISTICS.

Uses piezoelectric effect of a quartz crystal to control oscillator frequency.

Uses a feedback (tickler) coil to provide the proper phasing for oscillation and control of regeneration.

Usually has the primary coil tuned to the crystal fundamental frequency, with the *secondary (tickler) coil being* untuned. Not restricted to a particular configuration; may be *CE, CB, or CC as desired.*

Can operate on a fundamental, harmonic, or overtone *frequency if proper* tuned circuit and crystal are selected.

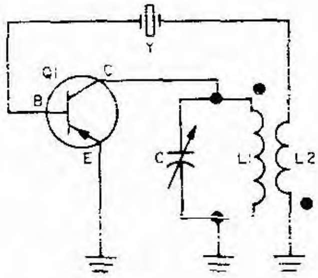
CIRCUIT ANALYSIS.

General. The semiconductor tickler coil crystal oscillator is basically a transformer-coupled oscillator. It may be either tuned or untuned, or partially tuned by stray and distributed capacitance. When the circuit is tuned, it is possible to operate the crystal on a fundamental frequency and tune the tank circuit to a harmonic, thus obtaining frequency multiplication, or to use overtone crystals for the same result. Like the electron-tube crystal oscillator, it may be crystal-stabilized or crystal-controlled. However, this circuit discussion will be restricted to the crystal-controlled type of oscillator. The ease of obtaining the feedback and controlling it makes *the tickler coil feedback* circuit popular. Since the polarity of each coil with respect to the other *is easily changed by reversing* the windings (at the time of manufacture), and since the coupling may be *made tight* by *spacing* the coils close together, or loose by spacing them apart, it is easy to obtain the proper amount *and polarity* (or phasing) of feedback. With the use of inductors to provide a low d-c resistance, the d-c resistance losses are minimized, and more output is obtained from the circuit with better efficiency. Since the transistor requires a certain amount of stabilization against bias and temperature changes, it is usually necessary to add stabilization resistors or reactances.

The use of a crystal operating in the series-resonant mode is more common with transistor oscillators because the crystal serves as a convenient means of permitting feedback at the resonant frequency by virtue of its low impedance series resonant circuit, but offers a high impedance to feedback at all other frequencies. When placed in series with the feedback loop, the crystal effectively controls the feedback. Use of the parallel-resonant mode is not obviated, however, *since sufficient flexibility* exists in the placement of the crystal in either the collector, base, or emitter circuit to match circuit conditions. For example, since the common-base circuit has a high output impedance, the crystal could be placed in the collector-to-base (or ground) loop and operated effectively as a parallel resonator. Actually, the possibility of three different basic circuit configurations, together with placement of the crystal in either the input or output circuits, poses a problem in the circuit discussion because of the numerous circuit variations that can be formed. The discussion will, therefore, be limited to a typical circuit considered most likely to represent present day use. It is assumed that placement of the crystal or choice of circuit configuration does not materially change the basic stability, but that it does affect the power output and efficiency of operation to *some extent.*

Since the crystal *power oscillator practically does not* exist in the semiconductor field (most outputs are on the order of *milliwatts*), the crystal is not restricted in its placement by power requirements or heat dissipation, but it *may be placed* so as to produce the best performance.

Circuit Operation. The basic common-emitter circuit configuration for the tickler coil crystal oscillator is shown in the accompanying illustration. For the sake of simplicity, bias and collector supply voltages are not shown and will be discussed later. It is assumed that forward bias is applied to the emitter-base junction and that reverse bias is applied to the collector junction. The discussion is based upon the use of PNP junction transistors, although the basic principles also apply to point-contact transistors. From the discussion of basic transistor operation in Section 3 of this Handbook, it will be recalled that the inputs and outputs of the common-collector and common-base circuits are of the *same polarity*, or in-phase, and that those of the common-emitter circuit are oppositely polarized, or *out-of-phase.* Thus, to obtain the desired polarity (phase) of feedback in the common-emitter circuit, *the two coils are oppositely phased.* In the illustration the feedback is from collector to base, with the input being considered from base to emitter. Since the polarity is reversed in the transistor collector circuit, the tickler coil, L2, is connected so that it also reverses the polarity, and feedback through the crystal (series-mode operation) arrives at the base properly polarized (or phased) to produce regeneration. Removal of the crystal, which is in series with the feedback loop, will prevent the occurrence of feedback; therefore, the circuit will not oscillate with the crystal removed. However, the circuit is normally designed to operate as a self-excited oscillator with the crystal short-circuited.



Basic Tickler Coil Crystal Oscillator, Common-Emitter Circuit

The operation of the circuit is similar to the operation of the electron-tube Tickler Coil L/C Oscillator described in Part A of this section. When the oscillator is switched on, current flows through the transistor as determined by the biasing circuit. Initial noise or thermal variations (initial current) produce a feedback voltage from collector to base through the crystal which is in-phase with the initial noise pulse. Thus, as the emitter current increases, the collector current also increases, and additional feedback through L1 and L2 further increases the emitter current, until it reaches saturation (or the collector voltage bottoms) and can no longer increase. When the current stops changing, the induced feedback voltage is reduced until there is no longer any voltage fed back into the base-emitter circuit. At this time, the collapsing field around the tank and tickler coils induces a reverse voltage into the base-emitter circuit which causes a decrease in the emitter current, and hence a decrease in the collector current. The decreasing current then induces a reverse voltage into the feedback loop, driving the emitter current to zero or cutoff. At this time a small reverse saturation current (I_{CEO}) flows, representing a loss of efficiency, but having no other effect on circuit operation. The discharge of tank capacitor C through L1 then causes the voltage applied to the base-emitter circuit to rise from a reverse-bias value through zero to a forward-bias value. Emitter and collector currents flow, and the previous action repeats itself, resulting in sustained oscillations.

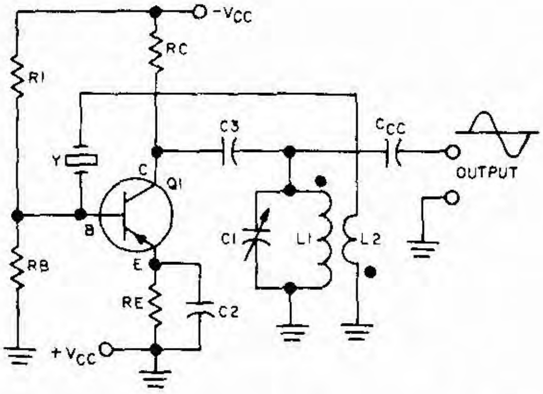
While this oscillatory action is going on, piezoelectric action occurs in the crystal; that is, as the feedback voltage is increased, the strain on the crystal is increased with maximum strain (and maximum crystal deformation) occurring at the peak of the cycle. Upon reversal of the feedback voltage the strain on the crystal is reduced; since the crystal is now changing shape back to its original form, a piezoelectric charge (potential) is produced across the crystal. This charge is opposite to that which produced the deformation of the crystal. For example, if the original charge which caused the deformation was positive, the crystal causes a negative potential to appear across itself when the strain is released. This potential is in the direction of the feedback (decreasing) so that alternate positive and negative charges are induced across the crystal as it vibrates. These potentials add to the feedback voltage; as a result, the crystal enhances the feedback, and the feedback increases the strength of the mechanical vibrations.

Since the feedback and piezoelectric action are regenerative, the transistor quickly reaches its saturation and cutoff points. By correctly proportioning the turns and coupling between the tank circuit and the tickler coil, it is easy to obtain the proper amount of feedback, although with the low potentials involved there is no danger of fracturing the crystal as in the vacuum-tube oscillator. The amount of feedback is adjusted to produce maximum stability. The crystal current is not nearly as great as the crystal current in an electron-tube circuit; in fact, the total transistor collector current is usually less (depending on the type of transistor) than the electron-tube crystal current.

Although the collector-emitter capacitance of the transistor is in parallel with the tank circuit, the use of a low L/C ratio (high-C) produces effective capacitance swamping so that variations in the collector supply voltage, which produce a change in this capacitance, have a minimal effect. For good stabilization, a Zener diode placed across the supply provides excellent regulation. By careful design, the short time stability of the semiconductor crystal oscillator can be made as high as 2 or 3 parts in ten million, which is better than the stability of the equivalent electron tube oscillator. The power output is, of course, very small; however, this fact increases the stability since any change of output load or tuning results in a smaller over-all change. Thus, the frequency stability of the circuit is less affected by load changes than that of the electron-tube (triode) circuit. The output may be taken from the emitter or collector, or even the base circuit, by means of either capacitive or inductive coupling.

The circuit operates at the natural or fundamental frequency of the crystal for the series mode; hence, the operating frequency is slightly lower than the tank resonant frequency. It is also possible to operate this circuit using the parallel mode (antiresonant operation) of the crystal by proper choice of circuit parameters. Although the crystal offers a high impedance at the antiresonant frequency, sufficient feedback can be obtained to sustain oscillation in this mode. In this case, the crystal appears as a high-Q inductor which is tuned by the total shunt capacitance (self, stray, and distributed) across it, and the tank is tuned to a higher frequency. This type of operation is particularly applicable to the higher frequencies, where the shunt crystal capacitance is appreciable. For operation in the parallel mode, the frequency stability is slightly degraded and the output is slightly less than the output in the series mode. Both types of operation are in use.

Bias and Stabilization. In practical circuits, bias and stabilization are usually combined. Bias is usually provided by a fixed voltage divider (R1 and RB), as shown in the accompanying illustration of a typical tickler coil crystal oscillator. Note that the base in this case is not bypassed for rf, although in some circuits it may be. When it is unbypassed, there is presumed to be a slight amount of degeneration, which enhances the circuit stability.



Tickler Coil Tuned Collector Crystal Oscillator

Collector resistor R_C serves two purposes, to drop the collector voltage and to provide resistance stabilization. If the d-c losses are serious, the resistor can sometimes be replaced by an r-f choke. Emitter resistor R_E, which is bypassed by capacitor C_2, provides the major stabilization by emitter swamping action, as explained in Section 3, paragraph 3.4.2, of this handbook. The tank circuit consists of L1 tuned by C1, with tickler coil L2 untuned, and is coupled to the collector through C3 in a shunt-feed arrangement. The crystal is in series with the feedback circuit with the tickler coil polarized so as to produce regenerative feedback. In similar circuits of this type using the tuned base configuration, the crystal is connected directly between base and collector, and the tank between base and ground. In this case, the operation is identical to the operation of the circuit described above; however, the feedback is basically controlled by the capacitance between base and collector, thus making the circuit more suitable for the parallel mode of operation.

Taking the output across the tank through capacitor C_{cc} effectively places the load across the tank and reduces the operating Q, but provides a good waveform because of the smoothing action of the tank circuit. Without the tank circuit, since the oscillations consist essentially of clipped pulses, the waveform would be quite distorted unless the circuit were operated with class A bias. The class of operation is usually class C, with the emitter resistor and capacitor (R_EC2) acting similar to a grid leak in tube oscillators. In the circuit shown, the initial bias is class A for easy starting, with the operating bias being determined by the values of the emitter RC circuit. With large values of capacitance for C2 fixed bias alone is provided, but as the capacitance is reduced to a small value the self-bias developed across R_E increases.

FAILURE ANALYSIS.

No Output. In addition to failure of the transistor, no collector voltage or excessive bias can cause a no-output condition. Transistor failure is not very likely under normal conditions, and the transistor should be replaced only after all other checks have been made. Lack of collector voltage can occur because of opening of the series collector resistor or short-circuiting of the tank coupling capacitor, which provides a path to ground through the tank inductor. An open emitter resistor will also cause lack of output. A short-circuited coupling capacitor will place the output load directly across the tank and could change the resonant frequency sufficiently to prevent feedback at the crystal frequency, and stop oscillation.

Reduced Output. Although aging of the crystal may cause a change in the resonant frequency, it is more likely to cause a drop in output as the crystal becomes less active. This condition usually results in a gradual change over a long period of time and is most easily determined by comparison with a known good crystal operating in the same circuit. A change in bias conditions or in the emitter RC network will probably reduce the output because of the amplitude regulating effects of these components. This condition could be caused by an increase in emitter resistance value or by a reduction in capacitance of the emitter bypass capacitor. These conditions are most likely to occur in miniaturized circuits where new component fabrication techniques have not been perfected. If a resistance analysis shows all circuit values normal, there is a possibility that the crystal is dirty and requires cleaning; however, this condition is not very likely to occur in sealed holders, and certainly will not occur in evacuated holders. Do not attempt to clean the crystal yourself. Return it to the crystal laboratory for servicing. Substitute a crystal known to be good for the suspected one to determine whether the crystal itself is at fault.

Incorrect or Unstable Frequency. Placement of the equipment so that it is subjected to a change in ambient temperature will cause a change in frequency if the change is not within the range of the temperature characteristic for which the crystal is cut. Likewise, small capacitance changes in the crystal circuit (particularly when the crystal is operated in the parallel resonant mode) will cause slight changes in frequency. Detuning of the tank circuit, if sufficient, may cause the crystal to pop in and out of oscillation with a slight change in frequency. Voltage variations will produce a change in the collector capacitance and cause a slight change in the operating frequency. At very low audio frequencies or at high frequencies near f_{max}, phase shift within the transistor caused by transit time effects may produce instabilities (such trouble is not encountered in properly designed circuits). In the crystal-stabilized circuit (which is not used in the Navy), changes in component values may cause oscillation at undesired frequencies outside the range of the crystal, but in the crystal-controlled circuit they cannot cause this effect because the circuit can oscillate only over a very narrow range about the resonant frequency or at an overtone. This can easily be determined by observing whether the circuit oscillates with the crystal removed. If the crystal is short-circuited, it is possible in the series mode of operation for the circuit to oscillate at the tank frequency, but not in the parallel mode of operation. Frequency changes can sometimes be traced to a defective crystal, but more often to varying supply voltages. If a crystal oven is used to keep the crystal temperature stabilized, a defective oven may cause the frequency to shift.

COLPITTS CRYSTAL OSCILLATOR.

APPLICATION.

The Colpitts crystal oscillator is used mostly at the higher radio frequencies as an extremely stable oscillator in receivers, transmitters, and test equipment. However, it may also be used at low and medium radio frequencies.

CHARACTERISTICS.

Uses piezoelectric effect of a quartz crystal to control oscillator frequency.

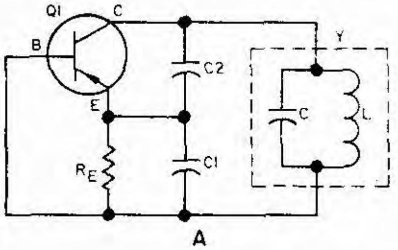
Feedback is provided through a capacitive voltage-divider arrangement, which is usually external, but it may be provided through the transistor element capacitances.

Normally does not use a tuned tank circuit adjusted to the crystal fundamental frequency (but may employ a tuned circuit for special applications).

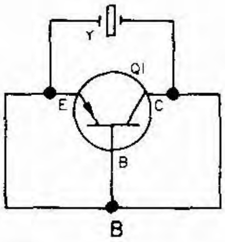
Operates class C if waveform is not important, and class A if good waveform is required.

CIRCUIT ANALYSIS.

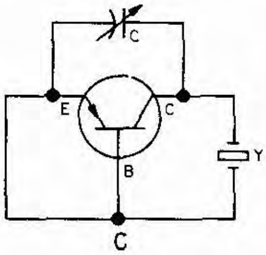
General. The Colpitts type crystal oscillator is usually used at the higher radio frequencies where the difficulty of tightly coupling the inductors in the inductive feedback circuits makes their use problematical. Actually, the so-called Colpitts version uses three basic feedback arrangements: (1) the external capacitive voltage divider with the crystal in shunt (or in series), (2) the crystal acting as a high-Q tank inductor similar to that in an ultraudion arrangement (parallel mode operation), and (3) the in-phase capacitive feedback arrangement, which is included in the Colpitts group solely because the feedback is capacitive (some texts may not regard this as a Colpitts, but as a special type of its own). The basic circuits of each type are shown in the accompanying illustration.



External Voltage Divider Arrangement (Parallel Mode)



Ultraudion Arrangement

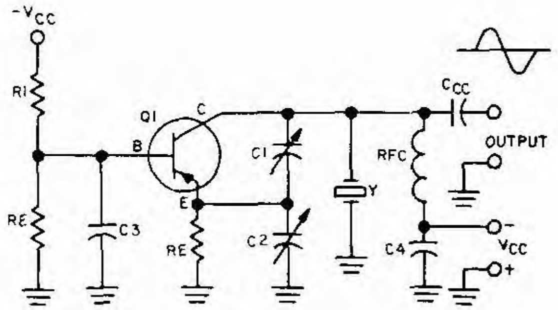


Basic Capacitive Feedback Circuits

Part A of the illustration employs the common-emitter configuration, and parts B and C use the common-base configuration. Actually, the circuit of part B can also use the CE configuration, and that of part C can use only the CB or CC arrangements, because the feedback must be between elements of the same phase or polarity. In the case of part C, the circuit is unique with semiconductors, since in electron tubes there is always a polarity inversion between input and output (except when used as cathode followers). The circuit of part B is analogous to the Pierce electron tube crystal oscillator.

For maximum power output, the input and output resistances of the transistor should be matched as closely as possible; this requirement accounts to a great extent for the numerous variations in circuitry, since it is usually possible to use any of the three basic circuit configurations and to ground any element. With the crystal determining the frequency stability of the circuit, it is only necessary to arrange the proper polarity of feedback and provide a small amount of excitation to start the crystal oscillating. Although in a few cases the phase relationships within the transistor may require tight coupling to provide oscillation, it is usually easier to obtain stable crystal oscillations than to obtain stable self-excited oscillations, because of the assistance of the piezoelectric effect. The Colpitts semiconductor crystal oscillator, like its electron-tube counterpart, is usually a vigorous oscillator in the high-frequency range. However, the use of a quartz crystal does not extend the maximum frequency of oscillation, although it sometimes does provide better performance in the region between the alpha cutoff frequency and f_{max}. Thus good design makes it mandatory to use a transistor capable of oscillating strongly in the desired radio-frequency region of operation regardless of crystal control. Although there are a number of circuits in use, there is not much evidence at the present state of the art that the Colpitts is much (if any) more stable than the tickler coil crystal oscillator. Its main use is to improve operation at the higher frequencies.

Circuit Operation. A typical common-emitter Colpitts circuit using the external capacitive divider feedback method is shown in the accompanying schematic.

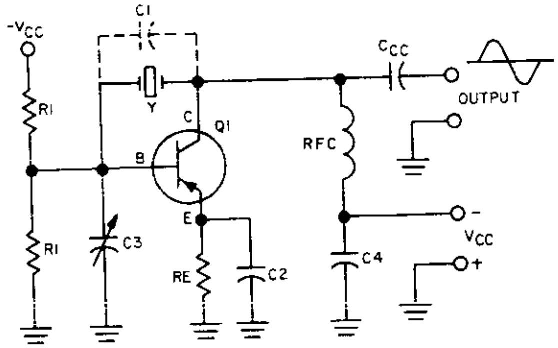


Untuned Colpitts Crystal Oscillator

Voltage divider bias is used for easy starting and is supplied by R1 and R_B, with R_E providing emitter swamping resistance for stabilization of the transistor. Feedback is provided from collector to ground. With the base effectively bypassed by C3, the capacitive voltage divider consisting of C1 and C2 is effectively connected between collector and base for rf. Both feedback divider capacitors are variable to permit adjustment and control of feedback. Capacitor C1 also serves to bypass rf around emitter swamping resistor R_E. Capacitor C2 is the primary feedback control, and is usually made variable to facilitate operation with more than one type of transistor and crystal. The crystal is connected between the collector and ground and operates in the parallel mode. The collector is series-fed through the RFC and conventional bypass capacitor C4. The output is taken capacitively through C_{cc} from the collector.

The operation of the Colpitts type of oscillator basically depends upon the action of the voltage divider consisting of C1 and C2. Assume that the oscillator is first turned on. With fixed class A bias supplied by bias voltage divider R1, R_B, collector current flows, and a voltage appears across the C1, C2 divider. The voltage appearing across C1 is in parallel with emitter resistor R_E. Assume that a noise pulse caused by thermal action in the transistor causes the collector current to increase. A portion of the noise pulse voltage is then fed back through C2 to the emitter, causing the collector current to increase further (this is a regenerative action). At the same time, this increase in noise voltage at the collector also appears across crystal Y. Thus, the crystal is slightly strained mechanically by piezoelectric action. When the collector reaches saturation, no further change in I_c occurs, and the regenerative action ceases. At this time, the electrostatic strain across the crystal begins to reduce as capacitor C2 discharges (the heavy current flow from collector to emitter effectively shunts the capacitor). Thus, the emitter to ground voltage is reduced, the forward bias is reduced, and the collector current starts to fall. This action is also regenerative, and the transistor quickly reaches cutoff. As the collector current reduces, the voltage across the crystal approaches that of the supply (becomes more negative), and the crystal is now strained in the opposite direction. As a result, as each cycle of this action continues, the crystal oscillates at its parallel-resonant frequency. Since oscillation of the crystal produces a voltage across it, once started into vibration, the crystal continues to oscillate. Since the crystal is connected in shunt from collector to ground, it effectively functions as a parallel-resonant tank circuit, and smooths out the pulses of oscillations into approximate sine waveforms. On the conducting portion of the transistor operating cycle, it is effectively reinforced by the ensuing pulse of collector current, and during the nonconducting portion of the cycle, it supplies what would otherwise be the missing half-cycle of oscillation by flexing in the reverse direction. Emitter resistor R_E and capacitor C1 form an amplitude limiting device similar to that of the electron tube grid leak. The output is taken from across the crystal, with C_{cc} acting as a d-c blocking and a-c coupling capacitor. It is evident that the crystal must be capable of handling the power developed, since if driven too hard it will fracture. However, at the normally low milliwatt outputs obtained with transistors, this is no problem. It does indicate, however, that the transistor crystal oscillator requires additional stages of amplification to produce the same r-f drive as an electron tube crystal oscillator.

A typical Colpitts crystal oscillator of the ultraudion form is shown in the following illustration and may be compared with the basic version. This circuit is analogous to the Pierce type crystal oscillator, and is more easily recognizable because the crystal is connected directly between collector and base. The common-emitter configuration is also used in this version, and feedback is provided directly through the crystal. Voltage divider class A bias is obtained by means of R1 and R_B for easy starting, with emitter swamping being provided by R_E, bypassed by C2.



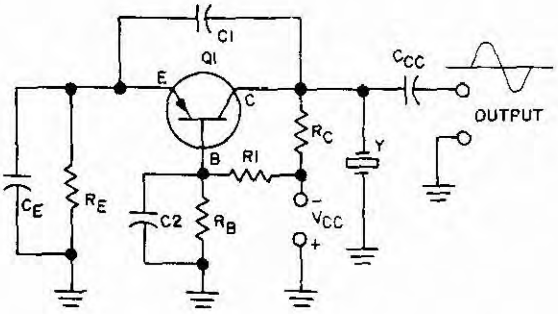
Ultraudion Colpitts Crystal Oscillator

The output is taken capacitively from the collector circuit through C_{cc}. In this instance, C3 is a variable control which permits adjustment for feedback and transistor variations. Both this circuit and the Pierce electron-tube circuit operate almost identically. The feedback capacitive divider in this case consists of the total shunt capacitance across the crystal (including holder and stray wiring capacitance, plus the internal collector-base capacitance, shown dotted as C1) and external capacitor C3 to ground. In this circuit version, the crystal and feedback network appear to be in the base circuit, rather than the collector circuit as in the other version. The difference is that, like the ultraudion electron-tube oscillator, the crystal is considered to be a tank circuit operating in the parallel mode, and since the capacitance of C1 and C3 is usually less than that of C1 and C2 in the previous circuit version (the emitter-collector capacitances is much larger than the base-collector capacitance), the ultraudion circuit tends to be operable at higher frequencies than the external capacitive-divider circuit. Also, phase shifts within the transistor due to transit time effects are such that they aid in producing the correct feedback polarity.

Now consider one cycle of operation. Assume that crystal Y is at rest and the circuit, as illustrated above, is inoperative with no collector voltage applied. At rest, the crystal is unstressed and there is no charge on either plate. When the collector voltage is applied, since the circuit is fixed-biased for class A operation by voltage divider R1, R_B, collector current flows similarly to that in a conventional amplifier. With the base connected to one plate of the crystal and the collector connected to the other plate, when one plate is negative the other plate will be positive. This is the same condition as when the crystal produces a piezoelectric voltage; it is also the same as the polarity for base-collector operation in the common emitter circuit (base polarity is opposite to collector polarity). Therefore, the instant the collector appears negative at turn-on time, the piezoelectric voltage across the crystal causes the base electrode to be positive; this small positive voltage, in turn, causes a reduction in I_c , producing a decrease in collector current. Thus, the collector voltage (of a PNP transistor) becomes more negative. This action is regenerative, and quickly drives the collector to cutoff. During this time the crystal is being deformed in the same direction. During cutoff a small I_{CEO} current flows which only affects the efficiency of the circuit. Since the value of I_{CEO} is steady, there is no change in feedback from the collector. Meanwhile, the small charge developed on C2 by the flow of emitter current through R_E leaks off, reducing the emitter bias and permitting the class A bias to again cause normal current flow. The increase in collector current now causes a reduction in collector voltage, in effect producing a positive swing. The crystal now changes polarity and flexes back toward its original shape. As a result of piezoelectric action, a negative charge now appears on the base electrode. This causes a further swing of collector voltage in the positive direction (this action is also regenerative), and at full current flow the crystal is equally deformed in the opposite direction. At this time the flow of I_c is again steady (corresponds to saturation current flow with self-bias). Since the emitter current flow through R_E produces a bias voltage, C2 now charges and the emitter bias is added to the fixed bias. Once again the collector current is reduced by the increasing bias, and the cycle repeats. Thus, in flexing back and forth in accordance with the changes in collector voltage, the crystal is caused to oscillate; in turn, it produces an in-phase piezoelectric voltage which enhances circuit action. The crystal oscillates at some frequency between that of series and parallel resonance. Actually, the phase shift of the feedback voltage from collector to base, which is necessary to produce oscillation, is produced by the crystal acting as a high-Q inductor which produces an initial 90-degree shift. An additional phase shift is caused by the base-emitter capacitance, which is sufficient to cause an effective feedback large enough to overcome any of the resistive losses in the circuit. Thus, continuous oscillation under control of the crystal is assured. Although the basic oscillation consists of distorted pulses of collector current, the effective tank circuit action of the crystal helps smooth out these pulses into approximate sine-wave oscillations. The output is taken through coupling capacitor C_{cc}, and appears as a resistive load in shunt from collector to ground.

The common-base arrangement of the Colpitts crystal oscillator using in-phase capacitive feedback is shown in the following illustration. Voltage divider bias is supplied by R_1 and R_B, and the base resistor is bypassed for rf by C2. Emitter resistor R_E, which is bypassed by C_E, provides conventional swamping of the emitter circuit, and R_C provides resistance stabilization in the collector circuit. The crystal is connected between collector and ground, but is effectively connected between the collector and base for rf by means of C2. The output is taken capacitively from the collector (across the crystal) through C_{cc}.

Since the emitter and collector in the common-base circuit are of the same polarity (in-phase), feedback is obtained by using C1 to apply a portion of the collector voltage to the emitter.



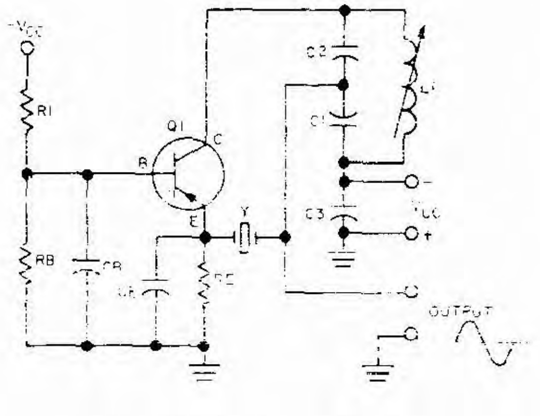
Colpitts Common-Base Crystal Oscillator

Now consider one cycle of operation. Fixed class A bias is supplied by voltage divider R1, R_B. When collector voltage is applied, Q1 conducts as in a conventional amplifier. Assume that a noise pulse occurs in the base circuit, which causes the collector current to increase. The voltage drop across collector resistor R_c appears as a positive-going pulse, which is applied through C1 to the emitter. This increase in emitter bias is in the forward direction, causing a larger flow of collector current. Thus, a regenerative in-phase feedback exists. The positive-going noise pulse is applied to crystal Y, which is in shunt from collector to ground, causing the crystal to be distorted in one direction by piezoelectric action. When the collector voltage bottoms (becomes almost zero), no further feedback occurs and the crystal flexes in the opposite direction. By piezoelectric action the crystal polarity is now reversed and a negative charge appears at the grounded electrode. Since the base is connected to ground through C2, the base now has a negative voltage applied and thus operates to reduce I_C. As the collector current reduces, the drop across R_C becomes negative-going and approaches the source voltage.

The feedback through capacitor C1 is also negative and reduces the forward emitter bias, causing a still smaller I_C to flow. This action is also regenerative and continues until cutoff is reached. At this point a small flow of reverse current (I_{CEO}) exists, but it has no effect other than to reduce the over-all efficiency of the circuit. Once the feedback stops, there is no further change in current, and C_E (which was charged negatively during this half-cycle) starts to discharge through emitter resistance R_E. When the emitter voltage drops to a value which again starts I_C flowing, a positive-going voltage is produced across R_C, and a positive voltage is again fed back through C1, and the cycle repeats. During this time the crystal is now flexing in the opposite direction and the polarity across it again changes, so that the crystal-induced piezoelectric voltage is in phase with the collector-base voltage. Actually, the crystal acts as a tank circuit, smoothing out the rough pulses of current into approximate sine-wave variations. By appearing as a high-Q inductance, the crystal insures that the proper feedback phase relationship is maintained, and, since it is a low-loss tank, the feedback through C1 need only be sufficient to supply the small tank losses to sustain oscillation.

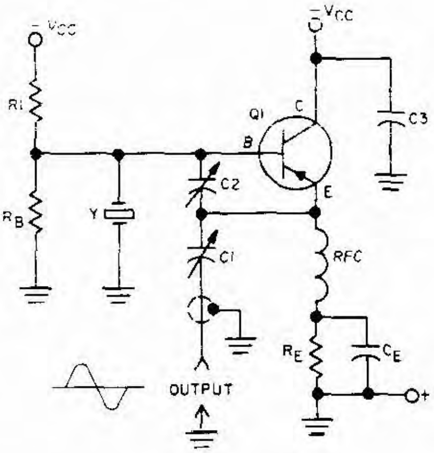
By properly proportioning C_E and R_E, the bias can be made to reach the region of class C operation for best *efficiency*, as in regular gridleak operation, while the fixed class A bias makes certain that starting occurs easily. The output is taken from across the crystal through coupling capacitor C_{cc}. Therefore, the load is in shunt with the crystal and tends to reduce the output somewhat as in the electron-tube Pierce circuit.

Circuit Variations. Because the Colpitts crystal circuit has so many variations, a few representative circuits are shown in the following illustrations to facilitate identification of this type of circuit. Parts are labeled as in previous illustrations where they serve the same function, and **the discussion is limited to the basic differences between these circuits and those considered previously.**



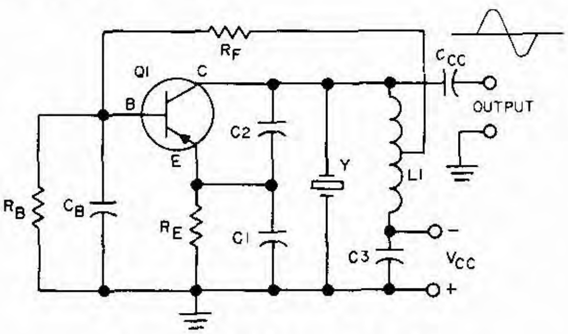
Tapped Collector Crystal Oscillator

In this circuit version, conventional voltage divider bias and emitter swamping are used for stabilization. The crystal is series-connected between the emitter and the collector by the voltage divider, consisting of C1 and C2, connected across L1. The operation of this circuit is based on a combined matching of impedances and a feedback connection. Connecting the crystal to the emitter through the capacitive voltage divider provides the proper feedback polarity, and the capacitances of C1 and C2 together with L1 form a tuned tank circuit which is resonant to the crystal fundamental (series-resonant) frequency. The input and output impedances of the transistor are matched by the proper capacitance ratios, producing the same effect as though the collector were tapped across L1. The output is taken between the tap and ground, that is, across the crystal. This type of circuit is usually used at the lower r-f frequencies. The use of a tuned tank helps provide a good waveform and permits frequency doubling or the use of an overtone crystal.



Grounded-Collector Colpitts Crystal Oscillator

A grounded-collector common-emitter version in which the voltage divider and crystal are located in the base circuit is shown above. Conventional voltage divider biasing and emitter swamping are used for stablization. The collector is grounded for rf by C3. Thus in effect the crystal is connected between base and collector similar to the Pierce grounded-plate electron-tube version. However, the crystal, although isolated from collector voltage, is still subject to the small bias voltage from base to ground. Feedback is provided through capacitive divider C1 and C2, with primary control of feedback being provided by C2. Capacitor C1 is used to tune (match) the output, which is taken between the tap and ground. This type of connection offers a low output impedance suitable for coaxial line matching. The RFC is used to keep the emitter above ground; otherwise, the load or output would be short-circuited through C_E. No particular claims are made for this version other than its output matching feature. The inverse feedback type of crystal oscillator utilizes a conventional Colpitts with an external feedback capacitive voltage divider and with the crystal in the collector circuit. Bias is obtained by a conventional voltage divider, and emitter swamping is used for stabilization. The bias is provided in conjunction with feedback by tapping R_F on L1. Thus, d-c bias is obtained through R_F and R_B, r-f feedback is obtained



Inverse Feedback Crystal Oscillator

through R_F and L_1. The basic feedback path is through the capacitive divider, C1 and C2, and the secondary feedback path is through L_1 via R_F. Placing the tap at the lower end of L_1 produces regenerative feedback, and placing it at the upper end produces degenerative feedback, because the polarization of the collector is opposite that of the base. Thus, by placement of the tap, the feedback can either enhance oscillation by regenerative action or stabilize operation by degenerative action. The possibility that unwanted resonances of parts in this circuit may tend to cause free-running operation makes this version of dubious value. With the output being taken from the collector, it is more likely that the feedback tap provides better input and output matching to the transistor, similar to the tapped collector circuit previously mentioned.

FAILURE ANALYSIS.

No Output. In tuned circuit oscillators, the loss of output can be due to improper tuning. Also, a defective crystal will prevent operation, in either tuned or untuned circuits. A suspected crystal can easily be checked by the substitution of a crystal known to be good. A simple resistance check will indicate continuity and general parts condition. A defective bias resistor producing a high bias voltage (in the divider arrangement) can prevent starting, and will be made evident by a resistance or voltage check. An open bias arrangement can prevent operation by causing a lack of bias, or by causing excessive internal bias due to feedback within the transistor. An open r-f choke, collector resistor, or coil will also stop operation. A shorted coil in the tuned circuit can stop oscillation, but the short will not be revealed by a resistance check. This condition is checked (after all other components have been eliminated from suspicion and a crystal known to be good has been substituted) by grid-dipping the tank for resonance. A defective transistor should be suspected only if all other parts check satisfactory and bias and supply voltages are normal.

Reduced Output. A low supply voltage or increased collector resistance can cause a reduction of output. A reduction of bias from class B or C to class A will also result in reduced output. Both of these conditions can be determined by a simple voltage check, preferably with a vacuum-tube voltmeter or a high-resistance ohmmeter. Reduced crystal activity, due to aging or semi-fracture, or a dirty crystal can also be a prime cause. In this case, substitution of a crystal known to be good will restore normal operation. A change in the value of the emitter swamping resistor or bypass capacitor can cause excessive bias, and consequent squegging or motorboating due to intermittent blocking of oscillations. In circuits designed for the higher frequencies, changing the lead dress or parts wiring during repair may change the distributed wiring capacitance sufficiently to detune the circuit and cause a reduced output. In the tuned tank versions of this circuit, reduced output can also be caused by a high-resistance tank circuit connection or a shorted turn.

Incorrect Frequency. A defective or dirty crystal can cause an abrupt change from one frequency to another; this can sometimes be corrected by adjusting the tank tuning, if an adjustment is provided. Aging of the crystal can also cause a slow change over a long period of time; this change can sometimes be compensated for by means of a small trimmer capacitor, if the frequency is higher than normal. (Do not add an unauthorized modification to accomplish this. In most circuits a trimmer is included to permit calibration to the exact frequency for which the crystal is ground.) Failure of the collector supply regulation (as well as the bias supply regulation) can cause the effective element capacitance of the transistor to change and cause slight off-frequency operation. In this case, check the supply voltage with a high-resistance voltmeter and observe whether there are occasional fluctuations of the voltage when the crystal is suddenly removed from its socket and reinserted into its socket or when the load is suddenly removed and replaced. If all components check normal and trouble is still present, the crystal is probably defective.

OVERTONE CRYSTAL OSCILLATOR.

APPLICATION.

The overtone type oscillator is used as an oscillator in receivers, converters, frequency synthesizers, and test equipment, and as an exciter in low-power transmitters. Its use is restricted to the high-frequency ranges (above 20 mc) where fundamental mode crystal operation is not practicable.

CHARACTERISTICS.

Uses piezoelectric effect of a quartz crystal operating on an odd overtone to provide stable high-frequency oscillations.

Has at least one tuned circuit at overtone frequency and may have two; it is never untuned.

Operates class C to help produce harmonic operation.

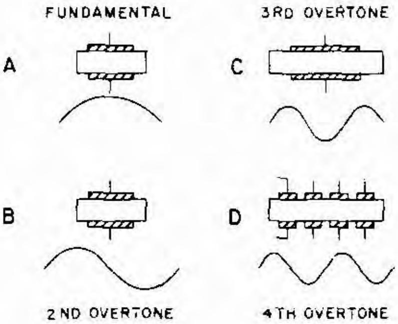
Regenerative feedback is usually provided through a tapped coil (Hartley principle).

Always operates as a crystal-controlled oscillator to avoid spurious frequencies.

CIRCUIT ANALYSIS.

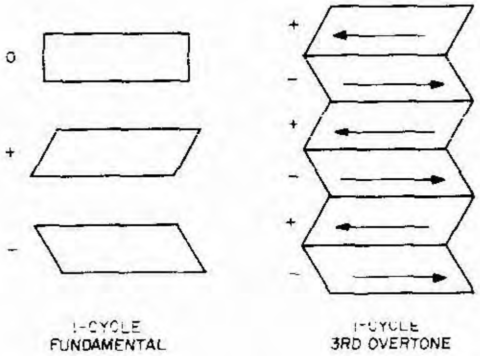
General. Overtone circuits are basically of two types: one type uses a crystal which is ground for fundamental frequency operation, and the other uses an overtone ground crystal. Since the circuits that use overtone crystals are usually designed for specific types of crystals, this discussion will be restricted to circuits which can use either type of crystal. If other types of circuits become more prevalent, they will be discussed in later issues of this handbook.

Since no discussion of basic overtone crystal functioning appeared in the introductory discussion of electromechanical resonators, some basic principles are given to facilitate an understanding of circuit operation. The following figure shows the basic flexural vibration modes for fundamental, second overtone, third overtone, and fourth overtone operation of a crystal bar. These modes are used at low frequencies only, where a bar producing lengthwise vibrations instead of a plate is used.



Crystal Flexural Vibration Diagrams for Lengthwise Vibrations

Part A of the figure shows the basic mode of operation at the fundamental frequency with the bar bending in the middle, and parts B, C, and D show second, third, and fourth overtone operation. In part B, note that the second harmonic flexing is of opposite direction, or phase, and that with a single plate extending the length of the crystal the bar cannot easily oscillate. On the other hand, the third overtone has the same motion or phase at both ends with the middle free to flex. In practice, the output on the third overtone is strong with a single plate, but the output on the second overtone, if not completely canceled, is so weak that it is unusable (the bar has practically no piezoelectric effect). By plating a single electrode and then dissolving the plating between nodes, it is possible to get free flexing and piezoelectric effect from even overtones, either separately through each set of plates, or by using one or the other of the end plates for excitation as shown in part D of the figure.



Thickness Shear Vibration Diagrams

In the high-frequency crystal a different condition exists. Here the thickness shear mode is the mode of interest, and it is illustrated in the following figure. It is clearly seen that the vibrations in this mode are as if the crystal were squeezed with a shearing motion, distorting it somewhat as shown. Since this motion is essentially lateral, the crystal may be clamped at the edges, without being appreciably affected by the spring pressure between the plates; that is, the mechanical friction is negligible. When operating on an overtone, the high-frequency crystal appears to be formed of layers with the motions occurring in opposite directions. It should be understood, of course, that the illustrations are exaggerated to convey the idea. Basically, a crystal does not oscillate on one frequency; it has numerous nodes and modes, which can be affected by changes in temperature and excitation. For example, it is possible to heat the crystal by overexcitation, and cause it to change from a mode of operation at one temperature to another mode of operation at a higher temperature. It is also possible to cut and grind it so that it oscillates most vigorously on a particular frequency. This then is the fundamental frequency for **fundamental** crystals, and the overtone frequency for **overtone** crystals.

Overtone operation is normally restricted to the odd harmonics on high-frequency thickness shear type crystals. In the circuit to be discussed, the crystal will operate only at the overtone frequency if ground for overtone operation. The circuit, however, will also operate at an overtone of a fundamental type crystal (which is some odd multiple of the fundamental frequency), but it will not operate at the fundamental frequency unless the tank is tuned to the fundamental frequency. It is possible to operate up to the third or fifth overtone with fundamental crystals and up to the ninth or higher overtone with overtone crystals.

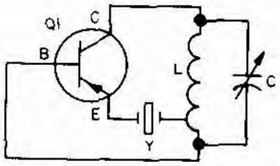
As a matter of academic interest, it should be noted that crystals have been made which will operate on even harmonics, but this is the exception rather than the rule; only crystals which operate on odd overtones are of practical interest.

Since the overtone crystal is usually very thin, its mounting is very important. Therefore, it is usually plated and connected to wire electrodes in a sealed container. It is also very sensitive to surface imperfections; for example, scratches that would not affect the operation of the fundamental crystal can prevent operation of the overtone crystal. Therefore, extra care should be observed in handling and cleaning operations.

For operation of an overtone circuit, regenerative feedback must be provided to assist in the starting of oscillations, but the feedback must not be strong enough to cause free-running oscillations. Most circuits of this type are first designed to operate as free-running oscillators, and the amount of feedback is then reduced by the manufacturer until only the crystal controls the oscillation. Oscillation is usually vigorous, and the output at the third and fifth overtones (using a fundamental crystal) is almost as large as that at the fundamental; at higher overtones, the output falls off quickly. The output depends so much upon the processing and manufacture of the crystal, however, that the highest overtone at which practical operation is possible is rather indefinite. Designers have produced satisfactory outputs on overtones above the 11th, but mostly with patented circuits and special components. In the transistor crystal oscillator, for example, overtone operation has been improved by the use of special transistors designed to minimize phase shift at very high frequencies. When this type of transistor is combined with an overtone crystal or a specially processed crystal, the results equal or surpass similar electron-circuit tube achievements, but the power output is less.

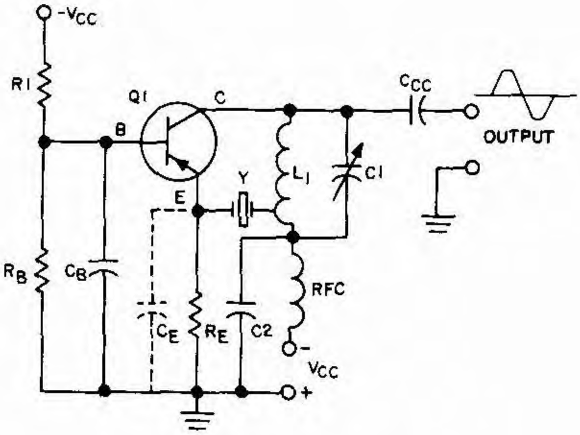
Basically, the overtone crystal oscillator uses an inductive form of feedback, but it is not necessarily limited to that type. It just happens that at the present state of the art the inductive type is more popular. Although the tapped coil is primarily a Hartley feedback arrangement, it is closely similar to the tickler coil feedback arrangement. At the frequencies used, the tighter coupling of the Hartley arrangement and the ease of construction make it a more natural choice.

Circuit Operation. A simplified schematic of the basic overtone semiconductor oscillator, using the common-emitter configuration, is shown below. It can be seen at a glance that this is the basic Hartley Oscillator circuit with a crystal in series with the emitter feedback connection. For simplicity, bias and supply arrangements are not shown. It is assumed that the collector is reverse-biased and the base forward-biased, and that PNP junction transistors are used. The crystal can be either a fundamental or an overtone type. The tank circuit, consisting of L and C, is tuned to the overtone frequency desired. The principle of operation is exactly the same as the principle of operation of the basic Hartley oscillator, with proper polarity of feedback between the oppositely polarized collector and base being obtained by means of the tapped-coil arrangement. The difference in operation is primarily in the amount of feedback, with the portion of the coil between emitter and base producing just enough feedback for easy starting with the crystal in place. In the self-excited Hartley, the tap on the inductor is normally at or near the center of the coil, the number of turns between emitter and base being selected for strong and stable feedback. In the overtone oscillator the feedback coil usually consists of a few turns (no more than 3 or 4), approximately 10% of the total number of tank coil turns. This corresponds very closely to the tickler coil oscillator arrangement used in regenerative receivers, where it is possible to just produce oscillation with the regeneration control all the way on. The overtone oscillator regeneration, however, is adjusted so that the circuit will not quite oscillate with the crystal out of the circuit, but will produce, strong stable oscillation at the crystal frequency only (no spurious self-oscillation) with the crystal in the circuit.



Simplified Overtone Circuit

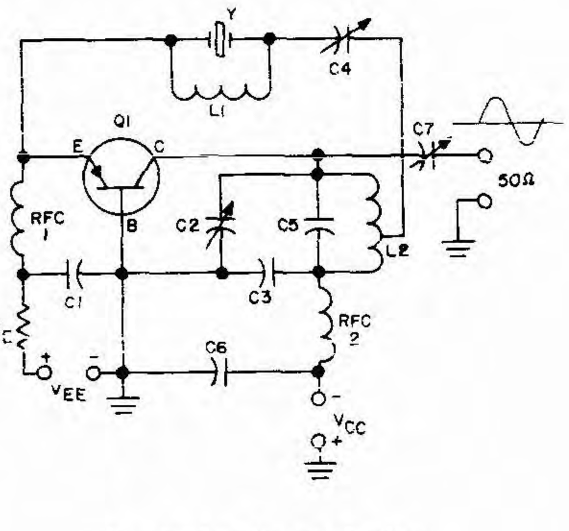
A typical overtone circuit with bias and supply connections is shown in the accompanying figure. The common-emitter circuit is used, and the crystal is in series with the feedback loop as in the basic schematic. Voltage divider bias is obtained through R1 and R_B, and the base resistor is bypassed for rf by C_B. An unbypassed emitter swamping resistor (R_E) is used for stabilization. Actually, at the high frequencies used, it is probable that the distributed capacitance (shown in dotted lines in the schematic) across R_E and the resistor itself form a grid-leak bias arrangement for amplitude control and that some designs may use a bypassed emitter. In the circuit shown, the collector supply is bypassed by C_2, with an RFC connected in series between the negative collector supply terminal and L1, as a conventional series-feed arrangement.



Overtone Crystal Oscillator

Now consider one cycle of operation. When collector voltage is applied, bias divider R_1, R_B supplies class A bias to the base, and collector current flows as in a conventional amplifier circuit. Assume that a noise pulse causes the collector current to increase and that a voltage is developed across the tank circuit (L1C1), which offers a high impedance at the resonant frequency. The voltage developed across the tank is positive with respect to the supply end. The crystal offers a low-impedance path to the emitter at series resonance. With the crystal connected *near the* supply end, that electrode is negative, and the electrode connected to the emitter is positive. Therefore, a voltage exists across the crystal, causing it to deform in one direction. The base of the transistor is connected for rf through C_B and C2 to the supply end of the *tank coil. Thus the tank* is essentially connected between collector and base, with the emitter tapped to the tank. This is equivalent to a typical Hartley-type of grounded-base feedback oscillator, which is effective only for the series-resonant frequency of the crystal. On either *side of resonance the increasing* crystal impedance quickly stops any feedback, and the circuit will not oscillate.

As the noise pulse causes the collector current to increase, the feedback to the emitter is positive and the base end of the coil *becomes more negative. Both the more* negative base and the more positive emitter cause an increase in forward bias and a greater I_c. The collector current increases until the supply voltage bottoms (cannot go any lower). During this time the tank capacitor, C1, is charging. The tank circuit now *discharges and the polarity* of the base and emitter feedback voltages change to produce a reduced forward bias and a lowering of I_c. This causes the collector voltage to rise toward the supply voltage and become more negative. At the same time, since the polarity across the crystal changes, the *crystal flexes* in the opposite direction as a result of piezoelectric action. This state of operation continues until the collector current cutoff point is reached; at this time a small flow of I_{CEO} (reverse current) occurs, but it has no effect on operation other than to cause a lowering of efficiency. When the feedback ceases, the crystal flexes back toward its original resting condition and generates a piezoelectric charge that starts collector current flowing again, and the cycle repeats. Emitter resistor R_E is affected only by the d-c current flow, and operates as a simple swamping resistor for thermal compensation and stabilization. In some circuits the distributed capacitance across R_E is considered to cause it to operate in a manner similar to that of the electron-tube grid leak. That is, the charge across this capacitance holds the circuit inoperative until the charge leaks off; too large a capacitance will effectively short the crystal. The capacitance is shown in dotted lines in the above illustration because it is not considered necessary for operation. The output is taken capacitively through C_{cc} between collector and ground, or, if desired, by inductive coupling to the tank circuit. The tank circuit is tuned to the overtone frequency, and the crystal also operates at the overtone frequency.



Grounded-Base Overtone Oscillator

Circuit Variations. A typical practical operating design used in a satellite transmitter is shown in the following figure. The grounded-base arrangement is employed. The tank circuit is connected between base and collector, and the *emitter is connected to the tap on the tank coil through* the series crystal and capacitor C4. Separate bias supplies are shown because their use provides almost perfect stabilization; however, voltage divider bias can be used if only one supply is available. RFC1, in the emitter circuit, is *used to keep the emitter above ground, and* R_E, which is bypassed by C1, provides emitter swamping (and also controls output). Forward bias is applied between the emitter and base by battery supply V_{EE}. Conventional series collector feed is provided through RFC2, which is bypassed *for rf by C6. The output* is taken capacitively from the collector through C7, which is adjustable to match a 50-ohm load. Capacitor C3 is a base blocking and coupling capacitor (it also affords a reduced tuning range for C2); it connects the base to the tank circuit for rf and isolates it from *the d-c collector supply;* otherwise, the supply would be short-circuited. Capacitor C5 is a trimmer capacitor across the tank, and variable capacitor C2 is the tank tuning capacitor. Feedback is obtained from the tap on L2, and applied through C4 and the series crystal to the emitter. In this *circuit, C4 adjusts the phasing* to ensure feedback of the proper polarity and to compensate for the phase lag in the transistor at high frequencies. It acts as a variable regeneration control to permit the use of various types of crystals and replacement transistors. Inductor L1 is used to resonate *out the effects of excessive crystal holder shunt capacitance* at the frequency of operation. At the series resonant overtone the crystal offers minimum impedance and supplies maximum feedback from collector to emitter. Although the emitter and collector are of the same polarity, or phase, L2 and C4 provide the necessary phase rotation to insure oscillation, since the feedback is taken from the end of the tank coil opposite the collector.

Now consider one cycle of operation. When voltage is applied, the fixed bias, which is less than cutoff, permits collector current to flow. Assume a noise pulse which causes an increased I_c. Since the tank is connected between collector and base, with the emitter tapped onto the coil, it is basically a Hartley-type oscillator. In this circuit L2 acts as an autoformer, with the emitter-base turns *coupled to the emitter-collector turns.* However, the emitter is not directly connected to the coil; it is connected through crystal Y and capacitor C4 in series. The capacitor offers only a small capacitive reactance to the oscillator frequency; the crystal offers a high impedance off-frequency, and a low impedance at its series-resonant frequency. Thus, feedback is permitted at the series-resonant frequency, but is stopped on either side of resonance.

The increased collector current induces a feedback pulse in the emitter-base portion of L2 in a direction which increases the forward bias, and, hence, the collector current. Capacitor C4 provides a phase-delay adjustment which can reduce the amount of feedback (or increase it, as desired) so that various types of crystals and transistors may be used. For the purpose of this discussion it can be considered as short-circuited, since it is only a production type of compensator, and is not necessary to basic operation. Since the feedback action is regenerative, the collector current continues to increase until the collector saturates and no further change can occur. At this time the crystal, which was initially deformed by the feedback potential between the emitter and collector, flexes in the opposite direction. The polarity across the crystal produced by piezoelectric action also reverses, and the flow of emitter current is reduced; since the collector current is also reduced, and the feedback is regenerative, the collector is driven to cutoff. At this time a small I_{CEO} (reverse current) flows, but it has no effect on operation except to lower the over-all efficiency. At this time C1, which was charging during the conduction period, now discharges through R_E. When the bias drops below cutoff, current again flows and the cycle repeats. During the reducing collector current period, the crystal is flexed in a direction opposite the initially caused deformation, and at cutoff it again flexes oppositely and resumes its original shape. Thus, the crystal is caused to oscillate, and in oscillating it provides a low-impedance path for the feedback. Because of its inherent stability, the crystal controls the frequency by permitting operation to occur at only one frequency. The basic tank circuit (L2, C2) functions in the conventional manner to supply energy during the nonconducting half-cycle, so that the negative output alternation may be completed. This flywheel effect provides a sine-wave output through coupling capacitor C7, instead of the distorted pulse which otherwise would occur.

The circuit described above is capable of providing an output of 15 to 30 milliwatts at an efficiency of 30 to 35% to a 50-ohm load, and a maximum output of 100 milliwatts at an efficiency of 40 to 45%. Under constant loading and controlled temperature, the short time frequency stability is plus or minus one part in one hundred million. The circuit uses a fifth overtone crystal operating on 108 megacycles and a diffused base transistor.

FAILURE ANALYSIS.

No Output. Loss of output will result from the loss of bias or supply voltage due to an open- or short-circuited component; this condition is easily determined by checking for the presence of voltage. An incorrectly tuned tank circuit will prevent the crystal from operating and could result from shorted turns or a shorted tuning capacitor, but at low voltages used, troubles of this kind are rather unlikely with ordinary components. In miniaturized circuits where the current-carrying capacity is low, there is the possibility that an overload can cause the inductor or leads to open. It is important, therefore, to use a meter having a very low full-scale current requirement, preferably in the microampere region. A VTVM is preferable to the standard 20,000-ohms-per-volt meter, although with care both can be used interchangeably. A check of the forward and reverse resistances of the transistor will quickly determine whether it is at fault. Because of the low potentials involved, a high resistance or poor soldered joint can introduce excessive resistance and stop the circuit from oscillating. A defective, partially fractured, or dirty crystal can also prevent oscillation; the crystal can be checked by substituting a crystal known to be good in its place.

Reduced Output. Since the output amplitude is primarily controlled by the emitter swamping resistor and bias voltage, changes in these parameters can cause reduced output. Opening of the bias ground return resistor will place a higher bias voltage on the transistor, and, depending upon the internal base-to-emitter resistance of the transistor, oscillations may be blocked entirely or hard starting may result. Hard starting is usually a clear indication of a dirty or defective crystal. The value of the emitter resistance and its bypass capacitor will determine the output amplitude to a great extent; therefore, a partially shorted capacitor or increased resistance in the emitter circuit will reduce the amplitude. Such troubles can be easily located by making a resistance check of the few components in the circuit. A reduction of output may also be caused by short circuiting of the transistor elements or by mismatching of the transistor due to a change in the circuit values. This too is easily checked by making a resistance analysis and by measuring the forward and reverse resistances of the transistor. A combination of low forward resistance and high reverse resistance indicates a satisfactory transistor. If the forward resistance is high or nearly the same value as the reverse resistance, the transistor is defective. If both resistances are zero, the transistor is short-circuited.

Incorrect Frequency. Since the crystal is the frequency-determining component, an appreciable change in frequency indicates a defect or a change in the crystal, except where the tuned circuit is actually tuned to another overtone. Under normal conditions it is practically impossible to tune the tank to resonance at a different overtone unless the tank circuit components are defective. Although a fundamental type crystal will operate within the tolerances marked on the holder, it must be kept in mind that for overtone generation of the crystal the tolerances will be multiplied by the overtone number (1, 2, 3, etc); hence, the tolerance range at the overtone will be much larger. Oscillation will occur, not over the entire range of tolerances, but at a specific frequency within the range. On the other hand, overtone crystals are rated for their actual tolerance at the overtone frequency; therefore, operation outside this range indicates a defective crystal or spurious oscillations. As a result of changes in circuit components and transistor parameters with age, excessive feedback may occur at certain resonant frequencies and produce free-running oscillations. Usually these signals have a much rougher or more raspy sound and are less stable than the controlled oscillations. In the case where calibration capacitors or feedback controls are provided, it is normal for them to control the frequency slightly so as to permit the crystal to be operated on its exact frequency. When no controls are provided, a change in ambient temperature can place the crystal in another class of temperature compensation and change the actual overtone frequency. The temperature tolerance is shown on the crystal holder and is standard for a MIL type crystal. Minute imperfections or partial fractures can also cause the crystal to operate at another frequency. Return defective or dirty crystals to the crystal repair activity for servicing.