

**LOW-FREQUENCY VOLTAGE AMPLIFIERS
FOR
SOUND AND TELEVISION**

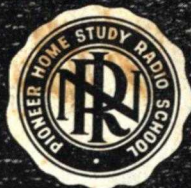
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STUDY SCHEDULE NO. 15

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. Audio and Video Amplifier Requirements Pages 1-4

The types of amplifiers, and the frequency ranges necessary for various types of radio services are discussed. This section also tells where voltage and power amplifiers are needed.

2. Basic Amplifier Operation Pages 4-9

Static and dynamic characteristics of amplifier tubes, and how the value of the load resistance affects amplifier operation are covered in this section. Answer Lesson Questions 1 and 2.

3. Distortion Pages 9-16

Here you learn how amplitude, frequency, and phase distortion are produced, and how they affect the signal that is being amplified. Answer Lesson Questions 3, 4, and 5.

4. Combination L, R, and C Loads Pages 16-20

This section tells how resistors, condensers, and coils, in different combinations, affect the amplification characteristics of a voltage amplifier. Answer Lesson Question 6.

5. Cascaded Voltage Amplifiers Pages 20-32

The RC-coupled, impedance-coupled, direct-coupled, and transformer-coupled amplifiers are studied. Answer Lesson Questions 7 and 8.

6. Practical Consideration in Amplifiers Pages 32-36

Here you learn how hum and "motorboating" are produced, and why a common ground should be used for each stage of a multistage amplifier. Answer Lesson Questions 9 and 10.

7. Answer Lesson Questions.

8. Start Studying the Next Lesson.

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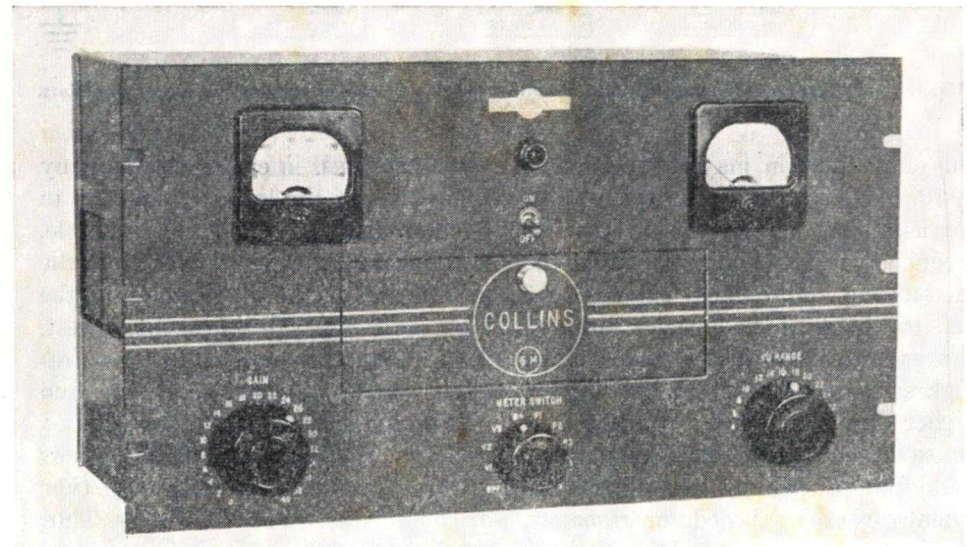
Audio and Video Amplifier Requirements

BROADCAST stations use amplifiers to raise the weak signal output of the microphone to a signal strong enough to modulate the transmitter. Likewise, the output of the r.f. oscillator, which determines the carrier frequency of the station, has a very low level, so that it, too, must be amplified before it is strong enough to radiate the desired power.

In a receiver, the signal picked up by the antenna is weak, and must be am-

plified before it is demodulated (detected). After detection, the resultant weak audio signal must again be amplified before it can drive the loudspeaker at the desired volume level.

In television, the output of the television pickup tube must be amplified before it can be used to modulate the r.f. section of the transmitter. The video signal in the receiver is amplified so that it will produce a satisfactory image on the picture tube.



Courtesy Collins Radio Co.

The Collins 6M is an example of the program amplifiers used in all broadcast stations. This unit is usually mounted permanently at the main studios or at the transmitter to amplify the program signal. The switch in the center of the panel at the bottom is used with the meter on the left to measure the voltages of the various stages and power supply of this amplifier. It is thus very useful for locating troubles. The meter on the right is a VU meter and the switch beneath it is used to change the VU range of the meter as desired. The control on the left is used to vary the gain of the amplifier in 2-db steps.

TYPES OF AMPLIFIERS

There are two general types of vacuum-tube amplifiers. One type amplifies a *narrow band* of frequencies, each frequency in this range being raised the same amount, the other type amplifies a *wide band* of frequencies.

An example of the narrow-band amplifier is the radio-frequency amplifier in a standard broadcast transmitter. Although the carrier frequency may be any value in the broadcast band from 540 kilocycles to 1600 kilocycles, the radio frequency components, as a re-

r.f. amplifier. We will not consider the tuned r.f. amplifier in this Lesson for we will study it in detail in another Lesson, and there we will see the influence of these circuits on the over-all audio or video signal.

An audio amplifier passing signals from 20 cycles per second to 16,000 cycles per second, or a video amplifier passing all frequencies from 10 cycles per second to 4.5 megacycles per second, are examples of wide-band amplifiers. Notice that the highest frequency

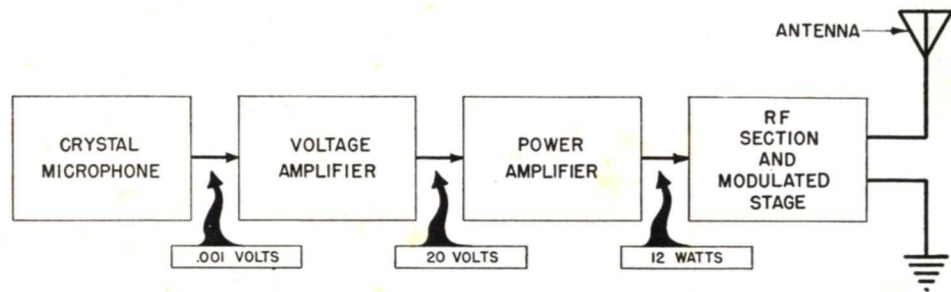


FIG. 1. Block diagram of communication transmitter showing the use of voltage and power amplifiers.

sult of modulation, may include signals 5, 10, or 15 kc. above and below this carrier. Thus, if the assigned carrier frequency is 1000 kilocycles, and the modulating audio signal extends to 5 kc., the band of frequencies radiated ranges from 995 to 1005 kilocycles. The highest frequency then, is but slightly higher than the lowest frequency. Because these frequencies are in a narrow band, it is quite simple to amplify these signals by using tuned, or resonant, circuits in the amplifier. In a receiver, such circuits are needed to exclude all but the desired carrier and its modulation. A resonant circuit, adjusted for r.f. application and used with a control-grid vacuum tube, is called a tuned

to be amplified in either case is many times that of the lowest frequency to be amplified. In the audio example, the highest frequency is 800 times the lowest, and in the video example, the highest is 450,000 times the lowest. These amplifiers are called low-frequency or broad-band amplifiers, and will be the subject of this Lesson.

► As we will notice shortly, amplifiers are also classified according to the type of coupling used between stages. Thus we have resistance-capacitance coupled amplifiers (called R-C amplifiers), transformer-coupled amplifiers, and direct-coupled amplifiers. The advantages and uses of each of these are discussed in detail later in this Lesson.

► We emphasize the application of low-frequency amplifiers in communication transmitters and receivers, even though the same amplifiers are used in public address systems, electronic phonographs, intercommunication systems, long-distance telephone lines, electronic musical instruments, photoelectric equipment, and industrial controls.

We will see how these amplifiers are designed to pass the desired range of frequencies, provide the desired gain, produce the required power output at the desired efficiencies, and at the same time keep the amount of distortion to an acceptable minimum.

FREQUENCY RANGES FOR VARIOUS SERVICES

High-fidelity amplifiers in f.m. transmitters and receivers must pass, with equal amplification, all frequencies between 20 and 16,000 cycles per second. Even though the average receiver responds only to audio frequencies between 80 and 4500 cycles per second, a typical broadcast transmitter has a frequency response of 30 to 10,000 cycles per second for the a.m. receivers of higher fidelity.

Amplifiers for radio-telephone work operate in a frequency range of 200 to 2500 cycles per second, because satisfactory intelligences can be transmitted with this limited range.

In contrast, the video amplifier in a high-definition television system must handle frequencies from 10 cycles per second to 4.5 megacycles per second to reproduce all the details of the television image. Such a wide pass band introduces special problems.

Fortunately, it is not always neces-

sary for the amplifier to pass a wide range of frequencies. We have already indicated that in some types of communications work, the intelligibility of the signal received is of primary concern, so that the frequency range is deliberately limited to discriminate against undesirable signals and noise. Other special commercial applications such as electronic phonographs, and intercommunication systems, do not require the wide range of frequencies that are needed in high-fidelity broadcasting and in television.

As a review, the frequency ranges that are usually used in low-frequency amplifiers for various services are listed as follows (values in c.p.s.):

Voice—200 to 2500.

Standard a.m. receiver—80 to 4500.

Standard a.m. transmitter—30 to 10,000.

High-Fidelity sound—10 to 16,000.

Television—10 to 4,500,000.

High-quality phonograph—80 to 6500.

Electronic control—0 (d.c.) to 100,000.

VOLTAGE AND POWER AMPLIFIERS

Signal power is needed to drive the loudspeaker in a receiver, or to modulate the carrier in a transmitter. Power, which is the product of voltage and current, must be supplied by the power amplifier tube or stage. Generally, the output level of a microphone or a detector is not enough to operate the output or power stage, therefore, we need voltage amplifiers to raise the voltage of the source to a level that drives the power stage.

An example involving voltage and

power amplifiers is given in Fig. 1. It takes 12 watts to modulate this transmitter, and the audio power amplifier delivers this power when excited with a 20-volt signal. However, the output of the crystal microphone is only .001 volt. Hence, voltage amplification is needed between the microphone and the power amplifier.

The amount of voltage amplification needed is 20,000, and is obtained by dividing the output voltage (20) by the input voltage (.001). This is a gain of 86 db. A single-voltage amplifier does not provide all this gain. Several stages of amplification are needed, each stage feeding into the next in what is called a cascade arrangement.

Basic Amplifier Operation

The most frequently used amplifier circuit is the class A R-C amplifier shown in Fig. 2. It is the purpose of low-frequency voltage amplifiers, first, to amplify the signal applied to them with as much gain as possible, and second, to reproduce the input signal as accurately as possible. In the amplifier shown in Fig. 2, an a.c. voltage, applied across the grid-cathode terminals of a tube, produces an a.c. current in the plate circuit. This a.c. current, flowing through the load resistance, causes the output a.c. voltage to be produced across it. Thus we see that both the gain and the fidelity of an amplifier depends on how the grid voltage controls the plate current of the tube. Let us consider how the grid voltage-plate current curve of a tube is obtained and used.

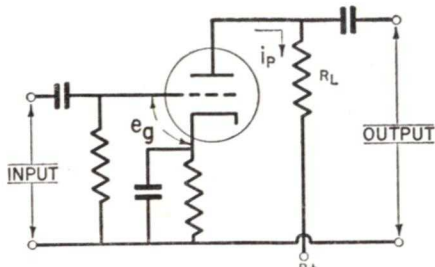


FIG. 2. The basic R-C amplifier.

STATIC CHARACTERISTICS

The "static" characteristic curve is the type of characteristic curve that is given by the tube manufacturer. Such static curves show how the tube operates when there is *no plate load*. Although we are chiefly concerned about

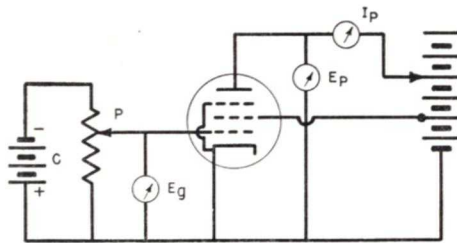


FIG. 3. The circuit for determining the static E_g-I_p curve of a tube.

the "dynamic" characteristic, that is, how the tube operates *with a load*, let us first study how static curves are obtained, for we can use them to obtain the dynamic characteristics.

To obtain these static curves, the circuit shown in Fig. 3 is used. Note that there is no load in the plate circuit. The grid voltage is set at a certain value by means of the potentiometer P, then the plate voltage is varied, and

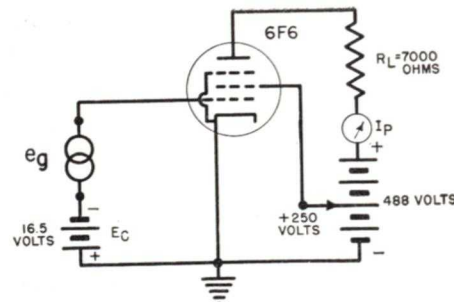


FIG. 4. An example of a low-frequency amplifier.

the plate current for each value of plate voltage is measured. The amount of plate current that flows for each value of plate voltage is plotted on a graph to form a curve for that grid bias. The grid bias is then changed, and a second E_p-I_p curve is obtained. This is continued until we have curves for several values of E_g . We call this series of curves a set, or family, of characteristics—in this case, a family of E_p-I_p curves. (Fig. 6 shows the E_p-I_p curves for a 6F6 tube.)

DYNAMIC CHARACTERISTICS

The dynamic characteristics of a tube can be obtained by measuring the response of the actual circuit, or from the static curves. For example, let us consider the amplifier circuit shown in Fig. 4. If we vary the bias voltage with no input signal, and record the resultant values of plate current, the results when plotted would be like those shown in Fig. 5, which is a dynamic E_g-I_p curve for a 6F6 tube with a 7000-ohm load. This curve gives us an exact picture of how this amplifier tube operates with this particular value of load.

In this Lesson we will study in detail the operation of class A amplifiers. One essential requirement for this class of operation is that the grid signal voltage must swing an equal and maximum amount in either direction without going beyond points s and t (the linear region), thus the no-signal position is

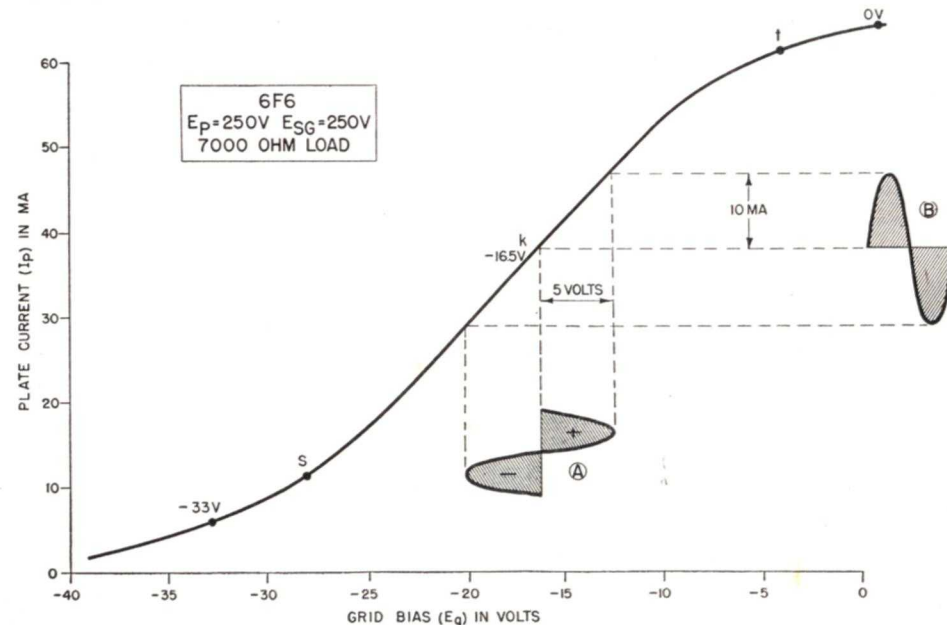


FIG. 5. The dynamic E_g-I_p curve for the amplifier of Fig. 3.

set by the grid bias voltage to the middle of the linear portion of the dynamic E_g-I_p curve. In Fig. 5, a grid bias voltage of -16.5 volts is the middle of the linear portion of the curve. The d.c. plate current at this point is 34 ma., and it will flow through the tube and the load when no signal is applied to the grid. This is the "operating point" k on the curve.

If the signal that this stage is to amplify causes the grid voltage to change by plus and minus 5 volts, as shown by curve A in Fig. 5, the plate current will change, as shown by curve B. The I_p scale shows that for this particular tube a 5-volt grid-voltage change causes a plate current change of plus or minus 10 milliamperes. Since the load resistance in the plate circuit is 7000 ohms, the load voltage will vary by plus or minus 70 volts (we arrive at this by multiplying 7000 ohms by .010 ampere). Since the output voltage (70) divided by the input voltage (5) is 14, the input signal is amplified 14 times.

Note that point s corresponds to a grid-voltage value of -28 volts, and point t is at -5 volts. The difference between these two voltages is 23 volts. If an operating point of -16.5 volts is chosen, a swing of 11.5 volts in either direction will still keep the amplifier operating between these points in the nearly linear region. To be sure, there will be some distortion, because the curve is not absolutely straight, but this may, in most instances, be tolerated. However, the more the grid voltage exceeds the limits s and t, the greater will be the distortion.

► Incidentally, remember that in a class A amplifier the grid never goes

positive, thus no power is taken from the signal source.

Graphical Method of Securing a Dynamic E_g-I_p Curve. By using a set of plate-current versus plate-voltage (E_p-I_p) curves for various grid bias values, we can obtain graphically the dynamic E_g-I_p curve of an amplifier. This is done by drawing a "load line" across the E_p-I_p curves as shown in Fig. 6.

This family of E_p-I_p curves can tell us any of the conditions that exist in the circuit. If we select several conditions for a definite load, we will have points of operation. By drawing a line through these points for a definite load, we obtain the needed load line. With a resistor load, the load line will be straight, so that we need only two points to draw this line. Let us select two obvious points.

First, if the tube were biased beyond cut-off, there would be no current flow through the tube or the load resistor, thus no voltage drop exists across the load resistor. The plate voltage of the tube E_p would then be the same as the supply voltage E_b . This is point p in Fig. 6; I_p is zero, and E_p is 488. Notice that this point does not depend on the size of the load resistor used, but only on the supply voltage.

To determine the second point of the load line, we need to take into consideration the effect of the load resistance on the circuit. To do this, let us assume that the grid could be driven so far positive that the plate resistance is zero. The current now flowing in the circuit is limited only by the load. With a supply voltage of 488 volts, and a 7000-ohm load, the current flow is 488 volts divided by 7000 ohms, or nearly

70 ma. This is point n on the curve; E_p is zero, I_p is 70 ma. Now if we draw a straight line between point n and point p, we have the load line. The intersection of this line with the grid bias lines of the E_p-I_p curves tells us what the plate voltage and plate current are in our circuit for the different values of grid voltage given.

Notice that the -16.5 volt grid bias line is also given. The intersection of this line with the load line is the operating point k, where E_p is 250 volts and I_p is 34 ma.

► Let us use the load line that we have drawn to find the plate current and voltage for other values of grid bias. What is the plate voltage and the plate current when the bias on the tube is -25 volts? To answer this, look at the chart and find the -25 volt grid-bias line. Notice at what point it

crosses the load line that we have just drawn. Now if you look straight down from this point, you will find that the plate voltage is 360 volts. By following directly to the left from this point, you read that the plate current is 18 ma.

Let us make a few simple calculations to check the value of the plate voltage that we have just obtained. The current through the tube and the load resistor is 18 ma. Thus, the voltage drop across the load resistance is 126 volts (.018 ampere multiplied by 7000 ohms). The plate voltage must then be 126 volts less than the supply voltage, that is, $488 - 126$, or 362 volts. This checks very closely with the 360 volts we read directly from the chart in Fig. 6. Thus we see that the load line is correct for any point between the two end points that we used to deter-

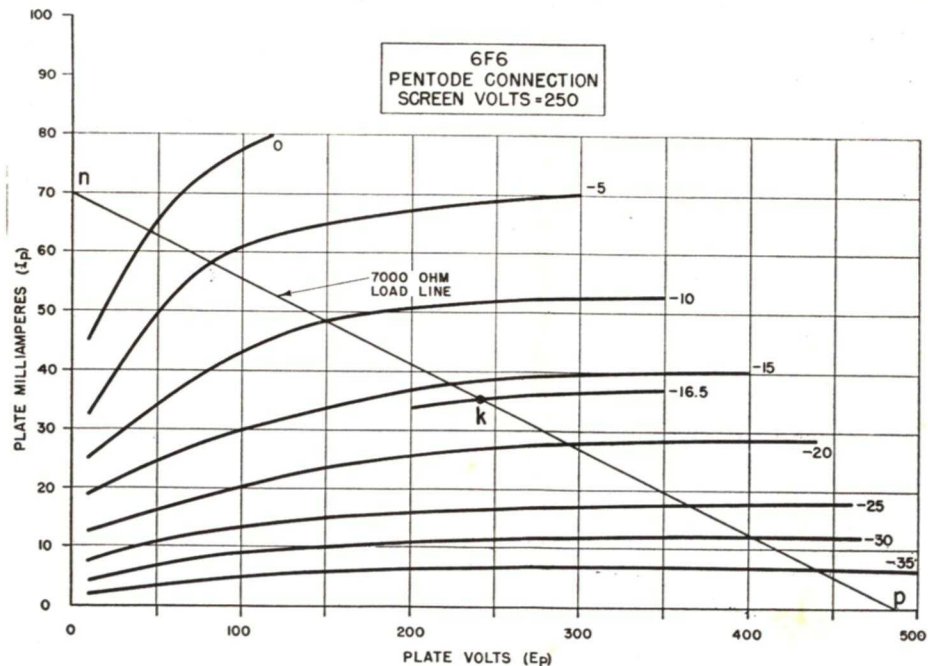


FIG. 6. How a load line can be drawn on a set of E_p-I_p curves to obtain graphically the dynamic E_g-I_p curve of an amplifier stage.

mine its position on the E_p - I_p curve.

We can now get the other points of the dynamic E_g - I_p curve for a 7000-ohm load in a similar manner. The values of e_g and i_p are given below, but for practice, check them by reading the

Tube 6F6	
$E_b = 488$ volts	
Load 7000 ohms	
E_g	I_p
0	63
-5	58
-10	48
-15	38
-20	28
-25	18
-30	12
-35	6

values of E_g and I_p on the load line of Fig. 6.

The E_g and I_p values given in this chart are the ones that were used to draw the dynamic load line of Fig. 5.

LOAD RESISTANCE AFFECTS AMPLIFIER OPERATION

Let us see what happens to the dynamic E_g - I_p line of a triode tube when we change the value of the load resistance. Curves for several values of load resistance for a 6J5 tube are given in Fig. 7. Let us assume an operating point of $E_p = 250$ volts, and $I_p = 9$ ma. Notice that as the load resistance is increased, the dynamic E_g - I_p curve of a triode tube becomes more nearly a straight line. This is desirable, as it means that we have less amplitude distortion in the output of our amplifier for a given a.c. input voltage. Remember, however, that the source voltage must furnish the plate voltage and the d.c. voltage drop across the load resistance. Thus if a 10,000-ohm load is used, the drop in it will be 90 volts

(10,000 ohms \times .009 ampere), so that the supply voltage must be 250 volts + 90 volts, that is, 340 volts. If the load resistance is higher, the voltage drop across it will increase, and the supply voltage must be increased to maintain the same operating point. For high values of load resistance, the supply voltage needed will be quite high. If we cannot obtain the necessary supply voltage, we must be satisfied with operation at a lower plate voltage. Which of these two methods is used depends on the gain and fidelity desired, and the signal levels handled. We will see later how we can overcome the need for high-supply voltage by using an inductance (a transformer, or a choke) in the plate circuit—the low resistance of an inductance causes little supply-voltage loss.

The dynamic load line for a *tetrode* or a *pentode* tube does not necessarily become more linear as the value of the

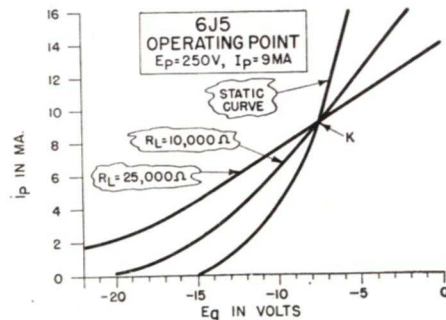


FIG. 7. How the dynamic operating curve of a triode tube becomes more nearly linear as the value of the plate load (R_L) increases.

load resistance increases. Actually there is no definite load value where a perfectly linear E_g - I_p characteristic is realized. It is necessary, therefore, for the tube user to draw several E_g - I_p curves from a family of E_p - I_p curves,

and then to choose one that most nearly fulfills all the requirements of the circuit.

As we will shortly see, one load value may give maximum voltage output, an-

other maximum power output, and another maximum undistorted power output. There is no simple formula for determining the value of the load for each of these conditions.

Distortion

The audio or video signal input to an amplifier is generally a complex wave; that is, it consists of many sine-wave components that differ from each other in frequency, in amplitude, and in phase. An amplifier should raise the voltage, or power level, of each of the component frequencies by the same amount without changing the phase relationship between the components, and without producing any frequency components in the output that were not present in the input. In other words, there should be no frequency distortion, no phase distortion, and no amplitude distortion. In practice, there is always some distortion, but this can be kept within acceptable limits.

FREQUENCY DISTORTION

The type of distortion that occurs when a radio circuit or device amplifies or transmits the different frequencies in its operating range *unequally* is

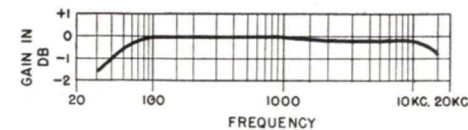


FIG. 8. Typical frequency response curve of a standard broadcast transmitter.

known as *frequency distortion*. For example, if a certain audio amplifier is to handle all frequencies equally well in

the range from 100 to 5000 cycles, the voltage gain (or power gain) of the amplifier must be the same for each of the frequencies in this range. If the gain is 10,000 for a 1000-cycle signal, it should be 10,000 for a 100-cycle or a 5000-cycle signal. The more nearly constant the gain of the amplifier at the various frequencies, the better is its fidelity (faithfulness of reproduction).

The manner in which a radio circuit or device amplifies, relays, or transmits the different signal frequencies in its operating range is called the *frequency response characteristic*. It is common practice to use a *frequency response curve*, like that shown in Fig. 8, to show how each frequency is amplified by a particular amplifier. The gain is usually expressed in decibels, since the ear and the eye, to some extent, respond according to this method of change representation. Notice also that the frequency in this, and in most frequency response curves, is plotted in a "logarithmic" manner, that is, the distance between the 100 c.p.s. and 1000 c.p.s. marks is the same as between the 1000 c.p.s. and 10,000 c.p.s. marks. This is done to allow us to see the low-frequency response clearly, and to show the response for a wide range of frequencies. The curve in Fig. 8 shows that the audio gain of a typical

broadcast transmitter is practically constant for all frequencies between 100 and 10,000 cycles, but drops slightly for frequencies above and below this range.

► Frequency distortion makes the voice or music signal sound unnatural. When the high-frequency response of an amplifier is low, and the bass response is boosted by the circuit design, or by a manual "tone control," voice and music may be "boomy," or sound as though they were coming from a bar-

rel. On the other hand, if the low-frequency response is poor so that only the high frequencies are reproduced, the output will sound "tinny."

AMPLITUDE DISTORTION

When a radio circuit or device does not produce current or voltage changes in the output that are exactly proportional at each instant of time to the changes in the voltage or current of the incoming signal, we have what is known as *amplitude distortion*.

Amplitude distortion results in the production of harmonics that are not present in the original signal; these undesired harmonics are the result of distortion in the wave form of the signal. In a vacuum tube circuit, amplitude distortion is caused by the operation of the tube on the non-linear portion of the E_g-I_p curve. Hysteresis and eddy currents in certain radio parts, such as transformers, can also cause amplitude distortion.

A video, or a good quality audio-frequency amplifier must amplify signals without changing their wave forms; this means that there must be no amplitude distortion.

The non-linearity of the dynamic E_g-I_p curves that causes amplitude distortion in amplifiers is of prime importance to the radio technician, because defects that change the operating voltages of a tube will cause the tube to operate on the non-linear portion, that is, the "bends" of the E_g-I_p curve.

We can see how this is brought about by considering the practical circuit in Fig. 9A, and its dynamic E_g-I_p characteristic shown in Fig. 9B. Three equal grid signal voltages e_1 , e_2 , and e_3 are shown. The grid-to-cathode bias for

this amplifier is obtained from the d.c. voltage drop across R_c . The condenser C_c by-passes the a.c. in the cathode circuit.

Let us see how a change of this bias voltage (from E_1 to E_2 or E_3) can cause distortion of the audio signal.

When the C bias is set to operate at the center of the E_g-I_p curve, the plate-current wave form i_1 is a true reproduction of the wave form of the input voltage e_1 ; that is, when the input is a sine wave, the output will also be a sine wave. Equal increases or decreases in input signal voltage produce equal increases or decreases in plate current. In passing through the load resistance, these plate current variations produce an output voltage having the same wave form as the current, and hence the same wave form as the input voltage.

Operation on the Lower Bend.

If the bias is made more negative, that is, changed from E_1 to E_2 , and the input signal is maintained the same $e_1 = e_2$, the plate current wave form i_2 flattens on the negative half of the cycle. The positive half of the cycle for the plate current is normal. This type of amplitude distortion occurs when the ohmic value of the cathode resistor R_c increases, or when this resistor "opens" and the by-pass condenser C_c becomes leaky, so that the IR drop across R_c and C_c approaches the cut-off bias of the tube. This amplifier is biased on the lower bend of the characteristic curve. The output voltage across the load resistor has the same wave form as the plate current i_2 through it,* and, therefore, it appears flattened on one half of the cycle.

Analyzing the wave form of this dis-

torted output signal, we find that even harmonics, such as the second, fourth, sixth, etc., have been added to the fundamental, as shown in Fig. 10.

Notice that there is also a d.c. component added, which causes the average plate current to *increase* when this distortion is present.

We now see that when a sine wave is applied to the input of an amplifier that has this form of amplitude distortion, there are even harmonics in the output signal that are not present in the input signal.

Operation on the Upper Bend.

If we make the C bias less negative, it shifts the operating point to E_3 , and flattens the positive half cycle as illustrated by i_3 in Fig. 9B. This distortion is produced if the cathode by-pass condenser C_c becomes leaky or short-circuited so that the bias voltage approaches zero. This causes the amplifier to operate in the upper bend of the characteristic curve.

The output wave is similar to the one produced before, except that it is upside down. It has the same components as those shown in Fig. 10, but they are shifted 180° in phase, and the plate current now *decreases* when a signal is applied.

► Therefore, if the d.c. plate current changes when a signal is applied to a class A stage, we know that amplitude distortion is occurring. If the d.c. plate current rises, we know that the tube is operating on the lower bend of its characteristic curve. (This operation is

*When the plate circuit contains an inductance or capacitance, the wave form of the output voltage may not be the same as that of the plate current. In this case the distortion may be even worse.

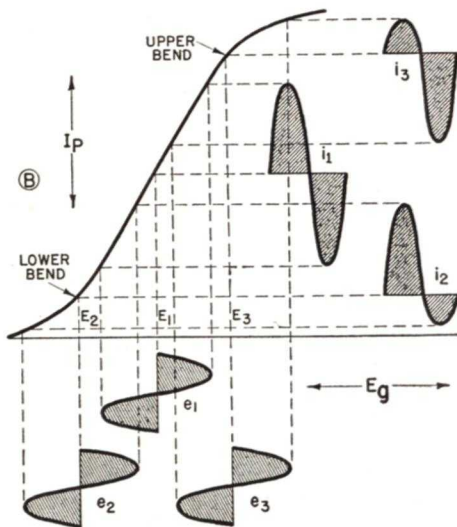
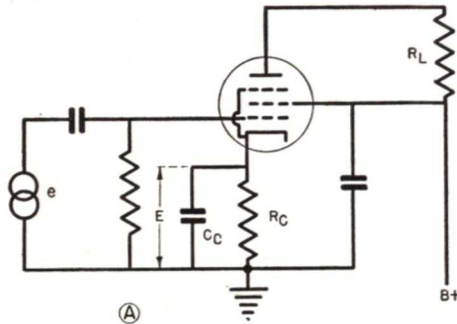


FIG. 9. A, a typical R-C amplifier, and B, its E_g-I_p curve showing how amplitude distortion is produced by operation on the bends of the curve.

caused by excessive bias, or by low plate voltage.) If the d.c. plate current falls, we know that the tube is operating on the upper bend of its characteristic. (This operation is caused by too little bias, or by a high plate voltage.)

From a practical test viewpoint, measuring the C bias before and after the signal is applied will be equally effective, for when the plate current changes, the bias changes in a like manner.

Operation over Both Bends. Another form of amplitude distortion occurs when the C bias is set at the proper value E_1 , and the input signal e_1 is so large that the tube is operating at both bends in the E_g-I_p characteristic. This flattens both the positive and the negative half-cycle peaks. Such distortion can occur even in properly biased amplifiers when sudden peaks of volume are imposed on it. At a transmitter, these sudden peaks can be avoided by automatic volume-limiting stages.

In the distortion that is caused by bends at both ends of the E_g-I_p characteristic, as shown in Fig. 11, odd harmonics are added instead of even harmonics. Here, the shape of the output wave indicates that the third, fifth, seventh, and other odd harmonics, are being added to the fundamental. This distortion is very noticeable to the ear, but it does not cause a change in the d.c. plate current or bias if both halves of the output wave are exactly alike. The radio technician must use a cathode-ray oscilloscope to "see" the wave form before he can find the stage producing this difficulty, unless there are additional clues.

► Amplitude distortion is readily de-

tected by the ear. The ear is more critical of odd-harmonic distortion

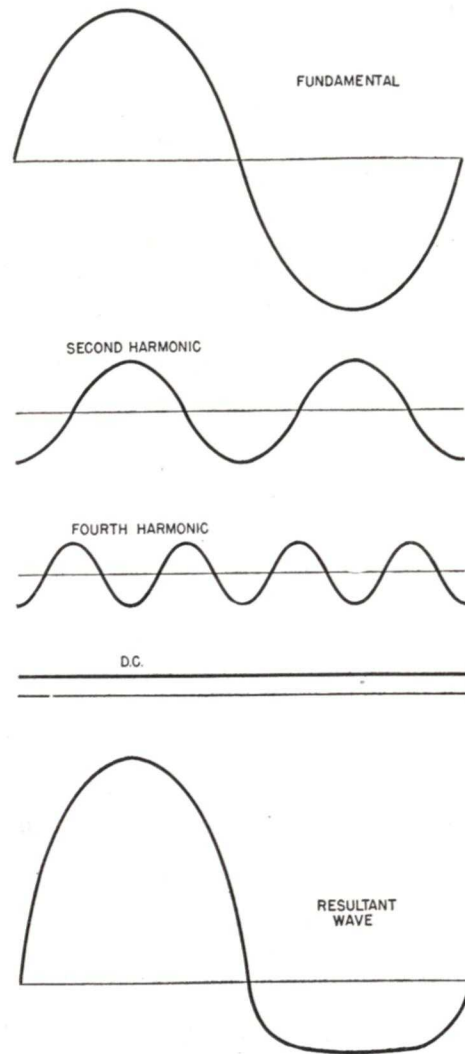


FIG. 10. An analysis of the wave i_2 of Fig. 9B. Notice that even harmonics are added, plus a d.c. component. Although we have shown only the second and fourth harmonics, there are actually small amounts of other even harmonics added. A phase shift is also involved, in that the harmonics are added 90° out of phase with the fundamental. This phase shift cannot be heard, but the added harmonics are noticeable. (In television, the phase shift is of importance also.) These harmonics of the fundamental cause a person listening to a signal with this waveform to recognize it as being distorted.

than it is of even-harmonic distortion. An odd-harmonic distortion is noticeable at about 5% or more, but an even-harmonic distortion of as much as 10% is relatively unnoticeable. However, distortions of 5% to 10% are noticeable only over long periods of time, by ear fatigue. Only high distortion, of 25% or more, is noticeable at once.

► In summary, amplitude distortion can be caused by operation on the non-linear portion of the dynamic curve because of (1) an improper amount of grid bias, (2) an improper amount of plate-supply voltage, (3) an improper value of load impedance, (4) an excessive grid input signal (even when the operating voltages and load value are correct).

INTERMODULATION

Harmonics of the original frequency are produced when a single sine wave is applied to an amplifier having amplitude distortion. However, most sound and video signals have a complex wave form, and when such a signal is applied to an amplifier having amplitude distortion, we find that not only harmonics of the component sine waves, but also beat-note frequencies are produced. This is called *intermodulation distortion*.

For example, let us suppose that we feed a complex wave, consisting of a 60-cycle sine wave and a 1000-cycle sine wave, into an amplifier having amplitude distortion. Harmonics of the 60 c.p.s. signal are then produced; that is, 120, 180, 240 c.p.s., etc. Also, harmonics of the 1000 c.p.s. signal are produced; that is, 2000, 3000, 4000 c.p.s., etc. In addition to this, these various frequencies beat together to

produce *sum* and *difference* frequencies. For instance, the 60 c.p.s. signal beats with the 1000 c.p.s. signal to produce frequencies of 940 and 1060 c.p.s. The 60 c.p.s. signal also beats with each of the harmonics of the 1000 c.p.s. signal, and the 1000 c.p.s. signal beats with each of the harmonics of the 60 c.p.s. signal. Furthermore, the various beat frequencies beat with one another to produce more frequencies. A tremendous number of new frequencies can be produced in this way. (Fortunately, most of them are of such small magnitude that they can be ignored.)

Because these beat notes, produced by intermodulation distortion, are not harmonics of the signals producing

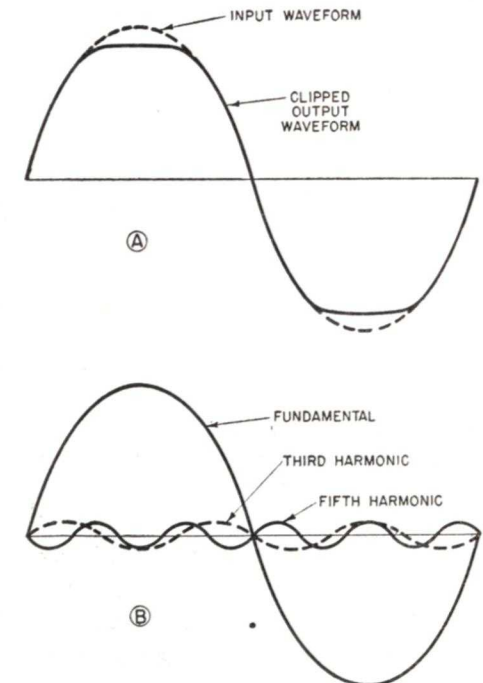


FIG. 11. The distorted wave form shown by the heavy line in A is produced by operating an amplifier over both bends of the E_g-I_p curve. Its components are given in B. Notice that ODD harmonics are produced, and that there is no d.c. component.

them, they are discordant. Experiments show that listeners are more likely to be annoyed by intermodulation distortion than by harmonic distortion. Therefore, the amount of intermodulation distortion present in an amplifier determines the quality of the amplifier. However, in practice, the worth of an amplifier can be judged by measuring either the harmonic or the intermodulation distortion, since they are closely related.

PHASE DISTORTION

Phase distortion is present in an amplifier when the phase relationship of the various components of the output is different from the phase rela-

components add up to give the wave form of the input signal. If, in the amplifier, both components are shifted in phase by such an amount that they come out in the same phase relationship, with respect to each other, as that with which they entered (assuming that there is no frequency or amplitude distortion), the wave form of the output signal will be exactly the same as that of the input signal. That is, there is no phase distortion of the wave form by the amplifier.

Suppose, however, that the higher frequency component is shifted in phase more than the other component, as indicated by the output shown in

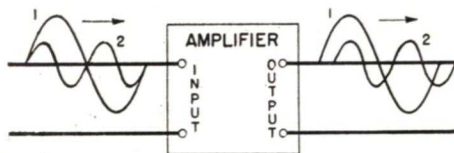


FIG. 12. The phase relationship of the components of a complex wave form can be altered by a low-frequency amplifier. This causes "phase distortion."

tionship of the components of the input.

Phase shift occurs, to some degree, in all amplifiers. The load circuit of an amplifier tube, as we shall shortly see, contains capacitance or inductance, as well as resistance. As the frequency of the signal changes, the impedance of the plate circuit also changes. The amount of phase shift, and, therefore, phase distortion, changes as the frequency of the input signal changes.

Let us see how phase distortion can change the wave form of a signal. In Fig. 12, the input signal consists of two components—numbered 1 and 2, the second having twice the frequency of the first. Fig. 13A shows how these

Fig. 12. The resultant wave form of the two components, as shown in Fig. 13B, differs distinctly from that of the input signal (Fig. 13A). In this case, the amplifier has phase distorted the signal.

A sound amplifier can have some phase distortion, because the ear is not able to distinguish between the relative phase differences of the various components of a sound signal, unless the phase delay is unusually long. This means that although phase distortion is present, the music or intelligence coming out of the amplifier sounds the same as that which entered it.

On the other hand, an amplifier with

phase distortion is entirely unsuited for television, since in television the picture that appears on the cathode-ray screen depends on the wave form of the signal applied to the cathode-ray tube. Distortion in the wave form appears as a distortion of the image on the screen, or as improper shading or synchronization of the various parts of the picture.

There is no phase distortion in an amplifier if the components take an equal amount of time to go through the amplifier, for the components of the output signal have the same phase, with respect to each other, as the components of the input signal.

How the Phase Shift and Time Delay Are Related. Let us see how the phase shift and time delay in an amplifier depend on the frequency of the signal to be amplified.

Let us assume that we have a sine wave with a frequency of 100 cycles per second, as shown in Fig. 14A. Now let us suppose that this signal is shifted

90° ($\frac{1}{4}$ cycle), as shown by the dotted line. Since the time for one cycle is $\frac{1}{100}$ of a second, the delay time caused by a phase shift of $\frac{1}{4}$ cycle, is $\frac{1}{400}$ of a second. Now let us consider the 200 c.p.s. signal of 14B. The time for one cycle is $\frac{1}{200}$ of a second, so that the time delay for a phase shift of $\frac{1}{4}$ cycle would be $\frac{1}{800}$ of a second. Thus, we see that the time delay for a phase shift of 90° at 200 c.p.s. is one-half as long as the time delay caused by the same amount of phase delay at 100 c.p.s. Therefore, as the frequency increases, the amount of phase angle shift must increase to provide the same amount of time delay; that is, *the phase shift must vary linearly with frequency if there is not to be any phase distortion.* If an amplifier has a phase shift of 6° at 500 c.p.s., then it must have a 60° phase shift at 5000 c.p.s., and a 0.6° phase shift at 50 c.p.s. in order not to produce phase distortion of the amplified signal.

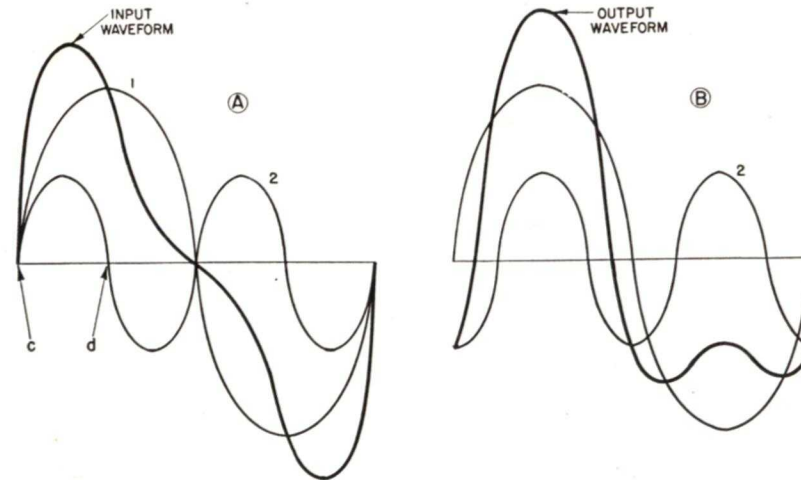


FIG. 13. A shows how the components of the input signal, applied to the amplifier in Fig. 12, combine to form the input signal, and B shows the different wave shapes obtained by combining the output components. Notice that component 2 has been shifted 90° .

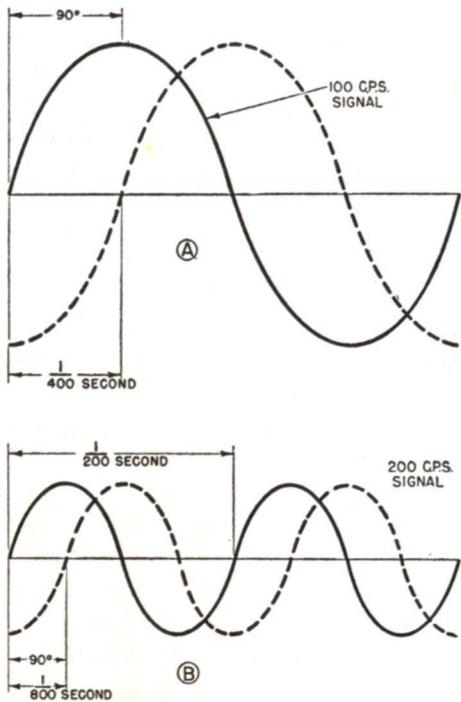


FIG. 14. How phase shift and time delay are related, and how the phase shift must decrease as the frequency is decreased in order to maintain a constant time delay, and thus prevent "phase distortion."

In the design of video amplifiers, where phase distortion is important,

the resistances, capacitances, and inductances are chosen to produce, as nearly as possible, a linear relationship between phase shift and frequency. The time delay is, therefore, nearly constant, and there is a minimum of phase distortion.

This problem of phase-angle delay and time delay is not readily grasped the first time. However, as you proceed with your studies it will be mentioned again, and we suggest that you review the preceding explanation at that time.

To Avoid Distortion. Let us remember these important points.

To avoid frequency distortion, the amplifier must be designed to have a flat frequency-response curve over the whole range of frequencies to be amplified.

To avoid amplitude distortion, operation must be restricted to the linear portion of the dynamic E_g-I_p curve.

To avoid phase distortion, the circuit must be designed to yield, as nearly as possible, a linear relationship between phase shift and frequency.

Combination L, R, and C Loads

We have studied the effect of the plate load resistance on the amplification of a single-stage amplifier. Let us now review this information, and see how it enables us to determine the frequency response characteristic of an amplifier with any type of plate load—resistive, capacitive, inductive, or any combination of these.

In Fig. 15 is shown how the amplification of an amplifier changes as the

load resistance is increased.* For large values of R_L , the amplification increases slowly, approaching a maximum equal to the μ of the tube. The "slowing up" occurs at the knee of the curve, that is, at point s in Fig. 15, and is caused by the lowering of the

*This graph is calculated from the formula:

$$\text{Amplification} = \mu \frac{R_L}{R_L + R_P}$$

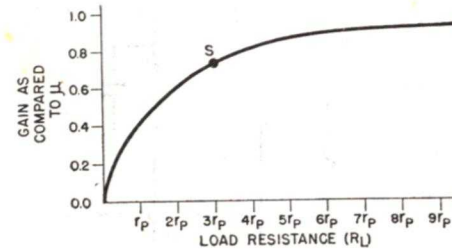


FIG. 15. How the plate-load resistance affects the gain of an amplifier.

a.c. plate current as R_L increases.

When the value of the load resistance is fixed, and the frequency of the input signal is changed, the frequency response is a straight line, as shown in Fig. 16, but only when we ignore tube capacitances, stray capacitance, inductance, and the effects of interstage coupling. We will shortly see why the response curve in a resistance-coupled amplifier deviates from this line at the high and low frequencies as shown by X and Y in Fig. 16.

INDUCTIVE LOADS

When a resistance is used as a load, it is necessary to increase the battery voltage as R_L is increased in order to maintain, unchanged, the plate-cathode d.c. voltage, and with it the amplification of the stage. This was assumed in presenting the characteristic shown in Fig. 15. The increase in battery voltage is necessary to compensate for the d.c. drop in R_L . When R_L is large, the

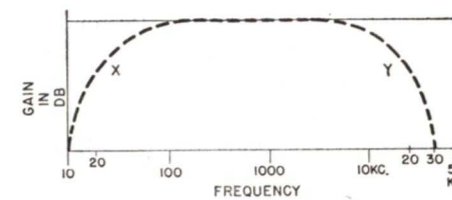


FIG. 16. The "theoretical" frequency response of a single-stage R-C amplifier.

battery voltage may reach an impractical value. It is possible to avoid this by using an inductance in place of R_L , as shown in Fig. 17A.

A pure inductance with no resistance presents no impedance to direct current; hence, the plate-cathode d.c. voltage is equal to the supply voltage. Since the inductances used for plate loads have a certain amount of resistance, the plate voltage of the tube is somewhat less than the supply voltage.

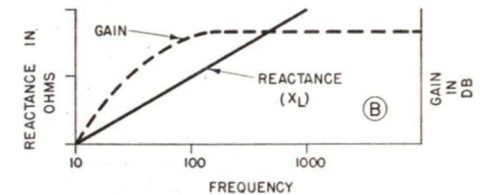
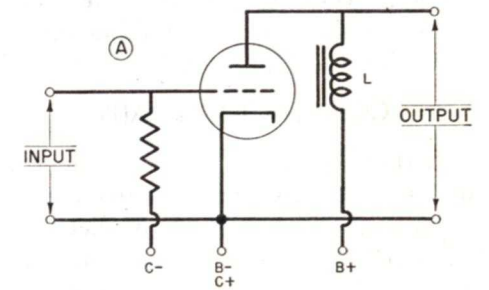


FIG. 17. The low-frequency response of an amplifier with an inductive load depends on the inductance of the choke.

For example, a 500-henry choke with a d.c. resistance of 4000 ohms has a 40-volt drop when the d.c. plate current is 10 ma. Thus if the plate-to-cathode voltage is 250 volts, the supply voltage is 290 volts.

With an inductance as a load, the amplification increases as the frequency increases. The reactance of an inductance X_L equals $6.28 \times f \times L$; f represents the frequency, and L the inductance of the coil. A 500-henry

plate-coupling choke, for instance, has a reactance of about 300,000 ohms at 100 c.p.s., 3 megohms at 1000 c.p.s., and 30 megohms at 10,000 c.p.s.

The load reactance and amplification-frequency characteristic of an amplifier with an inductance as a plate load is shown in Fig. 17B. At low frequencies the gain is low, because the reactance of the load is low. (At zero cycles per second d.c., the gain is zero, because the load impedance is zero.) As the frequency increases, the gain increases, and reaches a limiting value which is the μ of the tube.

COMBINATION LOADS

If the way in which the impedance of the load varies with the frequency is known, it is possible to predict the shape of the amplification-frequency characteristic curve of an amplifier with any type of plate-load impedance. This is done by comparing the impedance-frequency curve of the load with the amplification-resistance curve shown in Fig. 15.

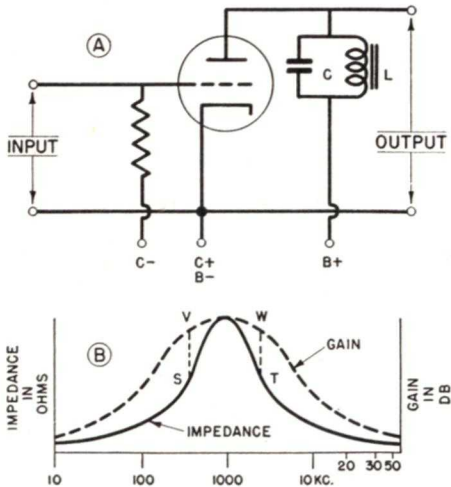


FIG. 18. An amplifier with an LC circuit resonant at 1 kc. as the load.

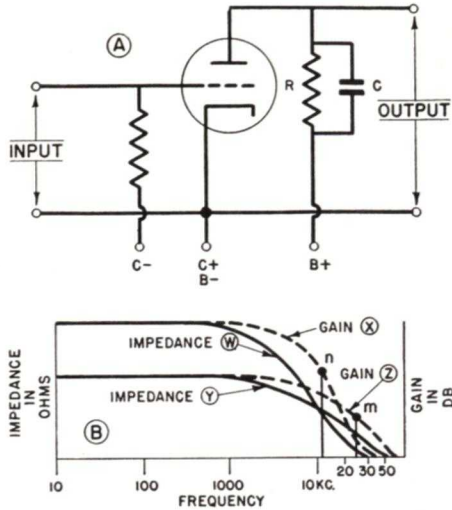


FIG. 19. How a condenser shunting the load resistor causes a decrease in impedance, and thus a loss of gain at high frequencies.

This method, though not exact, is accurate enough for many practical purposes. Suppose that the load consists of a coil in parallel with a condenser as shown in Fig. 18A. The impedance of such a load plotted against frequency appears in Fig. 18B. Since this is a parallel-tuned circuit, it has a maximum impedance at resonance.* At lower frequencies, the impedance is reduced, because the reactance of the coil is low. At higher frequencies, the reactance of the condenser decreases, and provides a low-impedance path in parallel with the coil so that the total impedance again decreases.

The amplification-frequency, or gain-frequency, characteristic for such an L-C load also appears in Fig. 18B. It is obtained by converting the impedance values to equivalent resistances and then, from the curve in Fig.

*Since all coils have a certain amount of resistance in addition to their inductance, the impedance at resonance is not infinite.

15, the gain for these values of equivalent resistance is determined. Note that the gain curve resembles the impedance curve. Within the region v to w, it does not peak as sharply as the impedance curve, in fact, it is impossible to get a greater gain, because the impedance has now increased to a value equivalent to the knee (point s) of the curve shown in Fig. 15. Further increase in impedance produces some, but not much, increase in amplification.

The performance of single-stage amplifiers having other types of impedances in the plate circuit is shown in Figs. 19, 20, 21, and 22. Note the close resemblance between the impedance curves and the gain curves as the frequency is varied.

A condenser across the load resistance is shown in Fig. 19A. Such a condenser is generally not connected in the circuit, but is present because of the plate-to-cathode capacity of the

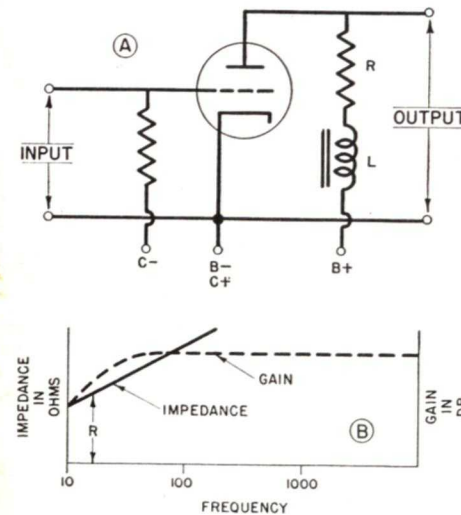


FIG. 20. How the low-frequency response of an amplifier, with an inductive load, can be increased by means of a series resistor.

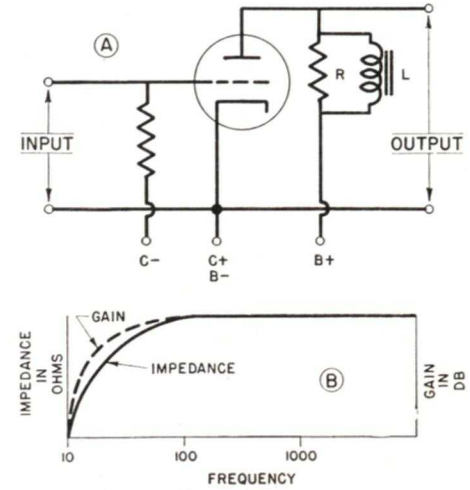


FIG. 21. A resistor in parallel with an inductance decreases the voltage gain.

input circuit, the stray capacity of the wiring in the output circuit, and the input capacity of the next stage. *This capacity reduces the high-frequency response of the amplifier.* For a particular value of R, the plate impedance will vary with frequency as shown by curve w of Fig. 19B. The gain for this impedance value is shown by curve x. If the value of R is reduced while C remains the same, the impedance will vary with frequency as shown by curve y, and its corresponding gain values will be as shown by z. However, the frequency m at which the response falls off to a certain ratio, generally 70 per cent of the maximum, is higher in curve z than the corresponding frequency n in curve x. *Thus the high-frequency response can be improved, at the sacrifice of gain, by reducing the value of R.* This is a very important fact, and use is made of it in the design of high-fidelity audio or video amplifiers.

In order to maintain a high impedance at low frequencies where the re-

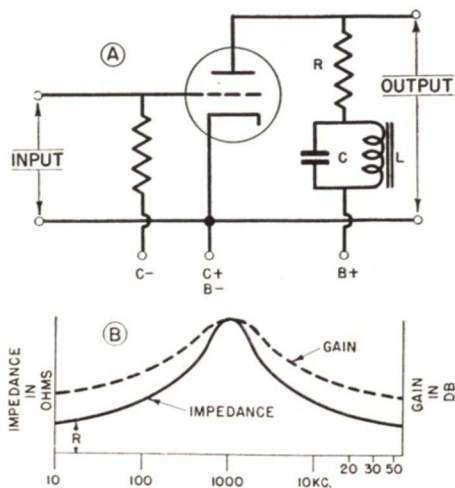


FIG. 22. How the over-all gain of an LC load can be increased by means of the resistor R.

actance of the choke is small, a resistor R is connected in series with the choke, as shown in Fig. 20A. Notice that the

plate impedance does not fall off to zero, as it did when the choke was used alone as a plate load.

The circuit shown in Fig. 21A shows the effect of shunting the plate choke with a resistance. There may be a resistor actually connected across this choke, or the one shown may merely represent hysteresis, eddy current, and I^2R (so-called "copper") losses in the plate coil. By comparing this with the response shown in Fig. 17, we notice that when a resistor shunts the inductance, the gain is reduced, but that the band width is increased.

The circuit shown in Fig. 22A is the same as that shown in 18A, except that a resistor has been added in series to boost the low-frequency impedance, and thus boost the low-frequency response.

Cascaded Voltage Amplifiers

The maximum amplification that can be obtained from a vacuum tube is the μ of the tube used, and in practice, even this value cannot be attained. Thus to secure larger gains, two or more stages are connected in cascade, that is, one following the other. Thus the signal applied to the first stage is amplified, then coupled to the second stage, and re-amplified. In video amplifiers, where the gain per stage is small (because of the low plate-load resistance needed to obtain a wide band width), several stages must be used to obtain the voltage amplification needed.

Let us study the requirements of the coupling between stages, and the meth-

ods used to obtain this cascading of gain.

First, the coupling between stages should transfer the output voltage of one stage to the input circuit of the next stage with a minimum of distortion.

The output circuit of a tube used as a low-frequency amplifier is generally at a high positive d.c. voltage with respect to the cathode of the tube, and the input (grid) circuit of the following stage is at a negative voltage with respect to its cathode. Since the cathodes of the two stages are usually either at ground potential or very close to it, there is a d.c. voltage difference be-

tween the output of one stage, and the input of the next stage. The second requirement, therefore, is that the coupling between stages must block this d.c. voltage difference, and still allow the signal to be transferred.

A condenser is used to couple the a.c., and to block the d.c. between stages of so-called resistance-capacitance coupled (R-C coupled) and impedance-coupled amplifiers.

In transformer-coupled amplifiers, the two windings of the transformer transfer the a.c. signal from one stage to the next, and at the same time isolate the d.c. of the plate circuit from the grid circuit of the following stage.

There is also a way of connecting the plate of one tube directly to the grid of another through resistors by adjusting the cathode voltages of the two tubes. This is a "direct-coupled" circuit, or sometimes called a "d.c.-coupled" circuit.

Let us now study in detail the types of coupling between stages; namely, (1) resistance-capacitance, (2) impedance, (3) direct, and (4) transformer.

R-C COUPLING

Preliminary Considerations. Let us first consider the simple class A voltage amplifier circuit shown in Fig. 23.

An automatic C bias is furnished by the d.c. plate current drop across resistor R_2 . This bias is applied to the grid through resistor R_1 which is high enough not to short out the source for the input signal e_g . R_1 also provides a path for stray electrons that land on the grid to leak off to ground, and so it is called a *grid leak*. Condenser C_1 is a by-pass condenser, serving as a low-

impedance path for the signal component in the plate current flowing from the cathode to ground. Condenser C_2 is also a by-pass condenser. It provides a low-impedance path to ground for the a.c. components of the plate current, and, therefore, keeps the signal out of the d.c. supply. The presence of the load resistance R_3 requires the supply voltage to be increased by the voltage drop in R_3 , so that the plate voltage is at the required operating value when there is no signal voltage e_g on the grid.

Since the tube is operated as a class A amplifier, the application of an a.c. signal e_g to the grid-cathode terminals causes an a.c. voltage of corresponding wave form to appear across R_3 . In a resistance-coupled amplifier, this output is coupled to the input of the following stage through the condenser C_3 .

The electrical value of the components in an amplifier of this type is usually not critical. Some typical ranges generally used, and the reasons for their selection, are as follows:

R_1 or R_4 —250,000 ohms to 2.5 megohms. (It must be 10 or more times as large as the impedance of the input signal source.)

C_1 —0.1 mfd. to 20 mfd. (The higher the frequency of the input signal, the lower C_1 may be. At the lowest frequency to be amplified, the impedance of this condenser should be one-tenth or less of the ohmic value of R_2 .)

R_2 —500 to 5000 ohms, calculate from the formula:

$$R_c = \frac{C \text{ bias desired (in volts)}}{\text{cathode current}^*}$$

*If a tetrode or pentode is used, the screen current must be added to the plate current to obtain the cathode current.

R_3 —2000 to 500,000 ohms. (See the recommended value in tables supplied by the tube manufacturer. In these tables E_b and the C bias are also specified. If the tube has a screen grid, the screen voltage and current are included.) Lower values of R_3 are required for wide-band amplification as in f.m. and television circuits; higher values are required for high-gain restricted frequency range voice amplifiers.

C_2 —2 mfd. or less. (It should have an impedance at the lowest frequency to be amplified not more than $\frac{R_3}{100}$.)

C_3 —.01 to 0.1 mfd. (High values are desirable for low-frequency amplification, as in f.m. and television circuits. Lower values are often used in broadcast and simple voice amplifiers where response below 100 c.p.s. is not needed.)

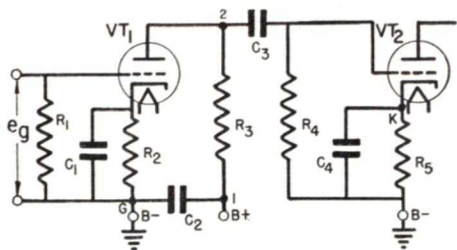


FIG. 23. Resistance-capacitance type of voltage amplifier circuit, using a resistance load and capacitance coupling.

Since the values of the components that are to be used with the various types of tubes are specified and published by the tube manufacturers, it is not often necessary to design special circuits. You should consult tube

manuals or handbooks to find the best values to use with a particular tube.

Frequency Response. In a practical R-C amplifier, the amplification does not follow the curve shown in Fig. 16, for two principal reasons.

First, the low-frequency response will drop off, as shown by the dotted line X in Fig. 16, because the reactance of the coupling condenser is large at low frequencies. The signal voltage across R_3 , shown in Fig. 23, is applied to C_3 and R_4 , and divides between the grid resistor and the reactance of the condenser. Since the capacitive reactance increases at low frequencies, the voltage across the grid resistor decreases. The low-frequency response may be improved (raised) by an increase in the capacity of the coupling condenser. However, as the condenser is made electrically larger, its physical size also increases, and its capacity to ground increases. This is undesirable, for it increases the effective plate-to-ground capacity of the stage to which it is connected.

Second, the plate-to-cathode capacity of the first stage, the grid-to-cathode, and grid-to-plate capacities of the following stage, as well as the distributed capacity of the leads used to connect the two stages, are all in parallel with the plate circuit impedance. If the latter is a resistance, the effect of these capacities at high frequencies is the same as it is in the circuit shown in Fig. 19A in which C represents these combined capacities. In Fig. 19B, notice that the amplification falls off as the frequency increases. This is caused by the *shunting effect of the tube capacities which reduces the*

equivalent plate-circuit impedance at high frequencies. This, then, is the reason for the decreased high-frequency response, shown by the dotted portion Y in Fig. 16.

To increase the high-frequency range over which there is uniform frequency response in a resistance-capacitance coupled amplifier (the portion between X-Y in Fig. 16.), it is necessary to *reduce the ohmic value of the plate load resistor.* This reduces the effects of any load-shunting capacities, but reduces the gain of the stage.

An amplification-frequency response characteristic of a resistance-capacitance coupled amplifier using tubes having low shunting capacities is illustrated by curve a in Fig. 24.

IMPEDANCE COUPLING

Impedance coupling is the term used for amplifiers whose loads are impedances such as those shown in Figs. 17, 18, 19, 20, 21, and 22. These impedances are used (a) to obtain increased amplification at certain selected frequencies, either at the sacrifice of, or in an attempt to improve the uniformity (or flatness) of the response curve, (b) to equalize* the response of other networks in which they are connected, and (c) to correct for time delay.

Fig. 25A shows a practical amplifier with an inductive load. The a.c. voltage, which is developed across coil L by the varying plate current of tube VT_1 , is fed to the grid of tube VT_2

*When an amplifier is equalized, the gain is the same for all frequencies in its range. Thus, if one stage of an amplifier has a low response at a certain band of frequencies, we can equalize the amplifier response by adjusting another stage to provide extra amplification at these frequencies.

through coupling condenser C, making the method of coupling exactly the same as that in the resistance-capacitance coupled amplifier circuit. Resistor R_g , which allows the automatic C bias voltage to act upon the grid of tube

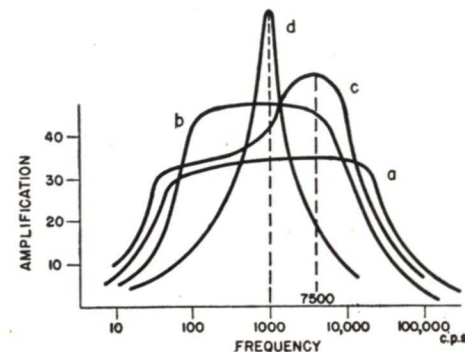


FIG. 24. Typical response curves for (a) R-C coupled, (b) impedance-coupled, and (c) transformer-coupled amplifiers. In (d) the response of an amplifier with an LC load circuit tuned to 1000 c.p.s. is given.

VT_2 , may be replaced with a choke coil if desired. If the resistance of R_g (or the impedance of the grid choke) is very high with respect to both coupling condenser C and plate load L, we can assume that L is the real load in this circuit.

Frequency Response. In Fig. 17B we noticed that the amplification, secured with an inductive load, increases with frequency; at very low frequencies (below 10 cycles) there is practically no amplification.* When the frequency is increased to a value that

*The low-frequency response of an impedance-coupled amplifier can be improved by using a choke that has a very high inductance. To insure good high-frequency response, the choke must also have a low distributed capacity, and tube capacities must also be low. The coil must, in addition, have low losses in order to provide maximum amplification.

makes X_L (the load reactance) more than 9 times as great as r_p (the a.c. plate resistance), the amplification becomes essentially equal to the μ (amplification factor) of the tube. It is common practice to select a value for L that will make X_L at least 5 times the value of r_p at the lowest frequency to be amplified. Sometimes an extra resistance R is placed in series with the load inductance L , as shown in Figs. 20, 22, and 25 to raise the plate load at low frequencies. Fig. 20B illustrates how the load impedance varies with frequency when this resistor is present.

Phase Shift. As we will note later, when the plate load of an amplifier stage is a pure resistance, the a.c. output voltage leads the a.c. grid input voltage by 180 degrees. If an inductance load L is placed in series with a resistive load R , as is the case in Figs. 20A and 25B, the angle of lead will be somewhere between 90 and 180 degrees;

if the resistive load is omitted, the angle of lead will approach 90 degrees (the plate resistance of the tube is still in the circuit, so that the circuit is not a pure inductance). The insertion of inductance in the plate circuit can shift the phase relationship of input and output a.c. voltages by nearly 90 degrees.

Time Delay. Earlier in this Lesson we discussed the relationship of time delay in an amplifier to the phase shift, and how phase distortion occurs unless the time of transmission is the same for all frequencies. To correct the time delay, it is necessary to control the phase shift over the frequency range that is being amplified. With impedance loads of the types shown in Fig. 25, it is possible to vary the phase shift, and, therefore, the time delay. The proper impedance depends on the amount of phase correction desired over the frequency range, and may be found either by experiment or by calculation.

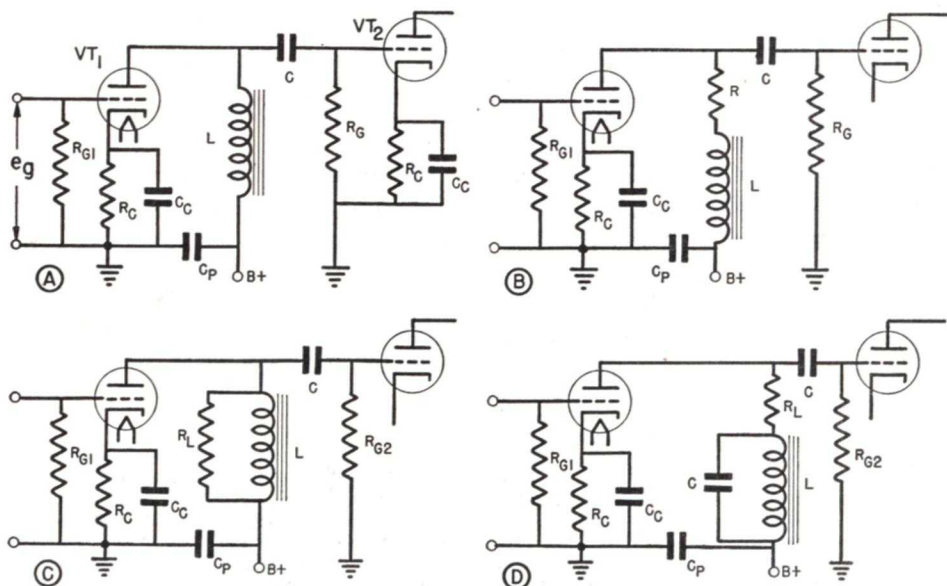


FIG. 25. These circuits illustrate various types of reactance loads for frequency amplifier circuits used for sound or television signals.

In the circuit of Fig. 25C, R_L may represent either the losses in coil L^* or a separate resistor shunting the coil. Amplification in a practical circuit of this type, with a fixed supply voltage, is higher than it is for a resistance-capacitance coupled circuit, because the coil allows almost the full d.c. voltage of the battery to appear between the plate and the cathode of the tube. However, the amplification is uniform for a narrow band of frequencies only. At low frequencies, the reactance of coil L decreases, making the load reactance low, and decreasing the amplification. As the frequency increases, the reactance of coil L increases to a very large value, so that R_L becomes the effective load. Amplification then rises to a level that is determined by the value of R_L , and remains constant until the frequency has increased to the point where the distributed capacity of the coil and the tube capacities shunt the load, and reduce amplification. This performance is illustrated in Fig. 21B. Curve b of Fig. 24 shows the amplification-frequency characteristic of an amplifier of the type shown in Fig. 25C.

Resonance Effects. No coil can be built without distributed capacity, so at very high frequencies, coil L in Fig. 25A, is, in effect, shunted by a condenser that somewhat reduces the load reactance. If the resonant frequency and the distributed capacity of L is in the range of audio or picture fre-

quencies that are being amplified, the load impedance becomes quite large at this frequency and boosts the amplification. For this reason, a resonant load is often introduced purposely, as shown in Fig. 25D, to raise the amplification of the stage at a particular frequency. Curve c of Fig. 24 shows the frequency-response characteristic of an amplifier of the type shown in Fig. 25D. The values of L and C in this case resonate at 7500 c.p.s.

If R_L , in the circuit shown in Fig. 25D is reduced to zero, and a low-resistance coil is used for L , the amplification-frequency curve d of Fig. 24 is obtained. Such a characteristic is very valuable when we want to amplify a single frequency, or a narrow band of frequencies in a circuit in which there are other extraneous or unwanted frequencies present.

► The type of coils used in impedance-coupled amplifiers depends on the frequencies to be amplified. Low frequencies usually require large inductances with coils wound on iron, or with laminated-steel cores. At video frequencies, the losses in the iron or steel core become excessive, and the performance of the coil is changed appreciably. However, at these frequencies, the inductance required is lower, and air-core coils, or coils with low loss powdered-iron cores are used extensively.

DIRECT COUPLING

For amplification of very low frequencies or very slow grid voltage changes, such as are found in photoelectric control circuits, the presence of the coupling condenser between stages is quite objectionable, because

*No coil, especially of the iron core type, exists that does not have a certain amount of power loss. Hysteresis and eddy current losses have the effect of placing a high resistance in parallel with the coil; this lowers the amplification somewhat, but gives a flatter frequency response, which is sometimes desirable.

of its high reactance at low frequencies, and its inability to pass a d.c. signal. The direct-coupled amplifier circuit, shown in Fig. 26 (also called the Loftin-White amplifier after its originators), is used for applications such as these, because of its excellent low-frequency response, and its ability to amplify d.c. voltages. Notice that the plate of the first stage of this type of amplifier connects directly to the grid of the second stage.

A Practical Direct-Coupled Amplifier. In a direct-coupled amplifier the circuit must be adjusted so that the electrode voltages, with respect to the cathode of each tube, are correct. Let us see how this is done in the practical circuit of Fig. 26. The first tube is a type 6SJ7 pentode* having a 75,000-ohm resistor load, and requiring the following electrode voltages: $E_p = 250$ volts; $E_g = -3$ volts; $E_{sg} = 100$

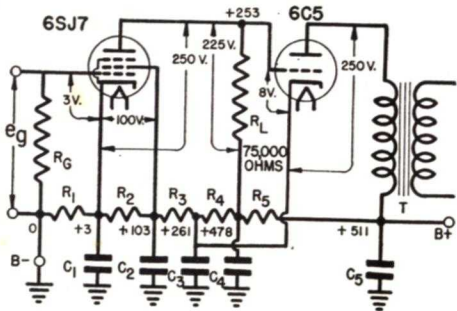


FIG. 26. Direct resistance-coupled or Loftin-White amplifier circuit. Numerals indicate d.c. voltage (with respect to ground) at various points in the circuit.

volts. This tube is coupled to a type 6C5 tube which requires: $E_p = 250$ volts; $E_g = -8$ volts. The type 6SJ7

*Pentode and tetrode tubes amplify exactly like triodes when the correct fixed d.c. voltages are applied to the extra grids.

tube draws 3 ma. of plate current under these operating conditions, hence the drop in load resistor R_L is $.003 \times 75,000$ or 225 volts; the plate-supply voltage for this tube must, therefore, be $250 + 225$, or 475 volts. Since a negative bias of 3 volts is required for the grid, the total supply voltage for this tube is 478 volts. The values of resistors R_1 , R_2 , R_3 , and R_4 in the voltage-divider circuit are chosen so that the electrode voltages for the type 6SJ7 tube are correct with respect to the cathode of the tube.

Now we must figure out the electrode voltage values for the next tube, a type 6C5 triode. Notice that the plate of the first tube, and the grid of the second, are connected directly together, and are at a d.c. potential of 253 volts with respect to ground; the cathode of the second tube must, therefore, have a potential of 261 volts with respect to ground if its grid is to be 8 volts more negative than its cathode. The plate of the 6C5 must be 250 volts more positive than its cathode, and must, therefore, be at a potential of $261 + 250$, or 511 volts with respect to ground. The electrode supply leads are by-passed to ground with condensers (C_1 , C_2 , C_3 , C_4 , and C_5) to prevent the a.c. currents from flowing through the voltage-dividing resistors. Since a transformer,* which has a very low d.c. resistance, is used as a plate load for the 6C5, no allowance need be made here for a d.c. voltage drop in the load.

Disadvantages of the direct-coupled amplifier are: the high supply voltage

*We cannot use a transformer to amplify d.c. or very slow voltage changes. The load must be connected directly in the plate circuit under these conditions.

it requires; the fact that the tube characteristics change with age and upset the distribution of voltages to the tubes in the circuit; the difficulties encountered in servicing such amplifiers. These limitations have precluded widespread use of this circuit. A direct-coupled circuit, however, must be used when d.c. signals and a.c. voltages below about 10 c.p.s. are to be amplified.

VOLTAGE AMPLIFIERS WITH TRANSFORMER COUPLING

A transformer is widely used for coupling one amplifier stage to another, as shown in Fig. 27. The load impedance in the plate circuit of the first tube is supplied by the primary of a step-up interstage transformer. The secondary of the transformer is connected in the grid circuit of the following tube. Secondary coil S has many more turns than primary coil P, so the secondary voltage e_s is many times as great as voltage e_p . The voltage e_p is developed by the flow of the plate current through the high-reactance primary winding. Magnetic coupling, through a common iron or silicon steel core, links the two circuits together in this case. Since the primary winding has a very low d.c. resistance, practically the entire plate-supply voltage is available for the tube. No grid resistor is needed across the secondary winding, for the winding itself provides a direct d.c. path from grid to ground.

Transformer coupling can boost the gain of an amplifier stage considerably, especially if the reactance of the transformer primary is high with respect to the a.c. plate resistance of the tube, and the turns ratio N (which is the number of secondary turns divided by

the number of primary turns) is made high. A high reactance for primary winding P insures that the voltage e_p , which appears across it, will be practically equal to the μ of the tube multiplied by the a.c. grid input voltage e_g . The secondary voltage e_s will then be N (turns ratio) times the primary voltage e_p . Thus the theoretical maximum

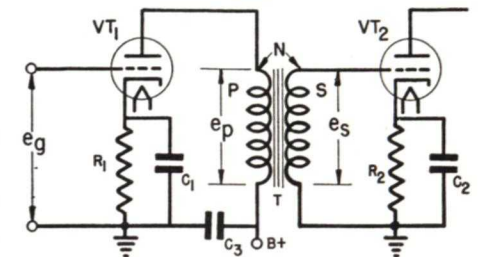


FIG. 27. The use of a transformer in coupling together two low-frequency amplifier stages.

amplification that can be secured per stage with transformer coupling is the *amplification factor of the tube multiplied by the turns ratio of the coupling transformer*. With other types of coupling, the theoretical maximum amplification is the μ of the tube.

In the early days of radio when the amplification factor of vacuum tubes was small, transformer coupling was needed in order to secure the gain desired. However, modern radio tubes have a high amplification factor, so that the extra gain of transformer coupling is not needed. R-C coupling is now generally used, because it has a better frequency response than transformer coupling.

The theoretical maximum amplification of a transformer-coupled stage is reduced somewhat by the following shortcomings of the iron-core transformer: (1) hysteresis and eddy current losses in the iron core; (2) leak-

age inductance due to the inability of the core to provide absolutely perfect magnetic coupling between primary and secondary; (3) losses in the coils; (4) the distributed capacity of each coil, and the capacities between the primary and secondary windings.

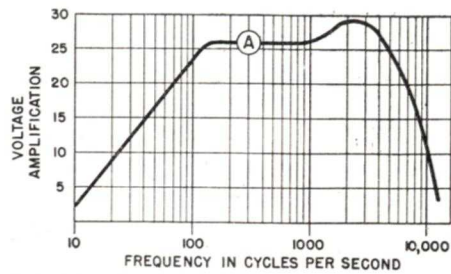


FIG. 28. This chart gives a comparison of the frequency-response characteristics of a transformer-coupled amplifier stage.

These effects vary with frequency, and instead of getting a flat response characteristic, the response curves are similar to the one shown in Fig. 28.

Frequency Response. How these effects influence the response of a transformer-coupled amplifier, such as shown in Fig. 27, is best analyzed by means of the circuit shown in Fig. 29A.

In the equivalent circuit, the source voltage is μe_g , and its resistance R_1 is the sum of the plate resistance of the tube and the resistance of the primary of the transformer. The equivalent circuit for the coupling transformer has been simplified by assuming a 1-to-1 turns ratio between primary and secondary. Thus, in order to convert the voltage output from the equivalent circuit to the actual output, we need only to multiply it by the turns ratio of the transformer. The eddy current and hysteresis losses of the transformer have also been neglected in this equivalent circuit.

In Fig. 29A, L_p is the inductance of the primary winding of the transformer; R_s represents the d.c. resistance of the secondary; L_s represents the combined leakage inductance of the primary and the secondary; C_s is the equivalent of the distributed capacity of the primary and secondary windings, and of the capacity between the two windings.

In the middle range of frequencies, the reactance of the primary winding of a properly designed audio transformer is so high that its shunt effect is negligible. Since C_s is a low capacity, measured in micromicrofarads, its reactance is high in the middle range, and can be ignored. Furthermore, the resistance of R_s , and the reactance of L_s , in the middle range of frequencies, are small with respect to R_1 , so that they, too, may be neglected. The equivalent circuit for mid-frequencies thus reduces to that shown in Fig. 29B. The output is practically equal to the μ of the tube times the input signal e_g . We would multiply this by the turns ratio N in order to find the output voltage of the transformer with a step-up ratio. This is the flat portion between 150 and 1000 c.p.s. of the response curve of the transformer-coupled amplifier shown in Fig. 28.

Usually there is a resonant peak in the response of a transformer-coupled amplifier at some frequency above the middle range. In the transformer response curve shown in Fig. 28, this peak occurs at about 3000 cycles per second. The reason for this peak is that as the frequency is increased, the reactance of L_s increases, and the reactance of C_s decreases. When they have the same reactance, L_s and C_s form a

series-resonant circuit as shown in Fig. 29C. This resonant circuit has a low value of Q because of the series resistance R_s and R_1 . This resonant peak, if it is not too pronounced, is generally desirable in a transformer-coupled amplifier, as it partially compensates for the reduction in gain that starts in the upper frequency range of the circuit.

Following the middle range, the response falls off rapidly as the frequency is increased, because the reactance of C_s decreases, shunts the output, and causes more of the signal to be dropped in R_1 , L_s , and R_s . This accounts for the response to frequencies higher than about 3000 cycles except for the rise due to resonance.

When the frequency applied is lower than the middle range, the response will again fall off. At these frequencies, we find that the shunting effect of L_p cannot be disregarded, since the reactance of L_p is low when compared to the

equivalent plate resistance of the amplifier. The equivalent circuit at low frequencies is shown in Fig. 29D. As the frequency decreases, the reactance of L_p decreases while the source resistance remains unchanged, and more of the signal is dropped in the source resistance, and less is available at the output. This, then, is the reason for the drop in response below 150 cycles per second as shown in Fig. 28.

Good response at low frequencies with a transformer-coupled amplifier can be obtained by making the inductance of the transformer primary high. Keeping the leakage reactance and the distributed capacity low, insures flat response at high frequencies, and high gain is secured by keeping the losses low, and using a high turns ratio.

Where transformers are used for coupling, they generally serve as loads for triode tubes. A triode with a plate resistance of about 10,000 ohms, and a

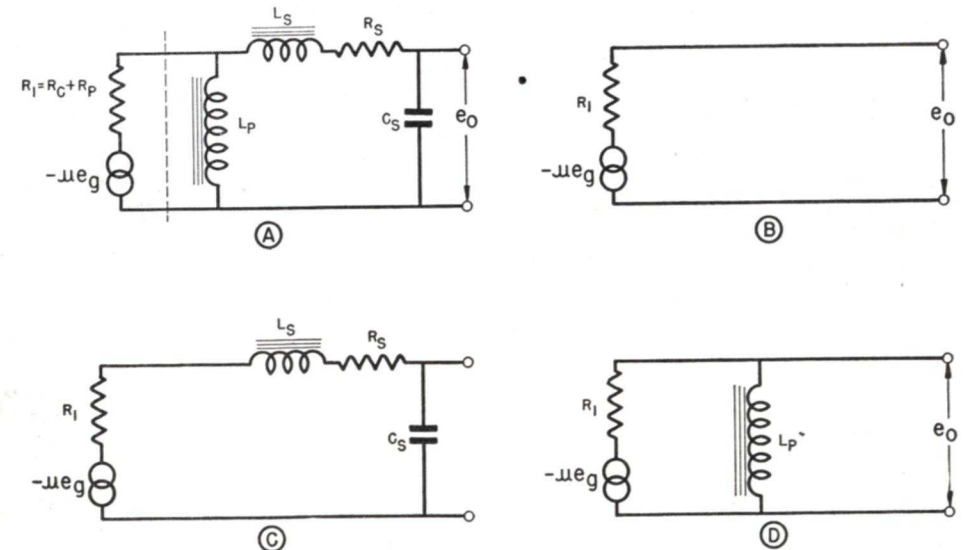


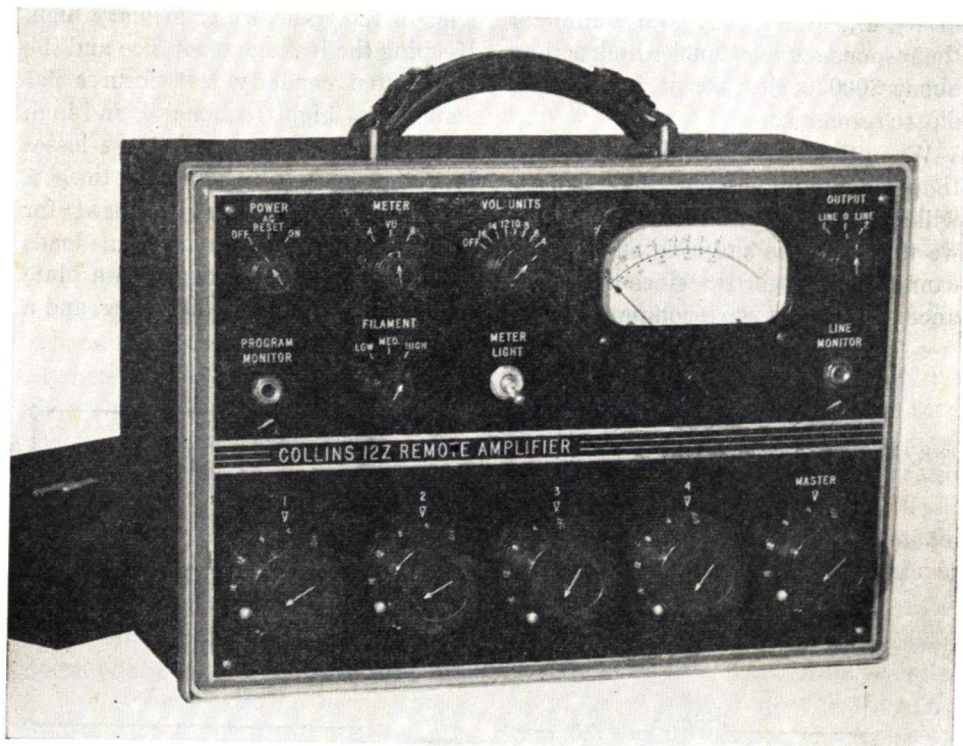
FIG. 29. The equivalent circuit of a transformer-coupled amplifier, and its simplified forms for various ranges of frequencies.

d.c. plate current of a few milliamperes, works very well with most interstage audio transformers. For best results an audio transformer should be used with the particular value of plate resistance and plate current for which it was designed. If the plate resistance is too low the high-frequency resonant peak is much higher than is desired. The reason for this is that when C_s resonates with L_s , the net resistance of R_1 , L_s , and R_s is less, and, therefore, there is a higher voltage output at the peak.

Likewise, referring to Fig. 29D, we see that the low-frequency response is boosted, because of the smaller voltage drop in R_1 .

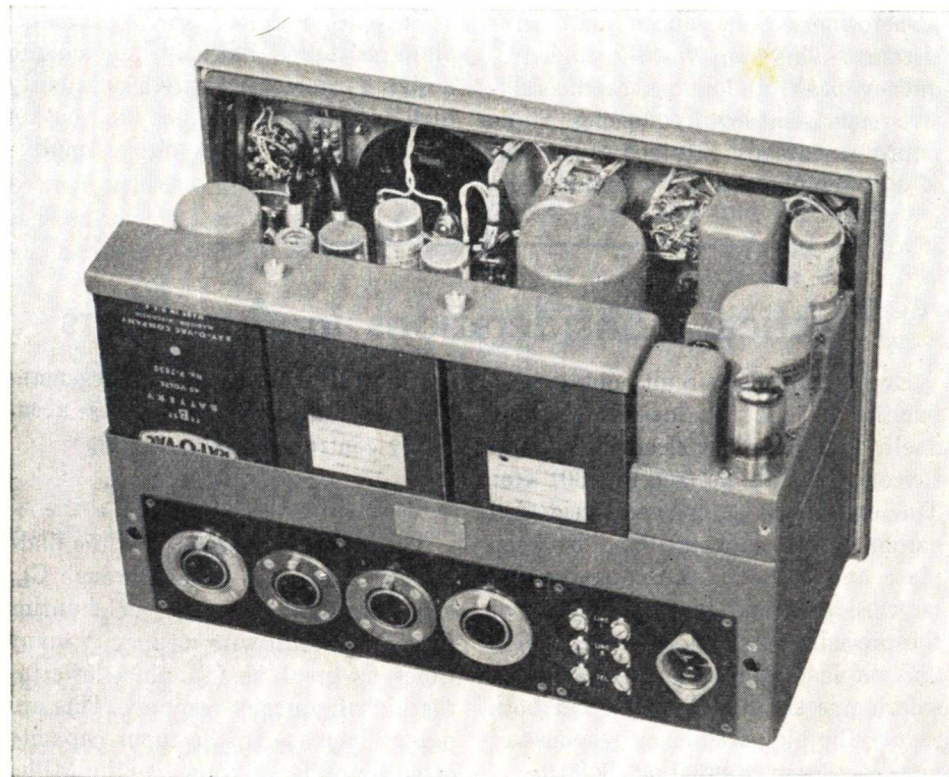
If the plate resistance is too high, the response drops off at the high and low frequencies, for then there is a larger voltage drop in R_1 in both of the equivalent circuits shown in Fig. 29C and 29D.

If the d.c. plate current is too large, it causes the transformer core to become saturated with flux, and to pro-



Courtesy Collins Radio Co.

This Collins 12Z remote amplifier is an example of a portable voltage amplifier used for on-the-spot preamplification of broadcasts which originate away from the main studios of a broadcast station. It is sometimes called a "nemo" (the trade term for remote) amplifier. The gain of this amplifier is approximately 90 db. The frequency response is flat within one db for all frequencies between 30—12,000 c.p.s., the distortion is less than 1% for the range of 50—7500 c.p.s., and the noise level is more than 55 db below the program level. Thus it can be used in high fidelity a.m. and f.m. broadcasting. Four microphones can be used at one time and each has an individual gain control and there is also a master gain control. The meter can be used either as an output VU meter or as a voltmeter to check the supply voltages. Power is generally obtained from a 115-volt a.c. source, but in emergencies, self-contained batteries are automatically connected to the amplifier.



Courtesy Collins Radio Co.

This is a back view of the Collins 12Z remote amplifier. Note the compact, neat construction. The microphones plug into the four receptacles on the back of the chassis. The six terminals to the right of these receptacles are for the two program lines and the telephone line normally used to connect this amplifier to the main studios. The 115-volt receptacle is to the right of the line terminals. Note the self-contained batteries which are used where a.c. line power is not available.

duce amplitude distortion in the output voltage. Furthermore, the inductance of the primary is low at low frequencies, and the gain is low. In order to use transformers with a wide variety of tubes, some of which draw more d.c. plate current than others, a small air gap is usually cut in the core of the transformer. The air gap prevents the core from becoming saturated.

Instead of iron or silicon steel, a material such as permalloy, having high permeability, may be used for the core of a transformer. This allows a smaller

core for a given use in an amplifier. The use of permalloy increases the frequency range over which a transformer, of a given physical size, can operate satisfactorily.

Transformer coupling is very useful in such applications as driving a push-pull power amplifier from a single-tube stage, or in cases where high amplification is needed, without particular attention to frequency response. Its frequency response is not as good as that of a low-gain resistance-capacitance coupled amplifier. To improve the frequency response, the secondary of the

transformer can be shunted with a resistance. This removes the high-frequency peak, and improves the relative response at low frequencies. These improvements are obtained at the cost of a lower over-all amplification.

Pentode tubes have such a large a.c. plate resistance that it is impossible to design a transformer with a sufficiently high primary reactance to obtain proper low-frequency voltage amplification.

Practical Considerations in Amplifiers

Every amplifier circuit contains capacities that are introduced by the tube itself. The three interelectrode capacities of a triode tube (see Fig. 30) are: The capacity C_{gk} , between grid and cathode; the capacity C_{pk} , between plate and cathode; the capacity C_{gp} , between grid and plate. The load of the preceding stage is shunted by C_{gk} , and the load of the stage we are considering is shunted by C_{pk} , and both reduce the high-frequency response of an amplifier as pointed out before.

The tube capacity C_{gp} , however, gives the most trouble, for it provides a path along which a signal can travel back from the plate circuit to the grid. Thus, as shown in Fig. 27, the primary voltage e_p can feed back, through the grid-to-plate capacity, to the grid of tube VT_1 . The phase of the voltage that has been fed back and applied to the grid source depends on the load, which can be resistive, capacitive, or inductive. *When the load is inductive, the voltage fed back is in phase with the grid voltage, re-enforcing the input signal, and the amplifier has more gain than normal; this is called regeneration. For other types of loads, that is, resistive or capacitive, the voltage fed back is out of phase, and there is some reduction in gain; this is called degen-*

eration. Regeneration and degeneration are both undesirable unless accurately controlled.

THE MILLER EFFECT

The feedback action, from the plate circuit to the grid circuit through C_{gp} , has the additional effect of shunting the input circuit with a capacity many times as great as C_{gp} , thus lowering the high-frequency response. This apparent increase in the input capacity of an amplifier is known as the Miller Effect. It is generally undesirable, and steps must be taken to eliminate, or reduce it in high-fidelity amplifiers.

Here are the fundamental facts that help us to understand the Miller Effect. When an a.c. voltage is applied to a condenser, current flows through the condenser. The amount of a.c. current that flows, increases when the capacity is increased. The current can also be increased by increasing the voltage that is applied across a condenser.

Notice in Fig. 31 that the grid lead connects to the plate through C_{gp} , and connects to the cathode through C_{gk} . Let us suppose that the grid voltage changes from zero to -1 during a part of the a.c. cycle. A certain amount of current then flows from the source to charge C_{gk} . Current also flows to charge

C_{gp} , but the amount of current is much greater than the amount that flows if only one volt were applied to C_{gp} . The reason for this is that if the tube has a gain of 50, the plate voltage increases 50 volts when the grid voltage decreases one volt. Because the grid voltage decreases and the plate voltage in-

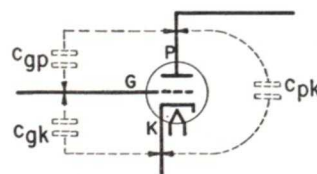


FIG. 30. The dotted lines here indicate the three interelectrode capacities that are present in a triode tube.

creases, the voltage difference between the grid and the plate is 51 volts. The voltage change across C_{gp} thus is 51 volts, so the current that flows from the signal source is 51 times as large as the current that would flow if the voltage change across C_{gp} were 1 volt. Since this current flows from the signal source, it means that so far as the signal source is concerned, C_{gp} has been increased *effectively* 51 times. As a matter of fact, the apparent size of C_{gp} is always one more than the gain of the amplifier.

For example, let us compute the apparent input capacity of a 6SF5 tube when the amplification of the amplifier is 50, C_{gk} is 4.0 mmfd., and C_{gp} is 2.4 mmfd. The gain plus one times C_{gp} gives an apparent C_{gk} of 122.4 mmfd. (51 times 2.4 mmfd.). When we add C_{gk} to this, the total input capacity is 126.4 mmfd. This is a large part of the shunting capacity which reduces the high-frequency response of an amplifier.

An audio amplifier, using a tetrode or pentode tube, does not have capacity feedback trouble, for the screen grid, which is grounded with respect to a.c., reduces the grid-to-plate capacity many hundreds of times. An example of this is the 6SJ7 tube. In this tube, the C_{gp} is only .005 mmfd. At high video frequencies, however, even this small amount of capacitance causes some loss of amplification in the amplifier.

HUM

When considering low-frequency amplifiers, it is important to know how undesired hum sounds and oscillations are produced.

Hum is the sound produced in the output of a low-frequency amplifier (the frequency is generally 60 or 120 cycles per second) when a part of the line voltage, or a part of a ripple component of the power-pack voltage gets

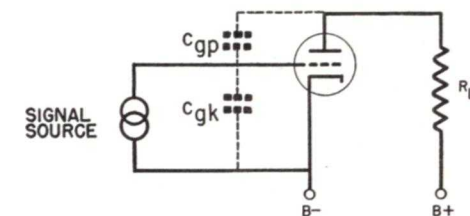


FIG. 31. The Miller Effect. The grid resistor and bias voltage have been eliminated to simplify the discussion and the drawing.

into the amplifier. In television, an excessive power line, or a ripple a.c. voltage in a video amplifier, causes a series of alternate light and dark bands of light on the face of the picture tube.

The hum level of a properly designed television or audio-frequency amplifier is about 60 decibels below the maximum output voltage. This means that

the hum is only one thousandth of the output voltage. Such a low level can be obtained only by careful consideration in the design and layout of the parts of the amplifier to prevent capacitive and inductive hum pickup.

Let us see how hum is produced in an amplifier. Iron-core transformers and

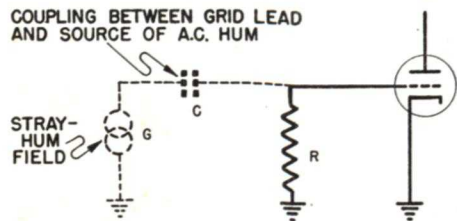


FIG. 32. How hum can be coupled capacitively into an amplifier.

chokes have leakage magnetic fields that exist in the space around them, and that frequently travel through the chassis. Most transformers and chokes use soft iron magnetic shields to limit this field. Nevertheless, audio transformers must be placed well away from power transformers and filter chokes in order to prevent hum pickup.

The wiring and placement of parts in an amplifier must be carefully considered to minimize capacitive and inductive a.c. pickup. Frequently, a simple change in the position of a part, such as rotating or tilting it at an angle, decreases the amount of hum. Since both capacitive and inductive coupling can exist between wires, any wires that carry large amounts of alternating current must be kept away from the grid and the plate leads to prevent hum. Thus a.c. filament leads are often twisted together so that induction from them to neighboring wires is minimized.

Grid leads in the low-level input circuits of an amplifier are generally shielded. This is done because the grid circuit has a high impedance, and is, therefore, very likely to have an excessive amount of hum pickup through electrostatic coupling. In Fig. 32, the stray-hum field is shown as a generator G, and the capacity between the grid wiring and hum source is shown by a condenser C. Of course, C is very small, and thus it has a high reactance. Since the hum generator feeds into the voltage divider formed by C and R, the hum voltage divides between the reactance of C and the resistance of R. When R is large, the hum-producing voltage between the grid and ground is a low impedance.

The amount of capacitive coupling between the grid wire and any source of a.c. voltage is greatly reduced by a grounded shield around the grid wire.

COMMON GROUNDS

In schematic diagrams, the ground connections may be indicated at several different points, even for a single stage of amplification, as shown in Fig. 33A. Actually, in wiring the amplifier, the ground connections for a single stage would better be made to the same point, as shown in Fig. 33B. If, for example, the cathode of the tube and the ground side of the grid resistor were connected to different points on the chassis, any stray hum currents flowing in the chassis between these points would produce a voltage drop in the chassis that would be in series with the grid-to-cathode circuit of the tube, and could cause hum. This is especially true in the low-level circuits of the am-

plifier where any hum is amplified by the stages that follow. (Regeneration and degeneration, which are caused by signal voltage and current flowing from one stage to another, can be prevented by this same precaution.)

MOTORBOATING

There can be feedback between stages of a low-frequency amplifier through the power supply, as well as through the ground connections. This feedback, when it is of sufficient amplitude and of proper phase, can produce oscillations that are called "motorboating," because of the "putt-putt-putt" sound they produce. If the frequency of oscillation is more than 60 c.p.s., the sound is a squeal.

► In order to understand how this motorboating occurs, we need to realize that the output of a single-stage vacuum-tube amplifier is 180° out of phase with the input signal. Let us consider the basic circuit shown in Fig. 33A. Notice that the voltage at point 1 of the load resistor is always equal to the supply voltage, but that when current flows through R_L , point 2 is at a lower voltage than point 1. That is, point 2 is *negative* with respect to point 1. Now let us suppose that a *positive* signal is applied to the grid of the tube. The plate current increases and the voltage drop across R_L increases so that point 2 becomes *more negative* than before. The voltage across the load resistor is, therefore, 180° out of phase with the grid voltage.

Of course, for two stages of amplification, the output signal from the second stage is 360° out of phase with the input to the first stage. This is one complete cycle, and the output is in

phase with the input to the amplifier.

Let us now see how motorboating can be produced in an amplifier. In Fig. 34, the a.c. plate current of tube VT_2 flows through the primary of the output transformer, through C_5 to the cathode of the tube, and thus through the tube. Therefore, the a.c. variations of an audio signal in this plate circuit create a voltage drop across C_5 ; the amount depends on the strength of the variations, and on the reactance of C_5 .

Since C_5 is the output filter condenser of the power supply, the audio variation across it is impressed on the

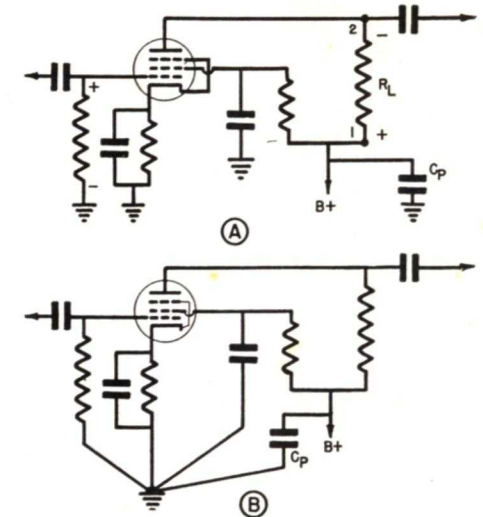


FIG. 33. Common ground points for each stage of an amplifier are used to prevent interstage coupling.

plate circuit of the other stages too. The plate supply voltage of VT_1 , in this example, is also varied at an audio rate. These variations are passed through the intervening stages, and applied to the grid of tube VT_2 . If they are in phase with the plate variation (as they are if there is one stage of amplification between VT_1 and VT_2), and of

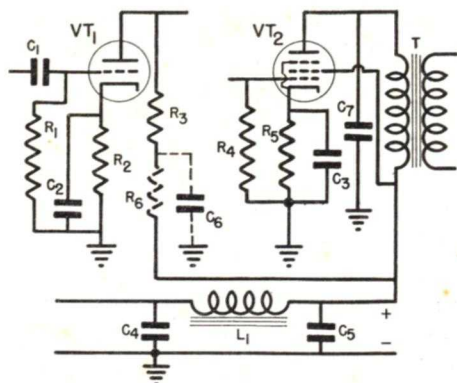


FIG. 34. R-C decoupling networks, such as R_6 and C_6 , can be used to prevent "motorboating" in a multistage amplifier.

sufficient amplitude, oscillation occurs. If VT_1 is coupled directly to VT_2 , the

feedback is degenerative, that is, out of phase, and the circuit does not oscillate.

In order to prevent such undesired audio oscillations, the capacity of C_5 is increased or quite frequently additional filtering is placed in the plate lead of the low-level stages, for example, resistor R_6 and condenser C_6 in Fig. 34. This is sometimes called a *decoupling network*.

The reactance of C_6 at the signal frequency is low, with respect to the resistance of R_6 . Since R_6 and C_6 form a voltage divider for the a.c. signal across C_5 , only a small part of this a.c. voltage can be applied to VT_1 .

Lesson Questions

Be sure to number your Answer Sheet 15RC.

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. If the power supply for an R-C amplifier supplies 300 volts, and the desired operating point of the tube is $e_p = 180$ volts, and $i_p = 2.4$ ma., what must be the value of the plate load resistance? 5,200
2. Does a class A amplifier take power from the driving source?
3. What type of distortion is produced when a tube operates on the non-linear portion of its dynamic E_g-I_p curve?
4. In a class A amplifier that is working with negligible amplitude distortion, will the dc plate current *increase*, *decrease*, or *remain the same* when an audio signal is being amplified?
5. Give four common causes for amplitude distortion in a class A amplifier.
6. In a low-frequency amplifier, will the gain be a maximum when the plate load resistance is *equal to*, *twice that of*, or *nine times* the a.c. plate resistance of the tube?
7. Draw a voltage amplifier showing two triode tubes coupled by a transformer. Include all by-pass condensers, and the connections to the plate-supply voltages, and the bias voltage.
8. If a defective coupling condenser in an R-C amplifier is replaced with a condenser of $\frac{1}{2}$ the capacitance of the original, will the *low-frequency response decrease*, *high-frequency response increase*, or will *no change occur in the over-all response*?
9. Is the load voltage in an R-C amplifier in phase, or out of phase with the input voltage?
10. Why are R-C decouplers used in the plate-supply circuits of low-frequency voltage amplifiers?

HOW TO START STUDYING

For some people, starting to study is just as hard as getting up in the morning. An alarm clock will work in both cases, so try setting the alarm for a definite study-starting time each day. Start studying promptly and definitely, without sharpening pencils, trimming fingernails or wasting time in other ways.

Beginning is for many people the hardest part of any job they tackle. So formidable does each task appear before starting, that they waste the day in dillydallying, in daydreaming, and in wishing they didn't have to do it. The next day, and the next after that are the same story. Indecision brings its own delays, making it harder and harder to buckle down to work.

Are you in earnest? Then seize this very minute; begin what you can do or dream you can. Boldness in starting a new lesson is a great moral aid to mastery of that lesson; only begin, and your mind grows alert, eager to keep on working. Begin, and surprisingly soon you will be finished.

J. E. SMITH