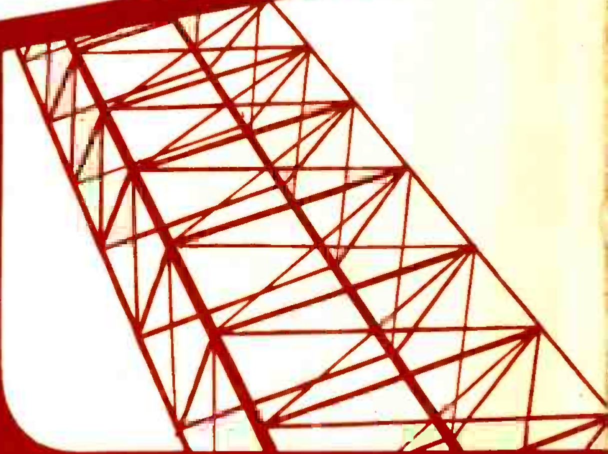
# ELECTRON TUBE OSCILLATORS

## Lesson RRT-8



DE FOREST'S TRAINING, INC.

2533 N. Ashland Ave., Chicago 14, Illinois

RRT-8

Radio Reception
and Transmission

## LESSON RRT-8

# ELECTRON TUBE OSCILLATORS

### CHRONOLOGICAL HISTORY OF RADIO AND TELEVISION DEVELOPMENTS

1895—Prof. Roentgen discovered rays which are liberated when electrons strike a metal target in a vacuum tube. Not knowing what these were, he called them X-rays.

1895—Guglielmo Marconi began his experiments in wireless transmission, and was able to transmit signals over a distance of one mile without wires. The following year he applied for his original and basic wireless patent.

1897—Sir Oliver Lodge took out his fundamental patent on tuning and the use of tuned coils in the antenna circuits of radio transmitters and receivers.

1897—Cathode-ray tube (then known as the Braun tube) was announced by Frederick Braun. In 1902 he showed how the tube could be used to trace a-c waves.

DE FOREST'S TRAINING, INC.
2533 N. ASHLAND AVE., CHICAGO 14, ILLINOIS

# RADIO RECEPTION AND TRANSMISSION

## LESSON RRT-8

## ELECTRON TUBE OSCILLATORS

## INDEX

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**The greater a man's knowledge of what has been done, the greater is his power of knowing what to do.**
**—Selected**

# ELECTRON TUBE OSCILLATORS

## OSCILLATIONS AND OSCILLATORS

According to the dictionary, the word oscillate means to vibrate, to swing back and forth or to pass from one state to another and back again. This is a rather broad definition as no mention is made regarding the nature of the variation which may be gradual and smooth or sharp and abrupt. Also, no restrictions are placed on the rate of variation which might occur once a century

A laboratory-type signal generator used for general test purposes. The essensential part of this generator is a crystal-controlled oscillator that covers a wide frequency range.

Courtesy Hickok Electrical Instrument Company or millions of times a second. Thus, it can be stated that the weather oscillates each year because it passes from winter cold to summer heat and back again to winter cold.

In mechanics, oscillation refers to a back and forth motion around a center or fixed point to produce movements like those of a clock pendulum, an automobile windshield wiper or the armature in the vibrator of an auto radio high voltage power supply. The rotor plates of the tuning condenser in the ordinary radio receiver have the same type of motion, but their rate and distance of movement does not follow any fixed pattern.

In electricity, the continual change and periodic reversal of alternating current and voltage meets the conditions of the definition and therefore can be said to oscillate. However, as each complete series of changes constitute a "cycle", and the number of cycles which occur in a given time determines the "frequency", these terms are used in most cases. Thus, the common electric power circuits are rated simply as "110-120 volt, 60 cycle a-c" and it is understood that the voltage and current values oscillate at a frequency of 60 cycles per second.

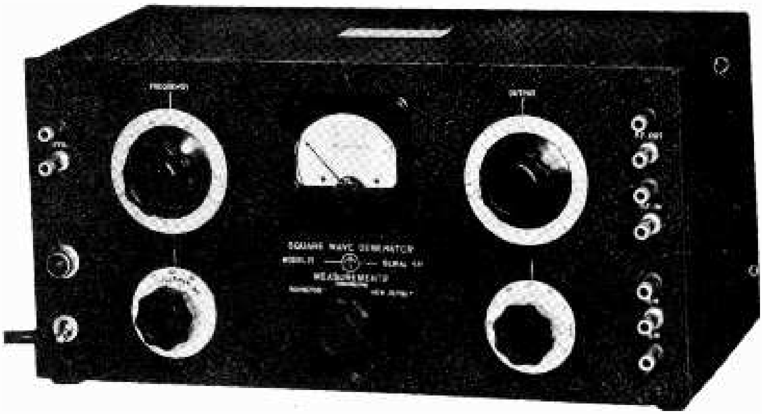
In Radio, Television and other electronic applications, the term "oscillate" refers almost entirely to the generation of a-c by means of electron tubes. Although there are no definite limits, in most cases, the frequencies of these oscillations are higher than those of the usual a-c power supply and may have values up to several thousand million cycles per second.

## OSCILLATORS AND THEIR APPLICATIONS

The primary purpose of an electron tube oscillator is to convert direct-current power into high-frequency alternating-current power. It has already been explained how amplifier tubes, controlled by an external source of signal voltage connected into the grid circuit, change the d-c power from the plate supply into a-c power in the plate load. Although the basic action of the tube does not change, as an oscillator it functions without the aid of an external source of control voltage. Thus, the electron tube oscillator is essentially an alternating-current generator, the waveform, amplitude, and frequency of the a-c oscillations which it generates depending only upon the circuit elements and the way in which they are connected.

As the oscillator has a wide variety of uses, it has become one of the most important applications of the electron tube. The high frequencies which can be generated by this means have made possible most of the modern developments in the communication art. Electron tube oscillators with power ratings from a fraction of a watt up to thousands of watts, are employed for a variety of purposes in modern electrical communication systems. The list of their specific applications is extensive, and for the present let it be stated that there are uses for oscillator circuits in all branches of electrical and electronic engineering.

The essential components of an electron tube oscillator are: (1) A high voltage d-c source which furnishes the direct-current power, (2) A tuned circuit, consisting of capacitive and inductive (or resistance) elements, in which the oscillations are produced, and (3) A switch (or its equivalent) that controls the period during which the d-c power is suppled to the a-c circuit.



Square-wave generator—a non-sinusoidal oscillator that develops a signal of square wave form for testing various types of electronic circuits.
Courtesy Measurements Corporation, Boonton, N. J.

## HOW ELECTRICAL OSCILLATIONS ARE DEVELOPED

The actions which produce electrical oscillations in an LC or tank circuit, can be explained by means of the simple circuit illustrated in Figure 1. Here, with the aid of switch S, condenser C can be connected across either the d-c supply B or the coil L. With the switch in position 1, the condenser charges to the voltage of the power supply, with the upper plate positive and the lower plate negative. In other words, a definite amount of electrical energy is stored in the condenser.

At the instant the switch is thrown to position 2, the circuit conditions are as illustrated in Figure 2A with the charged condenser connected directly across the coil L. With no voltage across L, the condenser immediately starts to discharge and there is a flow of electrons from its lower negative plate through L to the upper positive plate as indicated by the two broken-line arrows in Figure 2B.

Starting from zero, the discharge continues at an increasing rate but, passing through coil L, produces an expanding magnetic field which, by self induction, induces an opposing or counter emf. As in any inductive circuit, the counter emf prevents the current from increasing instantly to its maximum value and therefore causes it to lag the voltage. Thus, the action of Figure 2B continues until the electron flow and magnetic fields are both at maximum as indicated in Figure 2C. At maximum there is no change of current, the magnetic field is stationary and the counter emf dies out. Neglecting losses, the energy of the original condenser charge has been transferred to the magnetic field around coil L.

After reaching its maximum value, the current starts to reduce, thereby causing the magnetic field to shrink or contract and reverse the polarity of the self induced emf. Acting to oppose a change, the induced emf is now in a direction to maintain the current and thus becomes the source of voltage in the circuit. The condenser, the discharge of which built up the magnetic field, is now charged by the emf induced by the collapsing field. As indicated in Figure 2D, the electron flow continues in the same direction but charges the condenser to a polarity opposite that of Figure 2A. This action continues until the field is completely collapsed and its energy has been transferred to the condenser as indicated in Figure 2E.

Except for the reversal of condenser polarity, conditions of Figure 2E are the same as those of Figure 2A. Therefore the condenser discharges through coil L, building up the field of Figure 2F until it reaches maximum as indicated in Figure 2G. As explained for Figure 2C, here the energy has been transferred to the magnetic field which collapses and, as indicated by Figure 2H, charges the condenser to its original polarity of Figure 2A. With the original conditions restored, one cycle has been completed and the entire action is repeated.

Thus, the periodic transfer of energy from the electrostatic charge of the condenser to the electromagnetic field of the coil and back to the condenser produces an oscillating current in the circuit. The rate at which these transfers occur depends upon the capacitance of the condenser and the inductance of the coil. For example, with the voltage and inductance remaining the same, if the capacitance of the condenser is increased, more time will be required for its discharge and charge therefore the frequency of the oscillations will be reduced. An increase of inductance will produce the same action but a decrease of inductance or capacitance will cause an increase in the freqency of the oscillations.

## GRAPHIC EXPLANATION OF OSCILLATING CIRCUIT

The instantaneous values of voltage and current for the complete cycle as explained for Figure 2 can be shown by the curves or graph of Figure 3. Here, the current is represented by curve "i", the condenser voltage by curve $e_c$ and the voltage across the coil by curve $e_L$. As the condenser and coil act alternately as a source and a load, the solid portions of the voltage curves represent the source or supply voltage and the dashed portions represent the reactive or load voltage. As far as the oscillating current is concerned, the condenser and coil are in series and at all times, therefore the voltages across them will be equal in value and opposite in polarity.

The ordinates of Figure 3 are lettered to correspond with the circuit conditions of Figure 2. Starting at ordinate A, which corresponds to Figure 2A, the condenser is charged to maximum voltage and, although the current is zero at this instant, the voltage drop across the coil is equal to but opposite in polarity to the condenser voltage. As the condenser discharges, through ordinate B, its voltage reduces as the current increases. This action continues to ordinate C when the current has increased to maximum and the voltage has dropped to zero.

During this interval, the condenser is the source of voltage and the coil is the load. As explained for Figure 2B, the increase of current causes an expanding field around the coil and, by self induction, induces a counter emf. As we assume this simple circuit has zero resistance, this action causes the current to lag the voltage by 90°. Thus, at the instant the circuit voltage is zero, the maximum current causes the maximum magnetic field around the coil.

Immediately after reaching its maximum value, the current starts to reduce thereby causing the magnetic field to contract and induce an emf of a polarity to maintain the current. Because the induced emf is proportional to the rate of current change, as it decreases more rapidly the induction increases, as shown through ordinate D. The greatest rate of current change occurs as it passes through zero value therefore, as shown at ordinate E, emf induced in the coil is maximum.

With zero current, there is no field around the coil and therefore no induction but the condenser is charged to the maximum value of voltage, the increase of which is indicated by the broken line section of curve $e_c$, between ordinates C and E. During this interval, the induced emf in the coil is the source voltage and the condenser is the load, therefore the current leads the voltage by 90°.

Except for the reversal of polarity, the voltage values of ordinate E are the same as those of ordinate A therefore, with this exception, the action through ordinates F, G, H and A is the same as that explained through ordinates B, C, D and E.

The complete cycle consists of four distinct actions. During the interval A-B-C, the condenser discharges and transfers its energy to the magnetic field around the coil. During the interval C-D-E, the magnetic field collapses and by electro-magnetic induction transfers its energy to the condenser, charging it in the opposite polarity. During the interval E-F-G the condenser discharges, and transfers its energy to the magnetic field which during interval G-H-A transfers the energy back to the condenser. Notice here, the condenser charges and discharges during each alternation of current and therefore is charged and discharged twice during each cycle.

The greater the value of the inductance, the longer will be the time required for the condenser C to discharge through it. Likewise, the greater the value of the capacitance, the longer it will take to charge or discharge it. Since the velocity of electron flow is substantially constant, the values of both the inductance and the capacitance determine the period of time required for a complete cycle or oscillation. The value of this period T, in seconds, is equal to $2\pi\sqrt{LC}$, where L is the inductance in henries and C the capacitance in farads. Since the frequency "f" in cycles is equal to the reciprocal of T, the fundamental oscillation frequency of any LC circuit is the same as its resonant frequency and is given by the formula:

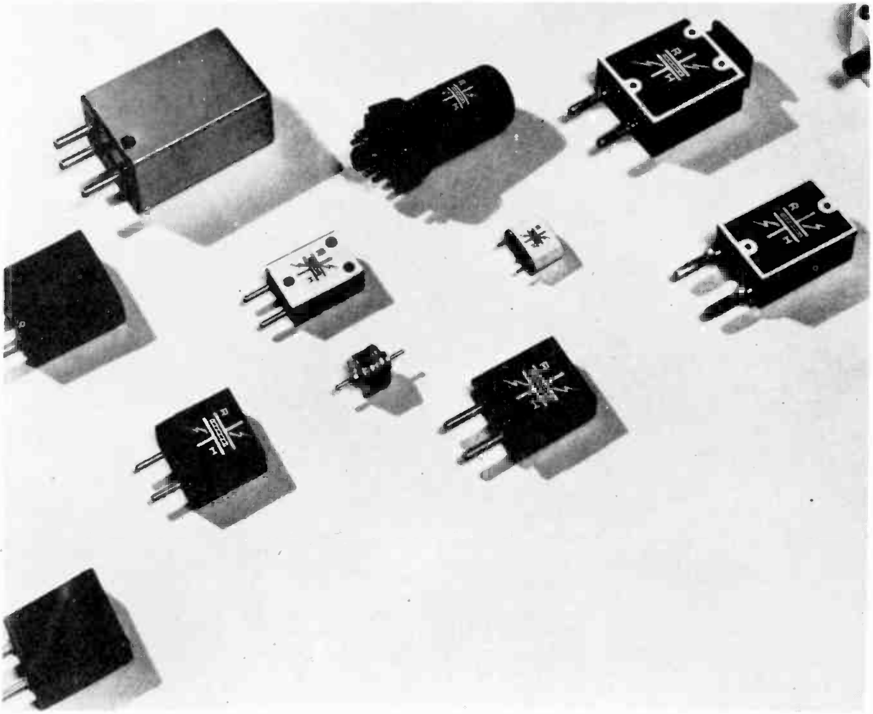
$$f = \frac{1}{2\pi\sqrt{LC}}$$

## FUNDAMENTAL OSCILLATOR ACTION

With a pulse of energy applied to the LC circuit of Figure 1, the oscillations are initiated, and would continue indefinitely if there were no resistance in the circuit. However, as is known, the total circuit resistance is made up of the resistance of the coil, the connecting wires, the condenser plates, and the various other connections. Therefore, due to the resulting loss, a small amount of energy is dissipated during each cycle, and unless this energy is replaced by an external source, the condenser will be charged to a slightly smaller voltage each time, as shown by the curve of Figure 4. The number of cycles which occur before the oscillations die out is inversely proportional to the amount of resistance in the circuit. Hence, to maintain oscillations, the LC circuit must be supplied regularly with additional energy.

Modern AM and FM superheterodyne tuner with speaker. Oscillators form essential units in receivers of this type.
Courtesy Espey Manufacturing Company, Inc.

As indicated by the curve of Figure 4, the oscillatory circuit has the property of storing more energy than is lost per cycle therefore it is not necessary to supply energy continuously to maintain the oscillations. Rather, the switching device can be arranged to connect the external source to the LC circuit only during a portion of each cycle, and it need supply only sufficient energy to make up for the amount lost during the remainder of the cycle.



Typical mounted and encased crystal units.
Courtesy Reeves-Hoffman Corporation

At the high or radio frequencies generated by most common types of oscillators, it is impractical to attempt to use any mechanical device to act as the switch of Figure 1 therefore it is replaced by an electron tube. A simplified version of an electron tube oscillator circuit is shown in Figure 5 which includes the B supply and oscillatory LC circuit of Figure 1.

The plate circuit of the triode tube V is connected in series between the oscillator or tank circuit and B supply negative. In earlier lessons, it has been stated that the grid cathode voltage of a triode tube controls the plate current, but for this explanation it can be considered as controlling the conductivity of the internal plate circuit. When the grid becomes more positive in respect to the cathode, the plate current and conductivity increase and when the grid becomes more negative, the plate current and conductivity decrease. Here, the grid voltage is induced in coil $L_2$ which is coupled inductively to plate coil $L_1$.

With the tube in operating condition, when the B supply circuit is closed there is an initial surge of current in plate coil $L_1$. This increasing current causes a voltage drop which charges condenser C and also sets up an expanding magnetic field that cuts coil $L_2$ and induces a voltage in it. This induced voltage is of a polarity which drives the grid positive with respect to the cathode, thereby increasing the plate current and conductivity of the plate circuit inside the tube.

As this action continues, the plate current increases, the drop across coil $L_1$ increases and the drop across the tube decreases until the condenser is charged to approximately the full voltage of the B supply. Thus, with maximum plate current, the $L_1$-C circuit voltage corresponds to that shown at A in Figures 2 and 3. At this instant, the condenser is fully charged, there is no charge or discharge therefore the current in its circuit is zero, as indicated by curve "i" of Figure 3.

In circuits of this type it is convenient and customary to consider that the total current in plate coil $L_1$ consists of two distinct components. (1) The d-c plate current carried by the coil and tube and (2) The circulating or oscillating current represented by curve "i" of Figure 3. Thus, with maximum plate current there is minimum circulating tank current.

Going back to the circuit of Figure 5, as the plate current approaches maximum, the induced voltage in coil $L_2$ dies out therefore the grid becomes less positive or more negative with respect to the cathode. This change of grid voltage causes a reduction of plate current thereby reducing the voltage drop across coil $L_1$. With a lower drop across the coil, the condenser discharges through it in a direction to maintain the current and thus, as explained for Figures 2 and 3, the oscillating current increases. When the total coil current decreases, the flux lines contract and the resulting emf induced in coil $L_2$, is of a polarity which drives the grid negative.

As this action continues, the grid is driven negative to plate current cut-off causing the tube to become non-conductive and the circuit conditions of Figure 5 duplicate those of Figure 1. The changing values of oscillating current maintain the grid at negative plate current cut-off as the cycle continues. Finally, the voltage induced in coil $L_2$ decreases to a value less than cut-off, the tube becomes conductive and the cycle repeats.

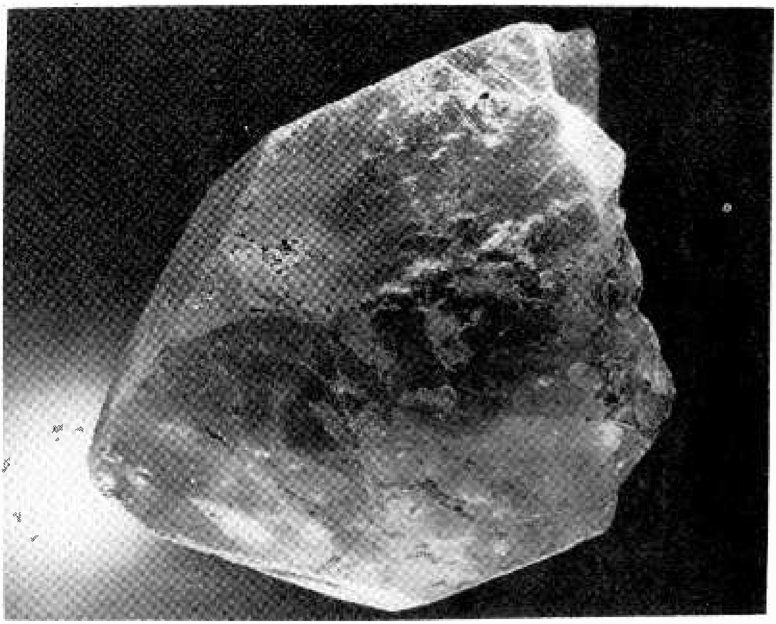
Thus, the vacuum tube is conductive during one part and nonconductive during the remainder of each complete cycle of the oscillating current. When conductive, the tube allows the condenser to charge to the full voltage of the supply and thus replaces energy lost during the preceding cycle. As a result, all cycles are of equal amplitude and the oscillations continue as long as the external power is applied to the circuit.

In the simplified circuit of Figure 5, the plate current varies from saturation to cut-off and as larger changes of grid voltage could not increase these variations, the maximum amplitude of the oscillations is limited by the "plate current-grid voltage" characteristics of the tube. Thus, the amount of d-c energy which can be supplied to the oscillatory circuit is limited by the tube, which acts as an automatic valve and tends to maintain the amplitude of the oscillations at a constant level.

As previously mentioned, an LC or tank circuit is capable of storing much more energy than is lost during any one cycle of oscillation and therefore a short pulse of d-c from the supply source is sufficient to maintain the action. In the simplified circuit of Figure 5, the tube is conductive for a considerable part of a cycle, and therefore the action is not very efficient. Also, the saturation current may be of sufficient amplitude to overheat and damage the tube electrodes.

To provide a more efficient and practical oscillator, the tube is operated class "C", that is, with a bias of about twice cut-off. The pulse of plate current sufficient for maintaining oscillations then occurs only during the most positive peaks of the grid voltage swing. However, if a fixed bias arrangement is employed, the negative grid voltage will prevent the initial pulse of current when the plate circuit is closed, and the oscillations will not start unless the grid circuit is supplied with a-c energy by some external source. In order to be self-starting, an oscillator of this type requires an initial zero bias which attains its normal operating value only after the circuit is in operation.

This change of bias voltage is provided by the grid-leak and condenser arrangement of $R_1$ and $C_1$ in the practical oscillator circuit of Figure 6. Careful study of this diagram reveals it to be simply a rearrangement of the components of Figure 5, with the addition of the bias elements $R_1C_1$ and the bypass condenser $C_2$. Condenser $C_2$ provides a low impedance path for the a-c between the B+ end of the tank circuit and the cathode of the tube.

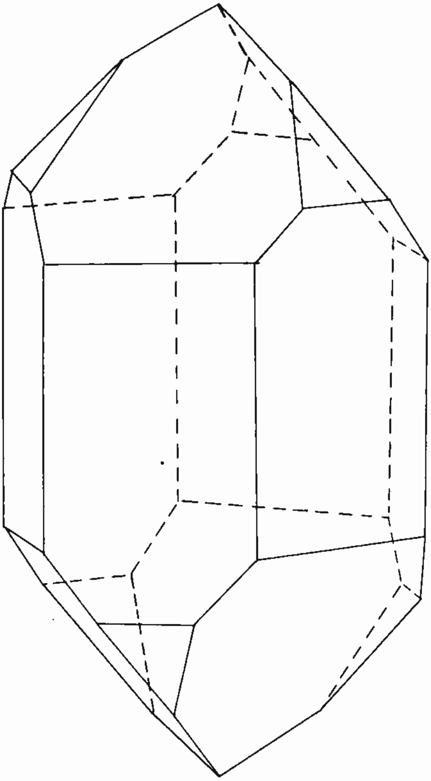


A piece of natural quartz crystal as it is found near the surface of the earth.
Courtesy North American Phillips Company, Inc.

Before the plate supply circuit is closed, the oscillator of Figure 6 is electrically at rest and there is zero bias on the grid of tube V. When power is applied, a pulse of plate current occurs, and the circuit goes into oscillation as explained for Figure 5. Whenever the grid is positive with respect to the cathode, there is grid current which, carried by resistor $R_1$, causes a voltage drop that charges condenser $C_1$ to the indicated polarity. Since the resistance of $L_2$ is very low, the d-c drop across it is negligible and thus the positive plate of $C_1$ can be considered at d-c ground potential. As the cathode of tube V is grounded also, the drop across $C_1$-$R_1$ is applied to the grid-cathode circuit and the grid becomes negative with respect to the cathode.

The grid is driven positive only during portions of the oscillation cycle therefore the grid current occurs in pulses, each of which charges condenser $C_1$ as previously explained. Between the pulses of grid current, condenser $C_1$ discharges through resistor $R_1$. In practice, the chosen values of $C_1$ and $R_1$ are relatively large for a given oscillation frequency, so that the condenser discharges but slightly before it is recharged again by a succeeding pulse of grid current. Thus, as the oscillations attain their normal operating amplitude, an essentially d-c grid bias voltage is developed across $C_1$ and the parallel connected grid resistor $R_1$.

In addition to the self starting action of the grid leak bias type oscillator, it serves also as an automatic amplitude control. The amount of positive grid swing, as well as the charge on $C_1$, depend upon the magnitude of the voltage induced in coil $L_2$. Therefore, any increase in the amplitude of the oscillations in the tank circuit results in a greater induced voltage which increases the grid current. The increased grid current causes a greater drop across R and thereby increases the negative grid bias. With greater negative grid bias, the plate current pulses are of shorter duration, less energy is supplied to the tank circuit and thus, the complete action tends to reduce the oscillation amplitude. On the other hand, a decrease in the amplitude of the oscillations results in a lower negative grid bias, allows more energy to be supplied to the oscillatory circuit, and thus tends to increase the amplitude.



Line drawing of a perfectly shaped quartz crystal.
Courtesy North American Phillips Co., Inc.

## TYPES OF OSCILLATORS

Electron tube oscillators may be classified in a number of ways, such as: (1) According to the frequency of the generated a-c, (2) According to the waveform of the output voltage, and (3) With regard to the circuit device or arrangement which makes oscillation possible. In none of these classes can a sharp line be drawn between the various types included. For example, the oscillator which produces radio frequencies in the broadcast range is a high-frequency oscillator compared to an audio signal generator, but it is a low-frequency device compared to a "microwave" oscillator.

Waveform classification places oscillators which generate pure or nearly pure sine waves into a group called "sinusoidal", all others being classed as "non-sinusoidal". This grouping is made in accordance with the fact that different methods of analysis may be applied to oscillators, depending upon whether their output is sinusoidal or not. However, again the distinction between types is not sharp, for in many oscillators the output wave can be made to vary without interruption from sinusoidal to non-sinusoidal by adjusting the value of some circuit element. The circuit of Figure 6 is an example of a sine wave oscillator, while the non-sinusoidal types, which include multivibrators, glow-discharge circuits, etc. will be taken up in later lessons.

## NEGATIVE-RESISTANCE OSCILLATORS

In the explanations of Figures 1 through 6 it was shown that oscillations can be set up and sustained if means are provided to replace the energy which is lost by the resistance in the oscillatory circuit. That is, the usual type of resistance element absorbs power from a circuit, whereas an oscillator requires the employment of an element which can supply power to the circuit.

For simplicity, it was assumed that there was zero resistance in the circuit of Figures 1 and 2, but, as such a condition is impossible in practice, the effect of resistance was shown by the curve of Figure 4. To indicate actual conditions, the circuit is redrawn in Figure 7A with the addition of resistor R which represents the resistance of the connecting wires and the coil L. Usually, the effect of the condenser resistance is negligible.

Referring to the earlier explanations, both coil L and condenser C absorb or store energy during a portion of oscillator cycle and then return it to the circuit during a later portion of the cycle. In comparison, energy absorbed by the resistance is dissipated, usually in the form of heat, and is lost as far as the circuit is concerned. Therefore, to sustain the oscillations it is necessary to supply only the energy lost in the resistance. In terms of power, this is known as the $I^2R$ loss.

In the circuit of Figure 5, the losses of energy in the tank circuit are replaced by the "B" supply which, for comparison, is indicated as resistance "$R_N$" in the simplified circuit of Figure 7B. Thinking only of circuit resistance, according to Ohm's Law, $I = E/R$ and, when the voltage E is reduced, the current I will reduce in proportion. However, with $R_N$ added to the circuit of Figure 7A as shown in Figure 7B, when the voltage E is reduced, the current I increases.

According to the relationship expressed by Ohm's Law, the addition of $R_N$ has caused a reduction of effective resistance and, in mathematics, a reduced total is obtained by the addition of a negative quantity. Therefore, from this point of view, $R_N$ is considered as negative resistance to distinguish it from the positive or normal ohmic resistance inherent in all electric conductors.

When any device equivalent to a negative resistance, $R_N$, is connected to an LC circuit containing ohmic resistance, R, oscillation in the tank circuit will either: (1) be sustained indefinitely, (2) increase in amplitude until the energy capacity of the system is reached, or (3) die out, depending upon whether $R_N$ is equal to, greater than or less than R.

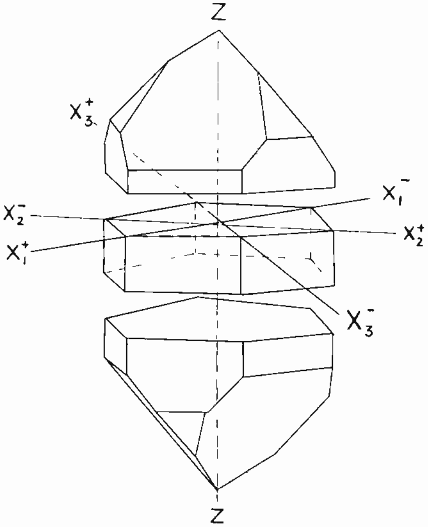
Of course, it must be understood that in actual circuits the negative resistance device represented by $R_N$ of Figure 7B does not have the form of the familiar carbon or wire wound resistor, and that the diagram is merely a way of picturing schematically the basic requirements of an oscillator circuit.

The third method of classification divides the generators into "negative-resistance oscillators" and "feedback oscillators". However, according to the explanations in connection with Figure 7, any oscillator circuit must include the negative resistance element $R_N$, or its equivalent.

Thus, basically both types mentioned are negative-resistance oscillators; however, in practice this name is applied only to those in which the negative resistance is inherent in the vacuum tube or in the tube and its associated resistors and condensers, and does not depend for this property on the arrangement of the tuned circuit. On the other hand, in the feedback oscillators, the negative resistance is dependent upon the action of the tuned circuit, as well as the way in which it is coupled to the tube.

## DYNATRON

The Dynatron type of negative-resistance oscillator utilizes the effect of secondary emission on the plate current of a tetrode. With this tube, the plate voltage-plate current characteristic curve has a negative slope in the region where the plate voltage is lower than the screen voltage. That is, as the plate voltage rises, the number of plate-emitted secondary electrons increase and, collected by the screen, act to decrease the net plate current, resulting in a situation wherein an increase in plate voltage causes a decrease in plate current, and vice versa.



Line drawing showing the crystal axes, and also how a slab is cut from the mother crystal.
Courtesy North American Phillips Co., Inc.

Since this action satisfies the conditions of negative resistance, the tetrode tube is therefore an element which is capable of releasing a-c power to the load. When connected in the position of $R_N$ in Figure 7B and operated at low plate voltage, it can be used to maintain oscillations in a tuned circuit.

## TRANSITRON

Due to its dependence upon secondary emission, the dynatron oscillator has two serious disadvantages. First: the amount of secondary emission, at given operating voltages, changes with the use or age of the tube and second, large differences are observed in the shapes of the characteristic curves of individual tubes of the same type.

The disadvantages of depending upon secondary emission are avoided in the use of the negative-resistance type known as the "transitron", or "negative-transconductance" oscillator, the circuit of which is shown in Figure 8. In this arrangement, the tank or oscillatory circuit LC, is placed in the screengrid circuit, from which the a-c power is supplied to maintain oscillations, and the suppressor grid is coupled to the screen grid through the condenser $C_1$. The value of $R_1$ and $C_1$ are chosen so that, at the operating frequency, the reactance of $C_1$

is low compared to the resistance of $R_1$, and therefore any change of screen grid voltage will be accompanied by a practically equal change of suppressor grid voltage.

Because of its location between the plate and screen, the suppressor grid, when negative, will return electrons that have passed through the screen grid thereby increasing the screen current. On the other hand, a negative swing of the screen grid voltage tends to decrease the screen current. As the suppressor grid is coupled to and changes voltage in step with the screen grid, the screen current is acted upon simultaneously by two forces, one tending to increase and the other to decrease its value. However, the effect of the suppressor grid voltage change is greater than that of the screen grid, and thus the net result is that a decrease or negative swing of screen voltage (and suppressor voltage) produces an increase in screen current. Likewise, an increase (positive swing) of screen voltage causes a decrease of screen current. Again, the condition of negative-resistance is satisfied, and in the circuit of Figure 8, the cathode-screen circuit of the tube becomes an element capable of supplying power to sustain the oscillations in the tank circuit LC.

It is not practicable to attempt to analyze all of the many oscillator circuits at this time therefore the details of the various types will be covered in the later lessons in connection with the particular applications in which they are employed. Since the lessons which follow immediately include explanations of broadcast-frequency receiver and transmitter operation, the radio-frequency sinusoidal feedback types of oscillator which are employed in this field, will be described at this time.

## FEEDBACK OSCILLATORS

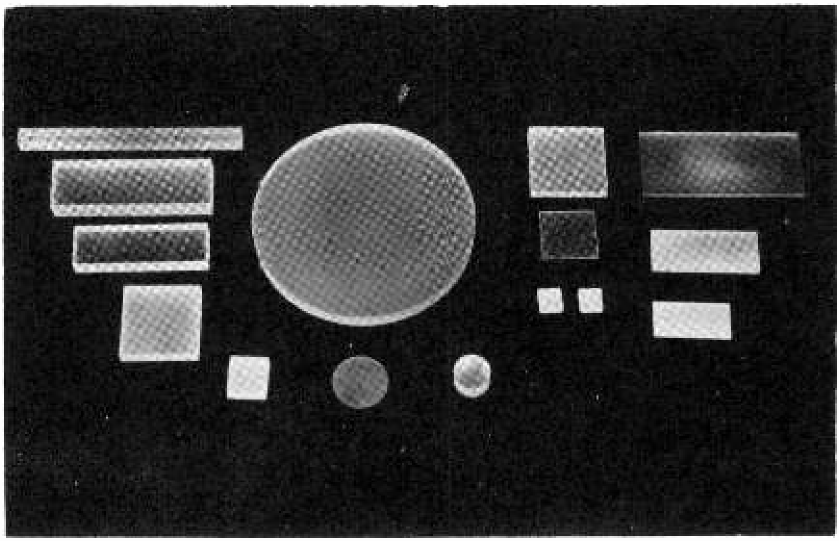
Although the feedback oscillator was defined previously as a particular type of negative-resistance oscillator, a more common analysis is to consider it as a self excited electron tube amplifier in which a portion of the output energy is fed back to the input circuit. This idea is pictured in the simplified diagram of Figure 9 where the input voltage $e_i$ is increased in amplitude by means of the normal amplifying properties of the tube V, and the output voltage $e_o$ is fed back to the input, in proper phase and amplitude, through some type of coupling arrangement.

Since the output contains more a-c energy than is needed to properly drive the input grid of the amplifier tube, the surplus power is available for external use, and may be coupled to the input of a conventional amplifier or other circuit. Though differing in details of circuit arrangement and components, all of the feedback oscillators to be described have the general form of Figure 9. Also, let it be repeated that no matter what means of circuit analysis is employed, the essential components required for oscillation are: the oscillatory circuit (LC or other), a source of d-c power, and a means of supplying this power to the oscillatory circuit in such a way as to sustain the oscillations.

## TUNED-PLATE OSCILLATOR

The circuit of Figure 6, satisfies the requirements of a feedback oscillator because a change in the grid voltage of V will be amplified by the tube and appear in the plate circuit. By means of the inductive coupling between $L_1$ and $L_2$, energy from the plate circuit is fed back to the grid and amplified again.

Connections between coil $L_2$ and the grid circuit are made so that, as the plate current increases, the grid is driven positive and the conductivity of the tube is increased. As a result of this action, the plate voltage decreases as the plate current increases and thus the tube provides the negative resistance, indicated as $R_N$ in Figure 7B, and supplies the power necessary to maintain the oscillations.



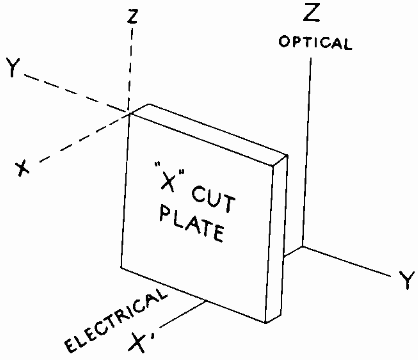
Various shapes of quartz blanks as they are cut from the solid crystal. The large round crystal is 3½ inches in diameter, and the rest are proportional in size.

Courtesy The James Knights Company

The tuned circuit, which determines the frequency of oscillation, is in the plate circuit of Figure 6, therefore this arrangement is known as a "tuned plate oscillator".

## TUNED-GRID OSCILLATOR

The tuned circuit may be located in the grid circuit of the tube, with the feedback coupling coil in the plate circuit. This arrangement, called a "tuned-grid oscillator", is shown schematically in Figure 10 where any change of plate current in coil $L_1$ induces a corresponding emf in coil $L_2$. As coil $L_2$ is connected across the grid circuit, energy is fed back from the plate circuit to the grid by the transformer action of $L_1$ and $L_2$. As in the circuit of Figure 6, in order to sustain oscillations, the coupling between the coils and their connections must be such that the feedback voltage has sufficient amplitude and proper phase.



Line drawing showing the axes of an X-cut crystal plate.

Courtesy North American Phillips Co., Inc.

Compared with Figure 6, the circuit of Figure 10 also illustrates a variation of the arrangement of the grid-leak bias components, $R_1$ and $C_1$. As far as the action in developing the grid bias is concerned, the two arrangements are alike; however, with the resistor $R_1$ in parallel with the tuned circuit, as in Figure 10, it acts as a "load" and provides greater stability of oscillation. Therefore, this method is an advantage as far as oscillators are concerned and is employed in practically all circuits of this type.

## HARTLEY OSCILLATOR

Perhaps the most common oscillator circuit is the Hartley, one form of which is shown in Figure 11A where a single tapped coil, made up of sections $L_1$ and $L_2$, performs the functions of coils $L_1$ and $L_2$, respectively, of Figure 10.

Tracing the d-c circuits, there is a path from "B+" to the tap on the coil, through section $L_1$ to the plate and through the tube to the grounded cathode and "B−". The grid connects to the cathode through resistor $R_1$. Tracing the r-f or oscillation frequency circuits, there is a path from coil tap "T" through section $L_2$, condenser $C_1$, resistor $R_1$ and condenser $C_2$ back to the tap T.

Remember here, the reactance of a condenser is extremely high at d-c or zero frequency but decreases as the frequency increases. Thus, for the d-c paths the condensers act as open circuits and the voltage across $C_2$ is equal to that of the B supply. In the same way, the d-c drop across $C_1$ is approximately equal to the voltage of the B supply which therefore does not affect the grid of the tube. Because of this action, a unit connected in the position of $C_1$ is known as a blocking condenser. For the comparatively high oscillation frequency, the drop across condenser $C_2$ is so low that tap "T" is at approximately r-f ground potential. In the same way, the drop across condenser $C_1$ is so low that the r-f voltages induced in section $L_2$ of the coil are impressed across $R_1$ and the grid cathode circuit with negligible loss.

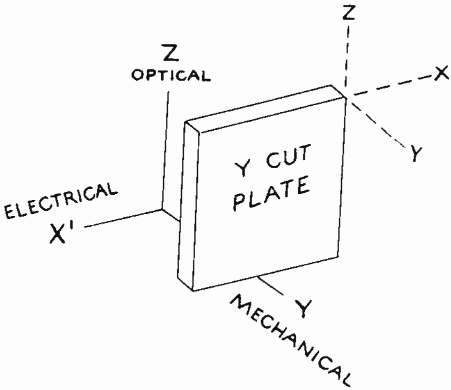
With these actions in mind, the operation of the Hartley oscillator of Figure 11A is essentially the same as that of the tuned grid oscillator of Figure 10, but there is one important difference. In the tuned grid oscillator, the tank circuit consists of coil $L_2$ and condenser C while the plate energy is fed back through the inductive coupling between coils $L_1$ and $L_2$. In the Hartley oscillator, the tank circuit consists of coils $L_1$ and $L_2$ connected in series across condenser C and therefore both will carry the oscillating tank current. Thus, with no inductive coupling between the sections of the coil, plate energy will be fed back to the grid and the circuit will oscillate.

For convenience and economy, in practice, sections $L_1$ and $L_2$ are wound as a single coil and proper phase relations are obtained by connecting the plate to one end and coupling the grid circuit to the other. The amplitude of the feedback voltage is controlled by the position of the tap.

## SHUNT AND SERIES FEED

Because the d-c supply and the coil section $L_1$ are in series with the tube plate, the circuit of Figure 11A is termed a "series-fed" Hartley. One disadvantage of this arrangement is that the tank circuit is placed at the high d-c plate supply potential with respect to ground, and thus constitutes a shock hazard to the operator. A second disadvantage is that the blocking condenser $C_1$ must have sufficient insulation to withstand the high d-c plate voltage.

These disadvantages are eliminated in the "shunt fed" Hartley circuit of Figure 11B which includes two parallel paths between the plate of the tube and ground.



Line drawing showing the axes of a Y-cut crystal plate.
Courtesy North American Phillips Co., Inc.

Starting at the plate there is a d-c path through the radio frequency choke, (RFC) and through the supply from B+ to B− and the grounded cathode. Starting at the plate again, there is an r-f path through condenser $C_2$ and coil section $L_1$ to tap T and ground. Here, $C_2$ acts as a blocking condenser and prevents d-c voltage across or direct current in section $L_1$ of the coil.

Variations of plate current produce corresponding changes of voltage drop across choke RFC and these in turn, cause inverse variations of plate voltage. These changes of plate voltage, impressed across the circuit made up of $C_2$-$L_1$ cause the oscillating or tank current and the resulting action is the same as explained for the circuit of Figure 11A.

With a d-c supply, the plate of tube V is always positive with respect to ground and changes of voltage drop across choke RFC increase and decrease its positive potential. Thus, with the tube in operation, there is a pulsating d-c voltage between plate and ground. Due to the blocking action of condenser $C_2$, there is no d-c drop across section $L_1$ of the coil. However, when the plate voltage increases, the condenser charges and when the plate voltage decreases the condenser discharges because, at all times, the plate voltage is impressed across it. Carried by coil $L_1$, these charge and discharge currents are in opposite directions therefore, the pulsating d-c plate voltage causes alternating or r-f current in the coil.

Although shown as an r-f choke, the distributed capacitance of the coil, plus stray capacitance of the wiring, provide conditions for resonance. Therefore, to prevent an excess absorption of power, the inductance of the choke must be of such value that the resonant frequency of its circuit does not approach that of the tuned tank circuit.

## COLPITTS OSCILLATOR

In all of these explanations, it must be remembered that a condenser is non-conductive and therefore prevents current through it. It is this action which permits $C_1$ of Figure 11A and $C_2$ of Figure 11B to act as blocking condensers. However, when connected across an a-c supply, a condenser periodically charges and discharges and the resulting displacement currents appear as alternating current in its circuit. The value of this a-c depends upon the applied voltage and the condenser reactance which is measured in ohms the same as for resistance. Thus, in a-c and especially r-f circuits, the current in a condenser circuit is considered on the same general plan as the current carried by an inductance or resistance.

In the Hartley circuit of Figure 11-A, the coil is tapped to provide the feedback voltage but, to obtain the same action, in the Colpitts oscillator circuit of Figure 12, the tank condenser is tapped. In other respects, the circuits are alike and operate on the same principles.

From a practical standpoint, the tank condenser is in two parts, $C_p$ and $C_g$, with the grid circuit across $C_g$, the plate circuit across $C_p$, and the coil L across both. Here, the amount of feedback is controlled by changing the relative values of $C_p$ and $C_g$. The smaller the capacitance of $C_g$, the higher its reactance and the greater the voltage across it.

While they are quite similar in operation, both the Hartley and Colpitts oscillators claim certain advantages. For example, the Hartley is simpler to tune, but the adjustment of the feedback or tap on the coil is more inconvenient. For the Colpitts, the feedback voltage ratio can be adjusted easily by employing variable condensers. With fixed condensers, the inductance of the coil can be varied, or plug-in coils covering a wide range of frequencies can be used without disturbing the feedback voltage ratio.

## TUNED PLATE-TUNED GRID OSCILLATOR

Another basic type of oscillator circuit, shown in Figure 13, includes a tuned circuit $L_2C_g$ connected to the grid, with another tuned circuit, $L_1C_p$, connected to the plate. Therefore, the arrangement is known commonly as a "tuned plate-tuned grid" type of oscillator. Compared with the circuit of Figure 10, there is no apparent coupling between the plate coil $L_1$ and the grid coil $L_2$. However, in order to maintain the conditions required for oscillation, there must be feedback from the plate to the grid circuit.

From the earlier explanations you remember that a-c signal circuits can be coupled inductively or capacitively. By comparing Figures 10 and 13, you will find the grid circuits are the same, but in Figure 10 the untuned plate coil $L_1$ is coupled inductively to the grid coil $L_2$. In Figure 13, the plate coil $L_1$ is tuned by condenser $C_p$ but there is no inductive coupling between it and the grid coil $L_2$. Instead, the circuits are coupled by the grid-plate capacitance of the tube, indicated by the broken line condenser $C_{gp}$.

To sustain oscillations, the plate circuit energy must be fed back in proper phase and with sufficient amplitude to replace the losses in the circuit. The oscillations occur at the resonant frequency of $L_2$-$C_g$ grid tank circuit and to provide the proper phase of the feedback voltage, the $C_p$-$L_1$ plate circuit is tuned to a slightly higher frequency. With triode tubes, the grid-plate capacitance usually is of sufficient value to provide the required coupling. However, the coupling capacitance can be increased by connecting a condenser externally in the position of $C_{gp}$.

## THE ULTRAUDION

In the circuit of Figure 14, we show one of the oldest types of tube oscillators, known as the ultraudion, which is not particularly stable at the lower radio frequencies, but has proven quite satisfactory in some ultra-high-frequency applications. On checking this circuit you will find it closely resembles that of the Colpitts of Figure 12, the main difference being that in the ultraudion, the coil L is connected across the capacitor $C_p$ only.

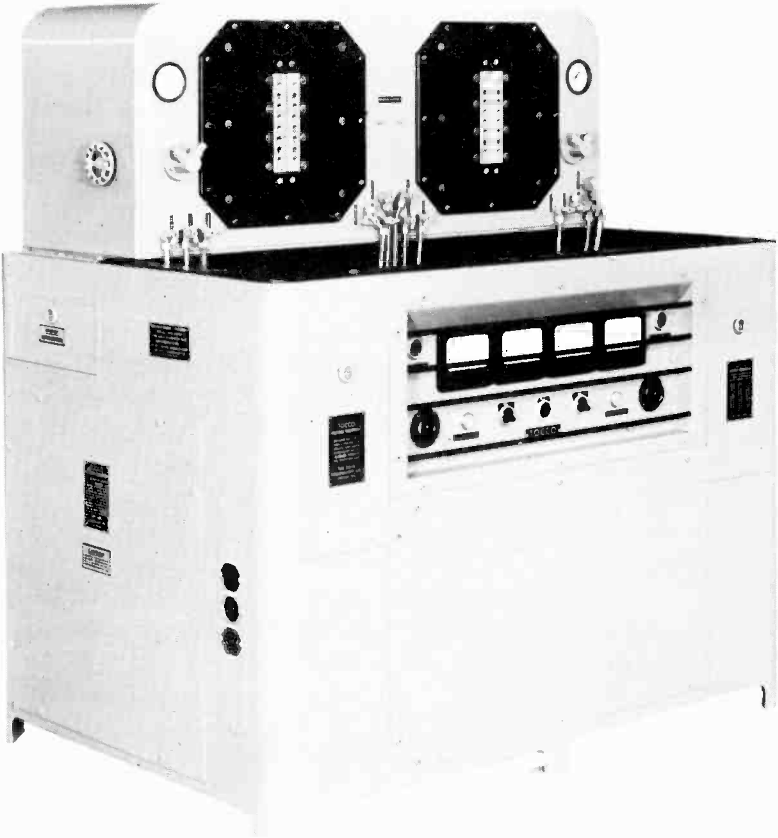
In operation, a change in plate current causes a change in plate voltage due to the drop across RFC. This drop is applied through condenser $C_2$ across the tank circuit $LC_p$ in series with condenser $C_g$. The portion of this drop which appears across $C_g$ is impressed on the grid through coupling condenser $C_1$ and resistor $R_1$. This is the grid excitation voltage which causes the system to oscillate, and its amplitude can be controlled by varying the capacitance of condenser $C_g$. The action of the ultraudion is explained also by assuming the tuned tank circuit, L-$C_p$, couples the grid and plate while the grid-cathode and plate-cathode capacitances of the tube form a voltage divider as explained for the Colpitts circuit of Figure 12.

## MEISSNER OSCILLATOR

To provide a higher degree of frequency stability, a "floating tank circuit", LC, is used in the Meissner oscillator of Figure 15. Since the tank is in no way connected directly to any other part of the circuit, it is not affected as greatly by changes in circuit voltage or impedance values. Coil L is coupled inductively to both $L_1$ and $L_2$ and therefore, current variations in plate coil $L_1$ act to supply energy to the oscillatory circuit, while the necessary grid voltages for the tube are provided by the signal developed across grid coil $L_2$ due to the coupling between it and the tank coil L.

## ELECTRON-COUPLED OSCILLATOR

All the oscillators explained so far are fundamental types, known as "Self Excited" and due to the feedback from the plate to the grid, any changes in the plate circuit have a tendency to cause variations in the generated frequency. Thus, any changes in the load circuit, supplied with



Oscillators are used industrially for generating high-frequency power for induction heating.
Courtesy Ohio Crank Shaft Company

energy generated by the oscillator, can cause changes of frequency. In most oscillator applications it is necessary to maintain a constant frequency, and to reduce the interaction caused by changes of load, circuits have been developed to isolate the plate circuit.

One common form of this type of circuit is shown in Figure 16, and like other oscillators, its frequency is determined by the values of inductance and capacitance in the grid tank circuit, $L_1C_g$. The circuit differs from those explained previously in that no capacitive, inductive or direct coupling exists between the grid and plate circuits.

Instead, it employs a tetrode or pentode tube in which the screen grid acts as the plate of a regular triode self-excited oscillator. To prevent confusion, when operating as a plate, the grid is known as an anode. Thus, the cathode, control grid and anode are connected as a triode tube in an oscillator circuit such as a Hartley or Colpitts. Neglecting for a moment the plate circuit in Figure 16, the remaining tube elements, along with circuit components $L_1$, $C_g$, $R_1$, $C_1$, $R_2$, $C_2$ and the RFC, make up a shunt-fed Hartley oscillator. Here, however, the screen grid of tube V performs the function of the oscillator anode, and resistor $R_2$ serves in place of the plate circuit RFC of Figure 11B. For this part of the circuit, a Colpitts or other type of oscillator could be used as well as the Hartley.

Since the screen grid or anode of the tube is made of a mesh material, by operating it at a lower potential than the plate, it will capture only part of the emitted electrons, while the rest will continue on to the plate. Only enough electrons to supply the driving power for the oscillator need be taken by the anode. Thus the electrons pass through the anode in pulses, the frequency of which is determined by the oscillation in the $L_1C_g$ tank circuit, and this pulsating current then releases power to the plate-circuit load $L_2C_p$. Because of this action, the only coupling between the oscillator and the load is the electron stream which passes through the anode, and thereby we derive the name "electron-coupled oscillator" (eco).

In regard to frequency stability, an important advantage of the eco is that an increase in plate voltage will shift the frequency in one direction, while an increase in anode voltage will shift it in the opposite direction. Thus, by supplying the anode through a voltage divider arrangement in the plate supply, the anode voltage can be adjusted to a value which will make the frequency independent of the plate supply voltage. Under these conditions, any change in frequency due to a slight change in plate voltage will be neutralized by an opposite change in frequency due to the change in anode voltage. In general, the stability will be best when the ratio of the plate to anode voltage is about three to one.

It is difficult to obtain good frequency stability as well as high power output from oscillators of this type. Therefore, instead of attempting to obtain both of these desirable characteristics from one unit, when high power output is required, an oscillator and power amplifier arrangement is most frequently employed. A low power oscillator is used to provide good frequency stability, and its output is fed to a power amplifier from which large power output is obtained. This arrangement is known as a "Master Oscillator Power Amplifier", commonly abbreviated "MOPA".

## PARASITIC OSCILLATION

In our explanations so far, we have assumed the frequency at which the oscillator operates to be controlled by the values of inductance and capacitance in the tank circuit. However, the inter-element capacitances of the tube may resonate with the grid and plate circuit leads, which can be thought of as one-turn inductors, to produce oscillations at a frequency much higher than the resonant frequency of the tank circuit.

This action is known as "Parasitic Oscillation", and is undesirable because it absorbs power, acts as a power loss, and therefore reduces the available power output. In the oscillator of Figure 16, the RFC in the grid circuit is a common arrangement to prevent "Parasitics". As the inductance of the choke offers a much higher impedance to higher frequencies, it detunes the circuit and thus prevents the generation of parasitics. Because of this action, you will find r-f chokes inserted in an oscillator grid circuit, plate circuit, or both.

Due to coupling through the circuit condensers, low frequency parasitics sometimes occur when r-f chokes in both the grid and plate circuits resonate at about the same frequency, As the inductance value of these chokes is not critical, one common plan is to use units of different inductance so that their resonant frequencies will be sufficiently different to avoid the tuned grid-tuned plate action of Figure 13.

## CRYSTAL OSCILLATOR

To provide an extremely high degree of stability, the frequency of an oscillator can be controlled by a piezoelectric type of crystal. Like those used in crystal microphones and phono pickups, a voltage is generated between opposite surfaces of the crystal when it is subjected to mechanical strain or twisting. Also, if an a-c voltage is applied across opposite faces of the crystal, it vibrates mechanically.

Every object has a natural period of vibration, or what might be called its mechanical resonant frequency at which it will vibrate when subjected to a sudden force. A good example of this is the sound produced by a drinking glass when struck by a knife or fork. The frequency of this vibration is determined by the size or shape and the elasticity of the material from which the object is made. Thus, a quartz crystal has a natural period of vibration, and if a force is applied and removed suddenly, the crystal will vibrate at its natural frequency. However, due to its piezoelectric properties, a vibrating crystal produces an electrical voltage of the same frequency as the mechanical vibration, hence the vibrating crystal becomes a voltage generator.

The crystals employed in oscillator circuits are cut from whole or parent crystals with the general appearance shown in the sketch of Figure 17. As indicated by the broken lines, the parent crystal has three major axes, with the letter X used to denote the electrical axis, Y the me-

Large triode tubes are used in industrial high-frequency generators for developing power for induction and dielectric heating.

Courtesy Machlett Laboratories, Inc.

chanical axis and Z the optical axis. The parent or "mother" crystal has a hexagonal cross section and the relative directions of the three axes can be seen more clearly in Figure 18.

The optical or Z axis coincides with the axis of the hexagonal rod or bar while both the X and Y axes are at right angles to it. The X axis extends through opposite corners of the hexagon while the Y axis is at right angles to opposite faces and thus there are three X and three Y axes in the complete crystal. For use in oscillator circuits, smaller pieces or plates are cut from the mother crystal and the resonant or natural vibration frequency of these plates is inversely proportional to their thickness. The thinner the cut, the higher the frequency.

There are several cuts which can be made from a parent crystal, and the main difference between plates cut in different ways is their temperature coefficient, that is, how much the natural frequency changes for every degree change in crystal temperature. A plate cut with its major surfaces perpendicular to an X axis is known as an X-cut plate and has a negative temperature coefficient. That is, when the temperature increases, the frequency decreases. For a Y cut crystal the plate is cut from the parent so that its major surfaces are perpendicular to a Y axis, and it has a positive temperature coefficient.

The fact that the temperature coefficient of X and Y cuts are opposite, led to the belief that somewhere between them it might be possible to cut a crystal with a zero temperature coefficient so that temperature would not have any effect on its frequency. Working along this line, the Bell Telephone Laboratories developed an AT cut, shown in Figure 18, at an angle of 35° with the Z axis, while RCA developed a V cut, both of which have temperature coefficients of 2 parts per million per degree Centigrade. This is the same as saying .0002 per cent per degree Centigrade.

A simplified circuit of an oscillator employing one of these cut plates or "crystals" is shown in Figure 19. This circuit compares closely to that of the tuned grid-tuned plate oscillator of Figure 13 except that the crystal replaces the tuned grid circuit. In both cases, feedback is obtained through the grid-plate capacitance of the tube. As indicated by the diagram symbol, the crystal plate is mounted between metal plates to which the circuit connections are made.

Here, when the tube is placed in operation, the initial surge of plate current produces a voltage pulse which is impressed across the crystal and causes it to start vibrating at its natural or resonant frequency. As the crystal vibrates it generates a voltage of like frequency which is impressed across the grid circuit. Like the other types of oscillators, the amplifying action of the tube causes the changes of grid voltage to reappear at greater amplitude in the plate circuit. Here, the changes of plate voltage are fed back in sufficient amplitude to maintain the vibration of the crystal and the oscillations continue.

This arrangement is known as a crystal oscillator and like the tuned plate-tuned grid type, the plate circuit must be tuned to a frequency slightly higher than that of the crystal. However, the exact frequency of oscillation is controlled by the vibration of the crystal and, within ordinary limits, is independent of the electrical circuit conditions.

In order to maintain the frequency well within the limits allowed by the Federal Communications Commission, when the oscillator is used to generate the carrier of a transmitting station, the temperature of the crystal must be maintained approximately constant. This is accomplished by placing the crystal in a constant temperature oven which is nothing but a well constructed, air tight box, having heat insulated walls and containing a thermostat and a small heater. The thermostat is quite commonly a bimetallic snap action automatic switch, while the heater may be simply a coil of resistance wire which carries an electric current.

When the temperature in the oven falls below that for which the thermostat is adjusted, the contacts close and allow current in the heater element. When the proper temperature is reached, the contacts open and the heater is made inoperative. As the oven is at a higher temperature than the room, the heat leaks out gradually until the temperature is again of such value as to operate the thermostat and the cycle is repeated. Thus, the temperature variation of the crystal is dependent only upon the sensitivity of the thermostat.

## IMPORTANT NEW WORDS USED IN THIS LESSON

**COLPITTS OSCILLATOR**—A form of feedback oscillator in which two tuning condensers are connected in series across the tank coil, while the junction between them is tied to the cathode.

**DYNATRON**—A 4-electrode or tetrode tube operated at plate and screen voltages such that an increase in plate voltage causes a decrease in plate current—the arrangement is employed in an oscillator known by the same name.

**ELECTRON COUPLED OSCILLATOR**—A type of oscillator in which the electrode connected to the load is coupled to the oscillator proper only by the electron stream within the tube.

**HARTLEY OSCILLATOR**—A form of feedback oscillator in which the tank circuit is connected between the grid and plate, while a tap on the coil is tied to the cathode.

**LC CIRCUIT**—A circuit containing inductance and capacitance.

**NEGATIVE RESISTANCE**—A condition or arrangement by means of which an increase of current occurs with a decrease of voltage.

**NEGATIVE SLOPE**—The inclination of a line that extends in a general direction from the upper left to the lower right, so that the tangent of the angle that it makes with the horizontal is negative.

**OSCILLATOR**—An electronic device for converting d-c into high-frequency a-c energy.

**PULSE**—A single voltage or current disturbance of short duration.

**SHUNT FED OSCILLATOR**—Any LC type of oscillator in which the d-c supply is connected only to a separate circuit, effectively in parallel with the tank circuit.

**SINUSOIDAL**—Varying in value in accordance with the sine of an angle, or, resembling a sine wave in form.

**SLOPE OF A LINE**—The inclination of a line or graph, defined mathematically as the tangent of the angle that the line makes with the horizontal.

**TEMPERATURE COEFFICIENT**—A numerical factor that indicates how much and in what direction the frequency of a crystal varies with changes in temperature.

**THERMOSTAT**—A device that detects changes in temperature, or that automatically maintains the temperature within certain limits.

**TRANSITRON**—A type of oscillator in which the tuned tank circuit is connected into the screen-grid circuit, and the plate is operated at a lower potential than the screen.

**TUNED GRID OSCILLATOR**—A form of feedback oscillator in which the tuned tank is in the grid circuit of the tube, and the feedback coupling coil is in the plate circuit.

**TUNED GRID-TUNED PLATE OSCILLATOR**—A form of feedback oscillator that employs a tuned tank in both the grid and plate circuits, and feedback is obtained through the internal grid-plate capacitance of the tube.

**TUNED PLATE OSCILLATOR**—A form of feedback oscillator in which the tuned tank is in the plate circuit, and the feedback coupling coil is in the gird circuit.

**RESONANT FREQUENCY CALCULATION**—Calculate the resonant frequency of a LC tank circuit which contains a coil L with an inductance of 10 microhenries and a condenser C with a capacitance of 40 micromicrofarads. Using the formula of page 8

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

**When:** $L$ = Henries
$C$ = Farads
$\pi = 3.14$

**Converting tank circuit values to fundamental units,**

$$f = \frac{1}{6.28\sqrt{.000{,}01 \times .000{,}000{,}000{,}04}}$$

$$f = \frac{1}{6.28\sqrt{.000{,}000{,}000{,}000{,}000{,}4}}$$

$$f = \frac{1}{6.28 \times .000{,}000{,}02}$$

$$f = \frac{1}{.000{,}000{,}125{,}6}$$

$$f = 7{,}960{,}000 \text{ cycles} = 7{,}960 \text{ kilocycles}$$

$$f = 7.96 \text{ megacycles (approximate)}$$

# STUDENT NOTES

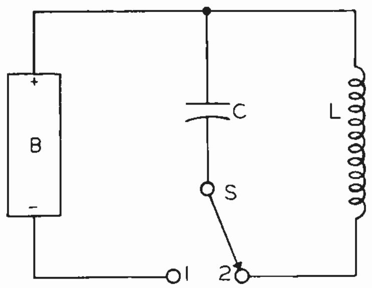


FIGURE 1

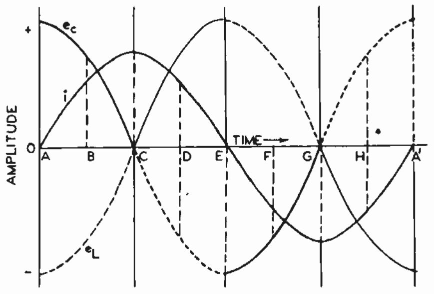


FIGURE 3

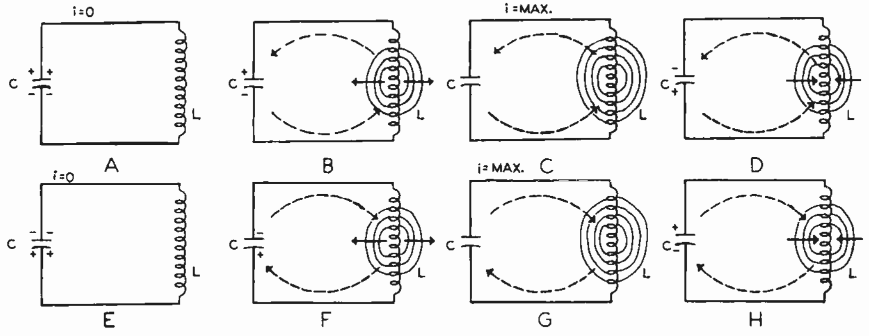


FIGURE 2

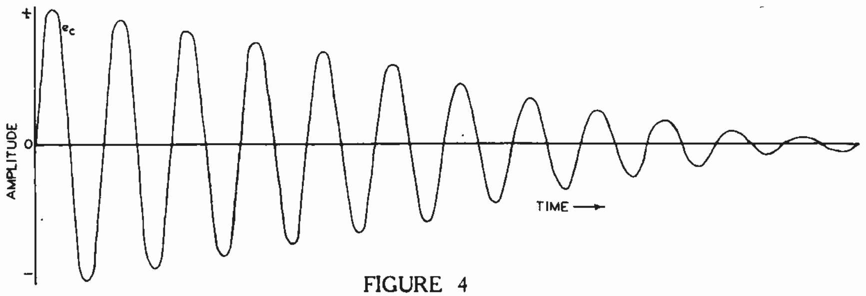


FIGURE 4

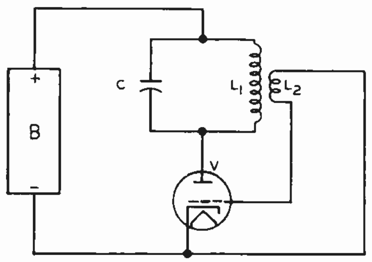


FIGURE 5

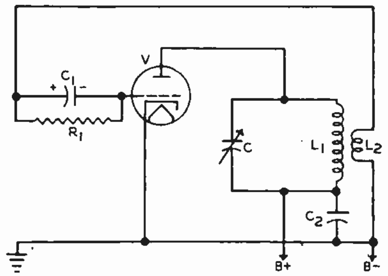


FIGURE 6

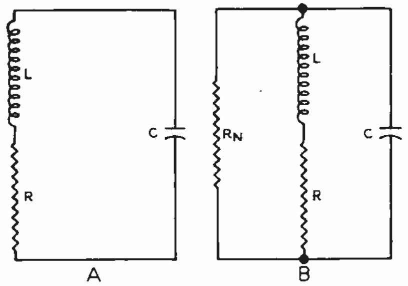


FIGURE 7

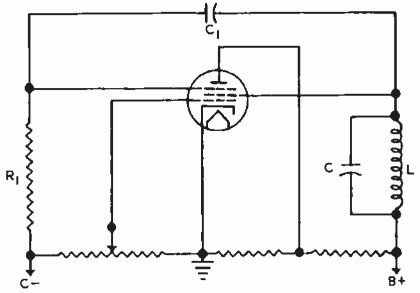


FIGURE 8

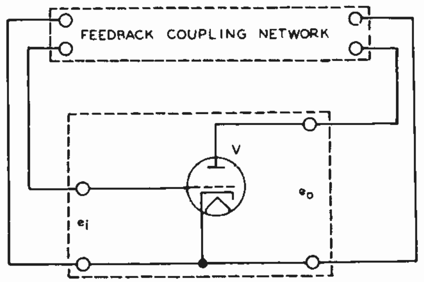


FIGURE 9

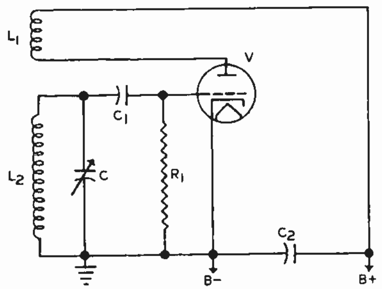


FIGURE 10

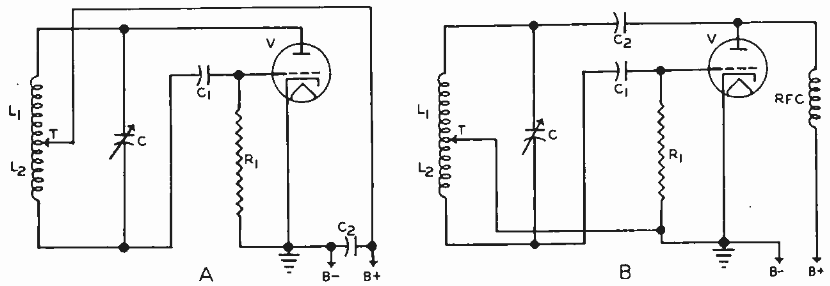


FIGURE 11

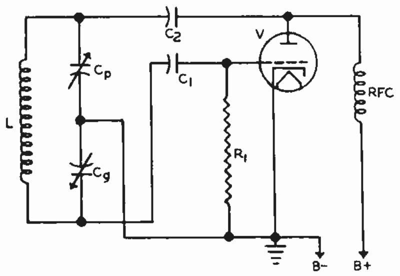


FIGURE 12

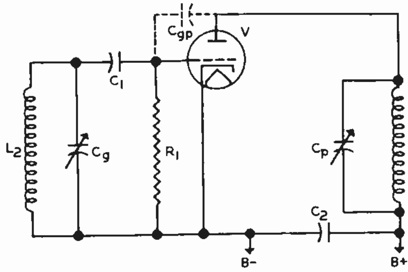


FIGURE 13

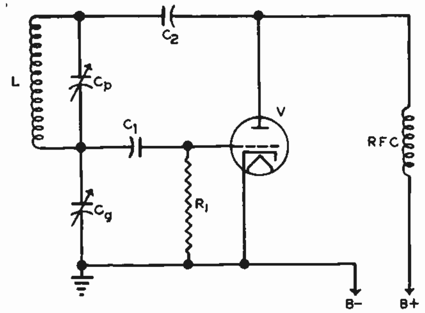


FIGURE 14

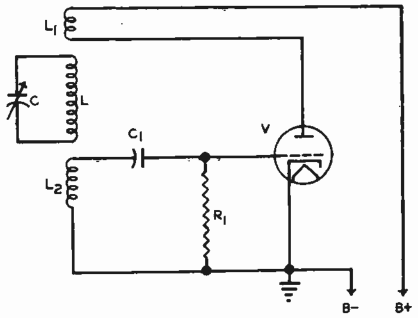


FIGURE 15

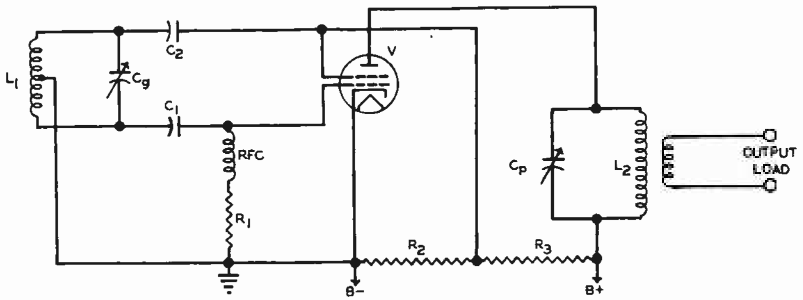


FIGURE 16

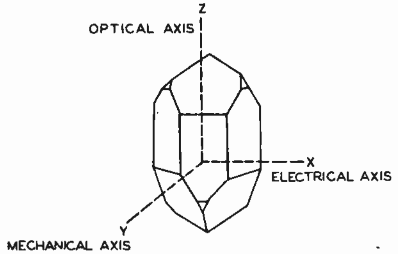


FIGURE 17

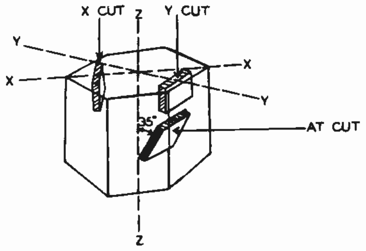


FIGURE 18

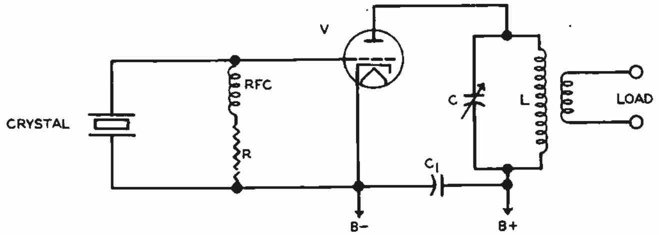


FIGURE 19