LOW-FREQUENCY POWER AMPLIFIERS FOR SOUND AND TELEVISION

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STUDY SCHEDULE NO. 16

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

☐ 1. How Power Is Supplied to the Load .... Pages 1-6

How the output of triode, tetrode, pentode, and beam power amplifier stages are transformer-coupled to a modulator or loudspeaker is covered in this section. Answer Lesson Questions 1, 2, and 3.

☐ 2. The Cathode Follower .... Pages 6-7

This very useful video-frequency amplifier and impedance-matching stage is discussed. Answer Lesson Question 4.

☐ 3. How Amplifiers Are Classified .... Pages 8-10

The efficiencies of class A, class AB, and class B, single-ended and double-ended audio-amplifier stages are discussed. Answer Lesson Questions 5, 6, and 7.

☐ 4. How Push-Pull Class A Amplifiers Work .... Pages 10-14

How the push-pull class A amplifier is connected, operates, and how this circuit reduces amplitude distortion is the subject of this discussion. Answer Lesson Question 8.

☐ 5. Other Push-Pull Amplifiers .... Pages 14-15

In this section you study the class AB and class B push-pull audio amplifiers. Answer Lesson Question 9.

☐ 6. Excitation of Double-Ended Amplifiers .... Pages 16-20

The transformer and phase inverter circuits used for coupling single-ended to push-pull amplifiers are studied here. Answer Lesson Question 10.

☐ 7. A Complete Audio Amplifier .... Pages 20-24

Here you will learn how to trace the signal through a complete amplifier, and you will also learn what difficulties may arise in operation.

☐ 8. Power Amplifier Tubes .... Pages 24-28

This section tells how the limitations of triode tubes led to the development of the tetrode, pentode, and beam-power tubes.

☐ 9. Mail Your Answers for this Lesson to NRI for Grading.

☐ 10. Start Studying the Next Lesson.

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LOW-FREQUENCY POWER AMPLIFIERS FOR SOUND AND TELEVISION

How Power Is Supplied to the Load

VOLTAGE amplifiers can build up the level of a low-frequency signal, but eventually a point is reached where more *power* is needed—for example, to operate the loudspeaker of a receiver, or to modulate the carrier of a transmitter. Voltage amplifiers are adjusted for maximum voltage gain, and so are incapable of efficiently delivering this power; in fact, ordinary voltage amplifiers cannot produce the 1 to 10 watts needed for loudspeaker operation, much less the high power that must be supplied in a transmitter. (For 100% modulation of a plate-modulated 50,000-watt broadcast station, the modulator must supply 25,000 watts!)

On paper, the power-stage diagram may be quite similar to that of a voltage amplifier. It is not until we notice the plate current values and the load that we see the difference. Voltage amplifiers cannot supply enough power for several reasons; for one thing, they do not draw enough power from the B supply. Receiving tubes designed primarily as low-frequency voltage amplifiers draw less than 1 watt from the B supply, so, if the plate voltage is 250 volts, the plate current is only 2 or 3 ma. Since the delivered a.c. power comes from the B-supply power and is always far less, power tubes must draw more current, if they are to operate from the same plate voltage. Therefore, receiver power tubes are designed to have greater emission and reduced plate resistance so that they can draw currents of 30 to 50 ma. Transmitter tubes are similarly designed for higher currents and higher B voltages for greater power output.

In addition to drawing more B-supply the power amplifier stage must be properly loaded. You will recall that, for maximum *voltage gain*, the load impedance must be made high. (For triodes, the load is usually 6 to 8 times the tube a.c. plate resistance.) However, for *power* output, an entirely different condition exists. We don't want to waste power, so we must arrange the circuits for delivery of power with the least loss. On the other hand, we don't want excessive distortion, so we must compromise to get as much power as possible, within the permissible distortion limits. Hence, the value of the load resistance that must be used for the various types of tubes for maximum power output, and for maximum undistorted power output, is of prime importance and is different for triode and tetrode, pentode, or beam power tubes.

MATCHING A TRIODE FOR POWER TRANSFER

In any triode vacuum-tube amplifier there is maximum power output when the resistance of the load is equal to the a.c. plate resistance of the tube. However, if the level of the signal fed to a triode output tube is raised sufficiently to deliver maximum power when the load resistance is equal to the plate resistance of the tube, there will be an excessive amount of distortion in the output, because the dynamic E_g-I_p curve of the tube is not exactly linear. However, when the plate load resistance is increased, the dynamic E_g-I_p curve becomes more linear, and thus the amount of distortion is reduced. The graph for a triode tube circuit, showing how the distortion and the power output vary, as the load resistance is increased, is given in Fig. 1. We see that an increase in the plate-load resistance causes a decrease in the power output; at the same time the distortion decreases. For a reasonable amount of undistorted* power output, the plate load resistance must be greater than the plate resistance of the tube.

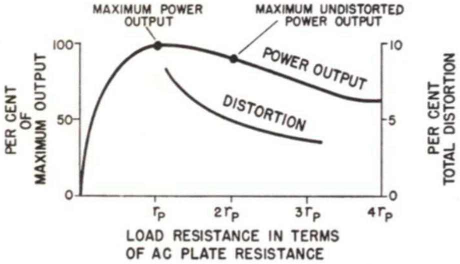

FIG. 1. The power output and total distortion in a triode class A amplifier depend on the load resistance. The load resistance for maximum power output is r_p; for maximum undistorted power output it is $2r_p$.

For amplifiers using low mu triodes operating in class A, it has been found that the *maximum undistorted power output* is delivered to the load when the load resistance is equal to twice the plate resistance of the tube. As an example of this, consider the type 845 transmitting triode tube which has a plate resistance of 1700 ohms when operated with a d.c. plate voltage of 750 volts and a d.c. grid bias voltage of —98 volts. The tube manufacturer recommends a load of 3400 ohms—exactly twice the plate resistance of the tube. When an 845 tube has a peak audio-frequency grid voltage of 93 volts applied to it, it is capable of supplying an output of 15 watts with 5% second-harmonic distortion. Note that this is not perfectly undistorted amplification, but it is an acceptable compromise between excessive distortion and high power output.

MATCHING TETRODE, BEAM, AND PENTODE POWER TUBES

There is no simple rule for determining what load resistance will give the so-called maximum undistorted power output for tetrode, beam, and pentode power tubes nor for high mu triode tubes operating in class B. The reason for this is that the dynamic E_g-I_p curves of these tubes do not necessarily become more nearly linear as the value of the plate load resistance is increased. As a general rule, however, it has been found that with tetrode, pentode, and beam amplifier tubes, a load resistance between one-tenth and one-fourth of the plate resistance of the tube gives the maximum undistorted power output. How the power output and total distortion of a 6V6 beam power tube varies for different values of R_L is shown in Fig. 2. Although the a.c. plate resistance of this tube is 52,000 ohms, the least distortion occurs when the plate load resistance is about 6000 ohms. This load value provides almost the maximum power output. Notice that the minimum amount of distortion is 6.5 per cent.

The correct value of load resistance for the different types of tetrode, pentode, and beam power output tubes must be determined experimentally, and this task is usually performed by the tube manufacturer. The correct load for maximum undistorted power output is generally a part of the "typical operating conditions" included in the handbooks of tube characteristics.

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*By "undistorted" we mean actually that the amount of distortion is so small that it is not easily noticed. In practice, 5 per cent distortion is considered acceptable in most audio power amplifiers, although in many inexpensive home receivers the amount of distortion is more than this.

THE LOAD IS RARELY A PURE RESISTANCE

Up to this point we have spoken of the load of a power-amplifier stage as if it were a resistor. Practically, however, a resistor is not used as a load, for if it were, all of the power applied to it would be lost as heat. In a radio receiver, the low-frequency power output is converted into sound, so a loudspeaker is the load. In a radio transmitter, the low-frequency power output is applied to the modulated radio-frequency stage so that it will modify (modulate) the carrier, and in this way the desired intelligence can be radiated through space to the radio receiver. Neither the loudspeaker nor the modulator stage are resistors, but as we shall shortly see, *they act*, as far as the audio amplifier is concerned, *as if they were resistors.*

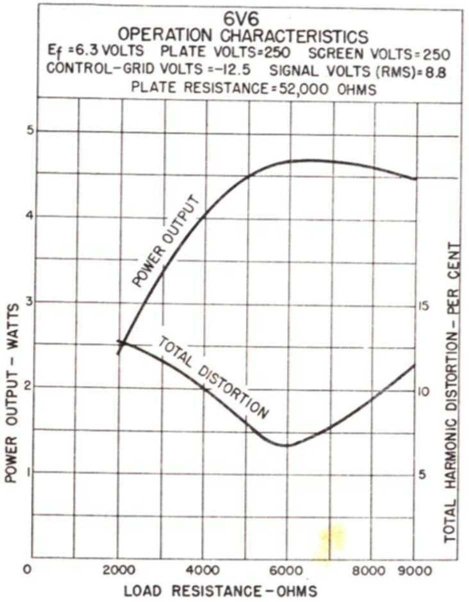

FIG. 2. The power output and total harmonic distortion for a 6V6 beam power amplifier tube depends on the value of the load resistance. The value of load resistance, 6000 ohms, for maximum power output also provides the minimum amount of distortion. This load resistance is about 1/10 of r_p.

A Loudspeaker as a Load. In the simple sketch of a dynamic loudspeaker shown in Fig. 3A, it would appear that the voice coil resistance and reactance would be the load in a power output stage. It would be the load if we locked (or blocked, as the speaker engineer says) the moving parts of the loudspeaker.

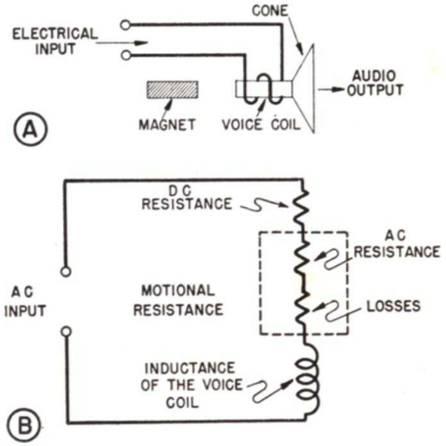

FIG. 3. As shown here, a dynamic loudspeaker consists of a voice coil free to move with respect to a magnetic field. (The field may be produced by a permanent magnet, as in the p.m. dynamic speaker, or by an electromagnet, as in the electrodynamic speaker.) The electrical input produces a magnetic field in the voice coil which, as it opposes or adds to the magnetic field of the magnet, makes the voice coil move forward and backward. The cone of the speaker, which is connected to the voice coil, thus causes a corresponding movement of air and the sound is produced. The electrical equivalent of a loudspeaker consists mostly of its motional resistance, as shown by B.

However, to produce sound waves, the air particles in front of the loudspeaker cone must be moved. The power needed for this must be furnished as electrical power at the input of the loudspeaker. This electrical power divided by the square of the input current is the effective resistance of the loudspeaker voice coil (from the basic formula $P = I^2R$; hence $R = P/I^2$).

This "motional" resistance, as it is called, is the true a.c. resistance of the loudspeaker when in motion. In general it is almost twice as large as the d.c. resistance and the a.c. reactance of the voice coil itself. However, the actual loudspeaker load is a combination of all the factors shown in Fig. 3B, and the resistance predominates. If it, the motional resistance, were the only element in the load, the loudspeaker would be 100% efficient; actually, even in the best loudspeaker arrangements, the efficiency is only about 50%, and in the average home radio it is only about 5%.

The a.c. impedance is determined by applying an a.c. voltage to the voice coil and measuring the resultant a.c. current. The effective impedance (found by Ohm's Law) is the a.c. voltage divided by the a.c. current. Since the a.c. resistance predominates, we can look on the impedance as being a resistor in action. This measurement is generally made at 400 cycles per second, because the load resistance varies with frequency. A value of 3 ohms is typical of the voice coils of dynamic loudspeakers.

The Modulated Stage of a Transmitter as a Load. One way to modulate the carrier of a transmitter is to introduce the low-frequency signal voltage into the plate circuit of the "modulated" stage of the transmitter. In the typical circuit of Fig. 4, the modulated stage uses an 807 tube as a class C* radio-frequency amplifier. The audio signal from the low-frequency power amplifier (6L6) tube is introduced into the plate circuit of the 807 tube through transformer T_2. In this circuit, C_1 is an r.f. by-pass condenser, and C_2 is an audio by-pass condenser.

When no audio voltage appears across the secondary of T_2, indicating no microphone sound pickup, only the d.c. plate-supply voltage will be furnished to the modulated stage. (We are assuming that the d.c. voltage drop in the secondary of T_2 can be ignored.)

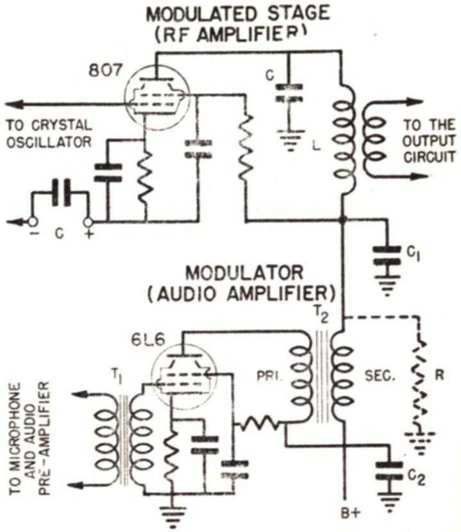

FIG. 4. This circuit shows how an audio power amplifier can be used to plate modulate a class C radio-frequency stage.

Now, when the microphone picks up sounds, and the resultant a.c. voltage is amplified by the modulator tube, an audio voltage exists across the secondary of T_2. This voltage adds to and subtracts from the d.c. plate voltage for the modulated stage. This causes the r.f. output of the modulated stage to vary, or to be modulated, because the output of a class C amplifier is at every instant proportional to the instantaneous supply voltage. The modulation voltage, therefore, causes the r.f. voltage across L to increase and decrease in step and strength with the audio signal voltage from the modulator output. This briefly, is the mechanics of plate modulation.

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*There is more information on the classes of operation later in this Lesson.

► The modulator is the source, and the modulated stage is the load for this audio driving circuit. To get the maximum undistorted power output from the modulator, its load must be a specific value. Therefore, the plate resistance of the modulated tube must be adjusted, by the proper selection of operating potentials, or else the load must be "matched" to the modulator by the transformer T_2.

HOW TRANSFORMERS MATCH THE LOAD TO THE SOURCE

Power audio amplifier tubes normally require loads of 2000 to 10,000 ohms. When such a tube is supplying power to a 3-ohm voice coil, the impedance of the two is so far different that there would be little power output and terrific distortion, if the two were directly connected.

When the modulator feeds the modulated stage directly, the mismatch may not be as large, but may still be so different from the recommended value that maximum undistorted power will not be realized. In Fig. 4, the 6L6 needs a 2500-ohm load, but the 807 tube operated in class C will have a resistance of about 5000 ohms.

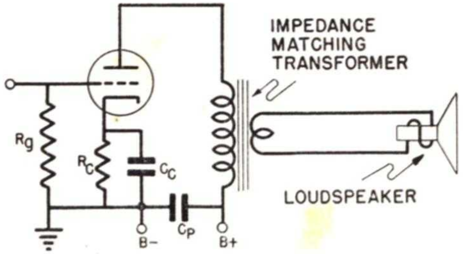

FIG. 5. This circuit shows how a transformer can be used to match a low-impedance loudspeaker voice coil to a high-impedance power output stage.

► We can change the impedance of the load as it is "seen" by the power amplifier by using a transformer with the proper turns ratio. To show how this is possible, let us reconsider the matching of a loudspeaker to a load.

The voice coil of the loudspeaker shown in Fig. 5 has an impedance of 3 ohms, and is capable of handling 12 watts of power. When fed with 12 watts, the a.c. voice-coil voltage is: $E = \sqrt{PR} = \sqrt{12 \times 3} = \sqrt{36} = 6$ volts.

Now suppose that the power output stage we are using is capable of supplying this 12 watts when its load impedance is 7500 ohms. With this resistance and power we can find the a.c. voltage across the 7500-ohm load by the formula:

$$E = \sqrt{P \times R} = \sqrt{12 \times 7500} = \sqrt{90{,}000} = 300 \text{ volts.}$$

The a.c. voltage across the primary is 300 volts when the output stage delivers 12 watts and the voltage across the load is 6 volts. To step 300 volts down to 6 volts, the transformer should have a voltage step-down ratio of 50 to 1.

A coupling transformer with this turns ratio will "match" the 3-ohm secondary load so that it appears to the power output stage as if it were a 7500-ohm effective load. We can check this matching by calculating the turns ratio another way—from the formula:

$$N = \sqrt{Z_p/Z_s}$$

This says that the turns ratio is proportional to the square root of the impedance ratio. Inserting our values in the formula, we have:

$$N = \sqrt{7500/3} = \sqrt{2500} = 50.$$

From the foregoing, you can see that the effective primary impedance (the effective load in the plate circuit of the tube) can be any desired value if the matching transformer has the proper turns ratio. We say that the load impedance is *reflected* into the plate circuit through the matching transformer. Adjusting the value of this reflected load to secure the best amplifier operation is called *matching* the load with the amplifier tube, and for this reason the transformer used is often called a matching transformer. Remember—reflected impedance is that value which appears across the primary terminals of a matching transformer when a load is connected across the transformer secondary.

The Cathode Follower

So far in this Lesson we have studied the coupling of the output of the usual type of class A power amplifier to a load. Before we study the other classes of operation of low-frequency amplifiers, let us first consider the cathode-follower type of class A amplifier.

The principal advantage of the cathode follower is that it can be used in a power amplifier at video frequencies. For this reason then, it is used in television transmitters and receivers. However, the cathode follower also has many other uses. For example, because the output voltage is in phase with the input it is used in a "phase inverter" circuit which we will soon study.

HOW IT OPERATES

The basic difference between the standard amplifier circuit and the cathode follower is that the load in the latter is in the cathode circuit (between the cathode and B—) instead of between the plate and B+. This simple change, shown in Fig. 6A, produces several differences in operation.

To understand the behavior of this circuit and how it differs from an ordinary amplifier, remember that in a single-stage amplifier with a resistance load, the load signal voltage is 180 degrees out of phase with the input (grid) voltage. In a cathode-follower, however, the output voltage is in phase with the input voltage. To see this, assume the instantaneous polarity of the input signal to be such that the grid is positive with respect to ground. This causes an increase in the plate current and an increase in the voltage drop across the load resistance R_L which now is in the cathode-to-ground portion of the plate circuit. This makes the cathode *more* positive than the ground. Then, when the input voltage swings the grid negative with respect to ground, the plate current will decrease, and the load voltage will also decrease. This makes the cathode less positive with respect to ground. If we assume the d.c. voltage value to be the signal zero level, the a.c. portion of the voltage across R_L has swung negative. Thus, the load a.c. voltage swings positive and negative in step with the grid voltage, so we say that *the input and output voltages are in phase.*

► By examining Fig. 6A, you will see that the load voltage e_o is between the grid and the cathode terminals. Its presence reduces the net excitation voltage by a degenerative effect. The *negative feedback* occurs because, as far as the tube is concerned, the output voltage opposes or subtracts from the input voltage. Remember, the input and output voltages are of the same polarity with respect to ground. Referring to Fig. 6A, we see that the *grid voltage* of the tube, that is, the voltage between the grid and the cathode, is the difference between e_i and e_o because of the way the polarities add. When the input voltage e_i increases, the output e_o increases simultaneously so as to maintain the grid voltage only slightly higher than before. Because of this, the voltage gain of a cathode follower is small; as a matter of fact, *the output voltage is always slightly less than the input voltage.* This degeneration has many advantages; it prevents large signals from overloading the tube and distorting the output.

► In the circuit of Fig. 6A, the d.c. voltage drop across R_L acts as the bias voltage. This bias is large, so the grid never swings positive. Hence, no grid current flows, and the source of e_i is not required to furnish any power. Thus the cathode-follower has an infinite input impedance. However, sometimes this system produces too much bias. Then, the circuit shown in Fig. 6B is used. Here, R_1 is the bias resistor, and R_2 is the load. The grid input voltage is developed across R_g, and is still the difference between e_i and e_o. Since this means that the voltage across R_g is less than e_i, the current flow through R_g will be much smaller than if R_g were connected directly across the input. Hence, insofar as e_i is concerned, the *effective* size of R_g is many times the actual size of the resistor.

► In an ordinary amplifier we noted that the high-frequency response was limited because of the shunting effect of the input capacity of the tube, and that because of the voltage gain, the effective size of the capacitance was quite large. However, in the cathode follower, the voltage gain is less than 1, and thus the *effective* size of C_{gk} is decreased. Hence, this circuit has a good high-frequency response and is used extensively as a video-frequency power amplifier.

IMPEDANCE MATCHING WITH A CATHODE FOLLOWER

The degeneration introduced by the cathode follower arrangement reduces the stage gain to slightly less than 1—that is, the output voltage e_o is slightly less than the input e_i. At the same time, the plate resistance of the tube is greatly reduced; in fact it is reduced to $\frac{1}{1+\mu}$ of the original value.* This means the proper load value need be only 200 to 500 ohms for the average triode. This makes it easy to match directly to low-impedance loads (such as transmission lines) and also improves the high-frequency response because the shunting effect of capacities across the output is reduced. This is particularly useful in television, where the frequency band being handled is wider than could be comfortably handled by an impedance-matching transformer. However, where transformers are permissible, they can be used for impedance matching when needed.

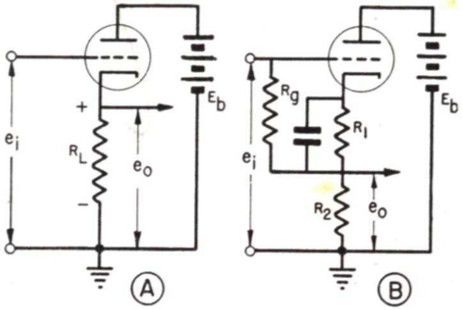

FIG. 6. The basic cathode follower circuit is shown at A. Another practical form is shown at B.

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*The tube amplification factor is equal to the mutual conductance multiplied by the plate resistance, or $\mu = gm \times r_p$. If the μ is reduced to $\frac{\mu}{1+\mu}$, as in this case, then to have the same gm (as we do) the r_p must be reduced to $\frac{r_p}{1+\mu}$.

How Amplifiers Are Classified

There are limits to the amount of power that can be obtained from a single tube of a particular type. Of course, a more powerful tube type might be used, but this may not always be practical. Where it is not, we must increase the efficiency of the stage, or we must get the increased power by using more tubes.

For low-frequency power amplification, we want the output signal to be an exact copy of the input signal. Otherwise, we have distortion, and there are definite limits to the amount of distortion that can be permitted. For this reason, a single power tube must be operated on the linear or straight portion of its characteristic curve, and its operating bias must be adjusted so that, with the signal applied, the grid will never go positive and draw grid current, nor will operation occur on the lower bend of the tube characteristic. This is the only way we can keep the distortion at a minimum. This operation is known as class A, and it is a form of amplification in which plate current flows at all times (it is never cut off) and the output signal is as true a reproduction of the input signal as it is possible to get.

Efficiency. The efficiency of an amplifier is the ratio of its a.c. power output to the steady d.c. power input in the plate circuit, expressed in per cent. If it were possible for all the d.c. power input to be changed to useful a.c. power, the efficiency would be 100%.

In the ideal class A amplifier, the maximum efficiency is only 50%. Even this amount is never realized in practical amplifiers, since it would require a dynamic E_g-I_p characteristic curve that was in a straight line right down to zero plate current, and the plate-cathode voltage would have to be zero when the plate current was at maximum. As these requirements are not met, efficiencies of only about 35% can be obtained with pentodes or beam power tubes or with triodes that are operated at high levels. However, the average class A amplifier has a much lower efficiency, down to about 20% where the grid swing is limited for least distortion.

► Of course, it is possible to put tubes in parallel. You would then have two tubes drawing plate current through the load, so you could get twice as much power as you could from a single tube. However, parallel tube operation is not used very much in low-frequency amplifiers. This operation will be described more fully in your study of r.f. amplifiers.

Today, if a single class A amplifier tube won't do the job, then double-ended or push-pull circuits are used. The push-pull circuit employs two tubes, and is coupled so that much of the amplitude distortion introduced within itself is canceled. This makes it possible to operate nearer the curved portion of the tube characteristic, and to apply a larger signal voltage to the grid. Thus its main advantage is that for the same percentage of distortion in the output, push-pull will give more output. Hence, push-pull permits class AB and class B operation, which are even more efficient than class A. The following table shows typical values.

Type of Operation	Efficiency
Single-ended class A	20-35
Push-pull class A	20-35
Push-pull class AB_1	35-40
Push-pull class AB_2	40-65
Push-pull class B	50-70

► What is meant by class B operation? Essentially, in class B operation, the operating grid bias is fixed at the plate current cut-off point, so that practically no plate current flows until a signal is applied to the grid circuit. Then, on the positive alternations of the signal voltage, plate current flows. The output of a single tube represents half the incoming signal. This ordinarily could not be used for low-frequency amplification, where the complete signal swing is necessary. However, the push-pull circuit, as you will learn later in this Lesson, permits this operation because one tube fills in the gap left by the other.

In class AB operation, the grid bias is somewhere between the normal class A bias and the normal class B bias. This class is sub-divided into AB_1 and AB_2. They have about the same bias, but the input signal is regulated in the class AB_1, so that the grid is never driven positive. In the class AB_2, the grid is allowed to go slightly positive on signal peaks. The latter class is closer to class B in its characteristics, and gives a higher output than the class AB_1.

Another class of operation, known as class C, utilizes a grid bias well beyond cut-off, and a very high input signal. However, the output signal in such a case is a distorted wave, so this class can be used only for amplification of single frequency signals, wherein a tuned circuit can be used to reconstruct the original wave shape. A class C amplifier is not suited to audio-frequency amplification, for the plate current flows for less than a half cycle, so that the input cycle cannot be reproduced by either a single- or a double-ended amplifier. You will learn more about class C operation in later Lessons.

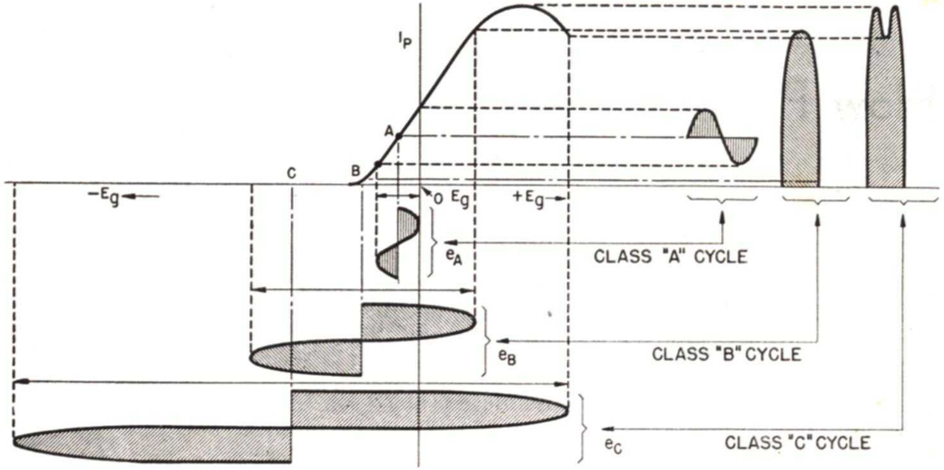

FIG. 7. Relationship between grid bias voltage, grid swing and plate current for class A, class B, and class C amplifiers. In class A, the grid never swings positive; in class B, the grid swings positive only over the linear region of the plate current characteristic; in class C, the grid swings beyond the plate current saturation point.

► To compare the signal input, grid-bias values, and plate current wave shapes, you should study Fig. 7. Notice that in class A, the input signal voltage is limited to an amount which will not drive the grid positive at any time. Plate current flows for a full cycle and is never cut off.

In class B operation, there is no plate current until a signal is applied, then a complete half-cycle is reproduced. Class AB operation is not shown in this figure, but will be discussed later in this Lesson.

As an example of the wide variation of power output represented by the various classes of operation, let's consider the 6L6 tube.

Two type 6L6 tubes operated in push-pull, class AB_1, will deliver a maximum output of approximately 18 watts, whereas each tube alone, operating as a class A amplifier, delivers a maximum of 6.5 watts of undistorted power. If the two tubes were to be operated in class AB_2 push-pull, with fixed bias, an output of 31 watts could be expected. This is almost five times that of a single tube. In class B, the two tubes operating push-pull can deliver about 50 watts without serious distortion.

► Now that you have a general idea of the classes of operation, let's go on to study push-pull stages in more detail.

How Push-Pull Class A Amplifiers Work

You have learned that, as the input signal to a single-ended class A amplifier is increased to obtain more power output, a limiting value is reached beyond which a further increase in input voltage results in an undesired amount of amplitude distortion in the output voltage. If the amount of distortion could be reduced, it would be possible to increase the input signal, and thus obtain more power output, provided that the tube is capable of handling this extra drive.

By the use of two tubes in a *push-pull circuit, all even harmonics* produced by amplitude distortion in the amplifier will be eliminated. Since most of the distortion in a single-ended amplifier is second-harmonic distortion, the total distortion is greatly reduced by a push-pull arrangement. Therefore, we can increase the excitation voltage in a push-pull stage considerably before the distortion level reaches that for a single tube.

Furthermore, with this type of circuit, the load resistance can be reduced to a value more nearly equal to the a.c. plate resistance of the tube to obtain greater efficiency and more power output. Two tubes connected in push-pull will, therefore, give considerably more than twice the undistorted power that a single tube can deliver. Now let us see how all these advantages are realized.

HOW A PUSH-PULL STAGE IS CONNECTED

Fig. 8 gives a typical push-pull circuit. The tubes VT_1 and VT_2 have identical characteristics, or as we generally say, they are "matched tubes." The grids of these two tubes are connected to the opposite ends of the secondary of the input transformer, and the center tap of this winding is connected to ground.

The center tap of the filament transformer secondary is grounded through resistor R_C so that the plate currents for the two tubes, flowing through R_C, provide a voltage drop which serves as C bias for both tubes. Tube VT_1 obtains its plate supply through one half of the primary (P_1) of transformer T_2, and tube VT_2 obtains its plate supply through the other half (P_2). When no grid input signal is present, d.c. current flow in the plate circuit of each tube is in the direction indicated by the arrows alongside i_1 and i_2; since the tubes have the same C bias, the d.c. plate currents will be *equal in value*, and because of the way the plates of the tubes are connected to the transformer, the two plate currents will flow *in opposite directions* through the halves of the transformer primary.

Current flowing through a coil of a transformer produces flux in the core of the transformer. D.C. currents produce d.c. or steady flux, and a.c. currents produce flux which varies in the same manner as the a.c. current itself. In this case, the d.c. plate currents flow in opposite directions through the transformer primary, so the resulting fluxes are canceled. Hence, there is no resultant flux in the transformer core when there is no audio signal input.

► Assume now that a sine-wave signal e_i is applied to the primary of grid input step-up transformer T_3; the secondary of T_3 will, therefore, have a larger voltage because of the voltage step-up ratio. Half of the secondary a.c. voltage is applied to the grid of VT_1, the other half to the grid of VT_2. Since point P is the center tap of the secondary winding of T_3, one-half of this voltage, say the voltage M to P, will be 180 degrees out of phase with the other half (between the terminals N and P) as shown by the grid input voltages e_1 and e_2, in Fig. 8. In other words, when e_1 is a maximum positive value, e_2 will be a maximum negative value.

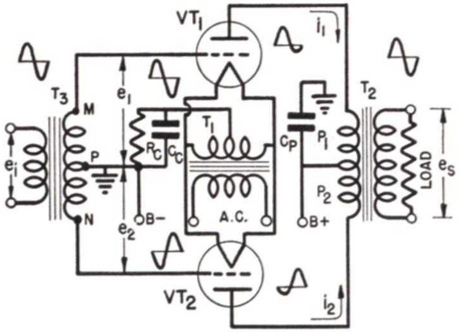

FIG. 8. The basic push-pull class A amplifier circuit.

Notice that in the plate circuit, each half of the primary of the midtap transformer will have its own reflected load resistance. The effective load for each of the two tubes will be equal.

Since tubes VT_1 and VT_2 and their effective loads are identical, we can use the same dynamic E_g-I_p curve for both; Fig. 9 therefore portrays *operating conditions* in a push-pull amplifier circuit.

Let's assume that the operating point is at the lower bend on the dynamic E_g-I_p curve (at 1, 3, 5 in Fig. 9B), so that positive grid voltage swings give much greater plate current changes than do negative grid voltage swings. This corresponds more nearly to class AB operation, which we are using in this example because it shows in a more pronounced manner how the push-pull circuit reduces the distortion produced by the curvature of the dynamic characteristic curves.

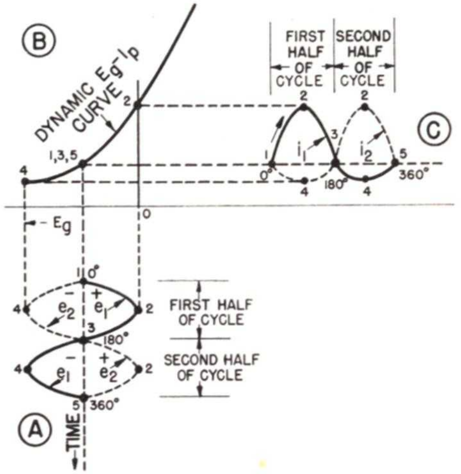

FIG. 9. The operation of a push-pull class A amplifier.

On the half of the cycle when terminal M in Fig. 8 (the upper terminal of the secondary winding of the input transformer) is positive with respect to P, the grid voltage e_1 of VT_1 will swing from 1 to 2 and then back to 3 as at A in Fig. 9. This causes the plate current i_1 of tube VT_1 to swing from its operating value (point 1 on the curve in Fig. 9B) to 2 and then down to 3 as at C in Fig. 9. During this same half cycle, terminal N in Fig. 8 will be negative, and the grid voltage e_2 of VT_2 will swing in a negative direction, from 1 to 4 to 3 on the dynamic curve of Fig. 9, and will cause plate current i_2 of tube VT_2 to swing from its operating value 1 down to 4 and up again to 3 as shown at C in Fig. 9.

Thus, you can see that for the first half of the cycle, a positive grid voltage swing e_1 on tube VT_1 produces a much greater change in plate current i_1 than does an equal negative grid voltage e_2 on tube VT_2. The same analysis can be applied to the currents for the second half of the cycle; in this case, the grid of VT_2 swings positive, causing the plate current i_2 to change from 3 to 2 to 5 (Fig. 9C), while a negative grid swing on tube VT_1 causes plate current i_1 to change from 3 to 4 to 5.

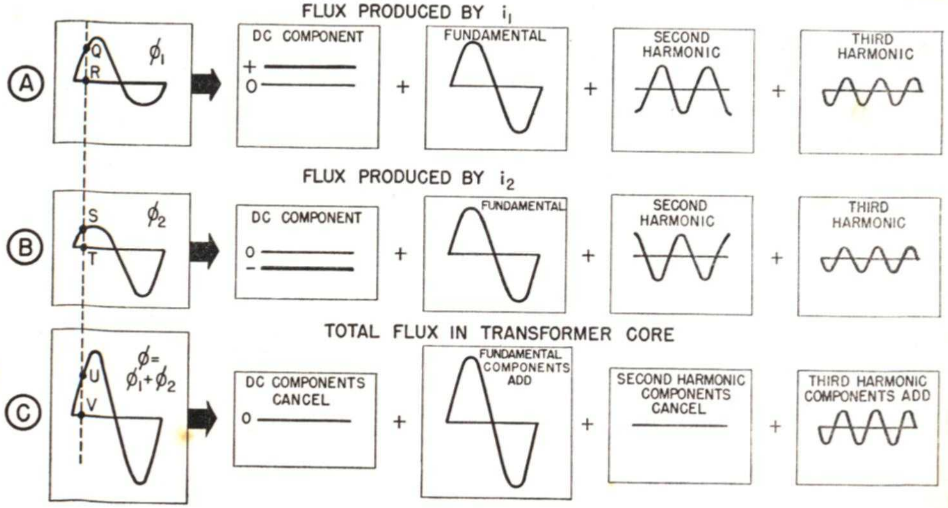

FIG. 10. How amplitude distortion is reduced by the output transformer in a push-pull class A amplifier.

HOW AMPLITUDE DISTORTION IS REDUCED IN CLASS A PUSH-PULL STAGES

Plate current i_1, flowing through primary winding P_1 in Fig. 8, produces in the transformer core a varying flux ϕ_1 whose wave form (shown in Fig. 10A) is exactly like that of plate current i_1 in Fig. 9C. At the same time, plate current i_2, flowing through primary winding P_2 in Fig. 8, produces a varying flux ϕ_2 (Fig. 10B). The two varying plate currents, i_1 and i_2, are 180 degrees out of phase, (since one increases while the other decreases), but they flow in opposite directions through the primary winding of the transformer, so the varying fluxes (ϕ_1 and ϕ_2) which they produce are in phase (the fluxes increase at the same time and decrease at the same time).

To determine the wave form of the resultant flux, we must combine these two. We could do this by combining ϕ_1 in Fig. 10A directly with ϕ_2 in Fig. 10B, getting resultant flux ϕ in Fig. 10C, but we will learn more about what happens to the undesired harmonics (that were added by operation of the tube over a curved characteristic) if we consider the harmonics of each flux component in this addition.

Flux wave ϕ_1 consists essentially of a d.c. component, the fundamental a.c. component, and a number of harmonics, as shown in Fig. 10A. Flux wave ϕ_2, Fig. 10B, has these same components, but the d.c., and the even-harmonic components, are out of phase with the corresponding components of flux wave ϕ_1. (These statements can be proved mathematically or graphically.) We can combine the effects of ϕ_1 and ϕ_2 by combining one component of each flux wave at a time.

First of all, consider the d.c. components of the varying fluxes. Since the d.c. components of ϕ_2 and ϕ_1 are opposite in polarity, they cancel each other. The fundamental components of ϕ_1 and ϕ_2 act in the *same* direction, so their effects add together. The second harmonic components act in *opposite* directions at any instant of time, however, so their effects cancel each other. The effects of the third harmonic components add, just as in the case of the fundamentals. If we continued the analysis for all harmonics, we would find that the effects of all even-harmonic components of flux cancel out, leaving only the fundamental and the odd-harmonic components. Fortunately, however, all harmonics above the second are weak so that the total harmonic distortion is greatly reduced by the removal of the second harmonic. The resultant varying flux (shown in Fig. 10C), will therefore be a good copy of the applied signal. In this example, we are using a sine wave, so the signal induced in the transformer secondary will be a practically pure sine-wave voltage as at e_s in Fig. 8.

► The action of a push-pull amplifier circuit can also be explained more briefly in the following manner: Currents i_1 and i_2 in Fig. 9C flow in opposite directions through the primary of the output transformer at any instant of time, producing the flux waves ϕ_1 in Fig. 10A and ϕ_2 in Fig. 10B. To combine these flux waves and find the resultant flux, we simply add the corresponding values on each wave. For example, we add Q-R in Fig. 10A to S-T in Fig. 10B, and U-V in Fig. 10C is the result. Carrying this process through for the entire cycle gives resultant flux wave ϕ in Fig. 10C. Distortion has been reduced because, considering the first half cycle, the larger-than-normal current i_1 (caused by the upward bend in section 1 to 2 of the dynamic curve) is offset by the lower-than-normal current i_2 (caused by the flattening of section 1 to 4 of the dynamic curve).

Push-Pull Cancels Only Its Own Generated Harmonics. Notice that push-pull operation eliminates *ONLY* the even harmonic components of the distortion *produced IN the amplifier stage. Any harmonics applied to the input of the amplifier will be amplified in the same manner as the fundamental.* This is just what we want—all harmonics in the original signal must be reproduced, and yet the introduction of new harmonics must be kept at a minimum.

► It should be emphasized that *the elimination of even harmonics in a push-pull Class A amplifier can only result from flux cancellation in the output transformer.* For this reason *the center-tapped output transformer is an absolute necessity.*

The transformer used should have all the desirable characteristics of those used in high-quality transformer-coupled amplifiers. In addition, the output transformer should have very low leakage inductance between the two halves of the primary, otherwise the second harmonic distortion components will not be completely canceled out. Similarly, the leakage inductance from each half of the primary to the secondary winding should also be small. Fortunately, since the d.c. flux in the core is canceled, there is none to saturate the magnetic circuit, so it is possible to get good transformers which are smaller and cost less than single-ended transformers of equal power-handling capacity.

► If the amplifier is operated in class AB_2 (that is, it draws grid current on the positive peaks of the input signal) the input transformer must also be designed so as not to introduce distortion in the signal voltage reaching the grids. When the grids draw current, the secondary of the input transformer actually has a resistance load,* and power from the driving source is required. Not only does the resistance load exist, but when the grid draws current it varies throughout the cycle. This is because the grid current does not vary in direct proportion to the applied grid voltage. The change in resistance seen by the transformer causes variations in transformer current, and the voltage drops in the leakage inductance, and the effective resistance of the transformer vary considerably from a normal value.

Since the source (the previous amplifier stage) must supply power, it must be made to match the load through a proper transformer. However, the load value will change during a cycle giving different amplifier efficiencies, and in this way produce distortion. This distortion can be reduced by using a low-impedance driver so that changes become negligible as do the voltage drops. The effective impedance of the source can be reduced by connecting the input transformer as a step-down transformer between the driver and the grids of the push-pull tubes.

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*No matter how a device works, its impedance is always the applied voltage divided by the current drain. The grid-cathode of a tube is no exception. In class A operation, no grid current flows even though a voltage is applied. This can be conceived only by thinking of the grid-cathode circuit as having an infinite impedance. In class AB_2 and class B operation, grid current flows and Ohm's Law tells us that we have an effective impedance load.

Other Push-Pull Amplifiers

Class B is the most efficient of the various classes of operation of low-frequency amplifiers.* This type of operation is efficient because the tubes used are biased to cut-off, so that power is drawn from the plate supply only when there is an input signal. The circuit for class B push-pull operation is similar to the circuit for class A push-pull operation except that the tubes in a class B amplifier are biased to cut-off. The bias cannot be obtained across a common cathode resistor R_C as was done in the amplifier in Fig. 8, since no plate current flows without excitation. Instead, either a separate fixed bias supply, or tubes whose plate current cuts off at zero grid bias may be used, thus eliminating the need for C bias.

CIRCUIT REQUIREMENTS FOR CLASS B OPERATION

The two essential requirements for a class B push-pull amplifier are: 1, the dynamic E_g-I_p curve of the tubes used must be essentially straight from the plate current cut-off point to the positive grid voltage value at which secondary emission from grid and plate just becomes objectionable; 2, the grid bias must be set at the plate current cut-off point of the tubes.

The push-pull circuit of Fig. 11 uses special high μ triode tubes designed especially for zero-bias class B operation. The type 805, 809, and 838 transmitting tubes are examples of this type. To see how the circuit works, let's assume a sine wave input signal e_g, and the proper load values for the tubes.

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*Class C amplifiers, although they are more efficient than class B amplifiers, are not used for low frequencies because of the excessive amount of distortion they produce.

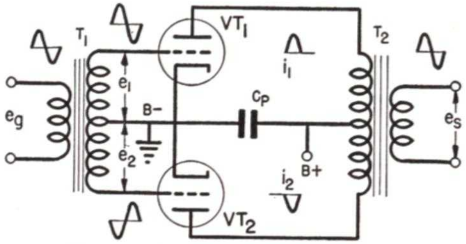

FIG. 11. The basic zero-bias class B audio amplifier.

On the first half cycle, the signal e_1 will swing the control grid of tube VT_1 positive, and a half-wave plate current pulse i_1 will flow through one section of the output transformer primary, inducing a half sine-wave voltage in the secondary of transformer T_2. No current will flow through tube VT_2 during this half cycle, for its grid will be negative and hence beyond the plate current cut-off point. Similarly, for the other half of the input voltage cycle, plate current i_2 will flow in the opposite direction through the lower section of the transformer primary, inducing in the secondary of T_2 a half sine-wave voltage of opposite polarity to the first. Adding the two will give the sine-wave output voltage e_s. Notice that VT_1, so to speak, pushes current through T_2 during one half-cycle and VT_2 pushes for the other half-cycle. Hence this type of circuit is sometimes called "push-push."

Distortion. *There is no cancellation of even harmonics in a class B push-pull amplifier,* for the harmonics are produced by only one tube at a time. Remember, in a class A push-pull amplifier, the plate current over-swing of one side is balanced out by an underswing of current by the other side.

The generation of harmonics can be reduced only by using tubes that are closely matched, and by loading them in such a manner that their dynamic E_g-I_p characteristics are as straight as possible.

Class AB Operation. Class AB operation is important in that it combines the advantages of both class A and class B operation. The class AB amplifier can be designed to act as a class A stage for low grid signal voltages and as a class B stage for high grid signal voltages. At low signal levels, then, even harmonics are eliminated. At high signal levels (which will be only intermittently required of the amplifier) distortion will be present, but this is permissible because distortion is less objectionable at high volume levels and will not be continuously present. Therefore, this amplifier is less subject to distortion for normal reproduction levels, and yet has much of the power-handling capabilities of the class B amplifier for peak requirements.

To realize the full power-handling capabilities of class AB operation, the C bias must be obtained in such a way that the plate current has no effect upon its value; in other words, a fixed C bias must be used. If this is not done, a large amplitude input signal will cause the bias to become excessively negative.

Excitation of Double-Ended Amplifiers

To function correctly, a push-pull amplifier must have the grids of its two tubes fed (excited) by signal voltages that are equal in magnitude and 180 degrees out of phase. This generation of one voltage 180 degrees out of phase with another is commonly termed *phase inversion.*

Fig. 8 and Fig. 11 show how this is done by the use of an interstage coupling transformer with a center-tapped secondary. With the center tap connected to ground, the two grids will receive voltages that are *equal* and exactly 180 degrees out of phase.

This tapped secondary input transformer type of phase inverter is generally used when the push-pull stage takes power from the source, for example, in class AB_2 and class B operation where the grids of the tubes are driven during part of the input cycle. However, where the push-pull stage takes no power from the source as in class A and class AB_1 operation, the transformer can be replaced by a resistance-coupled phase-inverter stage.

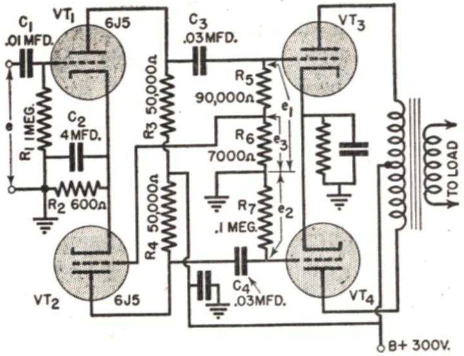

FIG. 12. Basic circuit of a tapped-output inverter.

There are many advantages of resistance coupling as compared to transformer coupling in a phase inverter. There is a definite saving in cost; the resistance coupling has inherent high-fidelity characteristics; and since there are no coils or cores, the possibility of magnetic coupling and hum pickup is eliminated. In addition there is a reduction in weight and a saving in space —important factors in portable and mobile equipment. Let's examine the circuits of several representative types.

BASIC PHASE INVERTER

The circuit shown in Fig. 12 is typical of phase inverters. Here, VT_1 is the usual driver or voltage amplifier, and VT_2 functions to invert the phase. Although shown as two separate tubes, VT_1 and VT_2 could be a dual triode enclosed in a single envelope.

This inverter depends for operation on the fact that the output of a one-stage resistance-coupled amplifier is 180 degrees out of phase with the input voltage.

The input signal e is applied to the grid of VT_1, where it is amplified and fed as e_1 directly to one push-pull tube VT_3. A small fraction e_3 of this same output voltage is also fed to an extra tube VT_2, which amplifies it and applies it as e_2 to the second push-pull tube, VT_4. Since the grid voltage e_2 arriving at VT_4 has gone through an extra tube, it is of opposite phase to the voltage e_1 arriving at VT_3.

For proper push-pull operation, the two push-pull grid voltages e_1 and e_2 must be exactly equal in amplitude. The signal e_2, however, has gone through the extra tube VT_2. If we had taken e_1 as the VT_2 grid voltage, then e_2 would have been much larger than e_1. To prevent this, the input to VT_2 must be reduced by an amount equal to the gain of stage VT_2. This is accomplished by splitting the grid resistor of VT_3 into two separate resistors, R_5 and R_6, so we get a voltage divider.

R_5 and R_6 in series are approximately equal to the resistance R_7, but their actual values depend upon the gain of VT_2. If, for example, the gain of VT_2 is 14, the voltage e_3 across R_6 is made only 1/14 of the voltage e_1. This means R_6 has 1/14 the resistance of R_5 and R_6 in series. If the gain of VT_2 had been 8, then R_6 would need to be only ⅛ the sum of R_5 and R_6 in series.

Balancing a Phase Inverter. When the exact gain of VT_2 is not known, the circuit can be balanced by using a high-resistance voltmeter or a vacuum-tube voltmeter. To do this, an audio voltage is fed into the input of the circuit from an audio signal generator. Then the voltage e_1, between the grid of VT_3 and the chassis, is measured. Voltage e_2, between the grid of VT_4 and the chassis, is measured and compared with e_1. The value of resistor R_6 is adjusted to make voltage e_1 and e_2 equal. If e_2 is smaller than e_1, then R_6 is increased in value and vice versa.

► Another method of obtaining a balance is shown in Fig. 13. This method can be used as long as the current rating of the output transformer is not exceeded. Temporarily disconnect one of the plate leads from the output transformer, and connect that plate lead in parallel with the other tube. Now both plate currents flow through one half of the output transformer in the same direction. When an input signal is supplied, the push-pull grids still receive voltages 180 degrees out of phase. This will make the plate currents of the two tubes out of phase so that they will tend to cancel each other.

However, if one tube receives a larger signal than the other, some sound can be heard in the receiver. Therefore, the amount of signal heard depends on the amount of unbalance of the grid voltages, and on the unbalance of the output tubes which may not be matched.

Resistor R_6 is adjusted for a minimum output signal. The output signal may not go all the way to zero because of a possible unbalance of the output tubes, but there should be a definite minimum obtained when the two input voltages have been adjusted to give approximately equal plate current changes. After the correct value for R_6 for minimum output signal has been obtained,* the parallel plate connection is removed, and the output transformer reconnected as in Fig. 12.

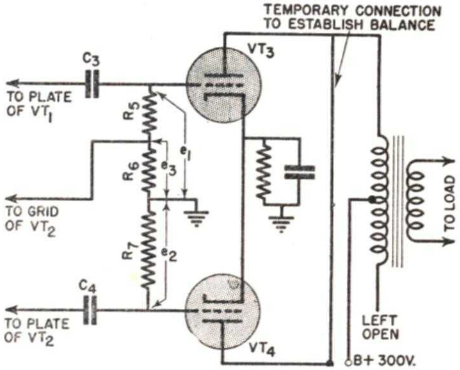

FIG. 13. Balancing arrangement for a tapped-output inverter.

At a cost of an extra tube, the tapped-output inverter eliminates the input transformer. There is, however, considerable danger that aging tubes will upset the voltage balance between the push-pull tube grids. Unequal push-pull input signals will cause distortion, as the harmonics will not balance out. This makes it necessary to re-establish balance from time to time if distortion is to be avoided.

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*When a circuit like that in Figs. 12 and 13 is actually balanced, a variable resistor of about 1/6 the value of R_7 would be used as R_6. In both cases this variable resistor would be adjusted for balance, then disconnected, and its resistance measured with an ohmmeter. A fixed resistor close to this measured value would be soldered permanently into the circuit as R_6.

SELF-BALANCING INVERTERS

The circuit in Fig. 14 does not have the troublesome balancing problem obtained with that of Fig. 12, because in Fig. 14 the resistor R_6 is connected so that degeneration gives a constant balance.

VT_1 operates as a straight resistance-coupled amplifier, feeding its output voltage e_1 directly to one push-pull tube VT_3 exactly as in Fig. 12. However, notice the position of R_6. It is made equal in resistance to R_5 and R_7. Through the divider action of R_5 and R_6, and with R_5 equal to R_6, one half of e_1 is fed to VT_2. This tube amplifies the signal voltage a second time, inverting the phase and feeding the other push-pull tube VT_4. The output voltage e_2 from VT_2 appears across R_7 and R_6. We see that R_6 is common to both input and output circuits of VT_2, and one half of e_2 is fed back across R_6.

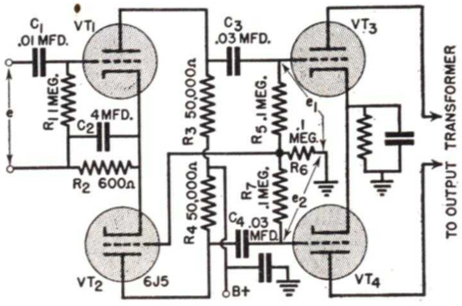

FIG. 14. Circuit of a self-balancing inverter.

Since the two voltages e_1 and e_2 are 180 degrees out of phase, the e_2 voltage will tend to cancel the voltage across R_6. This reduction in the input signal to VT_2 means that its over-all gain is reduced, that is, there is degeneration.

Such a high value of degenerative feedback drops the effective gain of VT_2 to slightly less than two, and this gain is practically independent of the characteristics of VT_2. This is exactly what is desirable, for it means that although VT_2 may age or its characteristics change with time, e_2 will always be equal to e_1, and the push-pull grid voltage balance will remain unaffected.

Note that degeneration is applied to VT_2 only, so the operation of VT_1 has not been changed. VT_1 still delivers full gain. This inverter, therefore, has all the characteristics of the tapped-output type, but the balancing trouble has been eliminated. Low driving voltages still give fairly high output voltages, and the frequency response is as good as the conventional resistance-coupled amplifier.

► Another self-balancing phase inverter uses only one tube as both driver and inverter by using a modification of the cathode-follower circuit. As shown in Fig. 15, the circuit is a combination of a cathode follower and a standard resistance-coupled amplifier. The load for the tube consists of resistors R_3 and R_4, of equal value. Notice that R_4 is in the plate circuit and that R_3 is in the cathode circuit.

By tracing the direction of electron flow from cathode to plate, we find that the end 3 of R_4 is negative with respect to terminal 4. Continuing around through the B supply, and through R_3 back toward the cathode, we find that terminal 2 of R_3 is negative with respect to terminal 1.

Now, let's consider terminal 4 of R_4 to be grounded through C_4 (insofar as a.c. signals are concerned), so that it connects effectively to terminal 2 of R_3. Comparing the voltages across these two resistors, we find that an increase in plate current makes terminal 3 of R_4 more negative at the same instant that it makes terminal 1 of R_3 more positive. Therefore, if we feed VT_2 from terminal 3 of R_4, and feed tube VT_3 from terminal 1 of R_3, the two tubes will be fed out of phase. R_3 and R_4 must be equal in size, of course, so that the voltages fed the push-pull tubes will be equal.

► Since R_3 is part of the plate load, but is also in the input circuit in such a way that the voltage developed across R_3 opposes the input signal voltage, this circuit is degenerative. For example, if the stage gain is 50, then 1 volt across R_1 (the grid resistor) will appear as 25 volts across R_4 and R_3 respectively. (25 plus 25 is 50, the a.c. voltage we would get from a gain of 50.) However, the 25 volts across R_3 must be subtracted from the voltage e applied at the input terminals, so to get 1 volt across R_1, we must apply an e of 26 volts. Hence, the over-all gain of VT_1 is only about 2 ($50 \div 26$ is about 2). As only half the output voltage is supplied to each of the push-pull tubes, the effective gain is one, so the input voltage e we supply must be the same as the voltage necessary to drive the grid of one of the push-pull tubes.

As the tube VT_1 ages, the voltage across R_3 and R_4 will tend to decrease, but this lets a slightly increased amount of voltage appear across grid resistor R_1, and conditions are restored approximately to normal. Furthermore, even if the input voltage increases to large amounts, the resulting increase in voltage across R_3 prevents overload. Thus, all the advantages of degeneration are added to this phase inverter stage.

► There is a disadvantage to this circuit—operating the cathode of the inverter tube at a high impedance above ground sometimes permits a.c. hum pickup from the filament directly through the cathode-to-filament capacity of the tube. This same capacity, also, will effectively shunt out some of the cathode output voltage at high frequencies, thereby unbalancing the circuit and promoting distortion. However, the latter effect usually occurs at such high frequencies that it is not serious.

Both a.c. hum pickup and loss of high frequencies can be minimized by operating the inverter tube on a separate filament supply that is not grounded, but this is not always possible since many power transformers have only one filament winding.

An alternate way to reduce a.c. hum and high-frequency loss is to lower the resistances of R_1 and R_2 if a slightly lower output voltage can be tolerated.

► Different manufacturers use phase inverters that are not exactly like those just described. Most of these circuits involve tricks which enable one tube to do the work of two. As an example, see Fig. 16 for a circuit used by one radio receiver manufacturer.

Here, the input signal e is fed directly to the grid of one of the push-pull tubes (VT_1) through condenser C_1. The grid resistor for this tube is R_1. This tube amplifies the signal in the normal way.

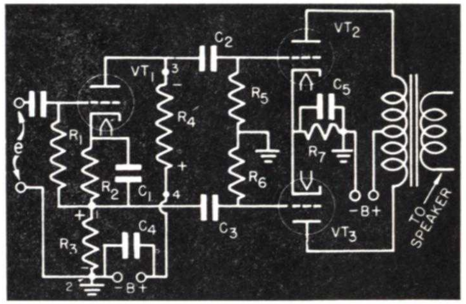

FIG. 15. Both push-pull tubes may be fed from a single tube in this unique phase inverter stage.

Inserted in the screen grid circuit of tube VT_1 is a small resistor R_4. This acts as a load resistor, in that a certain amount of the signal energy developed by VT_1 appears across this resistor. In other words, the screen grid acts like a triode plate, and taps off a

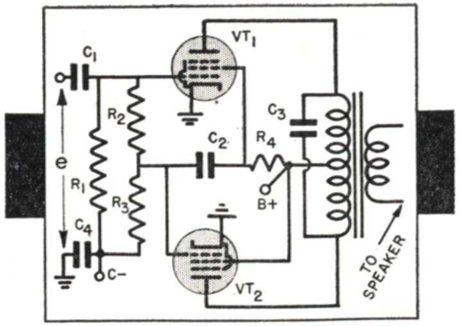

FIG. 16. A special phase inverter circuit used in certain Philco receivers. One of the output tubes is used as the source of the grid voltage for the other.

certain amount of the signal energy, with resistor R_4 acting as its load. The signal developed across R_4 is fed to the grid of VT_2 through C_2. Resistor R_3 is the grid resistor for this tube.

Thus, the tube VT_1 serves a dual purpose. It is one of the tubes in the push-pull amplifier, and also acts as the phase inverter for tube VT_2.

Considerable degeneration is necessary in this circuit to prevent distortion. This is furnished by resistor R_2, which is a resistance of higher value than either R_1 or R_3. Through it, some of the energy fed back through C_2 is applied to the grid of VT_1, opposing the original signal and causing degeneration in this tube. In addition, some of the input signal e is fed through R_2 to VT_2 so that it is out of phase with the C_2 voltage. Hence both tubes undergo a certain amount of degeneration. However, degeneration is not carried as far as in the phase inverters we previously described, because nearly normal performance is wanted from VT_1. Just enough is used to give reasonable fidelity.

► There are a number of other less commonly used phase inverter circuits. However, they all work essentially like the basic ones we have just described. For most applications, phase inverters have proved so superior in performance that they have replaced the input push-pull transformer almost entirely where a low impedance driver stage is not needed. *In class AB and B double-ended power amplifiers, the input split secondary transformer must be used.* The output transformer in a double-ended class A amplifier, however, is still necessary for the cancellation of undesired harmonic components in the push-pull circuit. Also, with all double-ended amplifiers, the output transformer is required for the additional function of providing an impedance match between the power tubes and a low-impedance load.

A Complete Audio Amplifier

Up to now we have considered basic low-frequency amplifier stages and their operation. To sum up these various facts, let us consider a complete audio-frequency amplifier, such as you might find in a public address system, or in the low-frequency amplifier of a transmitter.

The circuit diagram of a low-frequency amplifier which is capable of delivering 60 to 100 watts of undistorted power when the output of a dynamic or inductor type of microphone is fed to its input is shown in Fig. 17.* An analysis of this circuit will help one to understand the action of complete low-frequency amplifiers.

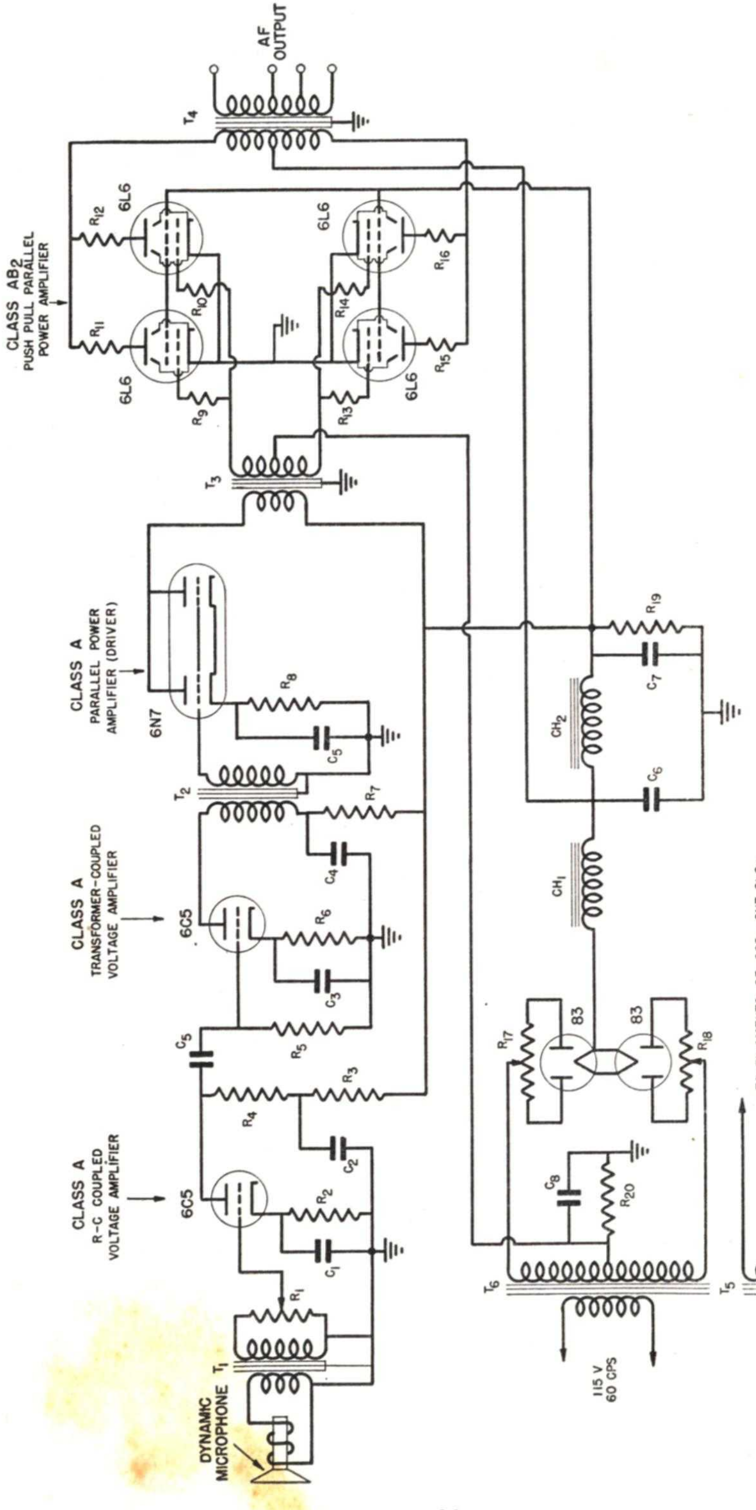

FIG. 17. This amplifier is capable of supplying 75-100 watts of audio power. It illustrates many of the basic amplifier circuits, and is typical of the types used in public-address systems. Similar types are used as the audio system of low-powered transmitters.

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*Notice that the filaments are omitted for tubes which have a cathode for an emitter. This is frequently done in diagrams to avoid complicating the drawing. Even though not indicated, however, the filaments are connected in the usual manner.

Since the inductor type of microphone is a low-impedance device, a matching transformer, T_1, is placed between it and the grid of the first amplifier stage. The microphone current flows through the primary of transformer T_1 and induces a voltage in the secondary. By means of volume control R_1 the desired amount of this signal is fed to the grid of the first 6C5 tube acting as a class A resistance-capacitance-coupled amplifier. The output voltage of the first stage is coupled to a second 6C5 tube acting as a class A transformer-coupled voltage amplifier. The input a.c. grid voltage in this stage causes an a.c. plate current to flow through the primary of transformer T_2, inducing in its secondary an a.c. voltage of similar wave form and of greater magnitude than the input voltage. The maximum possible amplification of this stage is the μ of the tube multiplied by the turns ratio of the transformer.

The secondary of transformer T_2 feeds a class A power amplifier or *driver* stage using a 6N7 twin triode* with the triode units connected in parallel. The two triodes in parallel supply the power required to *drive* the output stage. This power is consumed principally by the grids of the 6L6 tubes. These tubes are connected as class AB_2 amplifiers and hence draw grid current during operation. When properly driven, the output stage will deliver a power output of 60 to 100 watts. The large power output is obtained at high efficiency through the use of four 6L6 beam-power tubes connected in a class AB_2 push-pull circuit with the upper and lower pairs of tubes in parallel. The output power is delivered to the a.c. load (transmitter modulator, public address loudspeaker, etc.) through transformer T_4.*

C bias for the class A stages is provided by cathode resistors R_2, R_6, and R_8, each suitably by-passed for a.c. The final output stage gets its bias from the power supply—R_{20} is the bias resistor, and it is by-passed by C_8. This system provides reasonable bias stability if bleeder R_{19} is large. However, many amplifiers of this type have a separate bias supply. This is particularly true of the more powerful types.

Condenser C_2 and resistor R_3 in the first stage (and C_4 and R_7 in the second stage) serve to keep signal currents out of the power supply and thus reduce feedback between stages. The signal currents are returned directly to the tube cathode through the low-impedance path provided by condenser C_2 and R_4, and the resistors R_3 and R_7 cause the power-supply circuit to present a high impedance to the plate signal. The same combination of resistor and condenser also serves in the reverse direction by filtering out any a.c. ripple which gets past the power pack filter unit.

The power supply for this amplifier contains two type 83 mercury-vapor tubes connected to give full-wave rectification. Resistors R_{17} and R_{18} are used as suppressors to eliminate internal gas oscillation in these tubes. Transformer T_5 supplies the filament voltages required by the amplifier, and transformer T_6 supplies the high plate voltage required by the rectifier tubes. Chokes CH_1 and CH_2, together with condensers C_6 and C_7 form the filter circuit. Resistor R_{19} is called a *bleeder resistor* because it draws a current from the power pack at all times. The full rectified output voltage of the power pack is applied to the plates of the output tubes in the final stage by means of a tap between chokes CH_1 and CH_2. The other tube plates, and the screens of the 6L6 tubes, are supplied the filtered output from CH_2.

► Assuming transformer T_1 to be part of the inductor or dynamic type of microphone system, the two 6C5 stages together with transformer T_2 supply the principal part of the voltage amplification of the multistage amplifier. The first 6C5 stage is resistance-capacitance-coupled, so it will have a voltage amplification of approximately 14. The second 6C5 stage is transformer-coupled, and will have a voltage amplification of 20 times the transformer (T_2) turns ratio. The over-all voltage amplification of these stages is equal to 14 × 20, or 280, times the turns ratio of T_2. This amplification will supply sufficient voltage to operate the 6N7 stage at a power output of as much as 400 milliwatts.

PARASITIC OSCILLATIONS

Under certain conditions, undesired oscillations will occur in ordinary power amplifiers. They are called *parasitic oscillations,* and occur in circuits using tetrodes, pentodes, and large triode tubes having high transconductance and large interelectrode capacities. These oscillations are undesirable not only because of the distortion introduced, but because they consume power, and lower both the efficiency and the power output of the amplifier. Although oscillations will be considered in greater detail in a later Lesson, their existence as a parasitic in low-frequency amplifiers calls for a brief preview at this time.

Oscillations will persist in any circuit containing inductance and capacitance if there is a source of power available that will overcome the losses in the circuit. Therefore, power stages frequently are troubled with an undesired oscillation because of the high inductance and distributed capacities present, and because of the high power levels.

A pentode output stage is particularly subject to these oscillations, because such a stage has high gain, and has a tube with a relatively coarse screen-grid structure (so that the interelectrode capacity is high). This trouble is most common when the output stage is run as a class AB or class B push-pull amplifier, where a low-resistance input transformer must be used.

The oscillation occurs at frequencies where the leakage inductance and the distributed capacity of the transformers form resonant circuits, or where the transformer capacities remove the inductance effects, leaving the grid and plate leads to act as transmission lines because of their distributed inductance and capacity.

You will study more about feedback later, but briefly, sufficient voltage, in the proper phase, is applied to the resonant circuit so that this voltage essentially becomes an input signal. When sufficient power is so applied, the resonant circuit generates a signal at its resonant frequency. Most generally, the feedback occurs from the plate circuit, through the grid-plate interelectrode capacity, or through stray coupling between these circuits.

The "feedback" power may also come from the grid circuit. During that part of a cycle when the grid of a power amplifier is positive, the grid-cathode circuit of a tube may display a negative resistance* characteristic as the result of secondary emission from the

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***This is an all-metal tube containing two high-μ triodes in the same envelope. The triode units have separate external terminals for all electrodes except the cathodes and heaters.**

***Transformer T_4 has a number of taps on its secondary winding, to permit the use of loads which have different impedances.**

*By negative resistance we mean that as the voltage increases, the current through the load decreases. Therefore, instead of taking power as an ordinary resistance does when a voltage is connected across it, *a negative resistance will supply power to whatever is connected to it.*

grid. When this negative resistance shunts any parasitic resonant circuit, existing between grid and ground, high-frequency oscillations of the so-called "dynatron" type may occur.

Furthermore, in tetrode and pentode amplifiers, the E_p-I_p characteristic may contain a downward dip produced by secondary emission at the plate. This downward dip is essentially a negative resistance characteristic that will support parasitic oscillations in the plate circuit.

This parasitic oscillation does not occur in every circuit, of course. It may occur, however, in any circuit in which enough power is available, in which enough feedback exists, and in which the grid inductance and capacity can form a resonant circuit.

Parasitic oscillation causes severe distortion, weak reception, and perhaps a rushing noise or an exceedingly high-frequency whistle. The large amount of power consumed lowers all operating voltages. The output tubes may glow blue or even get so hot their elements melt. The rectifier tube, the filter choke, the power transformer, and the output transformer will be passing excessive current, so they will overheat.

An effective remedy is to insert resistances of 100 to 500 ohms in the grid and plate leads next to the tubes in the output stage. These resistors then appear in series with the parasitic tank circuits. They use up enough of the feedback power to prevent oscillation. Resistors R_9 to R_{16} in Fig. 17 are parasitic suppressors.

Power Amplifier Tubes

Let us now study the tubes used in power amplifiers. As we have already noted, triode, tetrode, and beam tubes are all used. Although triodes are generally used in high power amplifiers, pentodes and beam tubes are used extensively in low and medium power amplifiers. Therefore, we will first review the characteristics and operation of these tubes.

EVOLUTION OF PENTODE AND BEAM POWER TUBES

The limitations of the triode led investigators to work on new tube designs with emphasis on the following purposes:

1. To obtain higher plate currents with relatively low plate voltages.
2. To reduce plate-to-grid capacity so as to eliminate the instability and unsatisfactory performance caused by feedback from the plate-to-grid circuits.
3. To allow a low excitation voltage on the grid to control large amounts of power in the plate circuit, (this is high power sensitivity*). Thus, in a tube with high μ, a small grid signal voltage produces large variations in output voltages; likewise in a tube with high g_m, a small grid signal voltage controls large variations in plate current. A tube with high power sensitivity would then have a combination of as high a μ and as high a g_m as possible.

Although these were especially important in tubes for use with r.f. amplifiers, the development of tubes with these properties was followed by their immediate application to low-frequency uses.

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*Power sensitivity is obtained by dividing the power output by the input grid signal voltage.

TETRODE TUBES

The first step in realizing these objectives was the insertion of another grid between the control grid and the plate. Such a tube was called the tetrode because of its four elements. The purpose of the new grid is to shield or screen the plate from the control grid and thus reduce the plate-to-grid feedback. It is called a "screen" grid and is maintained at ground potential with respect to a.c. by means of a bypassing condenser between the grid and ground. It is operated at a positive d.c. potential somewhat lower than the plate potential. Because of its positive d.c. potential it accelerates electrons toward itself and actually has more influence on the number of electrons than does the plate voltage. However, few electrons are captured by the screen grid, because the large spaces between the grid wires permit most of them to pass on to be collected by the plate.

The reduced plate-to-grid capacity of the tetrode permits very large values of amplification to be obtained now that the feedback from plate to grid has been reduced substantially. The fact that the screen voltage controls the plate current more than the plate voltage does means that the ratio of plate-voltage change to grid-voltage change (needed for a particular current change) is high. This results in a much higher amplification factor. The characteristics of the tetrode, namely high amplification factor, high plate resistance, low feedback, and average values of g_m made it a valuable step toward the goal of higher voltage and power amplification.

► The behavior of a tetrode or screen-grid tube as an amplifier is expressed by the family of E_p-I_p curves given in Fig. 18.

For any one value of control-grid voltage, the plate current rises quite rapidly at first, as the plate voltage is gradually increased from zero. The screen grid has such tremendous electron-pulling power, however, that electrons approach it at very high speeds, pass right through its widely spaced wires and hit the plate with terrific impact, knocking electrons out of the plate; this effect is known as *secondary emission.* Some of these secondary electrons return to the plate, but a great number of them are attracted to the screen grid, which also is at a high positive d.c. voltage. For low plate voltages, the screen-grid current is actually higher than the plate current, indicating that the screen grid collects a high proportion of the electrons which "bounce" off the plate, and also attracts electrons directly (the screen grid is at a higher potential than the plate in the region to the left of line AA). It is for these reasons that, in the region between zero and 90 volts (labeled "VALUES UNSTABLE" in Fig. 18), increases in plate voltage actually cause the plate current to "dip" or to go down. For plate voltages above 90 volts, the plate current rises and the screen-grid current decreases

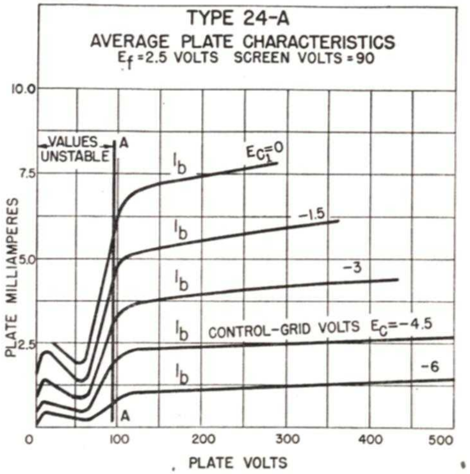


FIG. 18. The plate characteristics of a type 24A tetrode receiving tube.

gradually to a very low current value.

The part of the E_p-I_p characteristic to the left of line AA is known as the "dynatron" characteristic. When working in this region, the plates possess a *negative resistance* property, and if the plate load were a tank or tuned parallel circuit of the right values, the circuit would act as an oscillator as we noticed when we studied parasitic oscillations. If distortion in the output voltage is to be prevented in a tetrode amplifier, both the load resistance and the plate supply voltage must be selected carefully so as to keep the operating values away from the region to the left of the line AA.

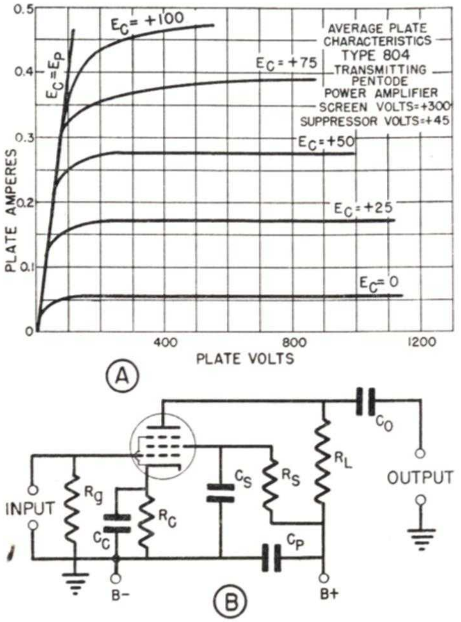


FIG. 19. The plate characteristics of a type 804 transmitting pentode power amplifier are shown at A, and the basic class A pentode amplifier circuit is at B.

PENTODE TUBES

It was soon realized by tube designers that the amplifying characteristics of a screen-grid tube could be improved effectively if some means could be found of forcing the secondary emission electrons to return to the plate. This was accomplished by the introduction of an extra grid between the plate and the screen grid. This new grid "suppressed" the effects of secondary emission and was called a *suppressor* grid. As the tube now possessed five elements (three grids, a cathode, and a plate) it was called a *pentode.*

The suppressor grid is connected to the cathode or to a terminal which is more negative than the cathode. When an electron either bounces from, or is knocked off the plate and tries to flow to the positively charged screen grid, it is repelled just enough by the suppressor grid to be forced back to the plate. Even when the suppressor grid is at zero or cathode potential, its action is sufficient to make secondary electrons prefer the plate to the screen grid.

The suppressor grid has very little effect upon the electrons flowing from the cathode to the plate, but a great deal of control over those which reverse their direction at the plate. An electron moving from the cathode through the control grid and the screen grid of the plate has developed so much speed by the time it reaches the suppressor grid that it goes right through the coarse wire mesh without slowing up at all, but secondary electrons coming from the plate have very little speed and are easily forced back by the suppressor grid. This one-way action of the suppressor grid is so efficient that it is even possible to operate the screen grid at the same potential as the plate, improving the electron flow to the plate without affecting secondary emission.

A family of E_p-I_p characteristic curves for a type 804 pentode tube is given in Fig. 19A; notice that the suppressor grid has eliminated the unstable region below the screen-grid voltage value which was present in the screen-grid tube characteristic curves in Fig. 18. The plate current of this pentode tube practically reaches its full value at low plate voltages, indicating that secondary emission is not depriving the plate of its current. A tube with characteristics like this can be made to swing over wide plate-current and plate-voltage values, giving maximum amplification and maximum power output for the tube. Fig. 19B shows a typical pentode amplifier circuit.

In power output pentodes, the suppressor allows the plate voltage to swing over large values, thus delivering a large power output with high gain —in other words producing high power sensitivity.

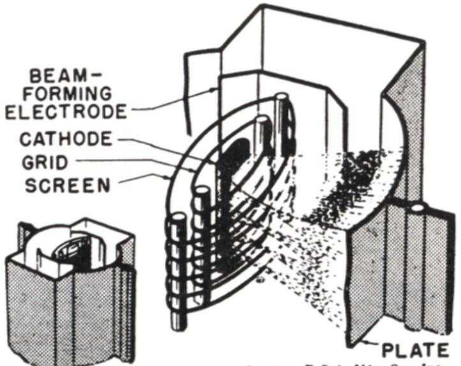
BEAM POWER TUBES

The beam power tube has provided the answer to the problem of obtaining pentode action in a high power tube. It is a tetrode in which the effect of a suppressor grid is achieved by means of a space charge between the screen and the plate. The internal structure of a beam power tube is shown in Fig. 20. Note that it has four electrodes, a cathode, a grid, a screen grid, and a plate. In addition, it has a pair of beam-forming or electron-focusing electrodes.

The beam-forming electrodes are connected to the cathode, so they are negative with respect to the plate and screen grid. They repel electrons, forcing the electrons to "bunch together" and to pass through the openings between these electrodes to reach the plate. Thus, the electrons are forced to form two streams or "beams." Any secondary emission electrons that try to move back from the plate toward the screen grid are met by this compact mass of electrons, and since this is a cloud of negative particles, the secondary emission electrons are forced back to the plate. Hence, this high electron density or space charge corresponds to a low potential which acts on the secondary electrons in the same manner as a suppressor grid. The action is more complete than that of a suppressor grid, since the suppressing field is continuous instead of broken up by the spaces between the suppressor grid wires.

In order to keep the current drawn by the screen to a minimum, the screen and control grid are made up of spiral wires arranged in such a manner that the control-grid wires shield the screen wires from the cathode. This causes the electrons to travel in sheets between the screen wires so that very few of them land on the screen.

The difference between the beam power tube characteristic and that of the conventional pentode is shown by Fig. 21. In the beam power tube the plate current rises rapidly with plate voltage and then flattens off sharply. As with the pentode, there is no conspicuous secondary emission dip.



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

FIG. 20. Sketch showing the arrangement of electrodes in the type 6L6 beam power amplifier tube.

A large and efficient cathode is used, and precautions are taken to keep the grids and the plate as cool as possible during operation. These features combine to produce a highly efficient tube which is capable of handling large

TABLE 1

	Pair of 6F6's as triodes	Pair of 6F6's as pentodes	Pair of 6L6's	
D.C. Plate supply voltage	350	375	360	volts
Peak a.f. grid-to-grid voltage	123	82	72	volts
D.C. Plate current (max. signal)	92	82	205	ma.
A.C. Power Output (max. signal)	13	18.5	47	watts
Power sensitivity	0.11	0.23	0.65	watts/volt
Plate Efficiency	40	60	64	per cent

amounts of power in comparison with its size and which has the best power sensitivity of any receiving tube.

► The performance of a beam power amplifier may be compared with that of pentode and triode amplifiers by consulting the tube manufacturer's handbook. Considering the use of two tubes connected in push-pull class AB_2, Table 1 compares the 6L6 beam power tubes with the 6F6 tubes connected as pentodes, and also with the 6F6 tubes connected as triodes.

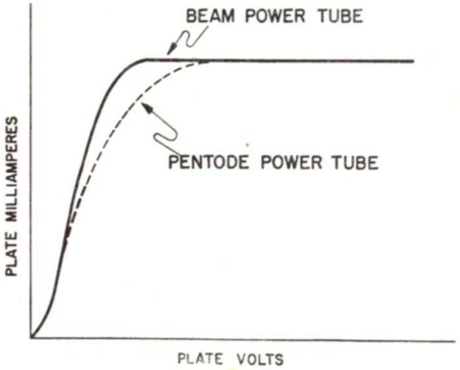


FIG. 21. This graph shows the difference between the plate characteristics of beam and pentode power amplifier tubes. Notice that in a beam power tube the plate current becomes independent of plate voltage at lower values of plate voltage than in a pentode tube.

It is seen that the beam power (6L6) tubes deliver almost three times the power output of the 6F6 pentodes. This is accomplished with a power drain from the B supply of approximately 2.4 times that drawn by the pentodes, hence the beam power tubes operate somewhat more efficiently. The plate efficiency is calculated from the ratio of the a.c. power output to the d.c. power supplied to the plate circuit. Hence, we find it by dividing the a.c. power output by the product of the d.c. plate supply voltage and the d.c. plate current. For the 6L6 amplifier this is 47 ÷ (360 × .205), or 64 per cent. Although the d.c. plate current is greater, the beam power amplifier has a power sensitivity of 2.8 times that of the 6F6 pentode amplifier. The power sensitivity is found by dividing the a.c. power output (47 watts for the pair of 6L6's) by the peak a.f. grid-to-grid voltage (72 volts for the pair of 6L6's).

Lesson Questions

Be sure to number your Answer Sheet 16RC.

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. Will an increase in the ohmic value of the load resistance for a triode tube make the dynamic E_g-I_p curve more nearly linear? yes

2. With a triode tube, is the maximum undistorted power output obtained when the plate load *is equal to; is one half of; or is* [✓ *twice*] the plate resistance?

3. Draw a simple diagram of a triode vacuum tube audio-frequency amplifier inductively coupled to a loudspeaker.

4. Is the output voltage of a cathode follower *more than, equal to,* or [✓ *less*] *than* the input voltage?

5. What is the main advantage of operating two tubes in push-pull rather than in parallel for an audio-frequency amplifier? cancel own even harmonics

6. During what portion of the excitation voltage cycle does plate current flow when a tube is used as a class B amplifier? positive

7. Why are amplifiers operated in class C not suited as audio amplifiers? distorti

8. Why is an output transformer with a center-tapped primary required in class A push-pull operation? flux cancels even harmonics

9. Are self-generated even harmonics eliminated in push-pull class B amplifiers? NO

10. Why does a class B audio-frequency amplifier require driving power? because it draws Grit current

FEAR LEADS TO FAILURE!

No matter how hard a person may work for success, there is nothing that can help him if he is always doubting his own ability—if he is always thinking about failure.

To be ambitious for wealth yet always expecting to be poor is like trying to get past a vicious dog when afraid of the dog, and uncertain of your ability to make friends with him—in each case, fear of failure is almost certain to result in failure. Success, on the other hand, is won most often *by those who believe in winning.*

Never doubt for a moment that you are going to succeed. Look forward to that success with just as much assurance as you look forward to the dawn of another day, *then work—with all that's in you—for success.*

J. E. SMITH