HOW MASTER OSCILLATORS WORK

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STUDY SCHEDULE NO. 18

For each study step, read the assigned pages first at your usual speed. Reread slowly one or more times. Finish with one quick reading to fix the important facts firmly in your mind, then answer the Lesson Questions for that step. Study each other step in this same way.

☐ 1. How Oscillatory Currents Are Generated . . . . Pages 1-6

In this important section, you learn how an L-C tank circuit will generate alternating currents when fed with pulses of energy. Pay particular attention to the effects of resistance, and notice that the frequency of the a.c. is determined by the L and C values.

☐ 2. Vacuum Tube A.C. Generators . . . . Pages 7-15

In the previous section you learned that a value was needed to "let in" the proper power pulses to the L-C circuit. Here you learn how a self-excited amplifier circuit, using a tube, will perform this function. Answer Lesson Questions 1, 2, and 3.

☐ 3. Common L-C Oscillator Circuits . . . . Pages 15-22

There are many ways of arranging the necessary feedback in L-C oscillators. Here you learn about these variations and also study the effects of loading the oscillator. Answer Lesson Question 4.

☐ 4. Crystal Oscillators . . . . Pages 23-32

The L-C oscillator is not sufficiently constant in output frequency for many applications. The crystal is used in such cases, because, with its temperature held constant, it is remarkable in its ability to produce an almost fixed-frequency signal. Answer Lesson Questions 5, 6, 7, 8, and 9.

☐ 5. Negative Resistance Oscillators . . . . Pages 32-36

Two special oscillators, that depend on negative resistance characteristics, are described here. Answer Lesson Question 10.

☐ 6. Mail Your Answers for This Lesson to NRI for Grading.

☐ 7. Start Studying the Next Lesson.

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HOW MASTER OSCILLATORS WORK

How Oscillatory Currents Are Generated

OSCILLATORS are essentially just modified amplifiers. However, their ability to generate an alternating current at any desired frequency makes them of special importance in radio. The operation of a superheterodyne receiver, for instance, depends upon a small r.f. voltage generated by a local oscillator located in the receiver. Oscillators also are used for the production of audible beat notes in communication receivers so that unmodulated carriers can be detected. They are used in many forms of test equipment as signal sources for testing and adjusting amplifiers, filters, attenuators, etc. And most important of all, in radio transmitters, vacuum-tube oscillators are used to generate radio-frequency power at the frequency of the carrier wave to be transmitted.

Oscillators, of course, can be designed to produce very high power. From a practical standpoint, however, it is found that oscillators generating sufficient power to feed the radiating antenna directly do not have good frequency stability. Since in modern radio communication it is extremely important for the transmitter to stay "on frequency" and thus not interfere with other services, we find the high-power oscillator is seldom used in the communications field.

On the other hand, if the transmitter oscillator is not called upon to deliver more than a nominal amount of power, say 5 watts, then it can be adjusted so that the frequency of oscillation will be very nearly constant. (This relatively feeble power then can be stepped up to higher and higher levels by radio-frequency power amplifiers.) In such use, the oscillator is appropriately called a "master oscillator," since it generates the original carrier frequency and thus controls the entire transmitter.

In this Lesson, we will be concerned principally with master oscillators of the L-C and crystal types—that is, oscillators in which the frequency-determining components are an inductance L and a tuning capacity C, or as an alternative, a piezo-electric quartz crystal. We shall limit our discussion, also, to oscillators employing ordinary tubes; this means the upper limit of oscillation will be somewhere between 30 and 80 megacycles. Above this range, because of interelectrode capacities and other factors, ordinary tubes become very inefficient and may fail to function entirely.

Special tubes must be used to generate ultra-high frequencies. For efficient operation, it also may be necessary to dispense with the ordinary inductance coil and tuning capacity and substitute a "quarter-wave line" or some other resonant device. Ultra-high-frequency oscillators of this type will be discussed in a later Lesson.

As the first step in our study of oscillators, let's learn just how an L-C circuit functions.

A BASIC L-C TANK CIRCUIT

Essentially, an oscillator circuit is a means of converting d.c. power into a.c. of the desired frequency. Hence, an oscillator must contain a means of "valving" the proper amount of d.c. into the circuit, and must have a frequency-determining network of the proper kind.

Suppose we have an inductance coil L, a capacity C, a switch SW, and a battery E arranged in the circuit of Fig. 1. With the switch in position 1, condenser C will be charged to the full potential of the battery. Now what happens in the L-C circuit if we suddenly change the switch position to point 2, thus removing the battery and closing the L-C circuit upon itself?

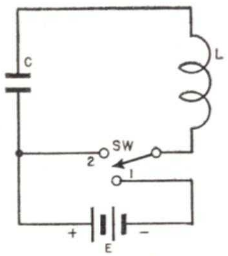


FIG. 1. A coil and condenser make a simple oscillatory circuit. If the condenser is first charged by switching in the battery, and the battery is then switched out, the circuit will oscillate momentarily of its own accord.

At the very instant of closing the switch to position 2, we will have the condition shown in Fig. 2A. *All the energy in the circuit is made up of the high charge on the condenser which is represented by the intense electrostatic field between the condenser plates.*

With the circuit closed, the condenser immediately starts to discharge. This means a current will begin to flow through the inductance. This sudden flow of current through the coil will build up an electromagnetic field around the coil which tends to prevent the current flow. We find, then, that the discharge current from the condenser at first is relatively small. This is the condition shown in Fig. 2B.

The condenser continues to discharge. Gradually, the inductive effects of the coil are overcome, and the discharge current gets higher and higher. Finally, at the time the condenser is completely discharged, the current through the coil reaches a very high maximum value. This is the condition shown in Fig. 2C. Even though the condenser plates have zero potential between them, the discharge current is very high, and the electromagnetic field around the coil has built up to an intense maximum value. *At this point, all the energy has left the condenser, and the total energy in the circuit is represented by the electromagnetic field surrounding the coil.*

With no condenser potential to keep it going, the discharge current then attempts to decrease. Any decrease in current through the coil, however, means that the magnetic field begins to collapse, producing a change in flux linkage through the coil. When this happens, a "back e.m.f." which tends to keep the current flowing in the same direction, is generated in the coil. The result is that the current does not cease immediately even though the condenser potential is zero. Instead, because of the collapsing magnetic field, the current through the coil continues and *proceeds to charge the condenser to the opposite polarity.* Fig. 2D illustrates this part of the current cycle.

Driven by the collapsing magnetic field, this "overshoot" current keeps flowing, though gradually diminishing until the field drops to zero. At this point, as shown in Fig. 2E, the current also becomes zero, and *the condenser is completely charged with the polarity reversed.*

Now that the magnetic field has disappeared, *all the energy in the circuit has been removed from the inductance coil and returned once more to the condenser.*

If we were to plot a curve showing the instantaneous values of current as illustrated in Figs. 2A to 2E, we would obtain the solid-line curve I in Fig. 2F. The numbers 1, 2, 3, etc., correspond to the conditions for Figs. 2A, 2B, etc., respectively. We see that the condenser discharge current starts out slowly as at 1, rises gradually through 2, to reach a maximum at 3. After this, the current then decreases to 4, and drops again to zero at 5. *This current curve is a perfect half-cycle of a sinusoidal wave.*

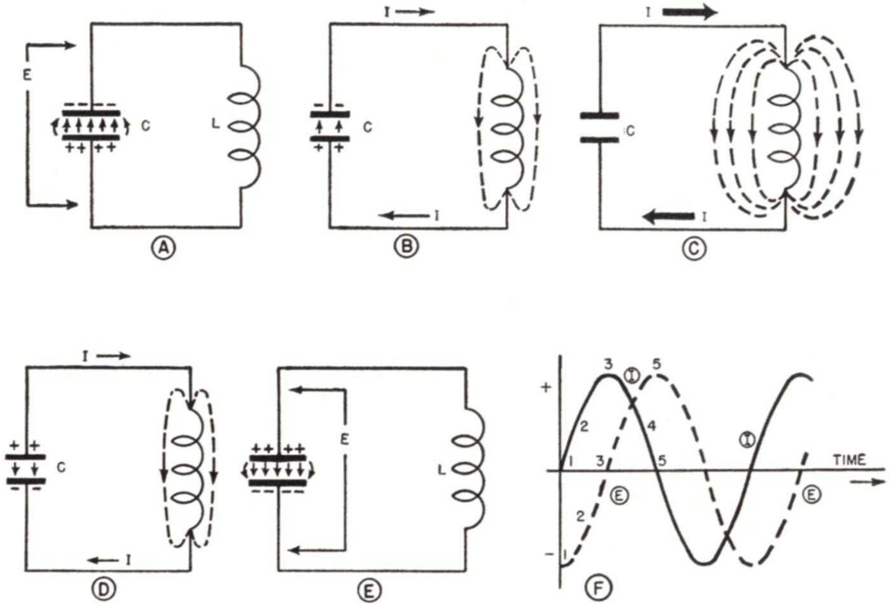


FIG. 2. Illustration of how an L-C circuit oscillates. After the condenser has been discharged, the "flywheel" effect charges it again in reversed polarity.

Similarly, if we plot the change in voltage across the condenser for all parts of the discharge cycle, we get the dashed curve E in Fig. 2F. As we know, the initial voltage at 1 is equal to the full battery potential. This decreases gradually through 2 to reach zero at 3—which marks complete discharge of the condenser. The collapsing magnetic field of the coil, however, does not allow the discharge current to cease. Accordingly, the condenser voltage begins to build up with *opposite* polarity, and the voltage curve in Fig. 2F proceeds through the point 4 to arrive finally at 5. *This curve, too, is a perfect half-cycle of a sinusoidal wave.*

But let us compare the two circuit conditions in Figs. 2A and 2E. In each case, the condenser is fully charged, the only difference being the polarity of the charge. Therefore, after the condition in Fig. 2E has been reached, the condenser will begin to discharge once more—this time with the current through the inductance coil in the opposite direction. The current and the voltage will go through the same sort of changes to return once more to the condition shown in Fig. 2A.

After this, the sequence will be repeated over and over again. In other words, the current will flow, first in one direction, then in the other, continuously charging and discharging the condenser a great many times. Both voltage and current follow many cycles of a sinusoidal wave.

From this we see that the simple inductance-capacitance circuit in Fig. 1 has taken the energy originally supplied by the battery in charging the condenser, and transformed it into an alternating current. *Such an L-C circuit, therefore, is really an oscillator.* This ability of an inductance and capacity to produce many cycles of oscillation after an initial direct current charge is really the familiar "flywheel" effect we have discussed earlier. We shall see that all oscillators depend upon this action in generating radio-frequency currents.

L, C, AND R VALUES

As you might expect, the values of the capacity C and the inductance L used in the circuit of Fig. 1 have a pronounced effect upon the performance as an oscillator. A large capacity takes longer to discharge than a smaller one. A large inductance also prolongs the time necessary for condenser charge and discharge.

It is not surprising, then, to find that the frequency of oscillation for such a tuned circuit is exactly the same as its resonant frequency. In practical cases, this frequency can be expressed by the formula:

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

when the frequency is in cycles per second and the inductance L and the capacity C are in henrys and farads, respectively. (2π has the numerical value of 6.28.)

This formula means, of course, that if the capacity C and the inductance L in Fig. 1 are sufficiently large, we can obtain a circuit oscillation at a very low frequency, say 20 or 30 cycles per second. On the other hand, if the inductance and the capacity are small enough in size, then the oscillation will occur at a radio frequency. (We can even generate ultra-high frequencies by this means.) Hence, we get the desired frequency by choosing the proper L-C values.

The Effects of Resistance. Up to this point we have not considered the effects of any resistance in the L-C oscillating circuit. Since in any actual circuit there is always some resistance (usually concentrated in the coil), it is well to examine the more practical circuit given in Fig. 3A.

In this figure, the resistor R represents not only the ohmic resistance of the coil L but also that of the connecting wires as well. And as you remember, in circuits of this type, it is customary to define the quality of the inductance coil L by its Q—which is the inductive reactance X_L (at the resonant frequency f) divided by the resistance R, or:

$$Q = \frac{X_L}{R} = \frac{2\pi fL}{R}$$

Now what effect will circuit resistance have upon oscillator operation?

If we could construct an L-C circuit *without any resistance whatsoever,* that is, $R = 0$ and $Q = \infty$, then, once started into oscillation, oscillating currents would continue to flow forever! This would produce a "continuous wave train" as in Fig. 3B. Since there is no resistance present in which energy can be dissipated in the form of heat, the condenser is charged *completely* each time, first with one polarity, then the other, the oscillating current going through an infinite number of cycles.

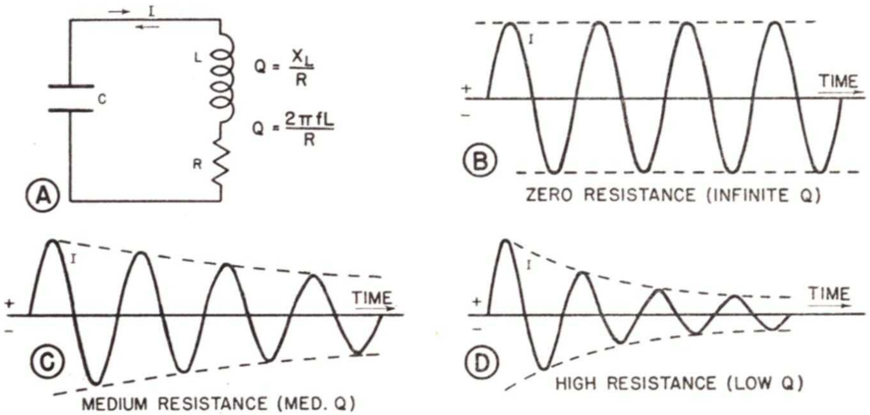


FIG. 3. Theoretically, if the resistance in a tuned circuit could be made zero, oscillations once started would continue indefinitely as at B. In actuality, circuits with medium resistance give the slightly damped wave at C. High resistance results in high damping as at D.

Of course, we would never have ideal conditions, because it is impossible to obtain zero circuit resistance. Nevertheless, if the resistance R in Fig.3A is extremely low so that the circuit Q is very high, oscillations may be maintained for a relatively long time. In this case, the amplitude of the oscillating current will change with time like the curve in Fig. 3C.

Since some energy is lost each cycle by the current flowing through and heating the resistance, the maximum potential to which the condenser is charged each time gradually becomes lower and lower. Eventually, both current and voltage oscillations die away to zero as illustrated. This particular type of wave is called a "damped wave train."

Of course, if the resistance R in Fig. 3A is made higher, then the energy lost each charge and discharge cycle will be increased. This means that the highest potential to which the condenser is charged each time decreases much faster. Thus, for a "heavily damped" circuit containing more resistance, and hence, one having a lower effective Q, the wave train will end abruptly as shown in Fig. 3D.

Supplying Energy. In modern radio, however, we ordinarily do not desire damped wave oscillations such as those in Figs. 3C and 3D. Instead, it is imperative that we generate continuous wave oscillations like Fig. 3B. Since we cannot devise an L-C circuit which has zero resistance, how is this accomplished?

Let us consider the oscillatory L-C circuit in Fig. 4A. If the switch SW is placed in position 1, charging condenser C, and then the switch is moved to position 2, we know we get a damped wave voltage train like the solid curve in Fig. 4B.

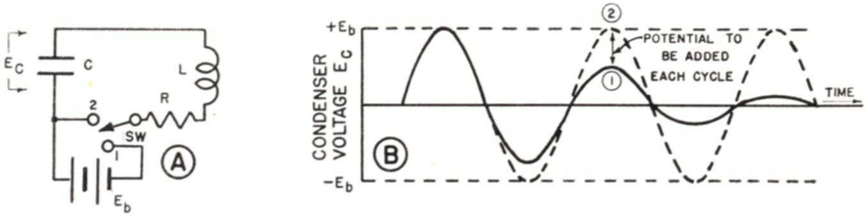


FIG. 4. If the switch in the circuit at A could be moved back and forth in phase with the oscillations so that the condenser would be charged completely once each cycle, a continuous wave would be generated as shown at B.

Suppose, however, we do not leave the switch *fixed* at position 2. Instead, let us assume that we can move the switch back and forth at a very rapid rate. If we then move the switch to position 1, *only for an instant,* and *exactly at the time the oscillating voltage starts its second swing in a positive direction,* we can succeed in *completely* charging the condenser once more. The condenser voltage, therefore, will be increased from point 1 in Fig. 4B up to the maximum potential at 2. Furthermore, if we arrange to move the switch for *every* positive swing of the oscillating voltage—that is, the movement of the switch is kept *in phase* with the oscillation voltage—we will obtain a continuous wave train as indicated by the dotted lines.

Of course, the condenser will not require full charging current from the battery each oscillation cycle. The only charging current flowing will be that necessary to bring the condenser potential from point 1 on the cycle up to point 2. *The only energy drawn from the battery, therefore, will be that small amount required to replace the energy lost in heating the circuit resistance.*

In actual practice, it is impossible to devise a manual switch capable of operating millions of times a second—as it would need to do in order to generate radio-frequency currents. The vacuum tube, however, can be made to handle this switching job easily, efficiently, and automatically.

All that we must do to make a continuous wave oscillator is attach a vacuum tube to an L-C circuit in such a way that the tube will act as a switch or "trigger" and release pulses of energy from a battery or other d.c. source at properly timed intervals.

Vacuum Tube A. C. Generators

Probably the easiest method of using a vacuum tube to charge the condenser in an L-C oscillatory circuit is to place a parallel-resonant circuit in the plate circuit of a tube as shown in Fig. 5A. With this arrangement, any plate current flowing to the tube must pass through the tuned circuit, and the voltage drop developed will charge the condenser C_1.

To maintain the tank circuit L_1-C_1 in continuous oscillation, however, we know it is necessary that the condenser C_1 be given a slight charge *for only a short time* during each oscillation cycle. To accomplish this, we must make the C-bias voltage E_c sufficiently great to block the flow of plate current most of the time. Thus, as illustrated on the e_g-i_p curve in Fig. 5B, the grid bias may be much greater than the plate current cut-off value. If we next apply to the tube an a.c. input voltage e_i of just sufficient magnitude to bring the instantaneous grid voltage past the cut-off point for positive peaks, the plate current will flow only in narrow pulses.

If the excitation input voltage e_i is of the *same frequency* as the oscillations in the tuned circuit L_1-C_1, and the *phase* of this grid voltage is correct so that the plate pulses always occur at the proper time, each charge given to the condenser C_1 will reinforce the charge already present. This additional charge then will be sufficient to bring the condenser voltage up to its maximum value, thus restoring the energy lost in the oscillating circuit so

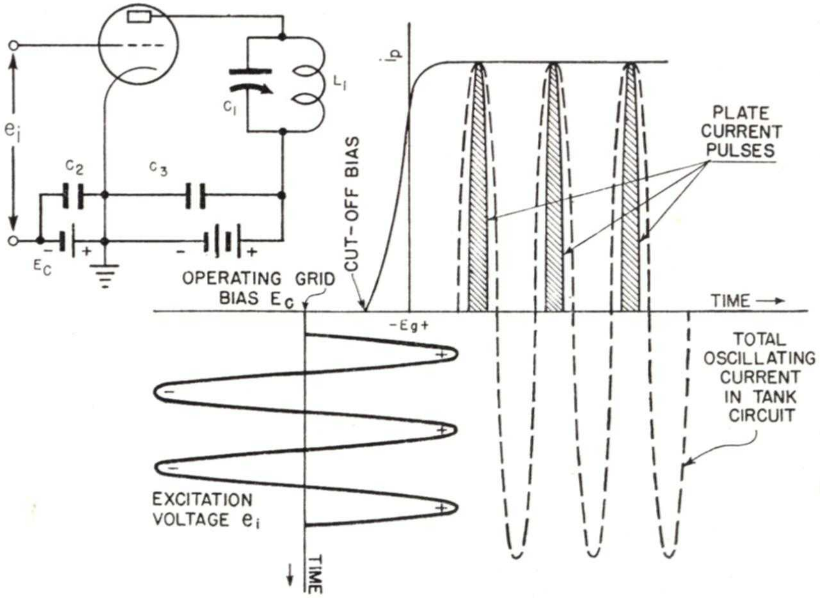


FIG. 5. When a vacuum tube is biased beyond cut-off, and proper grid excitation is supplied, the plate current pulses flowing through an L-C circuit charge the condenser sufficiently to maintain continuous oscillation.

that continuous oscillation will be maintained. As indicated by the dotted lines in Fig. 5B, the current actually flowing in the tuned circuit then will be a constant-amplitude alternating current, part of which is made up of the plate current pulses.

► But where do we obtain the input voltage e_i which is necessary to "trigger" the plate current at the proper instant? Since this excitation voltage must have the same frequency as the current flowing in the oscillating tank circuit, *why not let the oscillating current itself supply the grid input voltage?*

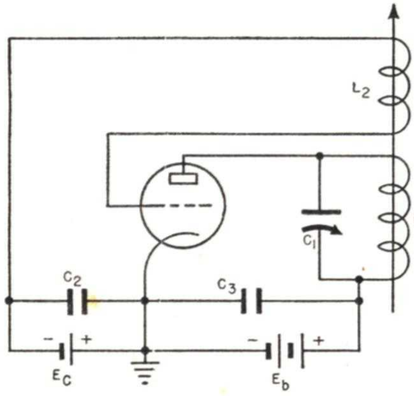


FIG. 6. Proper grid excitation can be obtained if a pickup coil is coupled directly to the oscillating tank circuit inductance. By the use of such positive feedback or regeneration the circuit becomes a "self-excited oscillator."

The simplest means of doing this is shown in Fig. 6, where we have inserted in the grid circuit a small pickup coil L_2 which is inductively coupled to the oscillating circuit inductance L_1. By transformer action, the oscillating current flowing in L_1 will induce a voltage in L_2 which is applied directly to the grid. If the positive peak of the grid excitation voltage obtained in this way occurs at the proper time—and it will if the pickup coil L_2 is connected correctly—plate current pulses will flow in exact phase with the current in the tank circuit L_1-C_1, so that oscillations will be maintained.

Since some of the energy in the plate tank is actually fed back to the grid, the arrangement in Fig. 6 is a feedback circuit. For proper phasing, whenever plate current starts to flow, the feedback voltage on the grid must become positive, thus increasing the plate current still more; and conversely, whenever plate current starts to decrease, the grid must become negative so that the plate current decreases even faster. This, of course, amounts to *positive* feedback or what we call "regeneration."

Looking back at the e_g-i_p curve in Fig. 5B, we see the tube is biased beyond plate current cut-off so that plate current flows during only a short period of time which is less than a half-cycle. This is class C amplifier operation. Hence, the basic oscillator circuit in Fig. 6 is a class C amplifier which is arranged to supply its own grid excitation. Such a self-contained source of alternating current, therefore, is commonly called a "self-excited oscillator."

A PRACTICAL OSCILLATOR

Although the oscillator in Fig. 6 is a fundamental one, the circuit itself is not arranged in particularly convenient form. What happens in the circuit, for instance, when we first apply power? Since the tube is biased beyond cut-off, no plate current will flow through the tank circuit L_1-C_1 to charge the condenser and begin oscillation. The oscillator, therefore, is not self-starting. Indeed, oscillation can be initiated only by charging the tank condenser C_1 from some external source or by dropping the C-bias voltage E_c momentarily to allow the flow of plate current. Such measures are undesirable, so the circuit is changed so that it biases itself and is self-starting.

Obtaining Automatic Bias. You will remember that the grid of a class C amplifier is always driven (on positive excitation peaks) into the positive potential region. During the time the grid is positive, considerable grid current flows. You will recall, also, that this grid current can be made to flow through a grid-leak resistor so that the d.c. voltage drop would be effective as grid bias for the amplifier. In this arrangement, the class C amplifier was said to be "self-biased."

Since the self-excited oscillator is actually a class C amplifier which is supplying its own excitation, this same method of supplying self-bias can be used. Thus, by removing the C-bias battery E_c in Fig. 6 and substituting a grid-leak resistor R_1, we obtain the self-biased oscillator in Fig. 7. The grid condenser C_2, as before, is actually a by-pass condenser which presents a low-impedance path to ground for alternating currents.

With this scheme, whenever the grid is driven positive by the feedback voltage induced in L_2, grid current i_g flows through the grid leak R_1 to ground as indicated. The resulting voltage drop E_c then becomes effective as grid bias for the tube. Note, however, that the condenser C_2 also is charged to this same potential. It follows, then, that during those portions of the oscillating cycle when the feedback voltage is negative and the grid is *not* drawing current, the condenser C_2 discharges through the grid leak R_1. In this way, a fairly steady average d.c. bias is maintained across R_1 even though the grid current i_g flows only in relatively short pulses during the time the feedback voltage drives the grid positive.

► But obtaining grid bias without a battery is not the only advantage offered by this self-bias arrangement. For one thing, when the oscillator in Fig. 7 is first turned on, there will be no oscillating current in the tank circuit L_1-C_1. This means there will be no voltage induced in the feedback coil L_2, and consequently, no grid current i_g will flow. Without current flowing through the resistor R_1, the grid bias for the tube will be zero so that the plate current i_p will rise to a high value. This sudden surge of current through the tank circuit will be more than sufficient to charge the condenser C_1 and bring about the start of oscillations. *We see then that such a self-biased oscillator is always self-starting.*

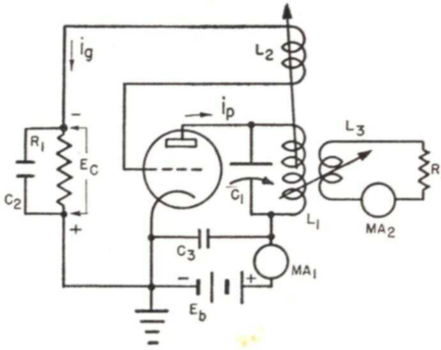


FIG. 7. Rectified grid current flowing through a grid-leak resistor will develop an automatic bias for an oscillator tube. Useful a.c. output power to a load can be secured by coupling a second pickup coil to the tank circuit inductance.

► There is one possible disadvantage to this self-bias scheme; should the oscillator ever fail to work because of insufficient feedback, excessive loading, or a tank circuit part failure, then there will be no bias and the plate current can rise to a high value. This may destroy the tube. However, this trouble is so rare that it is not considered in the stage design. It is up to the operator to avoid any adjustment that could cause this trouble.

HOW THE TUBE ACTS AS A VALVE

Oscillator circuits, like the one in Fig. 7, have several important self-regulating properties. When operating properly, the plate and grid voltages in these circuits adjust themselves so that the tube draws no more plate current than is necessary to supply the power needed to make up for the load requirements and the circuit losses. (The power taken from the B supply is the product of the supply voltage and the average current; hence, for a fixed B voltage, the power varies directly with the plate current.)

Oscillators operate in class C, so the plate current flows in pulses that exist for less than a half-cycle. *Therefore, the circuit is able to adjust its input power by altering either the peak value or the width of the plate current pulses* (or both) so that the required average current is drawn.

First let's study Fig. 8 to see how the pulse *width* may be varied. The e_g-i_p curve shown here flattens out. This may be the result of plate current saturation, or it may be the result of the action of the load, which we will explain in a few moments. Anyway, let's assume that this is the operating curve, and therefore the flattening of the curve will limit the *peak* value of the plate current.

When the circuit is first turned on, the plate current rises rapidly from zero to the value that would flow with zero grid bias. In so doing, the current flow through plate coil L_1 is of the proper phase to induce into feedback L_2 a voltage which would drive the grid positive. This in turn drives the plate current pulse all the way to the peak value (m in Fig. 8). Here, because the plate current cannot increase further, it is no longer changing, so the voltage induced from L_1 into L_2 will decrease. This drop in grid voltage will tend to force the plate current downward. The change in plate current from m toward n drives the grid of the tube negative. The plate current is actually cut off when the grid voltage gets beyond the cut-off bias value for the tube. However, the tank circuit is now oscillating, so C_1 is supplying energy to complete the a.c. cycle. (The oscillating tank current that is set up assumes the shape shown by the dotted curve I_t in Fig. 8.) When the oscillation has progressed to where the condenser has been charged with the opposite phase, and the condenser again starts to discharge, the grid voltage will come back in the positive direction. As soon as it passes the cut-off bias level, plate current will begin to flow again and will continue to flow, reaching its maximum value at the same time as the grid reaches its maximum positive value z. Once again the cycle repeats. Thus, the plate current flows in a series of pulses.

However, examine the grid voltage swings shown in Fig. 8. Notice that the grid is going more and more positive on each cycle, so the average d.c. grid current increases. However, this produces an increasingly negative grid bias E_c (shown by a broken line in Fig. 8) because of the current flow through R_1 in Fig. 7.

► Returning now to the plate current pulses, you will notice that the plate current pulse l-m-n is a complete half cycle of a sine wave. The pulse o-p, although of the same height as the first pulse, is narrower, and the pulse q-r is narrower still. This is because the grid swing is on the positive side of the cut-off bias value for smaller periods of time. Fig. 9 shows this somewhat more clearly. If the grid bias is just at the cut-off value, and the grid voltage swing is as represented by the cycle 1-2-3-4-5, the corresponding plate current pulse 20-21-22 will flow during the shaded portion of the grid voltage swing. This represents one-half a cycle.

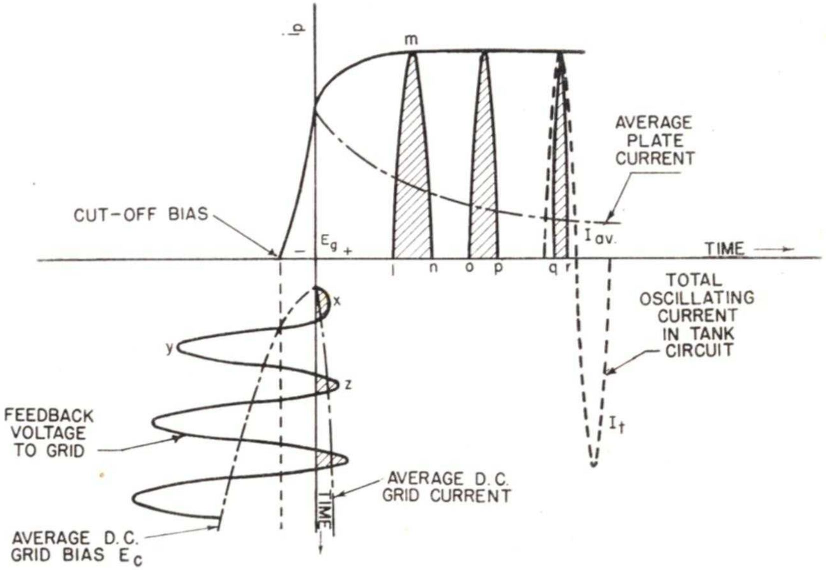


FIG. 8. As oscillations build up in an oscillator using automatic bias, the grid bias rapidly increases so that the time duration of the plate current pulses goes down, and the average plate current decreases.

On the other hand, if the grid bias is at a level well beyond cut-off, and the grid bias swing comes up to the same positive peak value as shown by the curve 6-8-10-11-12, then plate current can flow during only that portion of the grid voltage cycle from 7 to 8 to 9. This is less than the grid voltage half-cycle 6-8-10, so the plate current pulse 23-24-25 is less than half a sine wave.

► Thus, returning to Fig. 8, you can see that as the average grid bias E_c goes into the class C region, the grid swing produces a narrower plate current pulse. Since the average plate current depends on the time the current flows (the pulse width), the d.c. average current decreases as shown by the broken line labeled I_{av} in Fig. 8.

The actual grid voltage swing, and hence the grid bias and plate current pulse width, are fixed by the mutual inductance between coils L_1 and L_2. The plate current pulse will become narrower, to that point where the feedback voltage no longer can drive the grid further positive. At this point, the stabilization of the grid voltage fixes the grid current, and this fixes the grid bias. From then on, the grid oscillations are of the same amplitude, so the plate current pulses remain the same until some circuit condition is changed.

Peak Value Changes. The other limit on the plate current is its *peak* value (m in Fig. 8). This is the point where the operating curve levels off.

Of course, if the tube characteristic is such that the grid bias drives the tube to the plate current saturation region, then there will be the normal leveling off, because this represents the condition under which no more plate current can flow for that plate voltage.

More usually, however, when the oscillatory circuit starts to work, an artificial level is set by the plate load. As you know, a tube with a load operates over a dynamic characteristic that is much flatter than its static curve, and, the greater the load resistance, the flatter this curve will be. In Fig. 10, one curve is for a high Q tank (and hence a high load impedance because $Z = X_L \times Q$); another is for a lower Q; and the third is the tube's static curve, shown here for comparison.

You can see that the peak plate current for a particular grid voltage depends on which characteristic is being used. Thus, if the grid signal reaches the value represented by the dotted line A-A, the plate current pulse 1 represents the current for the high Q load, and pulse 2 that for the low Q load. *The pulse height is less for the high Q load.* (Pulse 1 is not as high as pulse 2.)

► You can see why this occurs by remembering that the plate current depends on *both* the grid and the plate voltages of the tube. Without a load, when the grid became positive, the plate current would go to the extremely high values permitted by the static curve. However, with a load, there will be a voltage drop caused by the plate current. With a resonant circuit as the load, the phase is such that, at the time the plate current is increasing, the load voltage is subtracting from the B supply, leaving less voltage as the actual plate voltage for the tube. Hence, this reduction in tube voltage limits the plate current to a maximum determined by the instantaneous plate and grid voltages. The higher the load, the less the true plate voltage becomes, and hence, the lower the plate-current peak. From this we see that *the higher the Q of the resonant circuit, the lower the peak amplitude which the plate current can reach.*

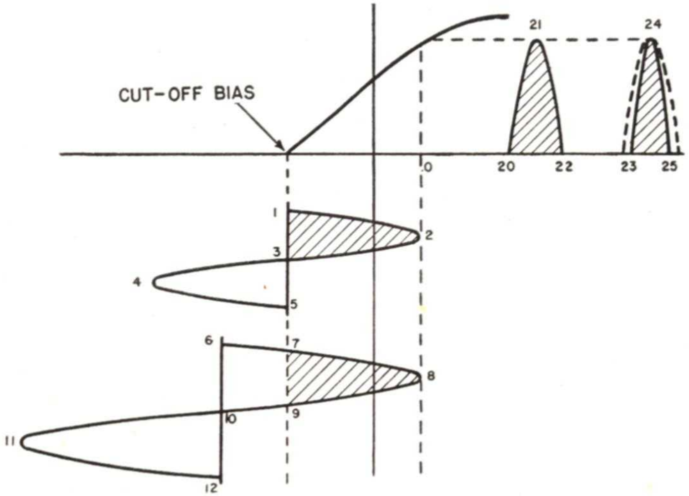


FIG. 9. When the bias is greater than the cut-off value, plate current can flow only for less than half a cycle.

► This is an important fact, because it shows how the circuit regulates and adjusts itself when loaded. Let us go back to Fig. 7; if we bring coil L_3 near L_1, so that power is delivered to the external load R_L, we are doing the same as introducing a resistance into the tank circuit, with the result that the tank Q is lowered. A lower Q means less tank voltage drop, more plate voltage, and operation on a dynamic curve that allows a higher peak plate current. This means more power is taken from the plate supply to make up for that taken by the load.

As even more power is needed, this self-adjustment may go further. The lowered Q means a lower tank circuit voltage, so the oscillatory current is less, and therefore, the voltage induced in L_2 becomes less. This allows the grid bias to drop back to a less negative value, so that a greater portion of the grid voltage swing is on the positive side of the *cut-off* bias point. This allows the plate current pulse to become broader. Thus, in two ways, this oscillator circuit can adjust itself to where it draws the proper plate current. Through this action, the oscillator always sets itself to draw just enough plate current to make up for the demand of the load and all the losses in the circuit. Of course, if we try to carry this too far, and load the tank circuit too heavily, then the voltage induced in L_2 will be insufficient to keep oscillation going. Under this overload condition, oscillation cannot continue and will stop abruptly.

Plate-to-Grid Coupling. Because of its self-regulation characteristic, the feedback adjustment of an oscillator usually is not extremely critical. There are, however, certain circuit adjustments which give optimum performance. What is the result, for instance, of varying the coupling between coils L_1 and L_2 in Fig. 7 so that the effective grid excitation is altered?

If the coupling is very small, the alternating grid voltage may be so low that oscillation will not be maintained. On the other hand, if we make the coupling between coils L_1 and L_2 somewhat tighter than necessary to sustain oscillation, we will find that both the grid excitation voltage and the resulting d.c. grid bias rise to high values. For this adjustment, since the plate

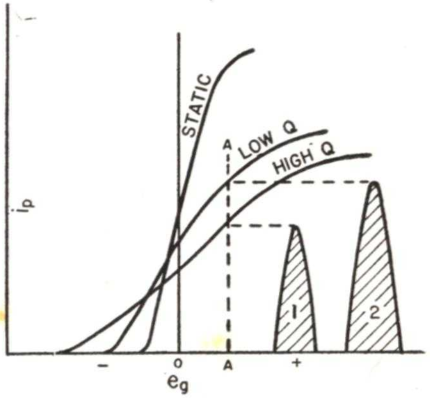


FIG. 10. When the plate tank circuit Q drops, the plate current pulse will reach a higher peak value.

current pulses will flow for a relatively shorter time, the average plate current will decrease, and the oscillator efficiency will go up. Up to a certain point, the greater the feedback excitation, the greater the oscillator efficiency will become.

► Excessive feedback, however, can be obtained. If the feedback is made so great that the grid bias developed across the resistor R_1 in Fig. 7 rises to an extreme value, the mutual conductance of the tube may be reduced sufficiently so that only feeble oscillation will result, the efficiency drops, and the average plate current tends to rise.

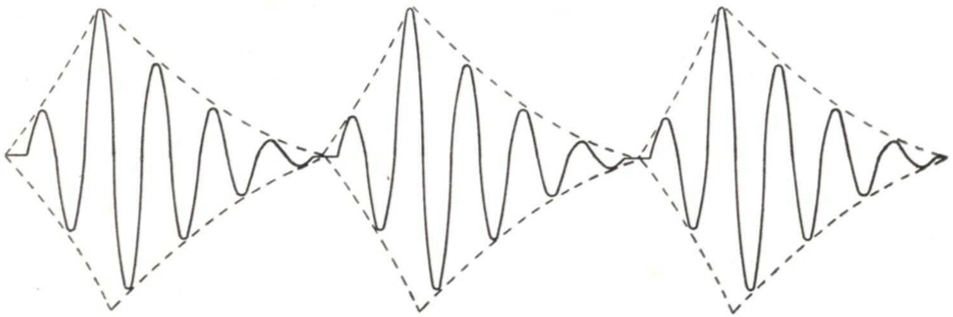


FIG. 11. The modulated output, consisting of a series of damped waves, from an oscillator in "intermittent oscillation." Such performance is the result of excessive feedback or a grid leak resistor that is too high.

In practical cases, the coupling between coils L_1 and L_2 is adjusted so that *minimum* plate current is noted on milliammeter MA_1. This indicates the most vigorous oscillation and a maximum of efficiency. Ordinarily, optimum adjustment also is indicated by a *maximum* reading of the r.f. meter MA_2 in the load circuit.

The Grid Leak Resistor. Since the oscillator grid bias is the result of the flow of grid current through the grid leak resistor (R_1 in Fig. 7), the greater this resistance, the greater will be the grid bias for a given amount of feedback voltage. And as we found before, the greater the effective bias, the better the efficiency of oscillator operation, up to a certain limit. In practice, the value of resistor R_1 also is adjusted for *minimum* plate current drain as measured by the milliammeter MA_1.

If, in an effort to get high-efficiency operation, the resistance of R_1 is made too high, the oscillator may break into what is called "intermittent oscillation." In this circumstance, when the condenser C_2 is first charged by a grid current pulse, the charge leaks off so slowly through the resistor R_1 that the effective grid bias remains too high, and subsequent plate current pulses are not sufficiently large to maintain oscillation. We find, then, that the amplitude of oscillation steadily decreases and drops to zero, where it remains until the charge on condenser C_2 has disappeared, and the grid bias is lowered sufficiently to allow oscillations to start again. This gives a series of damped waves like those in Fig. 11.

It is interesting to note that if the condenser C_2 and resistor R_1 in Fig. 7 are of suitable size, the rate at which oscillations are interrupted can be made an audible frequency. A radio frequency oscillator with an excessively high grid resistor, therefore, can produce an amplitude-modulated wave. Some of the cheaper signal generators use this principle.

However, the efficiency of such an oscillator is very poor, and worst of all, the frequency stability leaves much to be desired. In a transmitter master oscillator, such operation should be strictly avoided. Intermittent operation in an oscillator can usually be eliminated by reducing the size of the grid leak, by decreasing the feedback slightly, or by both.

Varying the Plate Voltage. Another important characteristic of a self-excited oscillator is that the tank condenser C_1 is charged so that its potential very nearly equals the full power supply voltage (actually, the power supply voltage minus the small tube drop). From this it is apparent that *the peak a.c. voltage developed across an oscillator tank circuit always is nearly equal to the applied plate voltage.*

What does this mean? It means simply that if we make the oscillator plate voltage high, the oscillator output voltage also will be high; and if the plate voltage is low, then the output is low. In other words, a self-excited oscillator could be plate-modulated exactly like the ordinary class C amplifier. If we vary the effective plate voltage of an r.f. oscillator by using an audio-frequency modulator, then we obtain an amplitude-modulated r.f. output.

In some portable or emergency radio equipment in which a power oscillator is used to feed an antenna directly, such plate modulation sometimes is employed. In such applications, however, it is difficult to get 100% modulation, because the oscillator tends to cease functioning at instantaneous low values of plate voltage. This introduces considerable distortion. Another more serious drawback is that the swinging plate voltage changes the oscillator frequency, thus introducing a spurious frequency modulation.

Because of this frequency instability, great care is taken in modern transmitters to see that the plate voltage supplied to the master oscillator does *not* vary. In this way, the frequency stability of the oscillator is improved, and the chances of "off-frequency" operation are greatly decreased, or reduced to zero.

Common L-C Oscillation Circuits

Reviewing what we have learned, we see that there are three important requirements which must be met in the construction of an oscillator:

1. We must have an L-C tank circuit which will oscillate and produce an alternating current because of its inherent "flywheel" effect even though d.c. energy is supplied in pulses from some external source.

2. A vacuum tube must be connected in some way to the L-C tank circuit in order to charge the condenser once each cycle so that circuit losses will be overcome, and a constant amplitude of oscillation will be maintained.

3. There must be a feedback from the tube plate to its grid so that plate current pulses will be allowed to flow during only the proper time for rein-

forcement of tank circuit oscillations.

Up to this point, we have considered only one practical oscillator arrangement—one in which the L-C oscillatory circuit is placed in series with the vacuum tube plate, and grid feedback voltage is obtained by using a small pickup coil.

This is, however, by no means the only practical circuit. Indeed, since the oscillator requirements outlined above are so simple, a very great many different types of oscillators have been developed. Most of these differ in the manner in which the vacuum tube is connected to the L-C circuit, and most particularly in the way the grid feedback in the proper phase is obtained. A few of the more commonly used oscillators are shown in Fig. 12.

OSCILLATORS USING INDUCTIVE FEEDBACK

In Fig. 12A we have repeated the circuit of Fig. 7, drawn in slightly different manner. Since the tank circuit is in series with the plate, this is commonly called a "tuned-plate" oscillator. Excitation to the grid can be controlled, of course, by adjusting the coupling between the tank inductance and the grid pickup coil.

The Tuned-Grid Oscillator. If we reverse the positions of the tank and pickup (or "tickler") coils, we arrive at the "tuned-grid" oscillator shown in Fig. 12B. In this case, the coupling between the tuned circuit and the plate tickler controls the total energy fed to the oscillating L-C circuit. When the tank circuit voltage would provide a higher grid voltage than is desired, the grid connection to the tuned circuit may be a movable tap as indicated.

The Meissner Oscillator. In Fig. 12C we have an oscillator wherein there is no metallic connection between the L-C circuit and the vacuum tube. Instead, we have two tickler coils—one for the plate and one for the grid. Energy which is transferred into the tuned circuit from the plate circuit can be controlled by adjusting the coupling between the plate tickler and tank circuit, and grid excitation can be regulated by moving the grid tickler coil. Since there is very little direct coupling between the two tickler coils, these adjustments are essentially independent of each other.

The Hartley Oscillator. The oscillator shown in Fig. 12D is a very common form. In this Hartley oscillator there is no tickler winding at all; instead, the tank coil is used as an autotransformer to supply grid excitation. Plate current flowing from the B-supply to the tap on the tank coil, through the upper part of the coil and thence to the plate, produces a magnetic field which induces grid excitation voltage of proper phase in the lower half of the tank coil.

Hartley oscillators are easily recognized because of the tank coil tap which can be moved along the coil for excitation adjustment. Moving the tap toward the plate increases grid excitation; moving the tap toward the grid lowers the grid voltage.

Note that in this circuit the grid resistor is not shunted across the grid condenser C_c but instead is connected directly from grid to cathode. This variation is necessary to prevent the application of the plate supply voltage directly to the tube grid. Automatic bias, however, is obtained just as before, because the grid current still flows through the resistor on its way to the cathode.

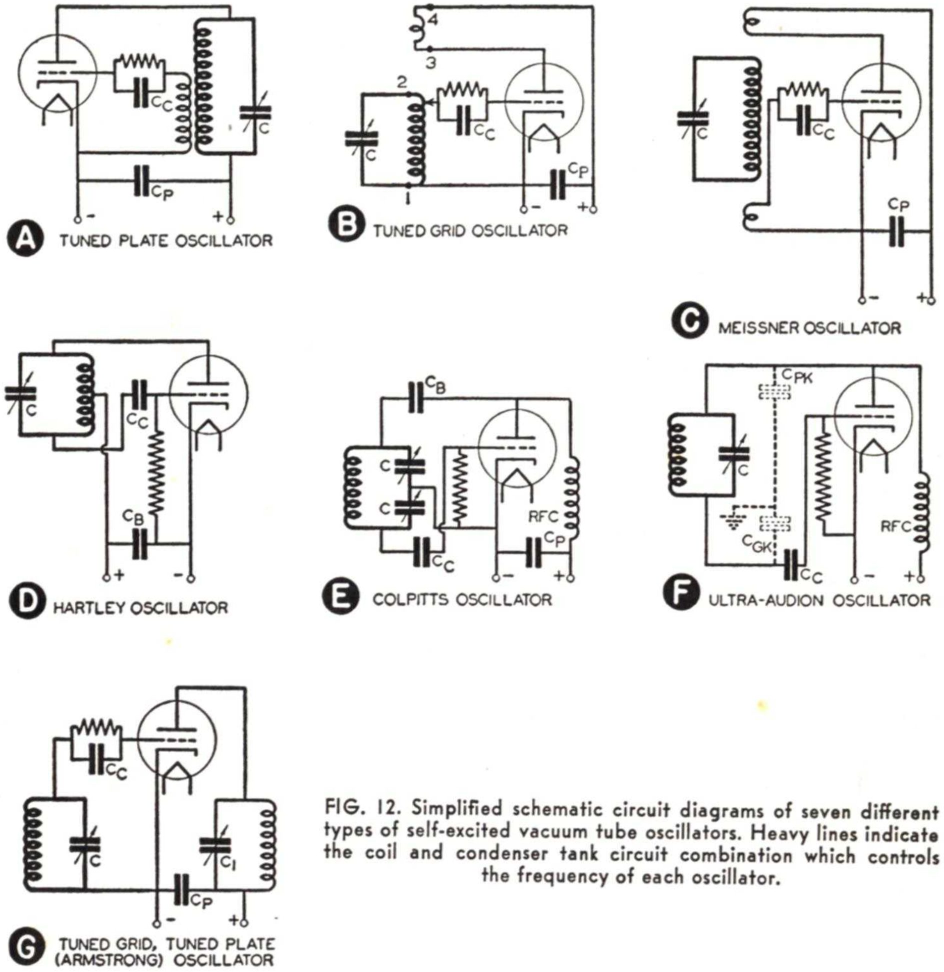


FIG. 12. Simplified schematic circuit diagrams of seven different types of self-excited vacuum tube oscillators. Heavy lines indicate the coil and condenser tank circuit combination which controls the frequency of each oscillator.

OSCILLATORS USING CAPACITIVE FEEDBACK

Instead of obtaining feedback voltage by inductive means, it is just as feasible to use a capacitive arrangement. The oscillators in Figs. 12E to 12G are some examples.

The Colpitts Oscillator. Instead of tapping the inductance coil of the tuned circuit, as is done for the Hartley, we can tap the tuning capacity side of the circuit by using two condensers in series and connecting their common point to the cathode. This gives us the Colpitts oscillator in Fig. 12E. With the tank circuit tap at cathode potential, and the grid and plate connected to opposite ends of the tuned circuit, grid and plate voltages will be 180° out of phase so that oscillation will result.

Excitation to the grid is adjusted by changing the capacity value of the condenser between the cathode tap and the grid. Making this condenser larger *reduces* excitation, and decreasing the capacity *increases* excitation. Of course, whenever this condenser capacity is increased or decreased to adjust excitation, the other tuning condenser in series also must be adjusted in an *opposite direction* to maintain the frequency of oscillation at the desired point.

The Ultra-Audion. The oscillator in Fig. 12F was used for a long time before its operation was fully understood. In this ultra-audion oscillator, the plate and the grid are connected to opposite ends of the tank circuit, but there is no tank circuit tap nor tickler coil of any kind.

Remembering that there is always interelectrode capacity between the elements in a vacuum tube, we can draw in the plate-to-cathode capacity C_{PK} and the grid-to-cathode capacity C_{GK} as shown by dotted lines in the figure. With these tube capacities added, it becomes apparent that the ultra-audion is actually a form of the Colpitts oscillator shown in Fig. 12E.

Since the tube capacities are relatively small, the ultra-audion usually works best at ultra-high frequencies. Since the tube capacities are fixed, the grid excitation is not easily adjusted. In some cases operation is more efficient if a small condenser is placed from the grid end of the tank coil to ground, thus increasing the effective grid-cathode capacity C_{GK}.

The T.P.T.G. Oscillator. For the oscillator shown in Fig. 12G there are two parallel L-C tank circuits, one in the grid circuit and the second in the plate circuit. Accordingly, this arrangement is called the "tuned-plate-tuned-grid" (abbreviated T.P.T.G.) oscillator.

At first glance there seems to be no provision for feedback, since there is no magnetic coupling between the two coils—and in fact, the two inductances are kept well separated to reduce stray coupling between them to a minimum.

You will recall, however, that a triode tube has considerable capacity between the plate and the grid. You will remember, also, as we found in an earlier Lesson, that sufficient r.f. current can flow from the plate to the grid through this electrode capacity to bring about oscillation. Indeed, in r.f. amplifiers using triodes we found it necessary to employ neutralization to prevent such positive feedback.

In the oscillator circuit in Fig. 12G, therefore, the ordinarily troublesome feedback current flowing through the interelectrode capacity is put to good use. In order for the grid feedback voltage to have the correct phase, it is necessary that the plate circuit be inductive at the frequency of oscillation. This means the plate resonant circuit is always tuned to a slightly higher frequency than the tuned circuit in the grid.

T.P.T.G. oscillators are adjusted by setting the plate condenser C_1 first at its minimum capacity, and then slowly increasing the capacity value. As the resonant frequency of the plate tank is brought nearer and nearer to that of the grid tank, the grid excitation increases, and the oscillator plate current drops as oscillation becomes more vigorous. The plate tank condenser C_1 must never be adjusted too far, however, else the plate tank will be tuned to the same frequency as the grid. When this happens, the plate load becomes resistive or capacitive, and oscillation will stop abruptly.

LOADING THE OSCILLATOR

Every oscillator, of course, is used primarily as a generator of r.f. alternating current. To be of any value, some of the r.f. energy flowing in the oscillator tank circuit must be extracted and applied to an external load, which is usually the grid circuit of a buffer amplifier. This is usually accomplished by one of the means shown in Fig. 13. (The load is represented by an equivalent resistance.)

Inductive Coupling. Fig. 13A illustrates a form of inductive coupling. This uses an r.f. transformer in which the oscillator tank inductance forms the primary winding, and a small pick-up coil attached directly to the load is the secondary winding. The r.f. voltage developed across the load, and hence, the power absorbed from the oscillator, is controlled by adjusting the coupling between the two inductances. The closer the coupling, the more power delivered to the load. This type of coupling is most often used when the load has a comparatively low resistance or impedance value.

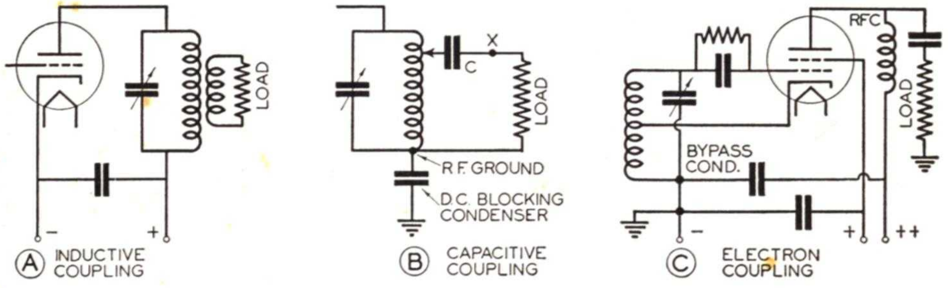


FIG. 13. Three common methods of coupling a load to an oscillator.

Capacitive Coupling. If a high-resistance load is used, a more convenient form of coupling is that shown in Fig. 13B. In this case, the load is attached directly to the tank inductance through the coupling capacity C. By moving the load tap up and down the tank coil, the loading can be varied over wide limits. Moving the tap *away* from the r.f. ground point, thus bridging more of the tank circuit, *increases* the loading; moving the tap downward *toward* ground *reduces* the power transferred to the load.

Adverse Effects of Loading. Since a load circuit actually draws energy from the oscillator tank, it should be expected that loading would influence the performance of an oscillator. We have already found that the average current drawn by the oscillator plate will increase to supply the extra energy demanded by loading. There are, however, other effects.

With either of the load coupling methods in Figs. 13A and 13B, the load circuit tends to alter the effective capacity or inductance in the tank circuit. This, of course, changes the frequency of oscillation, and we must retune the oscillator to the proper frequency each time the load coupling is adjusted. We may find, also, that the grid excitation is changed, and it is usually necessary to readjust the feedback for a new plate current minimum.

In addition to changing frequency and feedback, coupling the load also has the very serious effect of raising the apparent resistance in the L-C tank circuit. This means the Q of the tank circuit decreases, and the flywheel effect is reduced. A lowered flywheel effect means, of course, that the oscillator efficiency becomes less than that without loading.

► But worst of all, with a lower Q, the tuning of the L-C circuit becomes much broader. Instead of being forced to operate at or very near the desired frequency—as in the case with a high circuit Q and high selectivity—oscillations now may occur with equal ease at any frequency over a much wider band. We find that the oscillator frequency may "wobble" around to a much greater extent than before. In other words, *by heavy loading the frequency stability of the oscillator is very markedly reduced.*

From the foregoing, it becomes obvious that the less load applied to an oscillator, and hence, the less power the oscillator is required to deliver, the better its performance will be. It is for this reason that most modern transmitters use instead of power oscillators, a relatively low-power lightly loaded "master" oscillator required to furnish only that power necessary to excite a buffer amplifier.

Electron Coupling. Even the presence of a buffer amplifier disturbs a master oscillator to some extent, however, and in attempts to reduce loading to a negligible amount, the circuit of Fig. 13C quite often is used.

In this arrangement, a screen grid tube performs as both oscillator and coupling network. In this circuit, the screen grid acts as the oscillator plate, and the control grid, cathode, and screen grid are arranged in a Hartley oscillator circuit. (Other types of oscillator circuits may be used.) Notice that instead of being grounded as is customary, the cathode is left floating, and the screen grid is by-passed directly to ground. This keeps the screen grid at ground potential so that it is an effective electrostatic shield between the oscillator and the plate and load circuit.

With the control grid, cathode, and screen grid behaving as an oscillator, it is apparent that the current finally reaching the tube plate will be varying at the generated frequency. The plate circuit, therefore, contains r.f. energy which may be applied to the load through an appropriate coupling condenser. However, since the oscillatory circuit is independent of the plate circuit, the plate load may be varied in any manner without appreciably affecting the oscillator. Since the only connection between the plate circuit and the oscillator itself is the modulated electron stream, this method of supplying power to the load is commonly called "electron coupling."

Electron coupling, of course, is not perfect, for there is always some stray coupling between the plate and other elements within the tube. Nevertheless, electron-coupled oscillators usually have very much better frequency stability than more conventional oscillators using inductive or capacitive coupling.

STABILIZED OSCILLATORS

Even though we take great care to see that a self-excited oscillator is lightly loaded, we still may find that the generated frequency will not stay exactly constant over a period of time. There are two main causes for this frequency drift:

1. Changes in the electrical values of coils, condensers, and resistors used in the oscillator circuit.
2. Variations in the vacuum tube constants and characteristics.

► Nearly all the changes in circuit parts outside the tube are caused by temperature variations. These can be minimized by using sturdy, well-designed components which will not change in value of their own accord. In extreme cases, these parts may be enclosed in a temperature-controlled oven.

Variations in tube constants, however, are not so easily remedied. In general, there are three tube constants which may change and influence the frequency of an oscillator. These are the interelectrode capacities of the tube elements which are effectively in shunt with the L-C tank circuit, the effective grid-to-cathode resistance r_g and the plate-to-cathode resistance r_p.

Use of High-C Tank Circuit. The capacities between elements in a vacuum tube are not constant, principally because the spacing between electrodes changes as the tube temperature varies. Although these capacity variations cannot be eliminated, their effect upon oscillator frequency can be minimized by making the tuning capacity in the tank circuit quite large. When this is done, the tank capacity literally "swamps" the relatively small tube capacities. The total effective capacity in the L-C resonant circuit, therefore, cannot vary more than a very small per cent.

It is common practice to make the tuning capacity for an oscillator approximately twice as large as that ordinarily used for an r.f. amplifier. Such a high C circuit, of course, needs only a small inductance for resonance at a given frequency. The L-C ratio, or L/C, for oscillator tank circuits, therefore, usually is comparatively low.

Reactance Stabilization. Variations in the grid-cathode resistance r_g and plate-cathode resistance r_p of an oscillator may be caused by fluctuations in grid, plate, and filament voltages, aging of the tube, or changes in the operating conditions. Such changes, of course, cannot be eliminated entirely. Oscillator frequency drift caused by corresponding variations in r_p and r_g, however, can be substantially reduced in several ways.

One method is the insertion of an extra capacity or inductance in the oscillator plate or grid lead. For a Colpitts oscillator, a stabilizing inductance L can be included as shown in Fig. 14A. The exact inductance value for the added coil is determined by the values of L_1, C_1, and C_2 of the tank circuit. Frequency stability is improved because the reactance of the coil L introduces the proper phase shift between the tube and its tank circuit to make the frequency of oscillation practically independent of changes in grid or plate resistance. For best operation, however, the Q of the tank circuit should be made as high as possible—theoretically infinite in value.

Resistance Stabilization. Another practical method of stabilization is accomplished, not by making the oscillator frequency virtually independent of grid and plate resistance changes, but by reducing these variations as much as possible. This is usually done by inserting a high resistance in either the plate or grid lead of the oscillator.

Thus, as shown in Fig. 14B, with the stabilizing resistor R_1 added, the effective resistance shunted across the tank circuit L-C is not the tube plate resistance alone, but the extra high resistance as well. Then if the resistance value of R_1 is very much higher than the plate resistance, any changes in the latter will have little effect upon the

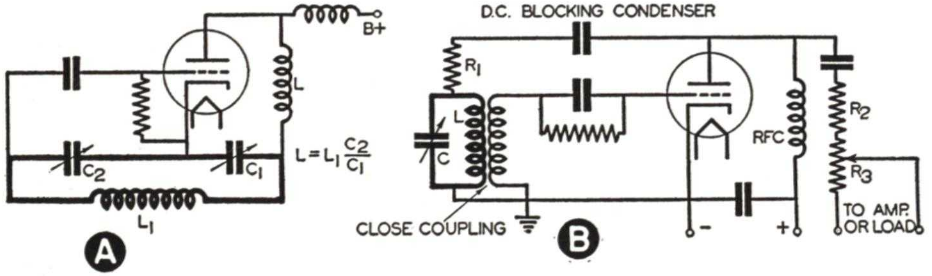


FIG. 14. Two methods of improving the frequency stability of an oscillator. At A, inductance stabilization is applied to a Colpitts oscillator. At B, resistance stabilization is used in a tuned-plate oscillator circuit.

resonant frequency of the tank circuit.

For best results, the resistance of R_1 should be made as high as possible, allowing just barely enough energy to sustain oscillation to reach the tank circuit. Since oscillations will be feeble, very close coupling between the tank circuit and the grid tickler coil will be necessary to obtain adequate grid-excitation voltage.

Since a vacuum tube oscillator is self-adjusting, if we make the *apparent* plate resistance as seen by the tank circuit very high, the grid resistance automatically becomes high also. The net result is that the oscillating tank circuit is very nearly completely isolated from the vacuum tube. Under these circumstances, if the L-C circuit initially has a very high Q, the loading imposed by the tube will be slight, and the effective working Q also will be quite high—a necessary condition for good frequency stability.

Output from the stabilized oscillator shown in Fig. 14B is obtained from the voltage divider resistors R_2 and R_3. To minimize loading and to prevent load fluctuations from affecting the oscillator performance any more than absolutely necessary, the resistance of R_2 is made much higher than R_3, and also much greater than the plate resistance of the tube.

These measures, taken to improve frequency stability, all greatly reduce the available output power. Because of their inherent characteristics, however, such a sacrifice of power seems to be necessary if good frequency stability is to be achieved in self-excited L-C oscillators.

Crystal Oscillators

The principal reason that transmitting stations are required to keep their frequency very nearly constant is to prevent unnecessary interference between various services which may be operating at the same time.

Each year, because of the increasing number of stations, governmental agencies, such as the Federal Communications Commission in the U.S.A., are demanding that frequency drift be reduced and that the carrier frequency be kept nearer the assigned value.

At the present time, the maximum permissible frequency drift for stations operating in the broadcast band is limited to 20 cycles. This means that a station operating at an assigned frequency of 1000 kc. (1,000,000 cycles), must keep its frequency constant within 0.002%—*two-thousandths of 1 per cent!*

It is difficult, if not impossible, to devise an ordinary L-C self-excited oscillator which will have this required frequency stability. It has been found, however, that if a quartz crystal is cut and ground to a specific size, and then incorporated in a special oscillator circuit, the generated frequency can be held within acceptable limits.

PIEZO-ELECTRIC CRYSTALS

Native quartz, which is a form of silica known as silicon dioxide, commonly occurs in clear, glass-like hexagonal crystals shaped like the drawings in Fig. 15. Actual size of the crystals varies from the microscopic to eight or ten inches.

Each crystal is said to have three major axes at right angles to each other; these are designated by the arrows X, Y, and Z in the figures. The X-axis is called the *electrical* axis, the Y-axis is called the *mechanical* axis, and the Z-axis is called the *optical* axis.

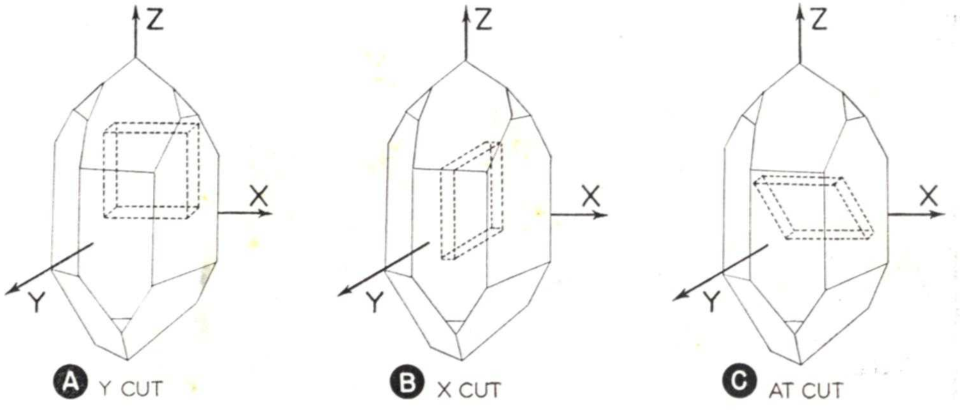


FIG. 15. Three ways of cutting quartz crystals for radio use.

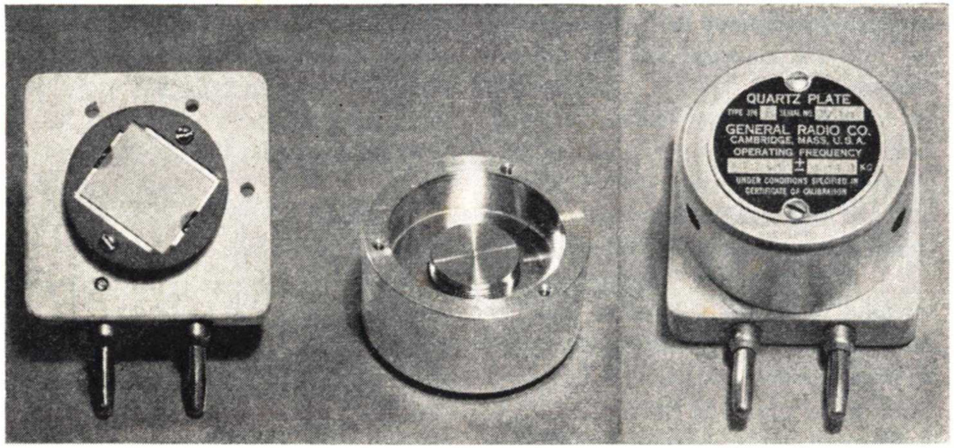
Crystal Cuts. For radio use, small slabs, or wafers, are cut from the mother crystal as illustrated by the dotted lines. If these wafers are cut with their faces *perpendicular* to the Y-axis as shown in Fig. 15A, they are called Y-cut crystals.

On the other hand, if a wafer is cut

with its faces *parallel* to the Y-axis, and hence, perpendicular to the X-axis, it is named an X-cut crystal. Fig. 15B illustrates this method of cutting.

For special purposes, various other cuts may be used, one of the most common being the AT-cut shown in Fig. 15C. This is really a Y-cut but with the face of the wafer making an angle of approximately 32° with the Z-axis instead of being parallel to it.

As we shall see later, these various cuts result in oscillator crystals with slightly different electrical characteristics.



Courtesy General Radio Co.

FIG. 16. Three views of a General Radio type 376-L crystal holder. The quartz plate itself can be seen inside its mounting ring in the view at the left. This unit is of the plug-in type; one prong connects to a metal electrode beneath the quartz plate, and the other prong makes contact with the machined metal cover (center) which serves as the upper electrode.

The crystal wafers — or simply "crystals" as they are called — are usually cut about one inch square. After cutting, both faces of the crystal are ground until nearly optically flat. Further grinding is then carried out until the thickness of the crystal is reduced as nearly as possible to a definite desired value—commonly measured to the nearest ten-thousandth of an inch. The frequency produced by the crystal depends on its thickness, so the crystal frequency is determined accurately, and the final grinding is made to produce the exact thickness needed for the desired frequency.

Crystal Holders. After being finished to a specified thickness, the crystal is then "sandwiched" between two metal plates which act as electrodes for connection to an external circuit. These electrodes, which must be at least as large as the quartz crystal, also are ground with faces as flat as possible. For convenience, such plates usually are "built-in" so that they form part of a dust-proof case called a "crystal holder."

There are now in use two distinct types of crystal mountings. One type uses an air gap between one-thousandth and five-thousandths of an inch thick between the quartz crystal and the upper plate. In another type of mounting, the upper plate rests directly on the crystal, the weight of the plate maintaining the proper coupling with the crystal. Assembled and unassembled views of one type of crystal holder are shown in Fig. 16. This particular holder uses plug-in pins for external connections.

Regardless of the type of mounting used, the holder itself is designed to keep the crystal free of grit, dirt, or any oily film. Even a speck of dirt or a greasy film may change the characteristics of the crystal. Therefore, the crystal holder should never be opened, nor should the crystal be handled. However, if it is ever necessary to take one apart, the crystal may be cleaned with a grease solvent such as carbon tetrachloride.

The Piezo-electric Effect. But what are the properties of a crystal?

If we were to compress or "squeeze" a quartz crystal, we would find that an electric potential would be developed between its two faces. The greater the compression, the greater this potential would be. On the other hand, if we could subject the crystal to tension, thus "stretching" it, the polarity of the potential between the faces would be reversed. *This ability of a natural quartz crystal to convert mechanical energy directly into electrical energy is called the "piezo-electric* (pronounced *pi-E-zo-electric*) *effect."*

The piezo-electric phenomenon, however, is reversible. Thus, if we apply a d.c. voltage to the electrodes of a crystal, the thickness of the crystal will change. For a given polarity, let us say, the thickness may *decrease*. If the polarity of the applied voltage is then reversed, the thickness variation also reverses, and the crystal thickness *increases*.

► From this, it is obvious that if we apply an *alternating* voltage to the crystal we can set the crystal into mechanical vibration. Furthermore, if the frequency of the alternating voltage is adjusted to the natural mechanical resonance of the crystal, the vibrations will be quite large. In turn, these mechanical vibrations produce an a.c. voltage having a frequency determined by the dimensions of the crystal.

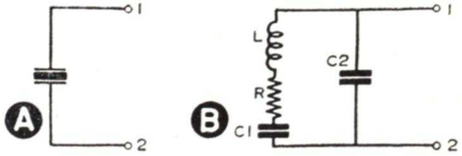


FIG. 17. The schematic symbol for a quartz crystal in its holder is at A. The equivalent electrical circuit of a quartz crystal is at B.

In general, the natural mechanical resonant frequency of a crystal is determined by the method of cutting, and quite precisely by the physical thickness. For an X-cut crystal, the frequency in cycles per second is approximately 3,000,000 divided by the thickness in millimeters; for a Y-cut, the frequency in cycles is about 2,000,000 divided by the thickness in millimeters. Crystals which vibrate up to 5000 kc. are quite easily made.

We see then that a quartz crystal is really a mechanical vibrator which not only can operate high in the radio-frequency spectrum, but also can be driven by electrical means.

The Equivalent Circuit. The quartz crystal in its holder is usually represented by the symbol shown in Fig. 17A. Since such a crystal oscillates when an alternating voltage is applied to its electrodes, and since when set into vibration, the crystal then generates an alternating potential of its own, the electrical impedance looking into the terminals will be very different for different frequencies, depending upon the nearness to the natural mechanical resonant frequency.

Indeed, we will find that the crystal behaves exactly as if it were composed of the L-C resonant circuit in Fig. 17B. In this equivalent circuit the apparent inductance L is the result of the mass of the crystal, the resistance R is the result of internal mechanical losses, and the capacity C_1 is the result of the stiffness of the crystal—the crystal's piezo-electric properties. The capacity C_2 is the capacity made up by the electrode plates, with the quartz crystal as a dielectric.

► Because of the mechanical properties of a crystal, the apparent inductance L is very high; also, since mechanical losses during vibration are very small, the electrical equivalent resistance R is almost negligible. *This means that a quartz crystal will perform as a resonant tank circuit that has a very, very high Q.*

As a matter of fact, crystals have an effective Q which is approximately 100 times greater than that ordinarily obtainable with the usual inductance coil and tuning condenser. Crystals, therefore, have extremely good frequency selectivity. And since, as we have already discovered, a high Q improves the frequency stability of a self-excited oscillator, it is not surprising that if we substitute a crystal for the ordinary L-C tank circuit, we can make an oscillator that has extremely good frequency stability.

CRYSTAL OSCILLATOR TYPES

The principles of operation of a crystal oscillator are exactly the same as those of the L-C oscillators we have already discussed. Crystal oscillator circuits, therefore, resemble quite closely those presented for conventional oscillators—and this resemblance will be even more marked if the equivalent resonant circuit of the crystal is substituted in each of the diagrams to follow.

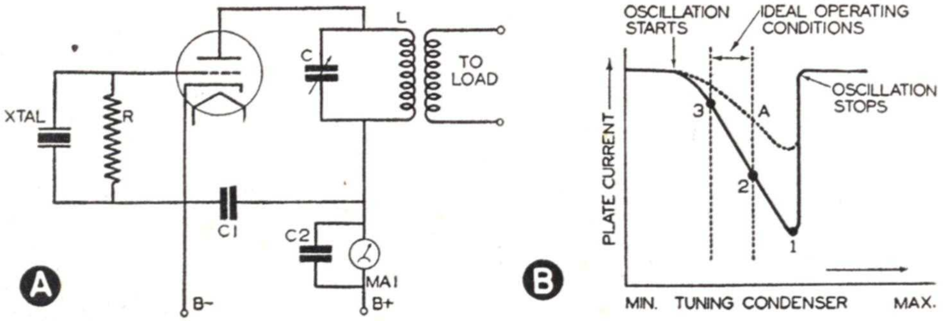


FIG. 18. At A is a simple crystal oscillator circuit using a heater type vacuum triode. Grid bias is supplied by the rectified grid current flowing through resistor R. Condenser C tunes the plate circuit. (The abbreviation "XTAL" is commonly used for "crystal" on circuit diagrams.) At B, the curves show how the plate current varies with tuning for a typical crystal oscillator circuit. The heavy curve represents the circuit not loaded; the dotted curve represents the circuit loaded.

The Basic Triode Oscillator. The crystal oscillator shown in Fig. 18A is probably the one most used. This is actually the T.P.T.G. oscillator given in Fig. 12G, with the crystal substituted for the grid tank.

As before, excitation to the grid is furnished by r.f. current flowing from plate to grid through the interelectrode capacity of the tube. Also, as previously, for proper feedback phasing, the plate circuit must be made *inductive* by tuning the plate tank L-C to a frequency *higher* than that of the crystal. Since the crystal is much more selective than the grid tank circuit which it replaces, the adjustment of feedback becomes more critical than before.

In general, as the plate tank condenser C is rotated from a minimum capacity position, the plate current drawn by the oscillator with no loading will vary as shown by the heavy line in Fig. 18B. As soon as oscillation starts, plate current will begin to decrease. This decrease will become more and more pronounced, going through points 3 and 2 as oscillation becomes stronger.

If the plate condenser C is turned too far, however, so that the plate circuit is tuned to the exact frequency of the crystal, and hence, is no longer inductive, oscillations will cease abruptly as at point 1. In practice, it is wise not to approach point 1 too closely, because minor voltage or current fluctuations might stop the oscillator. Instead, the plate tuning condenser is adjusted so that operation will be somewhere in the more stable region between points 2 and 3.

When loaded, of course, the plate current dip of the oscillator will not be as pronounced; it will follow the dotted curve. As before, however, too much excitation should not be attempted, and operation should be confined to the region between points 2 and 3.

The Pierce Oscillator. In Fig. 19 we have a crystal oscillator which uses no tank inductance or tuning capacity whatsoever. If you consider the crystal as being replaced by its equivalent resonant circuit (see Fig. 17B), you will see that this oscillator is actually the same as the ultra-audion oscillator in Fig. 12F—which, in turn, is a version of the Colpitts oscillator in Fig. 12E.

The amount of feedback and optimum grid excitation can be controlled to some extent by adjusting the capacity of C_1. The larger this capacity, the less the feedback. The exact capacity of C_1 in most cases is not too critical, and usually, once the best value is determined, other crystals of slightly different frequency can be switched in without further adjustment.

R.F. Crystal Current. In the circuits of Figs. 18A and 19, the r.f. current flowing through the crystal tends to be high. The crystal itself is the L-R-C_1 circuit of Fig. 17B, and, at resonance, the r.f. current is limited only by the low resistance of R. If the crystal current exceeds approximately 100 milliamperes, the crystal vibrations may become so violent that the crystal may shatter and thus destroy itself. Of course, the thinner the crystal

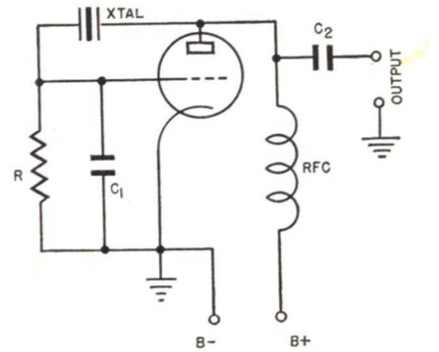


FIG. 19. The Pierce crystal oscillator, related to the ultra-audion, requires no tank inductance or capacity.

and hence, the higher its resonant frequency, the lower the safe current limit becomes. Many transmitters have an r.f. ammeter in series with the crystal to indicate this current.

To prevent possible damage to the crystal, the amplitude of oscillation in the circuits of Figs. 18A and 19 must be kept at a safe level. Usually it is not advisable to apply more than 250 volts to the tube plate. This plate voltage limitation, of course, substantially reduces the maximum output power that can be obtained from such oscillators.

The Basic Pentode Circuit. Tetrode and pentode tubes have less plate-to-grid capacity than do triodes, and hence, there is less feedback current to the grid when they are used in a crystal oscillator, such as in Fig. 18A. Therefore, these tubes give more output power than a triode without excessive r.f. crystal current.

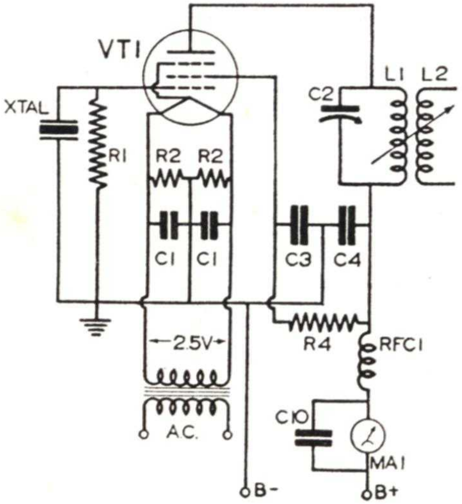


FIG. 20. A crystal oscillator using a pentode tube. Extra feedback is sometimes provided by means of a condenser connected from the plate to the control grid.

A typical pentode crystal oscillator is shown in Fig. 20. For this circuit a maximum plate voltage of 400 to 500 volts may be applied, resulting, of course, in considerably more output power. This circuit is very often used with crystals having resonant frequencies up to approximately 10,000 kc.—for which crystals must be ground so thin that they are extremely fragile and easily broken.

The tuning and adjustment of the pentode oscillator is exactly the same as that for the triode arrangement. Even though the screen grid very sharply reduces the grid-plate tube capacity through which feedback is obtained, for medium and high frequencies the remaining capacity usually is sufficient for optimum operation. For low r.f. frequencies, however, it may be necessary to increase feedback slightly by placing a small condenser directly between the plate and grid terminals of the pentode tube. This condenser must not be too large, however, or else the feedback will be excessive and the crystal may be damaged.

The Tri-tet Oscillator. Quartz crystals having a fundamental resonant frequency higher than 10,000 kc. are seldom used. For these frequencies, the crystals must be nearly paper-thin and hence are so easily damaged they can be used only in special circuits at reduced power.

A more practical way of getting crystal frequency control at ultra-high frequencies is to operate the crystal master oscillator at a low frequency, and then employ one or more doubler or tripler amplifier stages to multiply the frequency to the desired point. For transmitters of this type, the crystal-controlled "harmonic generator" in Fig. 21 is often used.

This pentode oscillator, commonly called the "tri-tet," is actually the crystal version of the electron-coupled circuit shown in Fig. 13C. The crystal and the resonant tank L_1-C_1 are connected to the control grid, the cathode, and the screen grid (which acts as oscillator plate) to form a modified T.P.-T.G. oscillator. The cathode tank L_1-C_1, therefore, must be tuned to a frequency slightly higher than that of the crystal in order to be inductive.

Since the screen grid is by-passed to ground, there is very little direct coupling between the actual tube plate and the oscillator portion of the circuit. The electron stream reaching the plate, however, arrives in the form of pulses which contain relatively large amounts of harmonic energy. If the plate tank L_2-C_2 is then tuned to a frequency *twice* that of the crystal, a considerable amount of output power at the second harmonic frequency can be obtained. Even if the plate is tuned to a frequency *three* times that of the crystal, a fair amount of third harmonic power will be delivered.

We see then that the tri-tet not only behaves as a crystal-controlled oscillator, but performs as a frequency doubler or tripler at the same time! The additional feature of electron-coupling also is desirable, because effects of load variations reaching the crystal are greatly reduced, and hence, do not influence the frequency to an appreciable extent.

In adjusting the tri-tet, the cathode tank condenser C_1 is first set to a frequency higher than resonance, so that oscillations occur. In this circuit, the usual parts values are such that oscillation will be maintained over a fairly wide range of C_1 adjustment. However, the crystal current increases very rapidly as the capacity is increased. Hence, tuning should start from the *minimum* capacity position and should progress *only* to the point of *normal* crystal current. (The crystal current can be measured by an r.f. milliammeter placed in the crystal circuit at point H. The current should be kept below 100 ma.)

Next, with no load connected, the plate tank condenser C_2 is adjusted for a *minimum* value of plate current, as indicated by a sharp dip of the milliammeter MA_1. Load for the tri-tet—which is usually the grid of a following buffer amplifier—is next attached. At this point, the condenser C_2 may need readjustment to bring the plate current back to a minimum—higher this time because of loading. Finally, the cathode tank condenser C_1 is adjusted for a maximum in harmonic power output which, in the case of the buffer amplifier load, will be indicated by a maximum flow of amplifier grid current. Watch the crystal current, however, to be sure that it does not rise above the safe limit.

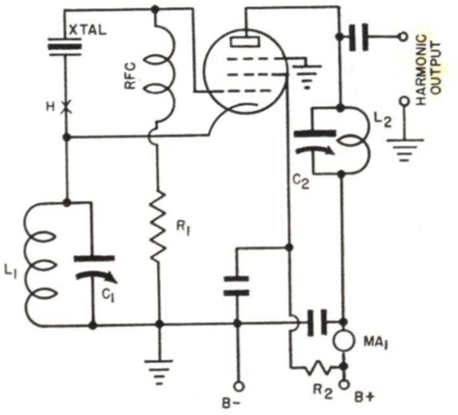
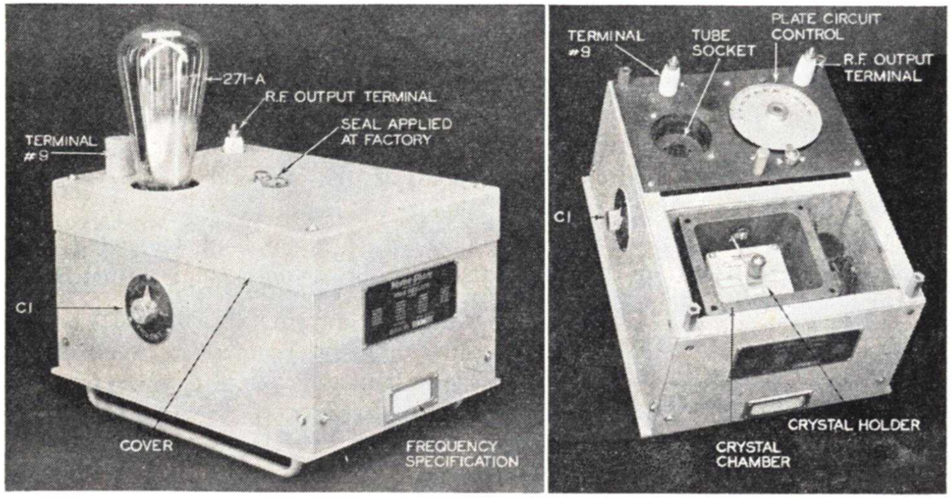


FIG. 21. The tri-tet harmonic generator, which gives substantial output power at frequencies two or three times that of the controlling crystal.



Courtesy Western Electric Co.

FIG. 22. Western Electric type 700-A crystal oscillator unit is shown at A. The shield cap over terminal No. 9 is removed when an external crystal is used. At B is an interior view of this crystal oscillator, showing the crystal chamber and the holder.

TEMPERATURE EFFECTS

Since quartz crystal plates are solids, their physical dimensions will change slightly with variations in temperature. We know that the resonant frequency of a crystal depends quite precisely upon its thickness. It follows, then, that temperature variations can bring about changes in the frequency of a crystal-controlled oscillator.

The frequency drift from temperature variation, of course, is quite small. As an average figure, both X-cut and Y-cut crystals shift about 25 cycles per million per degree Centigrade (sometimes written as cycles per megacycle per degree Centigrade)—which means that if a crystal has a frequency of 1000 kc. at one temperature, and the temperature changes by 1 degree Centigrade, the frequency will shift 25 cycles; if the temperature changes 2 degrees, the frequency will change by approximately 50 cycles, and so on.

For X-cut crystals, the temperature coefficient usually is *negative;* which means the natural frequency of oscillation will *decrease* as temperature is increased. The opposite is true for Y-cut crystals as they generally have a *positive* temperature coefficient.

Small though these frequency variations are,* it is obvious that ordinary temperature changes of 5 to 10 degrees will bring about frequency drift in a broadcast station transmitter which greatly exceeds the maximum allowable limit. As a consequence, the quartz crystals in the master oscillators of such transmitters must be kept at a very nearly constant temperature. This is usually done by enclosing the crystal in a thermostat-controlled, electrically-heated oven.

Special crystal cuts, such as the AT-cut previously described, may have a temperature coefficient of very nearly zero. Such crystals, therefore, may give satisfactory frequency stability without the use of a heating oven. As a rule, however, these low-drift crystals are not such active and vigorous oscillators as the older X-cut and Y-cut types. Consequently, they are used principally in lightweight or portable equipment in which the added bulk of a crystal oven is not justified or permissible.

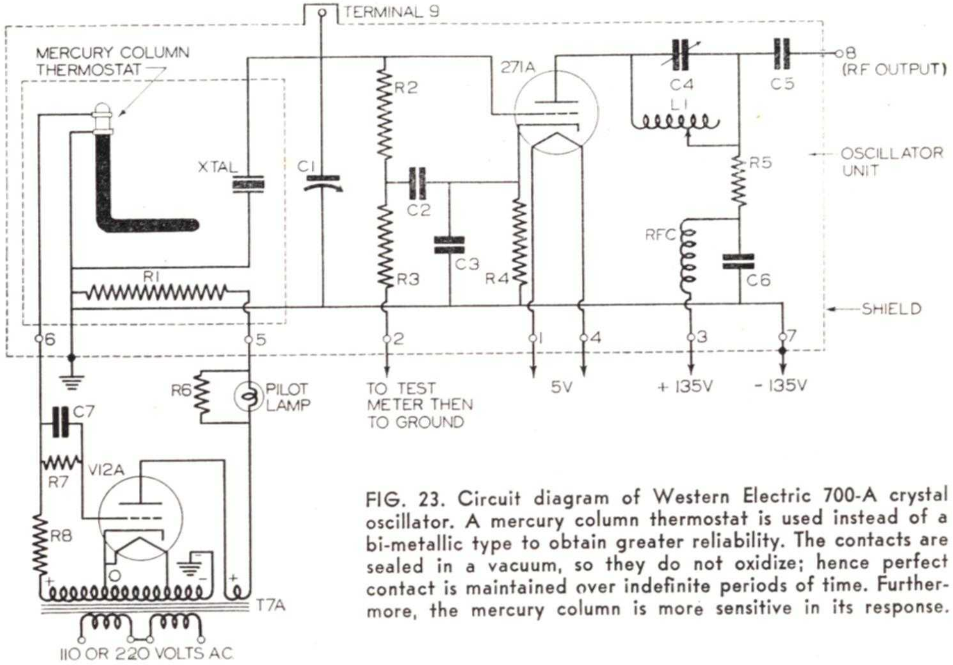


FIG. 23. Circuit diagram of Western Electric 700-A crystal oscillator. A mercury column thermostat is used instead of a bi-metallic type to obtain greater reliability. The contacts are sealed in a vacuum, so they do not oxidize; hence perfect contact is maintained over indefinite periods of time. Furthermore, the mercury column is more sensitive in its response.

A Typical Crystal Unit. For many years, it has been common practice to construct the master oscillator circuit of a broadcast transmitter, together with the crystal and crystal oven, all in one compact unit which can be easily mounted in the transmitter rack.

The Western Electric 700-A crystal oscillator unit illustrated in Fig. 22A is one which is used in many broadcast installations. This sealed and shielded case contains the triode tube, the tank condenser, the tank inductance, and other associated components, as well as the quartz crystal and holder, a crystal heater resistance, and a mercury-column thermostat.

Fig. 22B shows the oscillator unit with the cover and tube removed. Note that the cover to the thermally insulated crystal chamber also is removed, and that the crystal holder can be seen. The crystal heater resistor is below the crystal chamber case.

The schematic wiring diagram for this unit and for the crystal temperature-control circuit is shown in Fig. 23. The oscillator circuit is essentially the same as that of the basic triode crystal

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* Notice that these changes hold only for a 1000-kc. crystal. The shift is so much per million cycles (1000 kc.) so for any other frequency, the shift will be in the ratio of the actual frequency to 1000 kc. Thus, for a 25 cycle per million per degree Centigrade crystal, operating at 600 kc., a 1 degree temperature change produces 25 × (600 ÷ 1000), or 25 × .6 = 15-cycle change.

oscillator described earlier. The condenser C_4 and the variable inductance L_1 form the resonant plate tank. However, resistor R_5 is also part of the plate load; in fact the r.f. output from the unit is the voltage across this resistor, fed through the coupling condenser C_5. The condenser C_1 adds capacity across the crystal holder, and is used to change the frequency of oscillation slightly when necessary or desired. Power connections to the unit are made by spring contacts which engage when the unit is properly inserted in the transmitter rack.

The power transformer T7A supplies power for the crystal heater element R_1. A triode tube V12A is used as the rectifier, so that its output can be controlled by the need for heat in the crystal box. The grid voltage applied to this tube is in phase with the plate voltage—that is, both grid and plate are positive with respect to the cathode at the same instant. When the crystal temperature is too low, the contacts of the thermostat are open, and a large plate current flows through the rectifier tube and the heater resistor R_1. When the proper operating temperature is reached—usually about 50° C.—the thermostat contacts close so that the grid circuit is grounded between resistors R_7 and R_8. This removes the positive voltage applied to the grid and applies a negative voltage from the section of the secondary winding that is grounded. Hence, with the grid negative at the time the plate is positive, the plate current flowing through the rectifier tube and the heater element is cut off. When the crystal chamber temperature drops, the thermostat contacts open again, and the cycle is repeated. In normal operation, the pilot lamp which shunts resistor R_6 in the plate circuit of the rectifier will flash on when the unit is heating, so it should flash on and off periodically. Thermostat controls of this type can be made to control oven temperature within 0.2 degree Centigrade, and thus bring about a very high degree of frequency stability.

Negative Resistance Oscillators

Every oscillator must in some manner overcome the tank circuit resistance and make up for other losses in order to build up self-excited oscillations. This is a way of saying that when sufficient energy is supplied to an L-C oscillating circuit to replace that power lost in the actual positive resistance of the circuit, the *apparent* resistance drops below zero or becomes negative. Hence, we can say that in effect, an oscillator circuit adds a fictitious "negative" resistance to the tank circuit to cancel the real or "positive" resistance that is in the tank circuit.

In all the oscillators just described, this negative resistance effect was brought about by the use of some form of feedback. Thus, the grid tickler, the plate tickler, and other feedback arrangements are merely devices which serve to make the effective resistance of the tank circuit negative in character.

It is possible, however, to get a negative resistance sufficiently low for oscillation simply by applying operating voltages to a multi-element tube in an unusual manner and not employing feedback in the customary form at all. Oscillators made like this are commonly called "negative resistance" oscillators.

Since such oscillators ordinarily deliver but little power output, they are seldom used in transmitters. They do possess, however, considerably better frequency stability than the more conventional circuits, and for this reason they are often used as secondary frequency standards or for variable-frequency signal generators in general laboratory work.

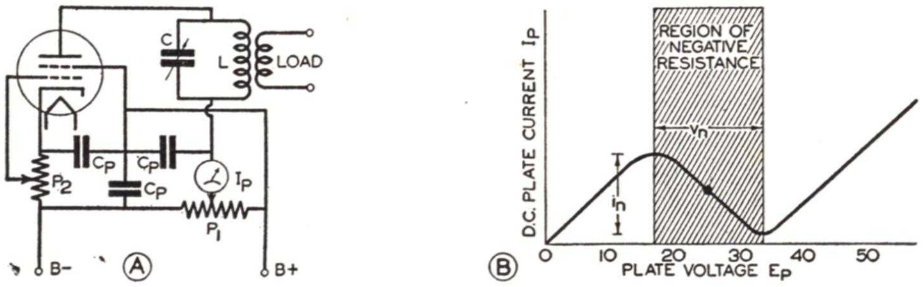

FIG. 24. A dynatron oscillator circuit, A, and its plate-voltage plate-current characteristic, B.

THE DYNATRON

A screen-grid tube is one device which can act as a negative resistance. One of the first circuit arrangements designed to take advantage of this characteristic is the "dynatron" oscillator in Fig. 24A.

Note that this is a true tetrode tube and it does *not* have a suppressor grid. It is important to note, too, that full B-supply voltage is applied to the screen grid, but the potential applied to the plate is substantially lower than that of the screen because of the voltage drop in the potentiometer P_1—exactly the reverse of the usual operating conditions for a screen-grid tube.

Use of Secondary Emission. When the plate is at a *lower* positive voltage than the screen grid, considerable secondary emission will take place at the plate, and these secondary electrons, instead of falling back to the plate, will be attracted to the screen. For slight increases in the plate voltage—up to but not above the screen grid voltage—the secondary emission will be increased, thus making the net plate current decrease.

For a given C-bias voltage, as determined by the setting of potentiometer P_2, a plate-voltage-plate-current characteristic like that in Fig. 24B is obtained. Notice that after E_p reaches approximately 17 volts, further increases up to about 34 volts actually reduce I_p. This is opposite to the effect we usually notice in a resistive circuit because, here, increasing the voltage causes a *decrease* in the current. This means that when the plate voltage of a screen grid-tube varies within the shaded region in Fig. 24B, *the tube plate circuit behaves as if it had a negative resistance equal in ohmic value to the voltage increase* v_n *divided by the current decrease* i_n.

In the dynatron circuit of Fig. 24A this negative plate resistance is connected across the L-C tank circuit. In effect, this negative value appears in the tank circuit (as you learned in another Lesson) and cancels the resistance in the tank circuit. Hence, this negative resistance characteristic resulting from secondary emission makes the tube act as a generator which supplies energy to the L-C tank circuit to overcome resistance losses. *Oscillation will occur in a dynatron circuit whenever the negative resistance of the tube is numerically greater than the resonant resistance of the L-C tank circuit.*

Oscillation is most stable when the d.c. plate voltage is in the center of the region of negative resistance as indicated by the dot on the curve in Fig. 24B.

Action in the Circuit. The physical operation of the dynatron may be more easily visualized as follows: If we assume that the L-C tank circuit in Fig. 24A is oscillating, at one point in the cycle, the tank condenser C will be charged so that the upper plate will be negative, and hence, have an overabundance of electrons. For a charge of this polarity, however, the potential across the tank circuit will *subtract* from the plate supply voltage so that the actual plate voltage is reduced. Looking at Fig. 24B, we see that for a lower effective plate voltage, the plate current actually is high. This means a comparatively large number of electrons will be arriving at the plate and thus act to charge the tank condenser C still higher.

For another part of the cycle, the tank condenser C will discharge and recharge with the opposite polarity. The electrons will leave the top plate, flow through the tank coil L, and concentrate on the lower plate of the condenser. In this case, the potential across the tank circuit will *add* to the plate supply voltage so that the actual plate voltage is increased. Referring to Fig. 24B, however, we see that this plate voltage increase makes the plate current go down. This means, then, that comparatively few electrons will arrive at the plate. The tank condenser, therefore, is allowed to reach a maximum charge with reversed polarity.

Thus the negative resistance characteristic of the tube acts to force complete charge of the tank condenser each time, first with one polarity, then with the other. In so doing, sufficient energy is supplied to the oscillatory L-C tank circuit to keep it in continuous oscillation.

A dynatron oscillator delivers a nearly pure sine-wave voltage to a load which is inductively coupled to the tank coil. Since this type of oscillator depends solely upon an apparent negative resistance which is not brought about by feedback in its usual form, the frequency of oscillation is more independent of voltage-supply fluctuations than the more conventional oscillators. The absence of a tickler coil, tank circuit tap, or other feedback device, also makes the dynatron very adaptable to oscillators that can be tuned over a wide range with little change in stability.

THE TRANSITRON

Even though useful in the dynatron, secondary emission from a vacuum tube plate is very undesirable in amplifier operation. Indeed, as we discovered in an earlier Lesson, the existence of the so-called "unstable" region in the characteristic curve of a tetrode led to the development of the pentode tube in which a suppressor grid was included to prevent secondary emission effects. Furthermore, in modern tubes, the plate surface usually is treated to reduce the possibility of secondary emission still more.

For these reasons, even though good dynatron action can be obtained with obsolete screen-grid tubes such as the Type 24A, with tubes of modern construction, negative resistance from secondary emission is very difficult if not impossible to achieve.

It is possible, however, to construct a negative resistance oscillator which does not rely upon secondary emission. This is done by using a modern pentode tube (which has the suppressor grid brought out to a separate base pin) in the circuit shown in Fig. 25. This particular form of oscillator is called a "transitron."

Action of the Suppressor Grid. The transitron gains its negative resistance characteristic from the unusual effect of the suppressor grid in dividing the total electron current between the plate and the screen.

In general, the effect of the suppressor grid voltage upon the *plate* current will be like that of any control grid. When the suppressor grid is positive, more electrons reach the plate, and the plate current goes up; when the suppressor grid is negative, fewer electrons reach the plate, so plate current goes down.

In a tube such as this, however, because of the shielding action of the screen grid, conditions at the plate have little effect upon the total space charge current. Indeed, the total electron flow current from the cathode tends to be *constant* at a value determined by the average screen-grid potential.

We find then, if the plate voltage is somewhat lower than that of the screen, when the suppressor grid is made *negative* so that plate current decreases, electrons which cannot reach the plate are simply forced back and are attracted to the screen. The screen current, therefore, actually *increases*. For a *positive* suppressor grid voltage, electrons pass through the screen with relatively high velocity and progress all the way to the plate. This means, of course, that the plate current increases, but the screen current *goes down*.

In other words, the suppressor grid tends to divide the constant-valued electron stream from the cathode. When it is positive, it allows most of the space current to reach the plate, but when it is negative, it blocks the path to the plate, forcing the electrons back to the screen grid.

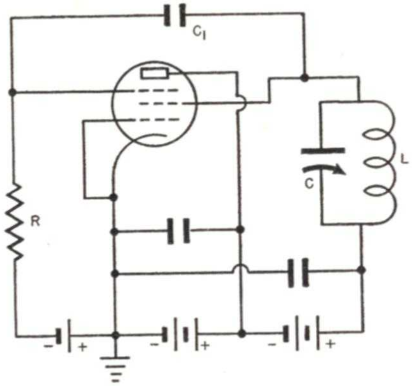

FIG. 25. The transitron oscillator which uses negative resistance obtained from the effect of the suppressor-grid voltage upon screen-grid current in a pentode tube.

Obtaining Negative Resistance. If a load is placed in the screen-grid circuit, the screen voltage will rise and fall according to the screen current; it increases (becomes more positive) when the screen current decreases (and vice versa). This screen voltage change thus will be in *the same polarity* as the voltage applied to the suppressor grid. All that is necessary, then, to get an apparent negative resistance in the screen grid circuit is to apply some of the screen voltage variations to the suppressor grid through the coupling condenser C_1 in Fig. 25.

When this is done, if the screen grid voltage tends to rise, thus becoming more positive, the suppressor grid also becomes more positive so that the screen-grid current is reduced and the screen voltage raised still more. On the other hand, when the screen voltage decreases (a change in the *negative* direction), the suppressor is driven more negative so there is an increase of screen current and a still lower screen voltage.

In this way, sufficient energy from the tube to maintain oscillation is supplied to the tank circuit.

► In general, the negative resistance obtained from a transitron is very much lower than that obtained in the dynatron. Transitrons, therefore, are more reliable and have even better frequency stability. As a matter of fact, when in optimum adjustment, a transitron may be so stable that it is comparable to a crystal oscillator in which the crystal is not temperature-controlled. This high stability, together with the fact that no tickler winding or tank circuit tap is necessary, makes the transitron extremely useful for wide-range variable-frequency laboratory oscillators.

Lesson Questions

Be sure to number your Answer Sheet 18RC.

Place your Student Number on *every* Answer Sheet.

Most students want to know their grades as soon as possible, so they mail their set of answers immediately. Others, knowing they will finish the next Lesson within a few days, send in two sets of answers at a time. Either practice is acceptable to us. However, don't hold your answers too long; you may lose them. Don't hold answers to send in more than two sets at a time or you may run out of Lessons before new ones can reach you.

1. In a self-excited oscillator employing only grid-leak bias, what results if oscillations cease?

2. In what way will a self-excited oscillator perform if an excessively high grid-leak resistance is used?

3 When the coupling to the load is increased, will the oscillator plate current: (1) increase; (2) decrease; or (3) remain the same?

4. What is the fundamental difference between the Hartley and the Colpitts oscillators?

5. Is it necessary that the surfaces of a quartz crystal be kept clean?

6. Briefly describe the procedure for adjusting a triode quartz crystal oscillator so that oscillations will occur.

7. If a condenser is used between the plate and the grid of a pentode crystal oscillator, what is the effect of making this condenser too large?

8. What is the average shift in cycles per million per degree Centigrade for an X-cut crystal, and is this shift: (1) to a lower; or (2) to a higher frequency, with temperature increases?

9. A transmitter uses a 1000-kilocycle crystal with a temperature coefficient of —4 cycles per megacycle per degree Centigrade. If the crystal temperature increases 6 degrees Centigrade, what is the frequency change?

10. What type of oscillator depends upon secondary emission from the anode (plate) for its operation?

THE FABLE OF DISCOURAGEMENT

Once upon a time, so the story goes, the devil held a sale. To any one who would pay the price, he offered the tools of his trade. On a table, each with its price label, were *hatred, despair, sickness, jealousy, greed,* and all the other causes of unhappiness.

Off to one side, however, lay a harmless-looking wedge-shaped instrument marked *discouragement.* It was old and worn, but priced the highest of them all. When asked why the price was so high, the devil replied: *"Because this tool is one I can use so easily. Nobody knows that it belongs to me, so with it I can open doors that are immune to all other tools. And once inside, I can finish the job with almost any of the other tools!"*

Few people know how small is the margin between failure and success. Frequently, the separation is just the width of that one word—discouragement.

You can combat discouragement by cultivating confidence in yourself. Whatever you may desire of life—whatever your goal may be—you have only to work for it wholeheartedly, confidently, with that one goal always in mind, *and you will reach it.*

J. E. SMITH