HOW RADIO-FREQUENCY AMPLIFIERS WORK

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STUDY SCHEDULE NO. 17

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. Characteristics of R.F. Amplifiers .... Pages 1-7

Here you learn the requirements placed on r.f. amplifiers in receivers and in transmitters; how tuned circuits eliminate the effects of the plate-cathode interelectrode capacity; and how selectivity is obtained. Answer Lesson Question 1.

☐ 2. R.F. Amplifiers in Receivers .... Pages 8-13

The t.r.f. receiver uses a number of r.f. stages in cascade to obtain the required gain and selectivity. On the other hand, the selectivity and gain of a superheterodyne is obtained in the i.f. amplifier. The use of dual tuned circuits requires a new definition of selectivity and fidelity, as given here.

☐ 3. Stabilizing Radio-Frequency Amplifiers .... Pages 14-17

The triode tube will oscillate unless feedback is controlled. Here you are introduced to neutralization in the forms used in early receivers.

☐ 4. Tubes With Screen Grids .... Pages 17-23

One way to avoid feedback is to use a screen grid. The tetrode tube has undesirable secondary emission effects, which led to the development of the pentode and beam tubes. The variable-mu tube used in receivers also is described. Answer Lesson Question 2.

☐ 5. Basic Transmitter R.F. Amplifiers .... Pages 23-30

For higher efficiency, transmitters use class B and class C stages. This is made possible by the flywheel effect of tuned circuits. Answer Lesson Questions 3, 4, and 5.

☐ 6. Class C Stages and Their Adjustment .... Pages 30-36

Pay particular attention to the procedure for neutralizing and tuning given in this section. Answer Lesson Questions 6, 7, 8, 9, and 10.

☐ 7. Start Studying the Next Lesson.

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HOW RADIO-FREQUENCY AMPLIFIERS WORK

Characteristics of R.F. Amplifiers

MUCH of the study of radio concerns the behavior of alternating currents that have frequencies in the "radio-frequency" spectrum—that extensive band of frequencies which has a lower limit just above the audible frequencies, and an upper practical limit near the incredible frequency of 30,000 megacycles per second (thirty thousand million oscillations per second).

We must use these radio-frequency (r.f.) currents as the "carriers"—the means of getting our radio signals to travel through space—because low-frequency currents will not radiate efficiently from an antenna system. To get radiation at a long distance for reasonable amounts of power, we must go to these higher frequencies, and must modulate them according to the sounds, scenes, or code messages we want to transmit.

Other Lessons will discuss radiation, modulation, and the generation of these r.f. currents, so here we will concentrate on the means of amplifying r.f. signals. Let's first see why amplification is needed.

Transmitter Requirements. The transmitter carrier frequency must be held quite constant to prevent undue interference between stations. In general, it is not practical to devise an oscillator that will have this required frequency stability and yet be capable of producing a substantial output of power at the same time. Consequently, a transmitter *oscillator* is designed to perform only one function—the generation of a small but very steady radio-frequency power. This "master oscillator" output is then stepped up in successive r.f. amplifier stages, the power becoming greater with each stage, until the desired power level is reached. In this way, the proper output power is obtained, with a maximum of frequency stability.

From this, the prime purpose of a radio-frequency amplifier in a transmitter is to increase the available carrier *power*. Because of cost considerations, the *efficiency* of the amplifier, or the ratio of its output power to what is put into it, also is of prime importance.

Receiver Requirements. In a receiver, the requirements of an r.f. amplifier are somewhat different. The voltage developed in the receiving antenna by a weak signal is quite small. It is necessary, therefore, to use r.f. amplifiers to increase this signal voltage, sometimes as much as a million times, to bring it up to the desired level.

Also, we do not wish to hear more than one station at a time. Therefore, a receiver must reject undesired signals and accept the desired one. To separate signals, it is necessary to tune the r.f. amplifier of a receiver.

Such amplifiers, therefore, perform two functions: they serve to give the receiver the necessary frequency selectivity for separation of various signals, and they supply the voltage gain between the antenna and the detector.

Although furnishing *voltage* gain in a receiver and *power* gain in a transmitter are actually two different service requirements, the amplifier circuits used are quite similar. They work into similar loads, and both are frequency selective. Let's consider a basic stage.

A BASIC R.F. STAGE

Suppose we have the simple circuit shown in Fig. 1. This is a triode vacuum tube arranged in a resistance-coupled amplifier circuit. If the load resistance R_L is of the proper value, and all battery voltages are correct so that the tube is operating over a straight-line portion of its E_g-I_p curve, then we know we can apply a small input voltage e_i and obtain an amplified replica e_o at the output. As you know, this circuit is commonly used as a low-frequency amplifier.

Can such an amplifier be used for radio frequencies? Suppose we gradually increase the frequency of the signal generator, keeping the input signal voltage e_i constant, and see what happens.

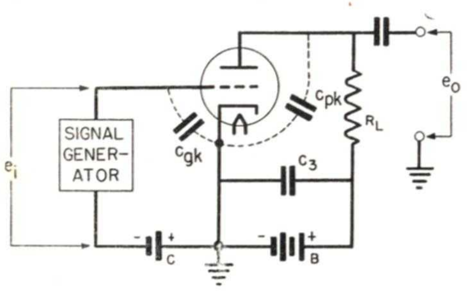

FIG. 1. A resistance-coupled amplifier circuit that shows the interelectrode capacities of the tube that limit the response of high frequencies.

At 20,000 cycles, or 20 kc., we will find the output e_o has decreased somewhat; at 30 kc. the loss in output will be quite severe; at 40 kc. and all higher frequencies, the output e_o may be even less than the input voltage e_i, thus indicating a loss instead of an amplification. Obviously, such an amplifier cannot be used with any efficiency at radio frequencies.

Fig. 1 shows why this happens. Notice the two capacities drawn in with dotted lines. These represent the internal interelectrode capacities of the tube, and their values are determined by the size, shape, and separation of the elements. These capacities begin to have an effect even at audio frequencies; and, as we increase the frequency of the signal, the reactances of the interelectrode capacities steadily decrease. At radio frequencies, the reactances drop to such low values that these capacities by-pass most of the signal, so the load resistor R_L is virtually short-circuited by C_{pk}. (The circuit is completed through by-pass condenser C_3.) The input capacity C_{gk} shunts the load of the previous stage (or the input device) in the same manner. From this we find that the high-frequency response of a resistance-coupled amplifier is limited primarily by the capacities between the tube elements.

Use of Tuned Circuits. Let us assume, however, that instead of the load resistor R_L we substitute a parallel-resonant circuit L_1-C_1 for the tube load, as in Fig. 2.

► It is important to note that since the B-battery is adequately by-passed by condenser C_3, the tube plate-cathode capacity C_{pk} is effectively in parallel with the resonant circuit L_1-C_1. This tube capacity, therefore, is across tuning condenser C_1. It now merely increases the tuning capacity, so a slight reduction in the capacity of C_1 will re-tune the circuit to the desired frequency. Thus, C_{pk} becomes part of the tuned circuit, and no longer will act to by-pass the signal.

Furthermore, since such a tuned circuit has a high impedance at its resonant frequency, it will perform as an adequate tube load at this frequency, and considerable amplification can be obtained.

Let us make a test of the circuit in Fig. 2. We shall assume first that the tuned circuit L_1-C_1 *with the tube plate-cathode capacity* C_{pk} *in parallel with it*, is resonant at a frequency of 1000 kc. Ignoring for the moment the effects of the tube grid-cathode capacity C_{gk}, let us also assume that the signal generator can supply sufficient input e_i to meet our test requirements. If we now attach to the output terminals an r.f. voltage indicator, we can measure the output voltage e_o and find the amplification for a number of different frequencies.

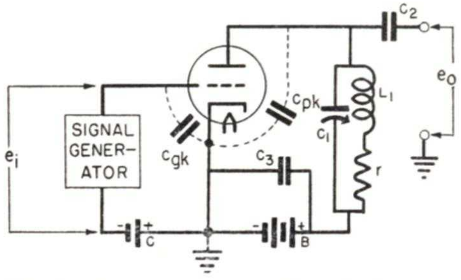

FIG. 2. The basic r.f. amplifier which uses a parallel-tuned circuit instead of a resistance plate load. Since the by-pass condenser C_3 is very large, the tube plate-cathode capacity C_{pk} is effectively in parallel with the tuned circuit L_1-C_1.

Starting at some frequency lower than the resonant frequency of the tuned circuit—980 kc., for instance—we first adjust the input voltage e_i to some fixed value, say 1 volt. We then read the output voltage e_o for this condition. *Keeping the input voltage* e_i *constant at 1 volt*, we next increase the frequency of the signal generator to some higher frequency such as 985 kc., and read the output voltage e_o again. This process is repeated over and over again, gradually increasing the signal frequency in 5 kc. steps each time, until we have passed the resonant frequency of the tuned circuit at 1000 kc. and gone about 20 kc. beyond, that is, to approximately 1020 kc.

By plotting the values of output voltage e_o that we obtained for each different input frequency, we find we have an amplifier response curve like the one in Fig. 3. As we expect, at the resonant frequency of 1000 kc., where the impedance of the tuned circuit is high, we have considerable gain. At this point the output voltage e_o is 60 volts, which is 60 times as large as the input voltage e_i of 1 volt, so the over-all gain is actually 60.

Also, for other frequencies that are higher or lower than resonance, the impedance of the tuned circuit is so low that the tube cannot work efficiently, and the gain, consequently, is dropped to small values. Thus, the gain at 980 kc. and at 1020 kc. is only about 4 and 10, respectively. Hence, this circuit favors the frequency to which it is tuned by giving it much greater amplification than others. And, this circuit is adjustable so that it is possible to tune it to the desired signal.

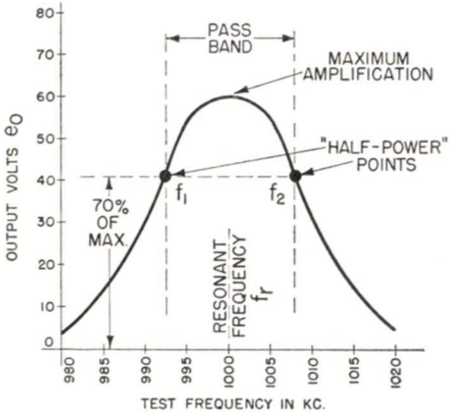

FIG. 3. The response curve of the basic r.f. amplifier in Fig. 2. The pass band is considered as that band of frequencies lying between the two "half-power" points.

► By the simple process of substituting a parallel-resonant circuit for a resistor load, we have done two things: For one, we have eliminated the troublesome by-pass effects of the plate-cathode capacity by making it part of the tuned circuit; and two, we have succeeded in making a radio-frequency amplifier which not only is capable of giving gain, but also has a certain degree of frequency selectivity. This is exactly what we want.

Definition of Selectivity. Now that we have a radio-frequency amplifier that amplifies some frequencies considerably more than others, how much frequency selectivity does it possess? How do we measure it?

Referring again to Fig. 3, we see the curve is not extremely sharp. Even though there is a maximum output at the resonant frequency of 1000 kc., for a small band of frequencies both higher and lower than this, there is still considerable amplification.

Let us consider, for example, the lower frequency f_1 and the higher frequency f_2 which are situated on the curve at points where the amplification is still 70% of the maximum value. For all frequencies between these two points, the amplification will be very nearly as great as that at the maximum. In fact, the voltage gain over this band does not vary more than 3 db. We might consider that between these limits the response curve has a definite "pass band."

As a matter of definition, the pass band of a simple selectivity curve like Fig. 3 is considered as that band of frequencies lying between the lower and higher frequencies at which the output voltage drops to 70% of its maximum value.

Since we know the power in any circuit is proportional to the *square* of the voltage, an output voltage of 70% of the maximum represents a power which is 0.7 × 0.7 = 0.49, or only about one-half of the maximum power. For this reason, the reference points f_1 and f_2 on the curve in Fig. 3 are very often called the "half-power" points.

We obtained a response curve like Fig. 3 because the impedance of the tuned circuit acting as tube load was not constant for different frequencies. As a matter of fact, this curve is almost identical to the curve we would get if we plotted the change of tuned circuit impedance over the same range of frequencies. We should expect, then, that the selectivity we get with any amplifier like Fig. 2 will depend a great deal upon the inductance L_1, the capacity C_1, and most particularly, upon the *quality* of both these components.

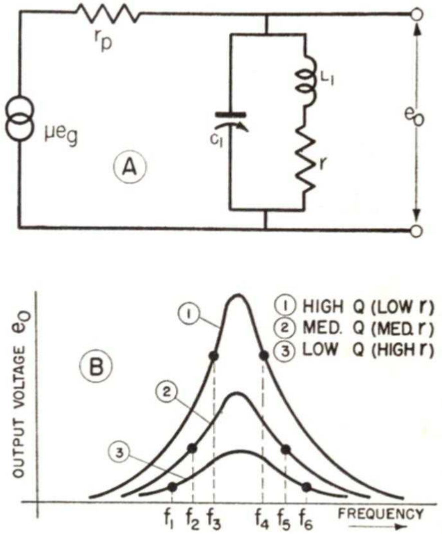

FIG. 4. At A is shown the constant-voltage equivalent circuit of the basic r.f. amplifier in Fig. 2. The response curves for three different values of tuned circuit Q are shown at B.

► Indeed, by defining selectivity as we have, it is now possible to determine the pass band (the band of frequencies that get about the same amplification) of the response curve by dividing the resonant frequency by the effective Q of the tuned circuit. We might write this:

$$\text{Pass band} = \frac{\text{Resonant frequency } (f_r)}{\text{Q of the tuned circuit}}$$

where the Q is approximately equal to the inductive reactance of the coil L_1 at resonance divided by the coil a.c. resistance r, or simply,

$$Q = \frac{\text{Coil reactance at resonance}}{\text{Coil a.c. resistance}}$$

$$Q = \frac{2\pi\ f\ L}{r}$$

As an illustration of what these relations mean, suppose we have a parallel-resonant circuit tuned to 1000 kc., in which the coil has an inductance L_1 of 100 microhenries and an effective resistance r of 15 ohms.* The Q of the circuit is:

$$Q = \frac{2\pi\ f\ L}{r} = \frac{2 \times \pi \times 1{,}000{,}000 \times 0.0001}{15}$$

$$Q = \frac{628}{15} = 41.9$$

If we use this tuned circuit with a Q of 41.9 in a circuit like Fig. 2, then we can expect the band width of the response curve at the half-power points to be:

$$\text{Pass band} = \frac{f_r}{Q} = \frac{1{,}000{,}000}{41.9}$$
$$= 23{,}800 \text{ cycles or } 23.8 \text{ kc.}$$

► This relation between the Q of a tuned circuit and its pass band is a very convenient one. For instance, rearranging the equation gives:

$$Q = \frac{\text{Resonant frequency } (f_r)}{\text{Pass band}}$$

In this form, the Q of a tuned circuit can be determined from its response curve by dividing the resonant frequency by the pass-band width. Thus, if we would like to determine the effective Q of the tuned circuit giving the response curve in Fig. 3, we can do so as follows:

From the curve, we see that maximum output occurs at 1000 kc. This gives:

f_r = 1,000,000 cycles.

Noting the frequency of the half-power points, we obtain:

f_1 = 993,000 cycles
f_2 = 1,008,000 cycles

and, since the pass band is the difference between these two, we have:

$$\text{Pass band} = f_2 - f_1 =$$
$$1{,}008{,}000 - 993{,}000 = 15{,}000 \text{ cycles.}$$

The Q of the circuit giving this particular selectivity curve is:

$$Q = \frac{f_r}{f_2 - f_1} = \frac{1{,}000{,}000}{15{,}000} = 66.7$$

Now, looking back over the examples just outlined, we see that a tuned circuit with an effective Q of 41.9 has a pass band 23.8 kc. wide, and one with an effective Q of 66.7 has a passband width of only 15 kc. This emphasizes the fact that the pass band is always inversely proportional to the circuit Q. *In general, low-Q circuits have a broad pass band, and high Q circuits pass only a comparatively narrow band of frequencies.* Let's learn more about this by examining the behavior of the parallel-resonant circuit in detail.

PARALLEL-RESONANT LOADS

You have learned that any vacuum tube can be replaced by an approximate equivalent circuit for study purposes. Thus, the basic radio-frequency amplifier circuit of Fig. 2 can be made to appear as in Fig. 4A, where we have a *constant-voltage* generator in series with a fixed resistance. This is known as a "constant-voltage generator equivalent" circuit. The generator voltage is made equal to the original grid input voltage e_g multiplied by the tube amplification factor μ, and the series resistance is equal to the plate resistance r_p of the tube. The output voltage e_o, developed across the tuned circuit, is about the same as that of the original circuit.

We have already discovered that the selectivity of such an amplifier de-

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***Instruments are available that will measure the Q of a coil directly.**

pends a great deal upon the Q of the tuned circuit. Furthermore, you know that the lower the coil resistance r, the higher the Q will be. The selectivity, therefore, should be greater for smaller values of coil resistance.

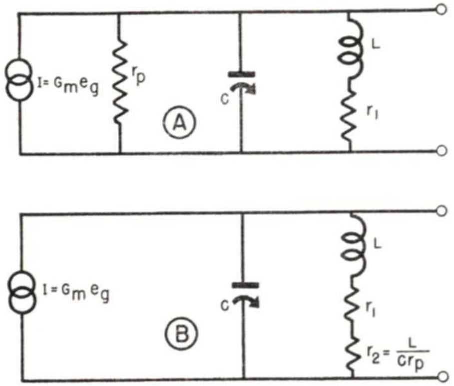


FIG. 5. The constant-current equivalent circuit of the amplifier in Fig. 2 is shown at A. The high plate resistance r_p in shunt with the tuned circuit has the same effect as a small additional resistance r_2 in series with the inductance L, as shown at B.

To illustrate what will happen to the response curve for different values of Q, let us use several values of r, and then run corresponding curves for the circuit in Fig. 4A. First, let us assume that the inductance coil L_1 is a very good one, so r is very low. For this case we will get a very sharply peaked response curve like curve 1 in Fig. 4B.

Next, to lower the circuit Q, we add a small resistor in series with the coil to increase the value of r somewhat. The response curve under this condition will look like curve 2 in Fig. 4B.

Finally, for a low-Q circuit, we add a much higher resistance in series with the coil so that r has a relatively high value. We will find that this last response curve is very much like curve 3.

Obviously, the Q value has a very pronounced effect, and as we stated before, the pass band is determined almost entirely by the effective value of Q. Thus, by noting the half-power points for the high-Q condition in curve 1, we see the pass band is very narrow, occurring between the frequencies f_3 and f_4. For the medium-Q circuit in curve 2 we have a somewhat wider pass band, between frequencies f_2 and f_5. For the low-Q circuit, the half-power points on curve 3 have separated so that the pass band occupies a very wide band of frequencies between f_1 and f_6. A low-Q circuit containing high values of resistance is not very selective.

Tuned-Circuit Impedance. Selectivity, however, is not the only thing determined by Q. In Fig. 4B, notice that the voltage output, and hence the over-all amplification, obtained from a high-Q circuit is considerably greater than for a medium-Q, and is very many times greater than for a low-Q tuned circuit. Since the output voltage from an r.f. amplifier is proportional to the load impedance into which the tube must work, the load impedances for low- and high-Q circuits are not the same.

► Then what is the maximum impedance of a tuned circuit when it is used as a tube load? In general, we will find that the impedance across the terminals of a parallel-resonant circuit like that in Fig. 4A is approximately equal to the inductive reactance of the coil at resonance multiplied by the effective Q of the circuit. We can write this in equation form, as:

$$Z = X_L \times Q = 2\pi f L Q$$

From this equation, the maximum value of impedance depends directly on Q; a high-Q circuit has high impedance, and a low-Q circuit has low impedance. The curves in Fig. 4B show that a higher Q makes a greater tube plate load, and hence, provides a greater amount of output voltage.

Loading by the Tube. The inductance and the resistance in a tuned circuit are not the only factors determining effective Q. What other items must we, therefore, consider in the circuit?

Let us consider Fig. 4A again. The tube plate resistance is actually across the resonant circuit and will affect its Q. This is easier to see if, instead of this "constant-voltage" equivalent circuit, we make a "constant-*current*" equivalent as shown in Fig. 5A. Here we have an imaginary generator supplying a constant current equal to the original grid voltage e_g multiplied by the mutual conductance G_m of the tube. In addition, a fixed resistor r_p equal to the tube plate resistance is shunted across the generator. The behavior of this equivalent circuit is identical to that of the amplifier in Fig. 2.

In this new arrangement, notice that the tube plate resistance r_p is in parallel with the resonant circuit. A fundamental rule for parallel impedances is that the total impedance is always less than the smallest one in the group. Hence, no matter how small we make the coil resistance r_1, the impedance offered the generator will never be greater than the plate resistance r_p which is shunted across the resonant circuit. The tube plate resistance, therefore, limits the effective circuit Q.

Another way of looking at this is shown in Fig. 5B. The plate resistance r_p is removed, and an additional resistance r_2 is placed in series with the coil. (Here, r_1 represents the a.c. resistance of the coil.) *Electrically*, Figs. 5A and 5B are identical, and they illustrate the fact that the effects of a high resistance shunted across a tuned circuit can be duplicated by a low resistance inserted in series with the inductance of the tuned circuit.

The resistance r_2 is approximately equal to the L-C ratio divided by the plate resistance r_p. If in any given case we have a very high plate resistance r_p, then the effective resistance r_2 in series with the coil is very low, and the tuned circuit Q is not disturbed very much. On the other hand, if the tube plate resistance r_p is comparatively low in value, then the equivalent resistance r_2 can easily be large enough to drop the effective Q of the resonant circuit to an unsatisfactory value.

► The plate resistance r_p, however, may not be the only resistance shunted across the tuned circuit. Whenever we attach any load to the output terminals of a radio-frequency amplifier, no matter whether it be the grid circuit of a following stage, an indicating instrument of some sort, or just a simple resistor, the added resistance in shunt lowers the circuit Q in exactly the same manner as would an additional resistance placed in series with the inductance coil.

From these considerations we see that the Q of a tuned circuit taken alone does not tell the whole story. It is the *effective* Q we obtain after all components are tied together in the circuit that determines the selectivity and general response of a radio-frequency amplifier.

R.F. Amplifiers in Receivers

The basic circuit shown in Fig. 2 could be used as an r.f. amplifier in a radio receiver. In most cases, however, neither the gain nor the selectivity afforded by a single amplifier stage is sufficient for satisfactory reception. It is necessary, therefore, to use two or more amplifiers in cascade; and to use a somewhat different circuit. Several methods of coupling the stages together are shown in Fig. 6. The coupling shown at 6D is the one most commonly used in receivers, but the others are worth brief study.

In the direct-coupled method shown in Fig. 6A, the output voltage across the tuned circuit L_1-C_1 is applied directly to the grid of the second amplifier VT_2 through the coupling condenser C_4. The grid resistor R_2 is necessary to provide a d.c. path to ground so that the grid may be supplied with the bias that is produced by the cathode resistor R_3. The value of the resistor R_2 should be quite high—at least ½ megohm—to prevent excessive loading of the tuned circuit and thus lowering its Q and its selectivity.

When two r.f. amplifiers are coupled together in this manner, both the plate-cathode capacity C_{pk} of the first tube VT_1 and the grid-cathode capacity C_{gk} of the second tube VT_2 are effectively in shunt across the tuned circuit. Both these tube capacities, which are shown by dotted lines in the figure, actually form part of the tuned circuit, and neither of them gives undesirable by-pass action. Their very presence, however, adds to the capacity of the resonant circuit, and for tuning to a given frequency, the capacity of the tuning condenser C_1 must be decreased slightly below the theoretical value.

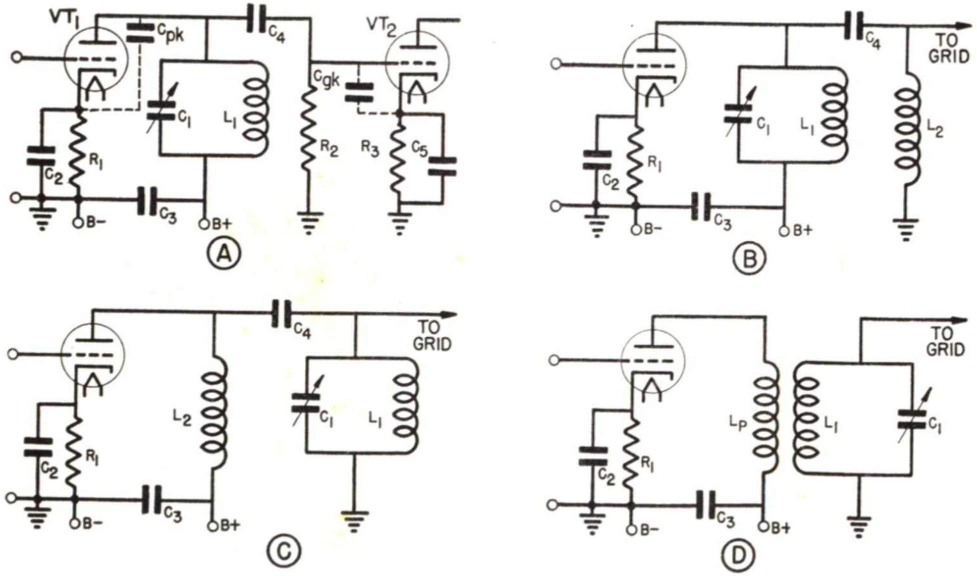


FIG. 6. Four methods of coupling r.f. amplifiers together for operation in cascade. In A, B, and C, both the plate-cathode capacity of C_{pk} of the first tube and the grid-cathode capacity C_{gk} of the second tube are effectively in shunt with the tuned circuit.

In Fig. 6B we have another direct-coupled arrangement in which the grid resistor has been replaced by an r.f. choke L_2. Because the grids of receiver amplifiers do not draw current, and a choke usually is more expensive to manufacture than a simple resistor, this circuit is seldom used.

If we interchange the positions of the choke and the tuned circuit, we arrive at the impedance-coupled circuit of Fig. 6C. With this scheme, the direct current to the tube plate is allowed to flow through the r.f. choke, but since this path has a high impedance to r.f. currents, the signal voltage is still applied to the tuned circuit which continues to act as the tube load. As the power supply voltage is no longer applied directly to the tuned circuit, one side of the coil and tuning condenser can be grounded. This makes considerably simpler construction. Such an arrangement also has the additional advantage that the coupling condenser C_4 can be made relatively small so that the tube plate resistance is not so closely coupled to the tuned circuit; the Q of the tuned circuit and the over-all selectivity thus may be increased.

A tuned radio-frequency transformer is used for coupling in Fig. 6D. The secondary winding L_1 with the tuning capacitor C_1 forms a *series*-resonant circuit, since the voltage induced in the secondary acts in *series* with the circuit. However, because of transformer action, the impedance "reflected" into the primary winding L_p still goes through a maximum high value at resonance. The frequency response of such a tuned transformer circuit, therefore, is very similar to that of the direct-coupled arrangements. It has the advantage that the winding turns on the primary L_p may be adjusted to make it a step-up transformer, or the coils may be separated enough to make the mutual inductance quite small so that the tube plate resistance does not load the tuned secondary too severely. In this way it is possible to obtain a high circuit Q and maximum selectivity.

TUNED R.F. AMPLIFIERS

As selectivity is so important in a receiver, all r.f. amplifiers are biased for class A operation. This means that each tube is operated only over the straight-line portion of its E_g-I_p curve. Thus, if we consider the characteristic E_g-I_p curve in Fig. 7, we see that the control grid is biased sufficiently negative with respect to the cathode to place the operating point in the center of the linear portion of the curve. By restricting the grid swing to the linear portion of the curve, the grid is never driven beyond zero or allowed to become positive enough to draw appreciable grid current. *If the grid draws no current, then its effective resistance is high. Under these circumstances, a tuned circuit attached to the grid will not be loaded appreciably, and the Q of the circuit will not be reduced.*

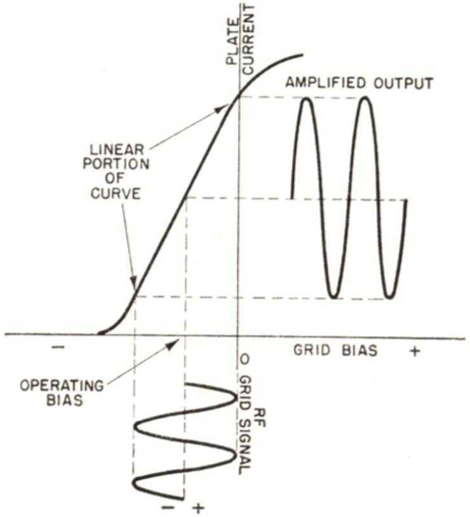


FIG. 7. A receiver r.f. amplifier is operated in class A so that its grid never swings sufficiently positive to draw appreciable grid current.

On the other hand, if the grid of an r.f. amplifier is improperly biased, or too much excitation voltage is applied so that the grid does draw current, then the effective resistance of the grid may drop to only a few thousand ohms; and as we saw before, whenever a tuned circuit is shunted by such a comparatively low resistance, the effective Q is markedly decreased and considerable selectivity is lost. Obviously, this condition is to be avoided.

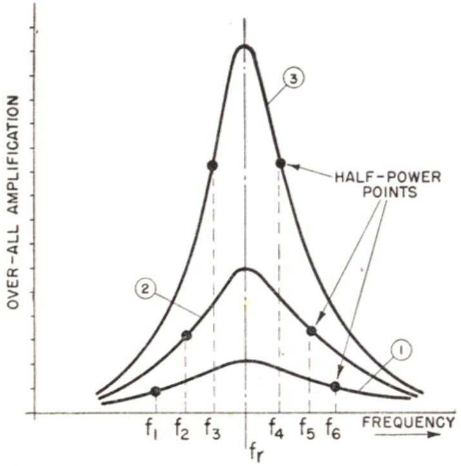


FIG. 8. Representative response curves for a single r.f. amplifier, two amplifiers in cascade, and three identical cascaded stages. Besides the increased gain, note the improvement in selectivity resulting from cascade operation.

Over-All Selectivity. So far we have considered the selectivity obtained from a single r.f. amplifier only. When two or more are arranged in cascade what is the selectivity?

In our study of audio-frequency amplifiers we found that the over-all gain from several stages in cascade was equal to the product of the gains in each stage. Hence, if we have three audio stages, each with a gain of 10, the over-all gain in cascade will be 10 × 10 × 10 or 1000.

The same sort of calculation can be applied to cascaded r.f. amplifiers. It must be remembered, however, that every r.f. amplifier has its own frequency-response curve. The over-all response curve we obtain from several of them in cascade, therefore, should be approximately equal to what we would get if we "multiplied" the individual response curves together.

As an illustration of what occurs, let us examine Fig. 8. Suppose we have three r.f. amplifiers just alike, the response of each one being like curve 1 in the figure. If we now arrange *two* of these amplifiers in cascade, then the over-all response curve will resemble curve 2. Because the two stages are just alike, and we have multiplied their responses together, curve 2 is actually the *square* of curve 1.

Similarly, if *three* of the amplifiers are used in cascade, then we get still another response like curve 3. In this particular instance, since the gains of each stage were made the same, curve 3 is the *cube* of curve 1.

In addition to the expected increases in gain, notice the *shapes* of the curves. By marking the half-power points on each of these response curves, we find that the pass band of a single amplifier as in curve 1 extends between the frequencies f_1 and f_6; for two amplifiers in cascade this is narrowed to the frequencies f_2 and f_5 on curve 2; and on curve 3, representing three amplifiers in cascade, the pass band is diminished still more and lies between frequencies f_3 and f_4.

This demonstrates the fact that operating r.f. amplifiers in cascade not only increases the gain tremendously, but also improves the selectivity to a great degree.

Plotting Curves. Curve 3 in Fig. 8 is getting rather tall, even though it represents a gain of only 27. Imagine how far the curve would extend if we plotted gains of 1 million—a figure fairly easy to obtain from three r.f. stages with a gain of 100 each!

To reduce such curves to more reasonable size, a logarithmic scale is used, as in Fig. 9A. As an additional convenience, the frequency scale also is changed to read in units of kilocycles above and below resonance. Although this method of plotting "shortens" the curve and actually distorts its shape, the gain and the true pass band as indicated by the half-power points still can be determined.

Even a plot like Fig. 9A sometimes is awkward because the values of amplification at and near resonance involve rather large numbers. In such cases, engineers plot what is called a "ratio resonance" curve. This is a curve obtained by dividing the amplification at resonance by the amplification at each test frequency and plotting the resulting ratios against frequency in the manner shown in Fig. 9B.

Instead of holding the test input voltage constant and noting the change in output for different frequencies as was done for Fig. 9A, the ratio curve is determined by setting the output at some arbitrary level at resonance, and then noting how much the input voltage must be increased to get the same output for other frequencies above and below resonance. Care must be taken in doing this, however, to be sure excessive input voltage is not applied to the receiver, or else overloading may occur and the results will be erroneous.

I. F. AMPLIFIERS

In the tuned radio-frequency type of receiver, several r.f. stages are cascaded. Even at best, however, the selectivity and gain are not equal to that obtainable from a superheterodyne, so the latter receiver is the preferred type.

Although a "super" receiver may use one or more tuned r.f. amplifiers, its gain and selectivity come from the use of fixed-tuned i.f. stages. (You will recall that the incoming signal is combined with a signal from a local oscillator in a converter stage of a superheterodyne. The intermediate frequency output of the converter carries all the modulation of the original carrier.) Since the i.f. amplifiers are fixed-tuned, these can be made more complex than the ordinary r.f. amplifier in order to obtain a selectivity curve which more closely approaches an ideal response.

Dual Tuned Circuits. Almost all i.f. amplifiers use some form of dual tuned circuit such as Fig. 10. This is an r.f. coupling transformer with both

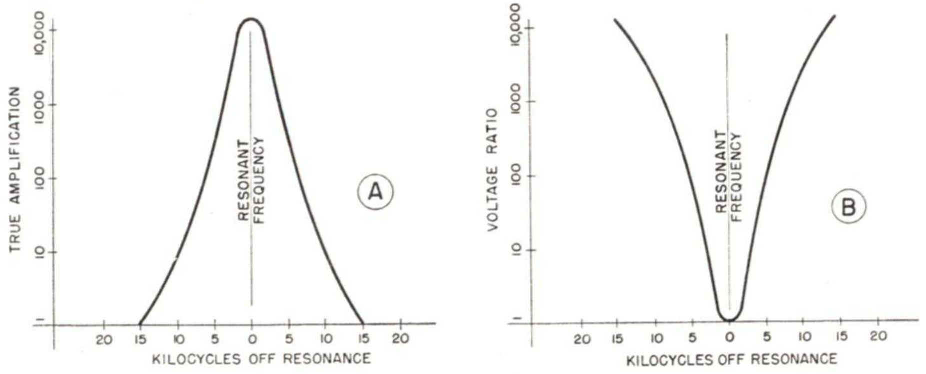


FIG. 9. By using a logarithmic instead of a linear amplification scale, we can plot high-gain response curves in smaller more convenient form. At left is a conventional true amplification curve. We obtain the voltage ratio curve at right by dividing the amplification at resonance by the amplification at each test frequency.

primary and secondary windings tuned to the same frequency. As you might expect, the response curve from such an arrangement will depend a great deal upon the respective Q's of the two coils L_1 and L_2. We find also that the gain and the selectivity are determined to a marked extent by the degree of coupling between the inductances.

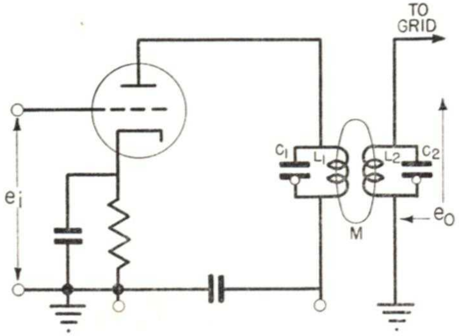


FIG. 10. The double-tuned transformer load circuit commonly used in i.f. amplifiers.

If we run a response curve with the two coils L_1 and L_2 widely separated so that their mutual inductance M is very low, we obtain the curve 1 in Fig. 11. Since the coupling is small there is very little energy transferred from the primary to the secondary winding, and consequently, the output voltage cannot rise very high.

With the coils closer together, so that there is a larger mutual inductance M, we get curve 2 of Fig. 11. As you might expect, with closer coupling, more energy is transferred, and the output voltage becomes greater.

We can continue to increase the output voltage in this manner by increasing coupling until we get to a maximum value as indicated by curve 3. *At this point we have what is called "critical coupling"—no greater output voltage can be obtained for any other coupling adjustment.*

Critical coupling occurs when the resistance "reflected" into the primary circuit from the secondary is exactly equal to the primary resistance. Under these conditions, the load resistance presented to the tube is equal to the tube plate resistance, and as we know, this is the condition for maximum transfer of energy.

If we go beyond the critical point and increase the coupling still more, we find the maximum secondary voltage drops slightly. This is shown by curve 4. Note, however, that instead of a single peak, the curve is beginning to split so that we have *two* "humps" of maximum response.

For still greater coupling, as shown by curve 5, the output drops still more, and the humps have been separated so that they are much more pronounced.

These curves in Fig. 11 are characteristic of all double tuned circuits. Curves of this type will be found no matter whether the two resonant circuits are coupled inductively as shown in Fig. 10 or are coupled by a common capacity or by means of direct coupling of some sort.

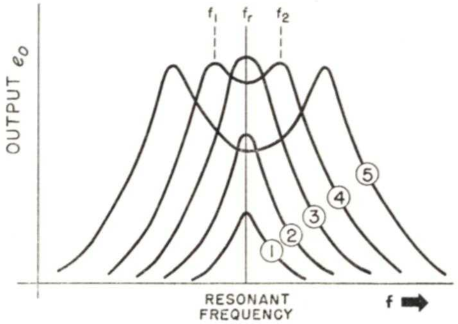


FIG. 11. Effect of variations in coupling upon the shape of the response curve for the double tuned transformer circuit in Fig. 10.

► As curve 4 in Fig. 11 shows, for the condition of coupling slightly greater than critical we do get two humps but they are not far apart, and the "hollow" between them is quite small. This seems like an ideal response curve, for if we have a signal carrier located at the resonant frequency f_r, we see that side-band frequencies as low as f_1 and as high as f_2 will be amplified very nearly the same amount. Because of this characteristic, such a curve is commonly called a "band-pass" response.

And indeed, a receiver having an over-all band-pass response like curve 4 in Fig. 11 will have better fidelity than one giving "peaked" response like that in Figs. 8 and 9. This is true because the side-band frequencies more removed from the carrier are not attenuated as greatly, and the higher audio frequencies of the signal are reproduced with their proper intensity.

A New Definition of Selectivity. Now that we have a band-pass response which has *two* peaks instead of one, the old definition of selectivity as determined by the half-power points becomes meaningless. We must, therefore, devise some new definition.

Suppose we examine Fig. 12. As shown by the dotted lines, a perfect or "ideal" band-pass response curve would be one in which the carrier and all side-band frequencies were passed with exactly the same amplification, and at the same time, all frequencies outside this band would be cut off completely.

It is not possible to get such an ideal curve, of course, but a good superheterodyne receiver using several band-pass i.f. stages can approach such a response fairly closely, as indicated by the solid-line curve in Fig. 12.

► Now what is good selectivity for a curve such as this? *As a matter of convention, a curve denotes good selectivity if the nearest adjacent channel carrier receives 1000 times less amplification than the desired station carrier and side bands.* This corresponds to a relative attenuation of 60 db. Since broadcast stations are 10 kc. apart, the solid curve in Fig. 12 shows good broadcast selectivity because the adjacent carriers A and B do strike the curve above the 1000 times ratio or 60 db mark.

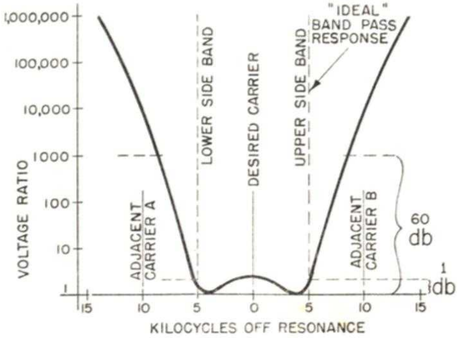


FIG. 12. A band-pass response characteristic showing good selectivity and high fidelity. For comparison, an "ideal" response is indicated in dotted lines.

► But we have already said the amplification given the desired carrier side bands affects the over-all fidelity. Because of this, it becomes possible to make a definition for good fidelity at the same time that we make a definition of selectivity. *For broadcast receivers, a response curve is said to indicate good fidelity if the variation in gain between the carrier and all of its side bands does not vary more than 1.25 to 1.* This simply means that there must not be more than plus or minus 1 db difference in amplification between the carrier and any side-band frequency. From this we see that the solid curve in Fig. 12 also shows good fidelity since the response to all side bands out to plus or minus 5 kc. lies below the 1.25 ratio or 1 db point.

Stabilizing Radio-Frequency Amplifiers

If we were to set up any of the r.f. amplifier circuits described so far, we probably would find they were very unstable. Indeed, they might "motorboat" or squeal loudly as we attempted to tune in a station.

To see why this occurs, refer to Fig. 13A, which shows a triode r.f. amplifier having tuned circuits in both plate and grid leads. Now, as we saw earlier, there are capacities between the tube elements. Thus, we have the grid-cathode capacity C_{gk} which serves to increase the capacity across the tuned circuit L_1-C_1, and the plate-cathode capacity C_{pk} which adds to the capacity of the plate resonant circuit L_2-C_2. But note the grid-plate capacity C_{gp} which we have not considered before. Indeed, this capacity, which is made up of the plate and grid acting as condenser plates, can be larger than either of the other two tube capacities. And worst of all, because of its position, it can have very adverse effects upon the amplifier operation.

For one thing, since the plate signal voltage variations are much larger than those of the grid, we find that r.f. currents tend to flow from the plate to the grid circuit directly through this interelectrode capacity. This causes an extra flow of current and because of it the effective grid circuit impedance is drastically changed.

In general, the effects of this plate-to-grid "feedback" are the same as those that would be obtained by shunting the grid tuned circuit with a resistor and an additional capacity. Thus, the tube capacities in Fig. 13A serve to change the effective circuit to appear as in Fig. 13B. Here we have the grid-cathode capacity C_{gk} as before, but in addition, we now have the capacity C_R and resistor R_R, both of which can be considered as the result of plate-to-grid feedback current flow.

Unfortunately, the values of these imaginary components, R_R and C_R, are not constant but vary tremendously with the tuning of the plate resonant circuit L_2-C_2. For different adjustments of plate tuning we find that the apparent capacity C_R changes as shown in Fig. 14. For plate tuning far above or far below the frequency of the incoming signal, the capacity C_R is quite small and has little effect. With the plate tuned to exact resonance, however, this capacity rises to a high value. In actual amplifiers, the capacity C_R becomes approximately equal to the grid-plate capacity C_{gp} *multiplied by the gain of the stage.*

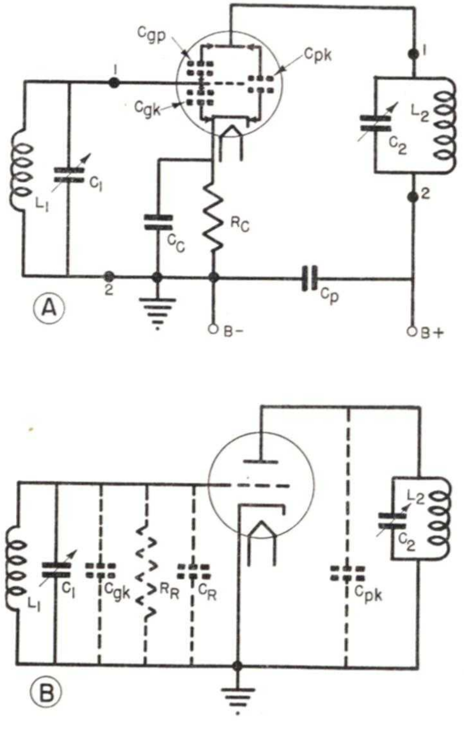


FIG. 13. In A, the three interelectrode capacities which enter into the operation of an R.F. amplifier are indicated by dotted lines. Then, at B, the circuit is modified to include only those parts which affect the tube as an amplifier. The effects of the grid-to-plate capacity C_{gp} are represented by R_R and C_R.

This means, then, even though the grid-plate capacity C_{gp} may be small, in an amplifier like Fig. 13B which has a high gain, the effective capacity C_R shunted across the tuned grid circuit may become so large that the circuit is seriously detuned.

► In a similar manner the effective shunt resistance R_R also changes with plate tuning. If the plate circuit in Fig. 13B is tuned *exactly* to resonance, then the resistance R_R is so extremely high it can be ignored. If the capacity of C_2 is increased, however, so that the plate circuit is resonant to a lower frequency, and hence, becomes *capacitive,* then the apparent resistance R_R drops in value so severely that the input circuit L_1-C_1 is loaded heavily. When this happens, the input voltage drops; also, the Q of the circuit and its selectivity are greatly decreased. The general effect, then, is to lower the gain of the amplifier stage and broaden its response. *Under these circumstances we have what is commonly called "degeneration" or "negative feedback."*

► On the other hand, if we tune the plate circuit L_2-C_2 in Fig. 13A to a frequency higher than that of the incoming signal so that the plate circuit becomes *inductive,* we find that other effects occur. When the plate circuit is inductive, the r.f. plate voltage is changed in phase so that the current flowing back through the grid-plate capacity produces an extra grid voltage which is *in phase* with the original signal voltage. *The feedback in this case actually increases the apparent signal voltage, and we have what is called "regeneration" or "positive feedback."*

For this condition, the apparent resistor R_R in Fig. 13B is said to become a *negative resistance.* It actually does not do so, of course, but the effect is the same as if it did, for the energy fed back to the grid from the plate circuit tends to restore all the energy normally lost in the resistance of the grid tuned circuit.

Since the feedback voltage actually aids the input signal, you would expect the gain of the amplifier stage to increase. It does. Also, since the negative resistance effect reduces the losses in the input tuned circuit L_1-C_1, you might expect the circuit Q and the resultant selectivity to be improved. This also happens. Unfortunately, however, the exact amount of feedback cannot be controlled readily, and in the usual case the signal fed back to the grid through the grid-plate capacity becomes excessive. As a result, the feedback voltage takes control of the amplifier, the output getting higher and higher until the amplifier bursts into oscillation. The amplifier, therefore, becomes an oscillator which generates an r.f. signal of its own. This spurious signal beats with the desired signal to give annoying squeals and howls.

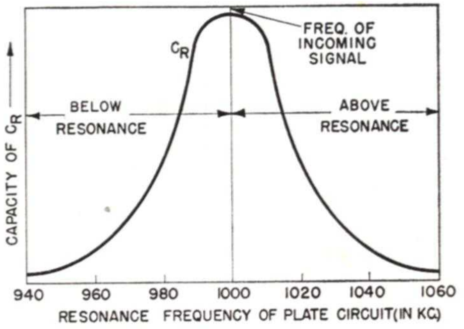


FIG. 14. This curve shows how the equivalent capacity C_R of the circuit in Fig. 13B varies when the plate tank circuit of an R.F. amplifier is tuned to, above, and below the frequency of an incoming signal.

► Looking back over the effects of current flowing from plate to grid through the common capacity of these tube elements, we see we may get either a loss in gain and selectivity for a capacitive plate circuit, or for an inductive plate, severe amplifier oscillation. Of course, practical receiver amplifiers do not use tuned circuits in both the plate and grid circuits. However, the effects of the tuned circuit in the following stages are transferred to the plate circuit so that either degeneration or regeneration is likely to occur. From this it is obvious that a stable, well-behaved r.f. amplifier cannot be expected unless some means of eliminating the plate-to-grid feedback is devised.

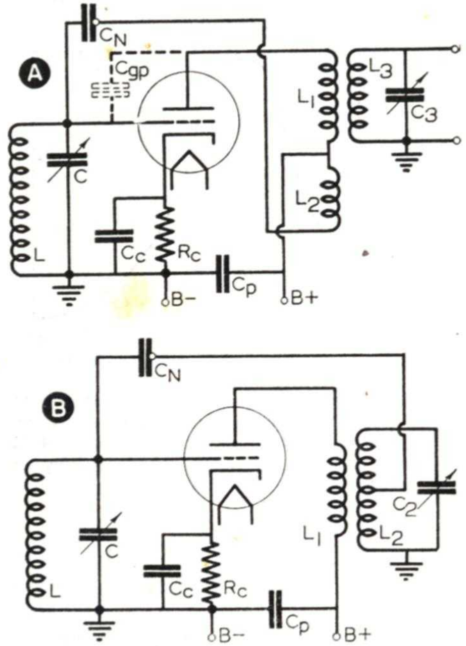


FIG. 15. An early neutrodyne r.f. amplifier circuit is shown at A, in which a special coil L_2 provides the required neutralizing voltage. At B, a tap on coil L_2 gives the required out-of-phase feedback voltage.

Reducing Feedback. Referring again to Fig. 13B, notice the position of the equivalent resistance R_R. As this apparent resistance tends to be *negative* in character when the stage is regenerative, it is obvious that feedback effects can be diminished by shunting an additional *positive* resistor from grid to ground. Thus if we load the grid circuit in Fig. 13A by placing a sufficiently low resistance across the points 1 and 2, we find that oscillation can be prevented.

A similar method of stabilizing an r.f. amplifier is to insert a "suppressor" resistor of about 100 to 10,000 ohms in series with the grid lead at point 1.

Both of these methods, however, accomplish stabilization principally by lowering the gain of the stage below the oscillation point. Accordingly, such schemes are not considered generally satisfactory.

NEUTRALIZATION

Instead of attempting to minimize the undesired feedback *effects,* let us try to cancel the feedback current itself. To do this, we add an extra feedback connection between the plate and grid circuits. If we then arrange this auxiliary circuit so that its new feedback voltage is equal to, but is 180° out of phase with that flowing through the tube capacity, then the two feedback voltages will cancel, and the resulting energy fed from plate to grid will be reduced to zero. *This method of cancelling one feedback current by adding another which is 180° out of phase is called "neutralization."* Fig. 15 shows two typical "neutrodyne" circuits.

In Fig. 15A, the auxiliary coil L_2 picks up a voltage in proper phase from the r.f. transformer L_1 and feeds it through the neutralizing condenser C_N to the grid of the tube. If both the coil and the condenser are adjusted properly, the voltage arriving at the grid from this circuit will be equal and opposite to that passing through the tube capacity C_{gp}. These two feedback voltages, therefore, cancel each other. When this is accomplished, then the amplifier stage will give full gain without danger of any undesired oscillation.

In the neutralizing circuit shown in Fig. 15B, the neutralizing voltage of proper phase is picked off from a tap on the secondary of the r.f. transformer.

Neutralization Disadvantages. Although neutralized triode r.f. amplifiers can be made to perform reasonably well, they do have many disadvantages. Chief among these is the fact that aging tubes, coils, and condensers can change their constants sufficiently to destroy complete neutralization. As a consequence, neutralized receivers often need periodic adjustment. Sometimes it is quite difficult to get satisfactory neutralization at both ends of the frequency band over which a receiver tunes. If we add to this the difficulties encountered in adding band-switching for an all-wave receiver, we see that the problems associated with neutralization become somewhat complex.

Since most feedback troubles in r.f. amplifiers are caused by the capacity between the plate and the grid in the triode amplifier tube, a great deal of work was expended in an effort to devise vacuum tubes having negligible interelectrode capacity. This naturally led to the development of the screen-grid tube which we will now study in some detail, for it is widely used in low-power transmitters and receiver circuits. However, we will come back to neutralization in our study of transmitters, because the use of triode tubes is very widespread where high powers are to be handled.

Tubes With Screen Grids

The capacity between the plate and the grid of a vacuum tube can be reduced by placing an electrostatic shield between these two elements. This is usually done by placing an additional grid in the space between the control grid and the plate. A tube so constructed is called a "screen-grid" tube.

If the screen grid is grounded, the feedback current which heretofore flowed through the grid-plate capacity now will flow instead to the screen grid and thence to ground as shown by the arrows in Fig. 16, and will not reach the control grid at all. Feedback effects, therefore, will be greatly reduced.

Since the shielding by the screen grid also reduces the effects of plate potential upon the value of plate current, it is necessary that the screen grid be made positive with respect to the cathode in order to obtain any substantial plate current. This potential usually is much less than that of the plate so that screen-grid current flow is kept relatively small. With this arrangement, the by-pass condenser C_2 becomes necessary, however, to keep a low-impedance path to ground for r.f. feedback currents. For stable operation, the

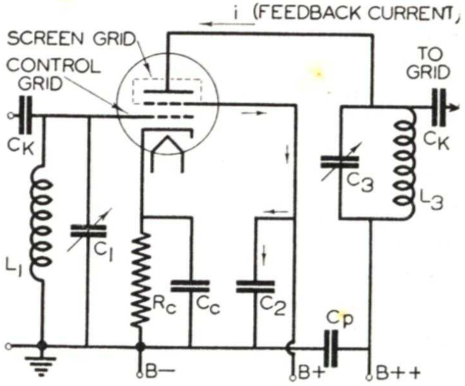


FIG. 16. R.F. amplifier circuit using a screen grid tube. In such screen grid tubes as the 24A, the screen grid completely surrounds the plate, as indicated by the light dotted lines, but the schematic diagram for a screen-grid tube generally shows only the heavy lines here indicated.

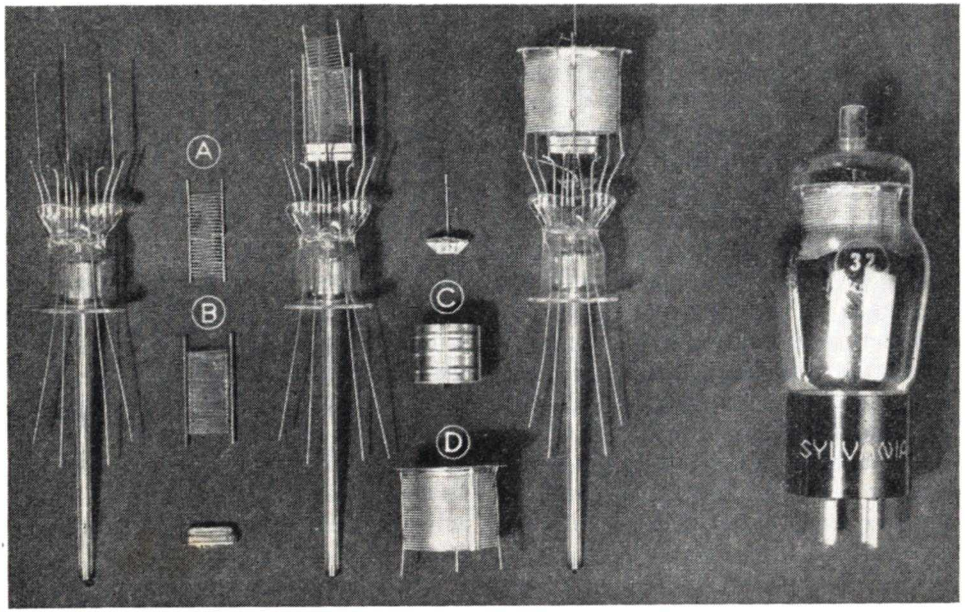


FIG. 17. Construction of a typical screen grid tube, a type 32 tetrode. The control grid is at A. The inner part of the screen grid (mounted between the plate and the control grid) is at B, and the outer part of the screen grid (which surrounds plate C) is at D. At the right is the completed tube.

capacity of C_2 should be many times greater than the interelectrode capacity between the screen and control grids — otherwise sufficient feedback current may get through to the control grid to result in oscillation.

A screen grid, of course, does not eliminate completely the plate-to-grid capacity, for there is always some leakage current from plate to grid. By completely surrounding the plate with the screen grid—that is, placing the screen outside as well as inside the plate—it is possible, however, to reduce this leakage to a very small value. Indeed, by using the construction which is illustrated in Fig. 17, the grid-plate capacity of a screen grid tube is made approximately 1000 times smaller than that for a triode. This reduction is more than sufficient to prevent regenerative feedback at ordinary frequencies. As a consequence, screen-grid tubes — or "tetrodes," as they are often called because of their four active elements—can be used in r.f. amplifiers without any neutralization whatsoever.

TETRODE TUBES

The insertion of the screen grid does much more than reduce the grid-plate capacity in a vacuum tube. As you might expect, since all plate current actually flows through the openings of the screen grid, the tube characteristics are changed quite markedly. If we were to plot the values of plate current versus plate voltage for different control-grid bias values, *keeping a constant screen-grid potential,* we would obtain a family of curves like Fig. 18.

The line A-A at 90 volts represents the screen-grid voltage. Observe that for plate voltages less than the screen grid potential, the plate current varies erratically. But most important, for plate voltages beyond the critical point, the curves are almost flat, the plate current increasing but little for quite large changes in plate voltage.

From Ohm's Law, when large voltage changes produce small current changes, the resistance must be high; therefore this shows that *the plate resistance of a tetrode is very high.*

In practical screen-grid tubes, since the feedback troubles are eliminated, it becomes possible to move the plate farther away from the cathode. This results in a much higher effective amplification factor *but it also increases the plate resistance still more.* As a result, most tetrodes have a plate impedance of approximately 0.5 megohm—substantially greater than the 10,000 ohms or so usually found in a triode.

► What effects does this increased plate resistance and greater effective amplification factor have on amplifier performance? For one thing, since there is negligible feedback, the control-grid impedance remains high. The input tuned circuit (L_1-C_1 in Fig. 16), therefore, is not loaded, and its Q and selectivity may be made quite high. Also, since the plate resistance is high, the plate tuned circuit (or the one in the following grid circuit) also is loaded but little; this circuit, too, may have high Q and good selectivity. But most significant of all, a tuned circuit with a high Q acts as a high-impedance plate load so the stage amplification will be increased—and this is enhanced still more by the higher amplification factor commonly built into a screen-grid tube.

Altogether then, the tetrode offers several important advantages over the triode for r.f. amplifier use. Not only can we get more gain and better selectivity, but also there are no neutralization worries. As a consequence, modern receivers use screen-grid tubes of some form in both r.f. and i.f. amplifiers.

PENTODE TUBES

In any amplifier, the actual tube plate voltage is the B supply voltage plus or minus the a.c. signal voltage across the plate load. This means, of course, that the instantaneous plate voltage varies from high to low values in accordance with the signal. But the plate potential of a screen-grid tube must not be allowed to fall too low, or the operation will extend into the unstable region, to the left of the line A-A in Fig. 18. Thus, the load resistance, as represented by the load line in Fig. 18, must be low enough in value to prevent the plate voltage from dropping below the potential of the screen grid at any time. This condition, of course, determines the maximum amount of voltage change that can be tolerated on the plate, and hence, the output voltage and the over-all stage amplification is limited.

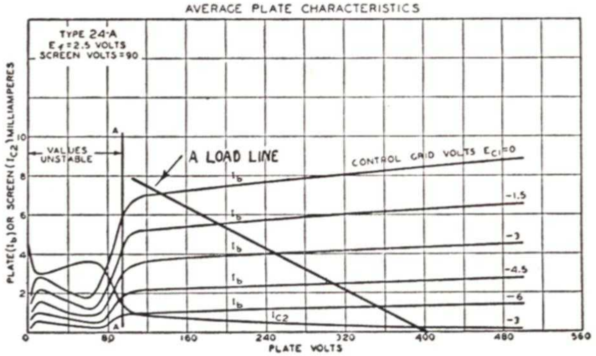


FIG. 18. Family of E_p-I_p characteristic curves for a typical screen grid (tetrode) tube, a type 24A tube. (I_p is here designated as I_b).

What causes the unstable operation

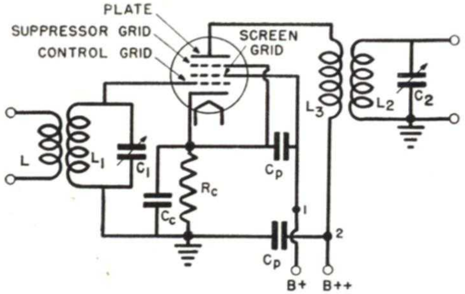


FIG. 19. R.F. amplifier circuit using a suppressor grid tube. In most pentode tubes like this, the screen grid does not cover the outside of the plate.

region in a tetrode? It so happens that when a screen grid is added to a vacuum tube, the electrons leaving the cathode are accelerated to such velocities that they strike the plate with terrific impact. This impact is so great that one electron literally may knock out several other electrons from the plate surface. These extra electrons are called "secondary" electrons, and the phenomenon is termed "secondary emission."

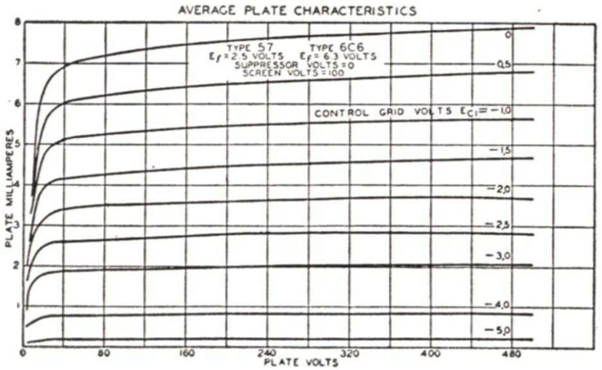


FIG. 20. Family of E_p-I_p characteristic curves for a typical suppressor grid (pentode) tube, the type 57 and its equivalent in the 6-volt series, the 6C6.

► Now what happens to these secondary electrons knocked into the space between the plate and the screen grid? If the plate potential is *higher* than that of the screen grid, then these extra electrons simply fall back to the plate, rendering no harm, and keeping the plate current at a perfectly normal value. However, if the plate potential is *lower* than that of the screen grid, then these electrons endeavor to flow to the screen grid instead of returning to the plate. In this case, the effective plate current may actually drop, and normal operation is not obtained. *It is this loss of plate current due to the flow of secondary electrons that accounts for the peculiar shape of tetrode curves in the unstable region.*

But how can we make the secondary electrons return to the plate for all values of plate voltage? This is most easily done by inserting what is called a "suppressor" grid between the screen grid and the plate. Since this extra grid makes a fifth active element, tubes using suppressor grids are commonly called "pentodes." As illustrated in the typical pentode amplifier circuit in Fig. 19, the suppressor grid ordinarily is connected to the cathode, but in some cases it may be connected to ground. In many tubes, this suppressor grid-to-cathode connection is an internal tube connection. In either instance, the suppressor grid has a high *negative* potential with respect to the plate. Any secondary electrons attempting to flow to the screen grid, therefore, will be repelled by the suppressor grid and promptly attracted back to the plate. In this way, secondary plate emission is prevented, even though the plate potential may become very much lower than that of the screen grid.

From this suppressor grid action we should expect the unstable region in the characteristic curves to be eliminated. It is. Note the typical pentode E_p-I_p curves in Fig. 20. Plate current rises sharply for very low voltages, and the relatively flat portions of the curves are quite extended. With characteristics like this, pentodes allow the use of very high load impedances, thereby permitting very wide plate voltage variations. As a result, these tubes give much more gain. Pentodes have replaced the earlier tetrodes in almost all receiver applications.

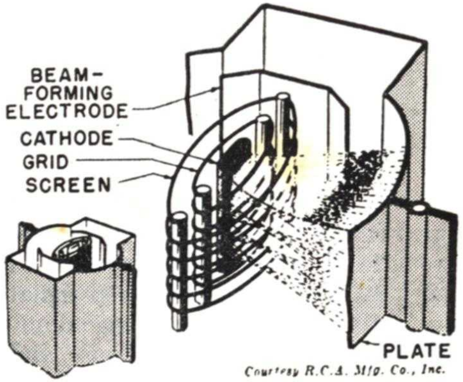
BEAM-FORMING TUBES

Using a suppressor grid, however, is not the only means of eliminating secondary emission. By placing the screen grid in the "shadow" of the control grid so that there is a relatively clear path between the plate and cathode for electron travel, and by adding two beam-forming electrodes as illustrated in Fig. 21, we can construct a "beam" tube having characteristics almost identical to the pentode. These beam-forming electrodes are a pair of specially shaped "plates" that are connected to the cathode. Since they are negative with respect to the plate, they serve to focus **the electron stream into two dense** beams. Thus, the electron concentration near the plate surface is made so great that secondary electrons leaving the plate are repelled by the electron field and forced back to the plate surface. The electron beam itself, therefore, serves as a suppressor grid, and no actual grid is necessary. The E_p-I_p characteristics of beam tubes are almost identical in shape to those of pentodes, and their respective performances also are quite similar.

VARIABLE-MU TUBES

In receivers that do not use automatic volume control (a.v.c.), the volume is usually controlled by adjusting the control-grid bias of one or more of the high-frequency amplifiers.

But what happens to the performance of an ordinary screen-grid or pentode tube when the control-grid bias is varied in this manner? Let us look at Fig. 22. As shown by the heavy curve, the tube's mutual conductance G_m, and hence, its amplification, drops rapidly with increasing negative control-grid bias.* Because of the very high amplification factor, however, the plate current cuts off sharply, and the mutual conductance drops to zero at relatively low bias voltages. This leads to numerous troubles.



Courtesy R.C.A. Mfg. Co., Inc.

FIG. 21. Sketch showing arrangement of electrodes in the type 6L6 beam amplifier tube. The electron beam provides its own suppression, forcing secondary emission electrons back to the plate.

If a strong input signal is applied to an amplifier tube for which the bias is adjusted close to **the cut-off point, the** signal itself may swing the grid suffi-

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*When the a.c. plate resistance of a tube is much higher than the load impedance, the circuit acts as a constant current circuit, and the output voltage depends on the mutual conductance and the load impedance ($e_o = g_m \times Z_L$).

ciently negative to stop plate current flow. This, of course, will give severe modulation distortion.

For another case, suppose we use an ordinary sharp cut-off tube as the first r.f. amplifier in a receiver. In this stage, the selectivity afforded by the single tuned circuit is not sufficient to reject strong local signals, and the tube grid may have both a weak desired signal and a strong undesired local signal impressed upon it. If this is the case, and we attempt to control the tube gain by increasing its control-grid bias, we may find that the strong local signal swings the control grid back and forth across the cut-off point. When this happens, the tube acts like a detector, and rectified audio frequencies from the local signal modulation are made to appear in the tube plate current. Unfortunately, these stray audio frequencies then proceed to modulate the desired weak signal carrier. We find, then, that the following amplifiers are excited with a single carrier containing the modulation signals from two different stations. The final result, of course, is that we hear two different programs at the same time.

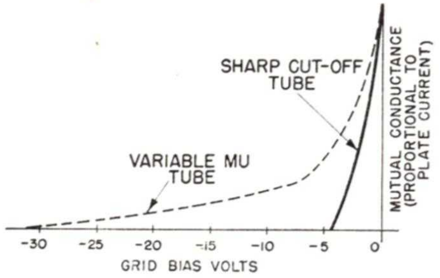

FIG. 22. Characteristic curves showing the sharp cut-off of ordinary tubes and the extended cut-off of variable-mu types.

This superimposing of one signal upon another is commonly called "cross-modulation." As we pointed out, it is due to the operation of a tube along a non-linear portion of its characteristic curve. If we wish to control gain by variation of grid bias, and yet prevent cross-modulation, then we must use some sort of tube that does not have a sharp plate current cut-off characteristic.

► The amplification factor of a tube, and hence its cut-off grid voltage, is determined principally by the grid wire spacing and the grid separation from the cathode. Suppose we make a tube in which either the cathode-grid separation, or, as illustrated in Fig. 23, the grid wire spacing is not kept constant. What sort of performance will this tube give?

For low-grid bias voltages, a large number of the electrons leaving the cathode will pass through the closely spaced portions of the grid, and the effective tube amplification factor will be *high*. For a high negative grid bias, the closely spaced portions of the grid reach cut-off quickly; however, electrons continue to pass through the widely spaced grid section. This tube, therefore, does not cut off abruptly, but instead begins to exhibit an effective *low* amplification factor. Of course, complete cut-off will be reached if enough grid bias is applied, but this point is greatly extended. This effect is illustrated by the dotted curve in the characteristic curve of Fig. 22.

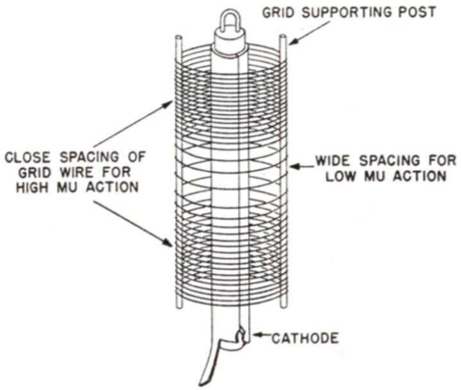

FIG. 23. This sketch shows the variable spacing used for the control grid wires in a variable-mu tube.

Tubes made in this manner are called "variable-mu" tubes because their effective amplification factor actually does change with increasing grid bias. Other names for them are "remote cut-off" or "super-control" tubes.

If we now compare the two curves in Fig. 22, we can see that the variable-mu characteristic has no sharp bends or sudden cut-off. Because of this, such a tube is very effective in reducing cross-modulation and distortion when amplifier gain is adjusted by a variable grid bias. Since most modern receivers apply variable a.v.c. voltage to every r.f. and i.f. stage, pentode tubes with built-in variable-mu action are usually used in these amplifier stages.

Basic Transmitter R.F. Amplifiers

Up to this point we have considered receiver r.f. amplifiers in which the prime consideration is *voltage* gain. Since receiver tubes draw little plate power, over-all efficiency usually is of secondary importance.

In transmitters, r.f. amplifiers are used expressly for increasing the available *power*—ordinarily from a low-power master oscillator. We now find amplifier *power* gain becomes the measure of performance. Also, since high power is expensive to obtain, we become interested in how much d.c. power fed into a given amplifier actually is transformed into useful radio-frequency energy which can be supplied to the antenna or some other load. Amplifier *efficiency*, therefore, is of major interest.

The basic transmitter r.f. amplifier is quite similar to the receiver amplifier already discussed. It consists, essentially, of an amplifier tube working into a resonant tuned circuit load as in Fig. 24. Here we have a triode tube with parallel-tuned circuit L_1-C_1 inserted in the plate lead.

When excitation power, say from a master oscillator, is fed to the tube grid through coupling capacity C_2, plate current will be varied in accordance with the excitation voltage, and an amplified amount of power will be developed in the tuned tank circuit L_1-C_1. Some of this power is then fed to the load—which may be an antenna, or a second higher power amplifier—by means of the inductive coupling between pick-up coil L_2 and the tank inductance L_1.

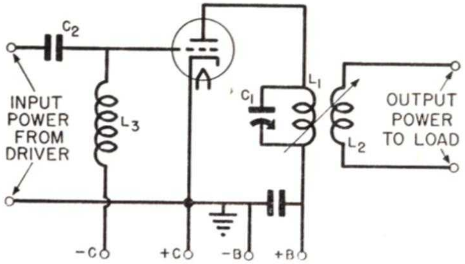

FIG. 24. The basic transmitter R.F. amplifier is simply a vacuum tube working into a resonant tuned circuit load.

What determines the amount of power output and the efficiency we obtain in a circuit such as this? We shall find that many factors affect amplifier behavior, but the most important of these are the plate voltage, grid bias voltage, and excitation level under which the amplifier is allowed to perform.

OPERATING AMPLIFIERS IN CLASSES A, B, AND C

You will remember that r.f. amplifiers in a receiver were operated under class A conditions. By inspecting Fig. 25 you will recall that this type of operation is obtained when a tube is biased at some point such as A on the linear portion of its E_g-I_p curve. The grid excitation voltage is never allowed to drive the grid more positive than zero or more negative than twice the bias voltage, and under these conditions the signal variations in the tube plate current are a nearly perfect reproduction of the original grid signal. Typical grid voltage and plate current changes in a class A cycle are shown in the figure.

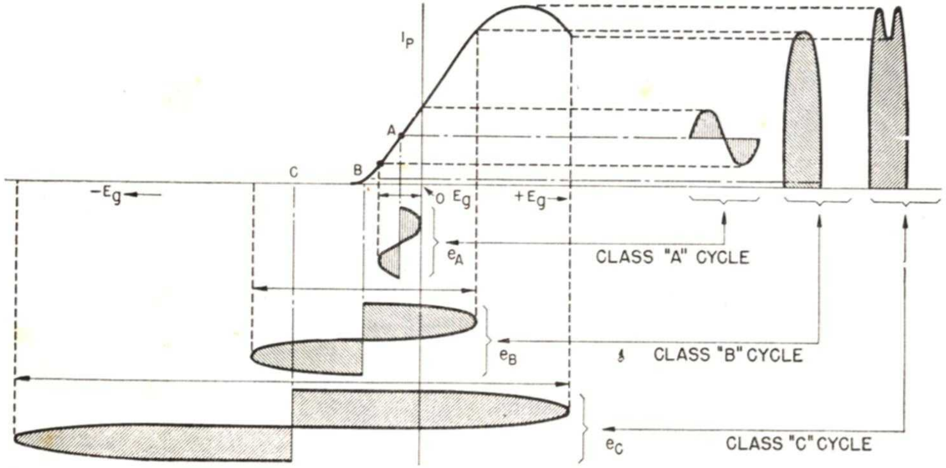

FIG. 25. Relationship between grid bias voltage, grid swing, and plate current for class A, class B, and class C amplifiers. In class A, the grid never swings positive; in class B the grid swings positive only over the linear region of the plate current characteristic; in class C the grid swings beyond the plate current saturation point.

Class A operation gives amplification with the least amount of output distortion. The efficiency of such amplifiers, however, is quite poor. Since the peak grid excitation voltage is never allowed to exceed the bias voltage, the *average* plate current always remains at the value for point A, no matter what the excitation voltage may be. Indeed, this same amount of plate current will flow if there is no excitation at all! The theoretical maximum efficiency for class A amplifiers is only 50%, and in actual practice this may be as low as 20 to 30%. As a consequence, class A r.f. amplifiers are never used in transmitters.

Class B Operation. If we bias an amplifier to the plate current cut-off point such as B in Fig. 25, then we obtain what is known as class B operation. This cut-off bias is determined by dividing the plate voltage applied to a triode tube by the tube amplification factor. Thus, if the amplifier in Fig. 24 has a plate-supply voltage of 1000 volts, and the tube an amplification factor μ of 20, then the *cut-off* bias will be:

$$E_g = \frac{E_b}{\mu} = \frac{1000}{20} = 50 \text{ volts.}$$

An r.f. amplifier biased in this manner behaves in the same way as the audio-frequency class B amplifier. Inspecting the class B cycle shown in Fig. 25, we see that no plate current at all flows from the negative half-cycle of grid input voltage. On the positive half-cycle, however, plate current does flow, and this current is made very high by driving the grid far into the positive region. Under these circumstances, the grid draws considerable current, its impedance drops, and we see that a definite amount of driving power must be furnished to the amplifier.

The grid, however, is never driven beyond the linear portion of the operating curve. The plate-current pulse which flows for exactly a half-cycle or 180° of the excitation voltage, therefore, is an amplified reproduction of the positive half of the grid input voltage. Since plate current flows only half the time, the efficiency of a class B amplifier is much higher than that for a class A amplifier. The theoretical maximum is about 78%, but the average practical efficiency is between 50% and 60%.

Looking at Fig. 25 again, notice that we get plate current during only the *positive* swing of grid voltage; for the *negative* grid swing which takes the instantaneous voltage below the cut-off value, we get no current at all. Surely this reproduction of only one half-cycle represents very severe distortion. In fact, you will remember we found it necessary to use *two* tubes in push-pull for class B audio amplifiers to avoid this distortion—the second tube acting to supply the missing half-cycle. However, for r.f. amplifiers operated in class B this push-pull arrangement is not necessary.

The Flywheel Effect. Assuming the amplifier in Fig. 24 to be operating in class B, let us consider the voltage distribution at the instant the grid reaches its maximum positive value. For this condition, the tube will be drawing a heavy plate current, and its plate voltage will drop to a low value. This means the voltage drop developed across the tank circuit load L_1-C_1 will be very nearly equal to the full power-supply voltage. This voltage drop, of course, charges the tank condenser C_1.

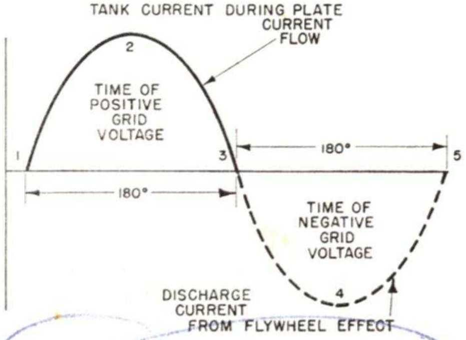

FIG. 26. Even though energy is supplied only half the time by a class B r.f. amplifier, the tank circuit flywheel effect produces a complete cycle of tank current flow.

If we now assume that the grid voltage decreases from its maximum value to zero and then becomes negative, the plate current flow will be cut off. With no more voltage drop across the tank circuit L_1-C_1, the condenser C_1 proceeds to discharge. Since it cannot pass through the tube which is cut off, the discharge current flows back through the inductance coil L_1.

Referring to Fig. 26, we see that the initial plate current flow during the portion 1-2 of the cycle charges the condenser. Then, during the portion 2-3 of the cycle, the condenser discharges through the coil.

You have learned that a coil opposes changes in the current flow through it. Therefore, while the condenser is discharging, the coil stores energy in its magnetic field. When the electron movement has caused the condenser voltage to drop to zero, the coil field collapses, and keeps electrons moving in the same direction. In Fig. 24, electrons leave the upper plate of C_1, flow through L_1, and are now forced into the lower plate of C_1. Hence, this charges C_1 again, this time with the opposite polarity. (If at first the upper plate was negative, now it is the lower plate.) This corresponds to the action over the 3-4 section of Fig. 26.

At point 5, the next cycle of plate current begins to supply energy, and the cycle repeats. In this manner, even though the tuned tank circuit receives energy during one half-cycle only, it literally "coasts" for the remaining half-cycle. The r.f. output current, therefore, is very nearly a perfect sine wave.

This action, in which a tank circuit accepts pulses of energy and constructs complete sine-wave cycles of a.c., is called the "flywheel" effect. It is depended upon in all single-tube tuned amplifiers to "round out" the missing half-cycle and produce a reasonably undistorted output.

► The fact that class B grid excitation is limited to the straight-line portion of the operating curve makes these amplifiers useful in several special applications. For example, since the output voltage is always proportional to the input voltage, the output power also varies in exactly the same manner as the excitation power. The excitation to a class B stage, therefore, may be an amplitude-modulated carrier. Such amplifiers are sometimes used to increase the power of transmitters which have amplitude modulation introduced in some earlier, relatively low-power stage. In such use, class B amplifiers are usually designed for very high power, and because of their operating characteristics, they are often called "linear" amplifiers. These will be studied in some detail in a later Lesson.

Class C Operation. Now that we have found that r.f. amplifier efficiency is improved by biasing the tube to cut-off and allowing plate current to flow for only the positive half of the grid excitation cycle, suppose we increase the bias still more and see what happens. If we make the grid bias voltage equal to at least *twice* the cut-off value, we have what is commonly called "class C" operation. Fig. 25 shows this operation at point C.

As you would expect, we get no plate current flow at all for the negative half-cycle of grid input voltage. In fact, there is no plate current even for part of the positive half-cycle until the time that the instantaneous grid voltage reaches the cut-off point. The plate current pulse that flows, therefore, does not last over a complete half-cycle, or 180°.

Unlike class B operation, for true class C performance, the grid excitation is not limited to the linear portion of the curve. To obtain a maximum of efficiency, the grid is driven very, very far positive—beyond the straight-line part of the curve into the plate saturation region. In fact, the grid is driven so far positive that the grid current flowing begins to "rob" the normal plate current flow. This accounts for the "notch" in the top of the plate current pulse shown in Fig. 25.

The shape of this plate current pulse shows that we get even more output distortion than for a single class B amplifier stage. Nevertheless, the flywheel effect of the tank circuit can be made sufficiently great to overcome this disadvantage so that reasonably undistorted sine-wave power output is produced.

What sort of efficiency do we get from such operation? Let us re-examine the class C operation cycle and see what occurs. For the negative half-cycle and part of the positive half-cycle of grid excitation, the plate current is cut off. With no plate current flowing, obviously, there is no power lost in the tube. For the short time that plate current does flow, its average

value is very high; nevertheless, this high current is flowing through the tube when the grid has a high positive potential and the tube resistance is very low. This means the power lost in heating the tube even during the high current pulse is relatively low. The average efficiency of a class C amplifier throughout its operating cycle, therefore, is extremely high. It is not uncommon in practice to find efficiencies between 70% and 80%.

APPLICATIONS OF CLASS C AMPLIFIERS

So far we have seen that class C operation is obtained when an r.f. amplifier tube is biased to approximately twice the plate current cut-off value and the excitation voltage is sufficiently great to carry the peak of the plate current pulse into the saturation region. Referring to Fig. 25 once more, we see that since the grid excitation is not limited to the straight-line section of the characteristic curve, it is obvious that such operation does not give linear performance.

This is not a serious limitation, however, and because they give higher efficiencies than any other type of amplifier, class C stages are used in almost every transmitter *where the available excitation power is kept at a constant level.* Thus, the low power from a quartz-crystal-controlled master oscillator may be stepped up to higher and higher powers by several class C stages in cascade. Such amplifiers used in this way accomplish two purposes: they not only increase power, but they also effectively isolate the master oscillator from severe load changes which might change its frequency. These amplifiers, therefore, are sometimes called "buffer" amplifiers.

Because of their high efficiency, class C amplifiers are used as the r.f. amplifiers throughout radio telegraph transmitters, and are used in radiotelephone transmitters as the r.f. amplifiers up to the point of modulation.

► The very fact that the class C amplifier is not linear also makes it useful as a so-called "frequency multiplier." Because its irregular plate current pulses contain many harmonic frequencies ordinarily erased by the tank circuit flywheel effect, we find that if we use a tank circuit which is tuned to *twice* the input frequency, considerable output power will be developed at the second harmonic frequency. The amplifier, therefore, performs as a frequency "doubler." The efficiency, of course, is somewhat lower than for "straight-through" operation, this being ordinarily about 30%.

In a similar manner it is possible to get frequency "tripling" by tuning the plate tank circuit to a frequency *three* times as great as the input frequency. The efficiency for this operation drops to about 10% to 15%.

Despite the lower efficiency, this is an important service—the frequency of a crystal oscillator can be multiplied many times by the use of several doublers or triplers. In this way a low-frequency quartz-crystal oscillator—which cannot be constructed in practical form for extremely high frequencies—can be made to control quite accurately the frequency of an ultra-high-frequency transmitter.

Modulated Amplifiers. High efficiency as a buffer amplifier or medium efficiency as a frequency doubler are not the only desirable characteristics of a class C amplifier. Because such an amplifier is driven to plate-current saturation, the power output is very nearly independent of the grid excitation. What is more important, under these conditions, *the peak r.f. output voltage developed across the load is determined almost entirely by the plate voltage applied to the tube.*

If, for instance, we should apply several different plate voltages to a class C amplifier and measure the peak r.f. output voltage obtained in each case, we would get a curve that is very nearly a straight line as shown in Fig. 27. Whenever we double the plate voltage, we double the output voltage, and when the plate voltage is halved, the output correspondingly drops to a one-half value.

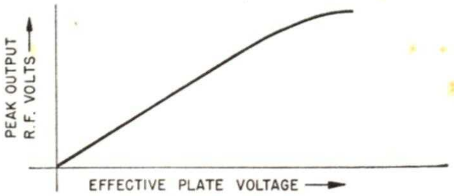

FIG. 27. A typical curve showing how the r.f. output voltage of a class C amplifier varies almost linearly with the applied plate voltage.

From this we can see that if we vary its plate voltage at an audio-frequency rate, the r.f. output voltage of a class C amplifier will vary in like manner, and we will obtain a modulated wave. Modulation accomplished in this manner is called "plate modulation."

A typical plate modulation circuit is shown in Fig. 28. Here we have the class C modulated amplifier VT_1 being fed a steady, non-varying excitation voltage from its driver stage. This is indicated by the wave form above the tuned grid circuit.

The plate voltage, however, is not constant. By means of the modulation transformer, relatively high audio-frequency voltages from the modulator amplifier VT_2 are superimposed upon the power supply voltage applied to the class C tube. The effective plate voltage on the r.f. amplifier, therefore, varies above and below the fixed power supply voltage, the instantaneous values depending upon the audio-frequency voltages coming from the modulator. If the peak audio-frequency voltages are just sufficient to double the effective plate voltage at one instant and reduce it to zero the next, then the r.f. output will be modulated 100% as indicated.

Of course, the modulator voltage must not be too great, or overmodulation will occur, and serious distortion will result.

A modulated r.f. wave has definite side-band frequencies besides the main carrier, and for 100% modulation, the additional energy in these side bands represents an output power increase of 50%. Now it so happens that a class C modulated amplifier when operating properly draws a constant plate current which does not change between zero and full 100% modulation conditions. Then where does this extra power come from? We find that this extra side-band power is supplied by the modulator. In other words, for 100% modulation possibilities, the modulator tube VT_2 in Fig. 28 must have an audio-frequency output-power capacity which is equal to at least one-half the d.c. power fed to the class C amplifier plate.

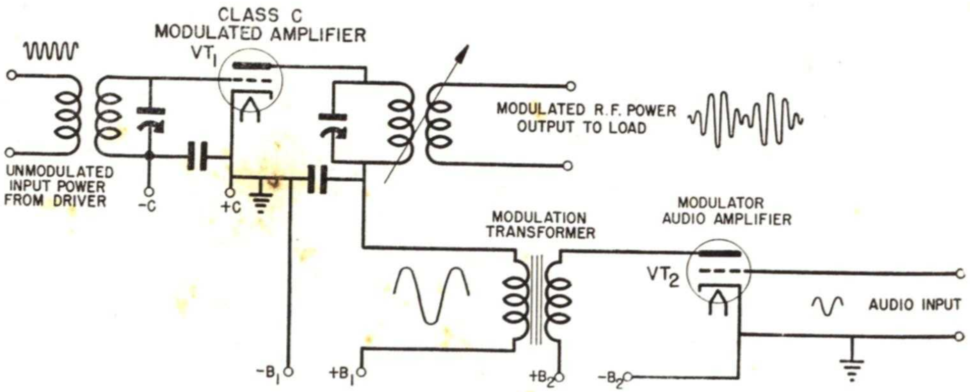

FIG. 28. A typical method of plate-modulating a class C amplifier. Audio-frequency voltage from the modulator is superimposed upon the power supply voltage applied to the modulated stage.

Stabilizing Class C Amplifiers. The operation of a triode amplifier in class C (and for that matter in class B) does not exclude the possibility that enough energy will be fed from plate to grid through the interelectrode capacity to make the amplifier burst into self-oscillation. If this happens to a class C buffer or modulated amplifier stage, its efficiency drops very drastically. Worst of all, this self-oscillation may not be at the same frequency as that of the transmitter master oscillator. The transmitter, therefore, may cause serious interference with other services. Obviously, this must be avoided.

In general, the principles of neutralizing transmitter buffer or modulated amplifiers are exactly the same as those for receiver amplifiers. One common circuit is that shown in Fig. 29A. Since the neutralizing voltage fed to the grid through the neutralizing condenser C_N is obtained from a section of the plate resonant circuit, this is ordinarily called "plate" neutralization.

When a tuned tank also is used in the amplifier grid circuit, the "grid" neutralizing arrangement of Fig. 29B is sometimes used. This is so named because the proper phase shift for the neutralizing current is obtained by using a section of the tuned grid circuit.

Both of the neutralizing systems in Fig. 29 work satisfactorily because they make it possible to feed through the grid circuit a neutralizing current which is equal to, but 180° out of phase with that stray current normally flowing through the plate-grid capacity of the tube. When properly neutralized, the total energy fed from plate to grid is reduced to a minimum, and self-oscillation cannot occur.

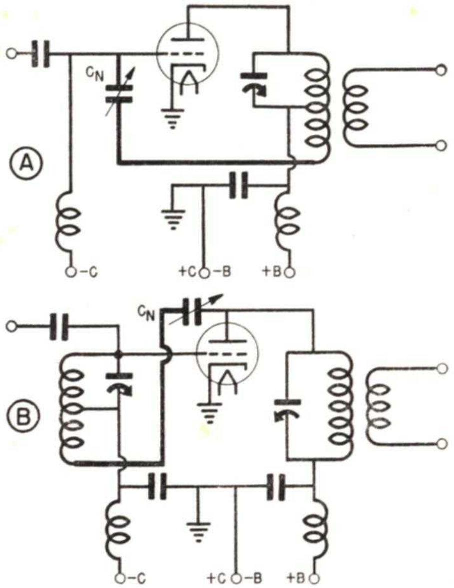

FIG. 29. Two common methods of neutralizing a transmitter r.f. Amplifier. At left, a plate neutralizing circuit, at right a grid neutralizing arrangement.

Use of Screen-Grid Tubes. In receivers, we found that amplifiers using screen-grid tubes do not require neutralization, because the inherent grid-plate capacity is so low that sufficient feedback for oscillation is not obtained. Can screen-grid tubes be used in transmitters? Indeed they can, and for low-power class C buffer stages, the lack of neutralization requirements makes them extremely convenient.

Transmitting screen-grid tubes however, have some disadvantages Since they usually are not made with suppressor grids, secondary emission effects with consequent reduced efficiency will set in if they are driven so hard that the plate voltage drops below the screen-grid voltage for any part of the excitation cycle. Secondary emission, therefore, limits somewhat the amount of r.f. output voltage that can be obtained from a screen-grid amplifier.

In addition, if a screen-grid tube is used as a modulated class C amplifier, it will be found that complete 100% modulation without distortion cannot be obtained unless the screen-grid voltage, as well as that of the plate, is varied by the audio modulator equipment. This requirement adds to the complexity of the transmitter and makes correct adjustment more difficult.

Also, for extremely high power applications, particularly where water-cooled types are desirable, screen-grid tubes are not available.

For these various reasons we find that screen-grid tubes are not used ordinarily except for low-power buffer amplifiers. Almost all high-power amplifiers—and especially class C modulated stages — employ triode tubes, which, of course, must be neutralized.

Class C Stages and Their Adjustment

Up to now we have considered individual class C stages only. How do we connect a number of these in cascade to build up higher and higher power in progressive steps?

Methods of Coupling. Almost any of the coupling methods used for r.f. amplifiers in receivers can be applied to transmitter amplifiers. Some of the more common forms are shown in Fig. 30.

In Fig. 30A we have a form of impedance coupling between a screen-grid buffer amplifier VT_1 and a neutralized triode amplifier VT_2. By means of a variable tap on the driver tank L_1-C_1, proper excitation voltage can be supplied through the coupling condenser C_C to the triode grid. The radio-frequency choke RFC serves as a low-resistance path for rectified grid current, and at the same time prevents appreciable signal current from flowing through the C-bias supply. As indicated, the two stages usually are electrostatically shielded from each other so that stray coupling currents will not prevent proper neutralization of the final stage. Since all excitation current flows through the coupling condenser C_C, this arrangement sometimes is called "capacitive" coupling.

In Fig. 30B is shown a common form of inductive coupling. This is really an r.f. transformer in which the tuned primary is the driver tank circuit L_1-C_1, and the secondary is the pick-up coil L_2. By varying the separation between the coils, and hence changing their mutual inductance, we can vary the excitation to the driven stage over wide limits.

In some cases, a second tuning condenser is placed in shunt across the pick-up coil L_2, thus making a double-tuned transformer.

Still another method called "link coupling" is illustrated in Fig. 30C. In this case we have *two* tuned circuits: one, the driver plate tank circuit L_1-C_1, and two, the grid tank L_2-C_2 for the input of the stage being driven. Coupled inductively to each of these are small coils of two or three turns which are connected in series by a relatively long twisted-pair line. The "link" circuit, therefore, is a very low-impedance transmission line. Excitation to the driven stage is easily adjusted by varying the position of one or both link coils.

Link coupling sometimes is convenient, because the two stages may be separated by several feet without resulting in excessive link losses. This increased separation makes shielding between the stages relatively easy, since stray coupling is reduced to a minimum.

Such coupling, however, does have some disadvantages. It is sometimes difficult to get adequate driving power by this means. The extra tuning control needed for the grid input tank circuit also may make it undesirable.

SHUNT AND SERIES FEED

Looking again at Figs. 30A and 30B, you will notice that the plate current to the driver tube in each case flows through the resonant tank circuit. This is commonly called "series feed." With such an arrangement, the entire tank circuit is at the same d.c. potential as the high voltage B supply, and both the coil and the condenser must be insulated adequately from ground. This may be inconvenient.

An alternate method of feeding plate current is used in Fig. 30C. Here the plate current flows directly to the tube through the r.f. choke RFC, which is shunted across the tank circuit. The r.f. output current, however, still flows into the tank circuit L_1-C_1 through the d.c. blocking condenser C_b. This coupling method is called "shunt feed" because the d.c. supply is fed to the plate through the parallel choke. With this scheme, the tank circuit can be grounded.

Nevertheless, there is a disadvantage

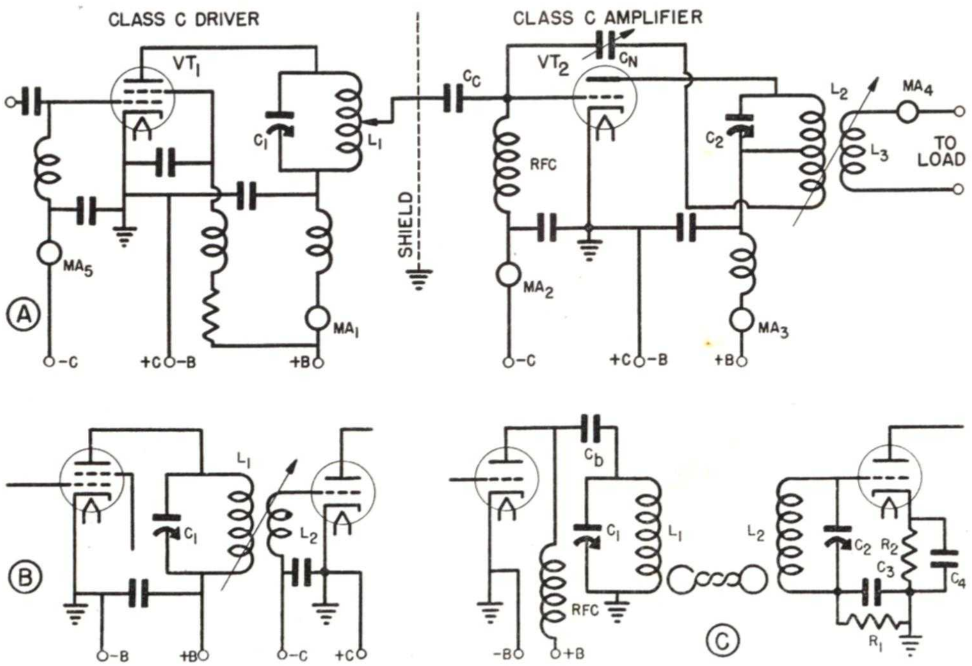

FIG. 30. Three common methods of coupling transmitter r.f. amplifiers: At A, capacitive or impedance coupling; at B, variable inductive coupling; at C, the use of a low-impedance transmission line—ordinarily called "link coupling."

to shunt feed. Since the r.f. choke RFC in Fig. 30C is attached directly to the "hot" plate, considerable energy may be lost unless this choke has adequate inductance and relatively low losses. In contrast, the r.f. chokes used in Fig. 30A are attached at points very nearly at r.f. ground potential, and they serve merely to prevent excessive r.f. currents from flowing through the power supply.

In general, either shunt or series feed can be used with any form of coupling. The choice usually is one of whether it is more convenient to insulate the driver tank circuit for series feed or to provide a low-loss, high-inductance r.f. choke for shunt feed.

OBTAINING GRID BIAS

Referring to Figs. 30A and 30B once more, we see that terminals are provided for C-bias connection. This indicates the negative C-bias voltage is supplied by some external power-supply source. The use of special C-bias power supplies is probably the most efficient and most "fool-proof" method of obtaining the necessary twice-cut-off (or more) value of grid bias for class C operation.

In Fig. 30C, however, no C-bias connection is indicated. Instead, we see a grid resistor R$_1$ which is properly by-passed for r.f. currents by the condenser C$_3$, inserted between the grid return and ground. Since the class C amplifier draws considerable grid current when properly excited, the flow of current through the resistor will develop a voltage drop which acts as bias for the tube. (The bias voltage will be the grid current multiplied by the value of R$_1$, the grid leak resistance.) If the driver output is adequate, and the resistor R$_1$ is of the proper value, the twice cut-off bias can be obtained in this way. For this arrangement, the tube being driven is said to be "self-biased."

Self-bias, of course, can be used with almost any type of coupling circuit. The grid current flowing through the grid resistor, however, represents a loss of power which must be supplied by the driving stage. For this reason, self-biased amplifiers usually require slightly more driver power than those using external bias supplies.

► There is one danger associated with self-bias methods. If for any reason the excitation to the self-biased stage should fail, then grid current will cease, and the bias voltage will drop to zero. With zero grid bias, the plate current then may rise to such a high value that the tube will be destroyed. To prevent this, it is customary to insert an additional resistor in the cathode circuit of the self-biased amplifier. This is indicated as R$_2$ in Fig. 30C. The condenser C$_4$ is merely an r.f. by-pass condenser. This cathode resistor is of such value that it gives little effective bias for normal plate current, but for excessive plate current, such as that resulting from excitation failure, the bias voltage developed across it is sufficient to prevent damage to the tube.

NEUTRALIZING PROCEDURE

The first step taken in adjusting a class C amplifier is to determine if the stage has been properly neutralized. With screen-grid amplifiers, of course, this is not necessary, but for stages using triode tubes, it is imperative that neutralization be complete before plate voltage is applied to the tube.

Suppose we are considering a class C amplifier such as VT$_2$ in Fig. 30A. One of the simplest tests for neutralization is made by applying excitation to the tube grid with the filament lighted, the grid bias applied, *but the plate voltage removed.* Grid current then will be indicated on milliammeter MA$_2$, but the plate current through MA$_3$ will be zero.

Without plate voltage, the grid-circuit current should be unaffected by any changes in plate-circuit tuning if the stage is perfectly neutralized. Thus, with proper neutralization, the current reading on MA$_2$ should not vary from a fixed value for any setting whatsoever of the plate tank condenser C$_2$.

On the other hand, if tuning the plate tank through resonance produces a pronounced dip in the grid current through MA$_2$, this indicates some energy is feeding directly through the grid-plate capacity of the inoperative amplifier, and the stage, of course, is not neutralized.

To neutralize the amplifier properly, it is necessary to employ some form of neutralizing indicator which will give a measure of the stray r.f. current flowing into the plate circuit. If the driver stage VT$_1$ in Fig. 30A delivers 5 watts or more of power, such an indicator may be a simple loop of wire connected to a small flashlight lamp or to a thermogalvanometer. For very weak driver power, a more sensitive indicator is made by connecting a 10-to-15 turn coil to a diode rectifier and d.c. milliammeter as shown in Fig. 31.

► The first step in neutralizing is to *remove the plate voltage*, this is necessary for two reasons: 1, so that the tube won't amplify (then the only signal passed to the plate circuit is that over the undesired path); and 2, so that the stage won't uncontrollably oscillate and perhaps ruin the tube. Then, with grid bias and excitation applied to VT$_2$ in Fig. 30A *but the plate voltage still zero*, the neutralizing capacity C$_N$ is next set at its minimum capacity. The neutralizing indicator next is coupled closely to the plate coil L$_2$, and the tank condenser C$_2$ is adjusted for plate-circuit resonance, which will be indicated by the flashlight lamp glowing brightly, or by a maximum reading of the indicator meter.

The neutralizing condenser C$_N$ next is increased in capacity quite slowly until the lamp dims and goes out or the indicator reading drops to a minimum. If the neutralizing condenser is increased in capacity still more, another point will be found at which the lamp lights up again or the indicating meter reading rises once more. The proper neutralizing point, therefore, has been passed, and the neutralizing condenser should be reduced in capacity again and set midway between the two points at which a minimum r.f. current has been indicated.

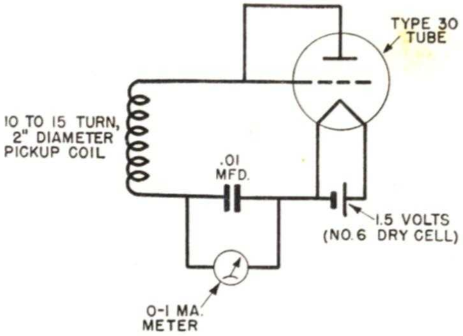

FIG. 31. A half-wave rectifier connected to a d.c. milliammeter and pick-up coil in the manner shown here can be used as a neutralizing indicator. A 1.5 volt (No. 6) dry cell is the only battery needed.

At this time it is advisable to vary the tuning of the tank condenser C$_2$ to see if some slight re-adjustment will again result in an indication on the neutralizing indicator. If so, repeat the neutralizing procedure.

For complete neutralization, the indicator will not light or give a meter reading for any setting of the plate tank condenser C$_2$; also, as mentioned before, the grid current through MA$_2$ should not vary as the plate circuit is tuned through resonance.

TUNING PROCEDURE

There are two forms of adjustment necessary for class C amplifiers. The first is a major tuning, such as may be necessary when a transmitter is first installed, or when its operating frequency is changed. The other is the normal day-to-day check-up and retuning. Let's take the major tuning steps as our first example of how this would be done.

All class C amplifiers are tuned in the same manner, whether the stage is one of low power or high power. This is a very important adjustment, because the power output from the stage depends upon the accuracy of the tuning adjustment.

Before a class C stage can be adjusted, it must have its normal input signal from a preceding stage (or from an oscillator). The input signal must not only be of the proper frequency, but also it must be exactly the amount required for most efficient operation of the class C stage. The amount of input signal determines the grid current, so the stage must be adjusted for normal grid current.

Let's suppose we have the two stages shown in Fig. 30A to adjust, and that a crystal oscillator feeds into the tube VT_1. The first step in the tuning adjustment would be to adjust the coupling to the crystal oscillator until the grid meter MA_5, in the grid circuit of VT_1, indicates normal grid current for this tube. Of course, the tube filaments are turned on. If VT_1 is a high-power tube, it would be standard practice to make this adjustment with no plate voltage applied.

When the tube grid is properly excited, a low plate voltage is applied to this stage only, not to VT_2 as yet. Then, C_1 is adjusted to resonance. With a triode tube, this resonance would be indicated by a dip (minimum) in the plate current. However, the plate current of a screen-grid tube is not so dependent on plate voltage, so MA_1 is not an accurate indication of resonance. Instead, refer to the grid meter MA_2 in the grid circuit of VT_2. The adjusting procedure is to set C_1 at the position which makes MA_2 read the maximum. If the reading on MA_2 becomes greater than the grid current should be for tube VT_2, then the plate voltage is removed, and the tap on coil L_1 is adjusted to a lower position. This changes the tuning of C_1, so it is again re-adjusted toward a maximum reading on MA_2. These steps are repeated; condenser C_1 is adjusted, and the tap on L_1 is moved until meter MA_2 comes up to read a maximum value that is also the recommended grid current for tube VT_2.

If the C_1 adjustment was made at a reduced plate voltage on VT_1, the plate voltage on this tube is now raised to the normal value, and C_1 is finally re-adjusted. Again, however, if the reading on MA_2 tends to exceed the normal grid current for VT_2, the tap on L_1 must be re-adjusted. Of course, if MA_2 does not reach a maximum which is at the recommended value for VT_2, then the tap on L_1 must be moved to give greater excitation.

When C_1 is finally adjusted at full plate voltage, we will have normal excitation for the grid of tube VT_2. However, before it will be possible to adjust the tank circuit L_2-C_2, it is necessary that VT_2 be neutralized, in the manner described earlier.

At the end of the neutralization procedure, VT_2 will have its filament on and normal grid excitation. It will be neutralized, and C_2 will be adjusted approximately to resonance. In this case, it will be safe to apply a *low* plate voltage. Transmitter power supplies are arranged so that plate voltages of approximately one-quarter to one-half normal operating voltages are available for tuning adjustment purposes. This reduced plate voltage is necessary, because otherwise, if the plate tank is far from resonance, it is possible for the tube to be ruined. The impedance of an off-resonance tank circuit is very low, so a large plate current can flow.

Continuing our adjustment of VT_2, the coupling between L_2 and L_3 is reduced so that very little energy is fed into L_3. Then, with a reduced plate voltage supplied, C_2 is adjusted for resonance, as indicated by a minimum plate current reading on meter MA_3. With no load—with L_3 loosely coupled to L_2—this minimum point will be very sharp, much like the solid curve in Fig. 32.

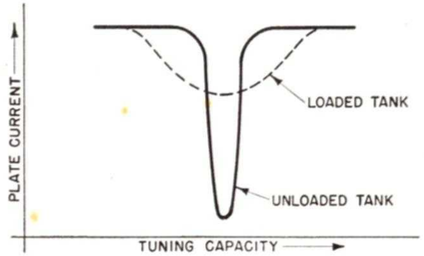

FIG. 32. When a class C amplifier is not delivering power to a load, the plate current dips very sharply as the tank condenser is tuned through resonance. When the amplifier is loaded, the tuning becomes broad, and the plate current dip is much less pronounced.

The next step is one of increasing the coupling between L_2 and L_3 so as to load the tuning circuit. This will probably mean a slight re-adjustment of C_2 is necessary to get a minimum reading on meter MA_3. However, as you increase the load on the tuned circuit, more power is fed into the load circuit, and it in turn acts to insert a resistance in the tank circuit, so the effective Q is reduced considerably. Therefore, the tank circuit impedance drops, and the minimum plate current point becomes broader and less pronounced. The dotted line in Fig. 32 shows how the plate current reading on MA_3 will vary with tuning when the tank circuit is fully loaded. However, the process of adjustment is still toward the least reading on MA_3. Now, it is safe to step up the plate voltage on this tube somewhat. When this is done, C_2 is again re-adjusted for a minimum plate current reading, and finally, full plate voltage is applied to this stage. After another adjustment of C_2, the coupling between L_2 and L_3 is increased until the current meter MA_4 reads the required value. Be careful not to increase the coupling between L_2 and L_3 too much, otherwise even the minimum plate current reading on MA_3 may be higher than the rated current value for this tube.

► When everything has been adjusted properly, the proper r.f. current will be delivered to the load circuit while the meters in the plate and grid circuits will indicate normal currents.

This completes the basic original tune-up procedure. However, from day to day, all the meter readings are checked and compared with the normal values. If any of the meter readings have changed, then the circuits may need re-adjusting. For example, the reading on meter MA_4 may drop, indicating less output from VT_2. If the tube is still good and normal supply voltages are applied, this may mean that the excitation at the grid of VT_2

is below normal. This would be indicated by a below-normal reading on MA_2. Therefore, tube VT_1 may need to have its tank circuit re-adjusted for the normal reading of MA_2. If the circuit is only slightly out of adjustment, it is possible to make this adjustment with full applied voltage. However, when dealing with very high-power equipment, it is still standard practice to drop the plate voltage to about two-thirds, even when making these minor adjustments, until you are very close to the proper resonance point.

► The foregoing details of neutralization and adjustments are intended to give you only a general idea of what is done to these stages. You will learn much more about this in later Lessons dealing with transmitter adjustments.

Lesson Questions

Be sure to number your Answer Sheet 17RC.

Place your Student Number on *every* Answer Sheet.

Most students want to know their grade 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. An L-C circuit is being used that has a very low Q. Will the pass band be: 1, narrow; 2, of medium width; or 3, very broad?
2. Why does a screen-grid tube normally require no neutralization when used as a radio-frequency amplifier? minimizing interlectrode capacity
3. If a triode tube has an amplification factor of 25, and 1250 volts is applied to the plate, what is the approximate cut-off bias? $\frac{1250}{25} = 50$
4. What is meant by the "flywheel effect" of a tank circuit?
5. What class of amplifier should be employed in the final amplifier stage of a *radiotelegraph* transmitter for maximum plate efficiency? C
6. Draw a simple diagram of an r.f. amplifier stage, illustrating the "shunt feed" method of applying plate voltage. Fig 30 c
7. In a self-biased r.f. amplifier stage having a plate voltage of 1250, a plate current of 150 ma., a grid current of 15 ma., and a grid leak resistance of 4000 ohms, what is the value of the operating grid bias? = E = I x R
8. If, upon tuning the plate circuit of a triode r.f. amplifier, the grid current varies, what defect is indicated?
9. Why is it necessary or advisable to remove the plate voltage from the tube being neutralized? prevent oscilation, Tell how much undesired sig. is being passed
10. In adjusting the plate tank circuit of a class C operated triode r.f. amplifier, is resonance indicated by: *minimum* plate current; or by *maximum* plate current?

Be sure to fill out a Lesson Label and send it along with your answers.

ACHIEVEMENT BRINGS SATISFACTION

From my own experience, I know that the greatest satisfaction comes from doing a *difficult* job well—from mastering a tough new subject, locating a particularly elusive trouble in a receiver, or getting a broadcast transmitter back on the air a short time after a breakdown occurs.

The more difficult the achievement, the greater is the satisfaction we feel. In the words of the French writer Moliere, *"The greater the obstacle, the more glory we have in overcoming it."*

Each achievement gives us the confidence to tackle still larger jobs and overcome greater obstacles. For instance, if this particular Lesson is harder for you to understand than previous Lessons, but you stick with it until you've mastered the important facts, you'll feel pretty good about completing it and you'll start the next Lesson with real confidence in your own ability.

My greatest satisfaction today comes from teaching others how to achieve success, so your achievements mean a lot to me.

J. E. SMITH