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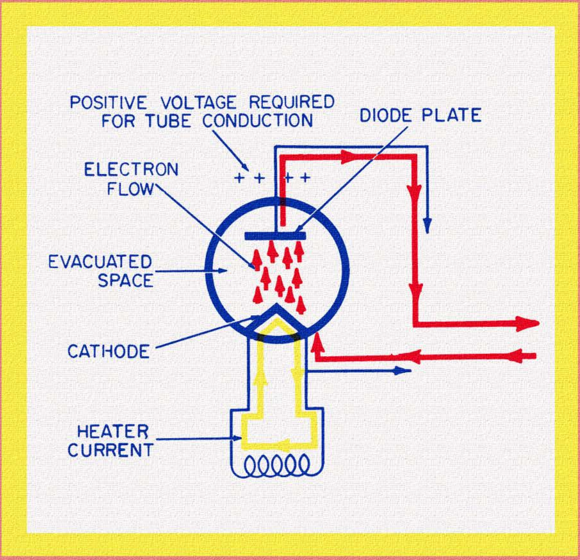
BASIC ELECTRONICS SERIES

AMPLIFIER CIRCUITS

by Thomas M. Adams

A dynamic new approach to the explanation of electronic circuit action, utilizing unique four-color diagrams to help you visualize what takes place inside amplifier circuits. Includes circuit fundamentals, plus an analysis of basic AF and RF circuits.



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Basic Electronics Series

AMPLIFIER CIRCUITS

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PREFACE

This is the second volume in the "Basic Electronic Series." While the content of this book does not depend on information contained in the previous *Oscillator Circuits* volume, readers with little or no background in electronics will find its 26-page discussion on electronic fundamentals helpful in understanding certain basic principles. However, it is not absolutely necessary to refer to the previous volume, since each circuit discussion in this book includes a complete description of the major electronic actions.

The same approach and analysis is used in describing the circuits in all books of this series. This approach consists first of clearly and unmistakably identifying every electron current at work in a circuit, and then of carrying out a detailed discussion of the movements of each current as well as the significance of these movements.

The circuit diagrams in this book treat electron currents as "moving parts." In any mechanical device, movements can be visualized and the motions of each part related to those of adjacent parts. The fact that these physical actions can be seen makes it easier to understand how the device works. Surprisingly, the same analytical technique can be adopted to explain electronic circuit actions. The ability to visualize the movements of electron currents is basic to a genuine understanding of all circuit operations. In addition, it will provide the background needed to understand the more advanced forms of circuit theory.

There are several ways amplifiers can be classified. The method in this book is the one most generally accepted; it is organized around the three broad groups of amplifiers likely to be encountered by the newcomer to electronics. These groups are:

Audio-frequency voltage amplifiers.

Audio-frequency power amplifiers.

Radio-frequency voltage amplifiers.

The study of amplification naturally includes the means by which voltages and currents are coupled from one circuit to another. The three most common means of coupling—resistance-capacitance, impedance, and transformer—are the bases for further division of the three broad groups of amplifiers into chapters. Feedback, both positive and negative, is closely associated with audio systems. It, too, has been analyzed by means of examples in the appropriate places. The reader who can understand how these circuits work is well-equipped to study more advanced applications of amplification. Because of the emphasis which has been placed on the book's primary object of explaining how circuits operate, and also because of its simplified approach, this material is considered neither too advanced for high-school students, nor too elementary for those at a college level.

The author is indebted to the same individuals named in the preface of the oscillator text for their valuable time in looking at some of the original drawings and for making various helpful suggestions.

THOMAS M. ADAMS

June, 1961

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Chapter 1

BASIC VACUUM-TUBE ACTIONS

An elementary understanding of the actions within a vacuum tube is essential before those which occur outside the tube can be understood. Most of this book is devoted to a study of common circuit actions which are regulated in some manner within the tube. These basic phenomena, which occur over and over in the operation of any tube include:

1. Free electron emission from a heated cathode.
2. Easy passage of free electrons through a vacuum.
3. Attraction of electrons to positive voltage points.
4. Repulsion of electrons from negative voltage points.

DIODE TUBES

The diode is the earliest, and also the simplest, vacuum tube. The discovery of the Edison effect by Thomas Alva Edison led to the invention of the diode. Edison had observed that when one of two conductors terminated inside an evacuated glass envelope was heated, a small electric current would flow between the conductors under certain other conditions of applied voltage. Although he recorded his observations, he made no immediate attempt to explain or apply them.

The phenomenon he observed can be fully explained by examining the operation of the diode vacuum tube. Fig. 1-1 reveals its essential construction details in symbolic form. The two elements, called electrodes, are the *cathode* and the *plate* (sometimes referred to as the anode).

Three conditions must be met in order for electric current (meaning electrons) to flow across the evacuated space between the cathode and plate of the tube:

1. The cathode must be made hot enough that free electrons will actually "jump" off the cathode.
2. A positive voltage must be applied to the plate in order to attract the negative electrons which have left the cathode.
3. The space between the electrodes must be evacuated of all air molecules, so that there will be nothing within the tube to hinder the movement of electrons.

The relative ease or difficulty with which electrons will leave the heated cathode is called the *work function* of the cathode material. When any material is heated, a tremendous increase in molecular motion occurs. This molecular agitation results in the releasing, or "shaking off," of many of the electrons from their orbit around the nuclei of the various molecules. Once it is released from its planetary orbit within a molecule, such an electron becomes what is known as a "free" electron. Some electrons from the molecules immediately adjacent to the surface will not only jump free of their parent molecules, but may jump free of the surface of the metal also. Any electron which has done the latter becomes available for making up *space current* (the name applied to the electron current drawn across vacuum tubes, from cathode to plate).

This process of releasing electrons into the tube by heating the cathode can be likened to the familiar pot of boiling water. If you observe the boiling water closely, you will be able to see tiny droplets jumping off its surface. This analogy gives rise to the fairly common expression that electrons "boil off the cathode."

Gravity normally causes the droplets of water to fall back onto the surface. Electrons, however, do not respond to gravitational force but to electric forces. Since all electrons carry one negative electric charge, they are repelled by each other, and hence by any negative voltage, however small. By the same token, they are all attracted by positive voltages. It thus becomes a simple matter to attract electrons across the vacuum tube by applying a suitable positive voltage to the plate. The amount of positive voltage determines to some extent the number of electrons that will cross the tube, and the size and shape of the cathode itself is another factor.

Fig. 1-2 shows a common graphical representation of the voltage-current characteristic of a 2X2A diode tube. A curve of this nature reveals the *amount of current* that will cross the tube for any particular plate voltage. As an example, a plate voltage of 100 volts (which is read on the horizontal scale) indicates that approximately 15 milliamperes of current will flow across the tube (this being read on the vertical scale as shown by the dashed line). Another dashed line shows that if 200 volts is applied to the plate, about 35 milliamperes of current will flow.

Literally hundreds of different diode tubes are available, all operating in the same fundamental fashion described. These tubes will differ in construction, depending on the amount of plate voltage it is necessary or desirable to apply and on the amount

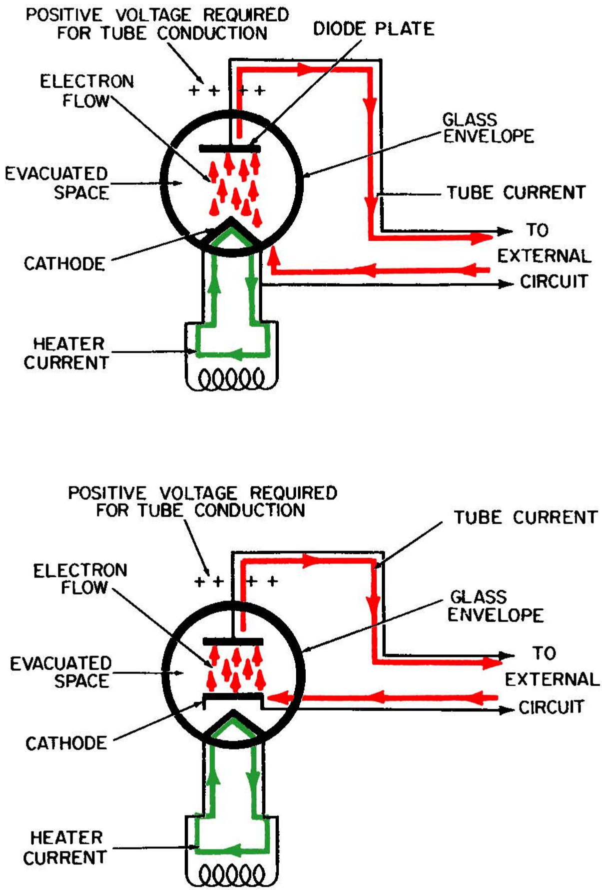


Fig. 1-1. The diode vacuum tube.

of plate current (tube current) desired. The amount of current required is dictated by external circuit considerations, some of which are discussed in later chapters.

Diode vacuum tubes are used extensively as rectifiers and detectors. The term *rectifier* is usually applied to a circuit for converting low-frequency alternating current into direct current.

The term *detector,* on the other hand, is usually applied to a circuit employed to *demodulate* a high-frequency (usually a radio-frequency) alternating current. That is, a detector separates the low-frequency component of a signal from the high-frequency component it is superimposed on. A detector cannot demodulate without first rectifying the alternating current. Therefore, only unidirectional currents will flow as a result of this rectifying action. (A unidirectional current is one that, although varying in amplitude, always flows in one direction.)

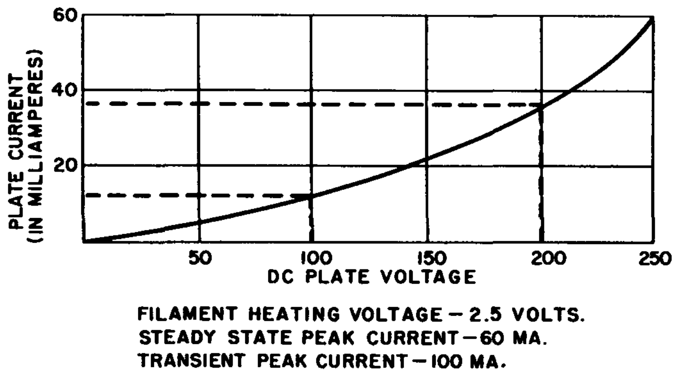


Fig. 1-2. Plate voltage-current characteristics of a typical diode

TRIODE TUBES

Fig. 1-3 shows the commonly accepted symbol for a *triode* vacuum tube. The triode differs from the diode in that a third element, called the *control grid,* has been added between the cathode and plate. The control grid is constructed of very fine mesh wire, and because it is between the cathode and plate, any electrons which flow from one to the other must pass through the mesh itself. The control grid is usually much closer to the cathode than to the plate. The wire-mesh construction and this closeness to the cathode make it possible to regulate, or control, the electron stream through the tube by varying the voltage of the control grid.

The control grid, invented early in the twentieth century by Dr. Lee de Forest, made it possible to *amplify* small signals—perhaps the most important single function performed by electronic circuitry. Tubes used as amplifiers are so constructed that a small charge in voltage at the grid will cause a relatively large change in the current flowing through the tube. The changes in tube current flowing through the external load will then develop a correspondingly large variation in the voltage present at the plate of the tube.

To understand how a tube amplifies, it is necessary for you to understand its characteristic curves. There are three quantities in question, and a change in any one will affect the amount of amplification attainable. These three quantities are the grid voltage, plate voltage, and plate current.

(The term *grid voltage* is sometimes taken to mean the *difference* in voltage between the grid and cathode. However, a more correct term for this voltage is *grid bias*. If the cathode is maintained at zero voltage (ground), then the actual voltage at the grid is also the grid bias. However, when the cathode is maintained at some other voltage, as is more frequent, the voltage at the cathode must be subtracted from the voltage at the grid to arrive at the proper "grid voltage" to be used with the characteristic curves of the tube.)

Fig. 1-4 shows the plate characteristic curves for a 6BN4. This is a triode tube which is used primarily as an RF amplifier in television receivers. The abscissa, or horizontal scale, is measured in volts and represents the possible range over which the plate voltage of the tube may be varied. The ordinate, or vertical scale, is measured in milliamperes and represents the range over which the plate current will vary for the various grid voltages during operation.

The curves across the face of the graph represent particular values of grid voltage (grid bias) which is designated as E_c. The curve farthest to the left represents a grid voltage of zero. Each point on this line tells us how much plate current will flow through this tube, for the particular value of plate voltage, when the grid voltage is zero.

As an example, the vertical line which represents 100 volts of plate voltage intersects the zero grid-voltage curve at point *A*. The dashed horizontal line, which also intersects point *A*, indicates that approximately 19 milliamperes of plate current will flow through the tube for this combination of grid and plate voltages. As long as the combination of 0 volts on the grid and 100 volts on the plate is maintained, 19 milliamperes of current will flow through the tube.

Voltage amplification cannot be demonstrated adequately from a single example. By taking a second example, however, we can come closer to describing its meaning. Consider now what would happen if we should change the grid voltage from zero to -1 volt, without changing the plate voltage. The grid-voltage line for -1 volt intersects the plate voltage line for 100 volts at point *B*.

Reading horizontally from point B to the left edge of the graph, we see that approximately 9 milliamperes of plate current will flow through the tube for this new combination of grid and plate voltages.

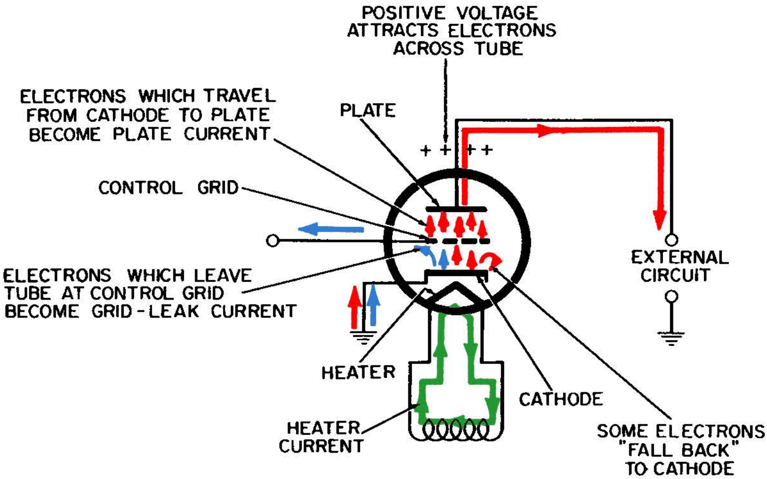


Fig. 1-3. The triode vacuum tube.

The most important point to grasp from these two examples is this—by reducing the grid voltage (meaning to make it more negative), we can reduce the amount of plate current which flows through the tube. By the same token, when we increase the grid voltage (meaning to make it less negative—or more positive), we can increase the amount of current through the tube.

These two examples enable us to arrive at a definition of the *mutual transconductance* (g_m) of a tube. Mutual transconductance is defined as the ratio between a small change in the plate current and the corresponding change in grid voltage which caused it, *when the plate voltage is maintained constant.* Transconductance (the name it usually goes by) is measured in mhos or micromhos. (From Ohm's law we know that the ratio of voltage to current is a measure of resistance, which is measured in ohms. Therefore, since transconductance is just the opposite—the ratio of current to voltage—it has been given the unit of measurement of a *mho* which is ohm spelled backwards.)

Since plate current is normally measured in milliamperes, it becomes more convenient to measure transconductance in millionths of a mho, or micromhos. Values of several thousand micromhos are normal; the 6BN4 tube used in this example has a transconductance of 7700 micromhos.

Many tube testers have their meters calibrated directly in micromhos. One of the commonest symptoms of vacuum-tube failure is a decrease in the transconductance; this automatically implies a decrease in the total emission of electron current within the tube.

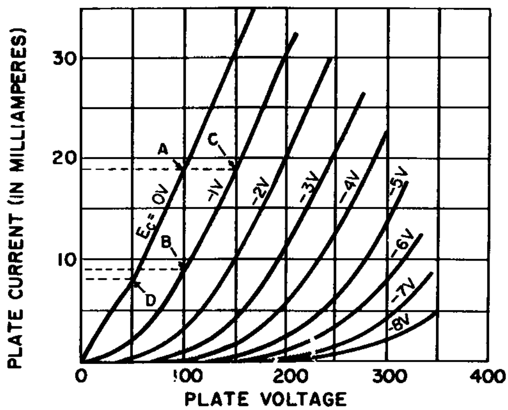


Fig. 1-4. Plate characteristic curves of a typical triode.

The second important rating factor of vacuum tubes is the *amplification factor.* It is the ratio between changes in grid and plate voltages, *when the plate current is maintained constant.* Fig. 1-4 can also be used to describe this rating factor. Suppose a line is drawn horizontally through point *A* until it intersects the next grid line, which is for a grid voltage of −1 volt. The point of intersection with this grid-voltage line has been labeled point *C*. It is evident, from the bottom scale for plate voltage, that point *C* represents a plate voltage of 150 volts. This is 50 volts greater than is represented by point *A*. Thus, a 1 volt change in grid voltage corresponds to, or has the same effect on plate current as, a 50-volt change in plate voltage. The amplification factor is the ratio of these two amounts, or:

$$\frac{50 \text{ volts}}{1 \text{ volt}} = 50$$

In other words, a tube with these values is said to have an amplification factor (μ or *mu*) of 50. This value of *mu* tells us the grid voltage is 50 times more effective than the plate voltage in controlling the flow of plate current.

The third important rating factor for vacuum tubes is a mythical quantity known as the *plate resistance,* the symbol for which is r_p. It is the resistance (in ohms) of the path between the cathode and the plate of the tube, which, of course, is not measurable with a meter. It is equal to the ratio between a small change in plate voltage and the corresponding change in plate current, *when the grid voltage is maintained constant.* This can also be understood from Fig. 1-4. The two points used to illustrate this quantity are *A* and *D,* both of which are on the same zero grid-voltage line. The change in plate current between these two points is evidently 19 − 8, or 11, milliamperes. This is read from the vertical scale at the left.

The change in plate voltage, read from the horizontal scale at the bottom, is evidently 100 − 50, or 50 volts.

These two quantities enable us to compute an approximate value of plate resistance for the particular operating conditions, as follows:

$$r_p \text{ (in ohms)} = \frac{\text{change in plate voltage (in volts)}}{\text{change in plate current (in amperes)}}$$

$$= \frac{\text{50 volts}}{\text{11 milliamperes}}$$

converting milliamperes to amperes, we have

$$r_p = \frac{50}{.011}$$

$$r_p = 4545 \text{ ohms}$$

Because of the curvature of the grid-voltage lines in Fig. 1-4, the locations of points *A* and subsequently B, C, and D will have some bearing on the exact amounts calculated for the three quantities. If point *A* had initially been positioned on a different grid-voltage line (or for a different combination of plate current and plate voltage), the *changes* in these quantities—represented by moving to points *B, C,* and *D*—will of course be different. Likewise, the calculated values of transconductance, amplification factor, and plate resistance will be changed somewhat.

Each of these quantities—*mu*, g_m, and r_p—is of great significance in the mathematics of electronic tube actions. (These mathematical considerations are beyond the scope of this book.) Transconductance (g_m) probably has the greatest everyday significance to the technician, since some tube testers are calibrated directly in transconductance. Also, any decrease below a specified level will instantly identify tubes which have "failed" (cannot deliver the proper amount of electron current from cathode to plate).

TETRODE TUBES

A refinement in vacuum-tube functions is made possible by the addition of a second grid between the control grid and plate as shown in Fig. 1-5. This screen grid, as it is called, is also a fine wire mesh. All electron current which eventually reaches the plate must pass through the grid wires.

The screen grid has two important functions:

1. Its screening action between the plate and control grid serves to isolate the voltage changes at the plate from those at the control grid, thereby preventing undesirable feedback between plate and grid.
2. It speeds up, or "accelerates," the plate-current stream flowing through the tube. In this way, electrons are prevented from accumulating around the cathode and impeding the plate-current flow. This accumulation is called *space charge.* In addition, the amount of plate current flowing is almost independent of the plate voltage, thus making a higher amplification factor possible.

To understand the screening action, it is first necessary for you to understand the nature and effects of interelectrode capacitance between the plate and control grid. In a tube, these two elements act like plates of a capacitor (capacitor action is covered in subsequent chapters). Suffice it to say here that whenever a radio-frequency voltage exists in the plate circuit, a radio-frequency current at the same frequency will also be present. During each cycle this current will drive a small quantity of electrons on and off the plate. As electrons are driven onto the plate, from its external circuit, an equal number will be driven off the control grid and into the grid circuit. Likewise, as electrons are drawn off the plate, an equal number of electrons will be drawn onto the grid from its external circuit. Thus, this feedback action induces an RF current/voltage combination in the grid circuit, with results that are generally undesirable.

Primarily because it is closer to the plate than to the control grid, the screen grid will exhibit much more capacitance to the plate. Consequently, it acts as an electrostatic shield between the plate and control grid. That is, radio-frequency voltages at the plate will in effect be isolated from the control grid. As a result, a similar RF current/voltage combination will be set up in the screen-grid circuit, where it can easily be diverted, or bypassed, to ground.

The screen grid normally is connected to a B+ supply voltage, whic is about the same value as the plate voltage; or through a

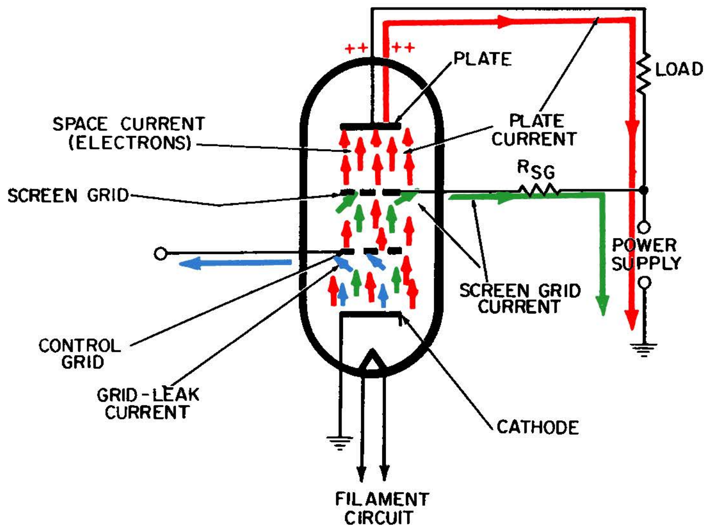


Fig. 1-5. The tetrode vacuum tube.

resistor, which results in a somewhat lower screen voltage. Because it is between the plate and the cathode, and has a high positive voltage on it, the screen grid provides an extra attraction to the electrons leaving the cathode. Thus, they are drawn away from the cathode area more easily, and in greater quantity, than if the screen grid were not there.

PENTODE TUBES

Fig. 1-6 shows the conventional symbol for the five-element tube called the *pentode.* (The filament and the connecting pins to it, required for heating the cathode, are not considered elements.) The pentode tube has three different grids between its cathode and plate. In addition to control and screen grids, (the functions of which were described for triode and tetrode tubes), the pentode has a third grid, called the *suppressor grid,* between the screen and plate.

Recall that when a high positive voltage is applied to it, the screen grid draws the electron stream toward it from the cathode, at a much higher velocity than if there were no screen grid. Most of this electron stream passes through the mesh of the screen grid and is then in position to be attracted by the high positive voltage of the plate.

Traveling at such a high velocity, these electrons will bombard the plate and discharge, or "knock off," other "secondary" elec-

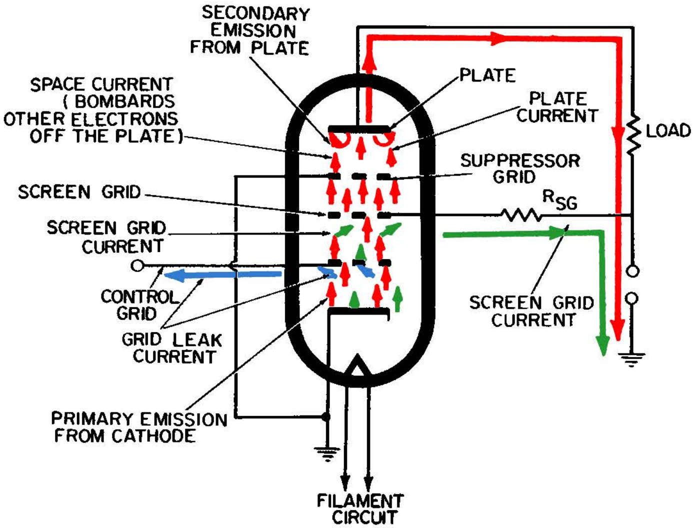


Fig. 1-6. The pentode vacuum tube.

trons. Once they have entered the open space between plate and screen grid, these secondary electrons are subjected to the positive voltages of the screen grid and plate. Under these conditions, a large percentage of the secondary electrons would probably be attracted to the screen grid and exit from the tube via it.

This phenomenon of electrons being knocked off the plate and re-entering the electron stream is called *secondary emission.* It is disadvantageous in two ways:

1. It will increase the total amount of screen-grid current, but in such an unpredictable manner that precise operation of the tubes and their circuits is very difficult.
2. It will decrease the total plate current by an equal amount and thereby largely nullify one of the principal reasons for adding a screen grid in the first place—namely, to increase the amount of plate current through the tube.

These disadvantages are circumvented by the suppressor grid between the screen and plate. The prime function of this grid is to suppress secondary emission of electrons from the plate of the tube. It is usually connected to the cathode and exhibits its same low voltage. Secondary electrons from the plate, upon entering the space between the plate and suppressor grid, will now "see" this low voltage instead of the high positive voltage of the screen grid. Therefore, the high positive voltage on the plate will exhibit a much stronger attraction for these electrons than the low suppressor grid voltage. As a result, most of them will return to the plate.

The plate-current stream must of course pass through the wire mesh of the suppressor grid. However, the electrons in this stream will be relatively unaffected by the low voltage on the suppressor grid, because their own inertia carries them beyond it. Once these electrons have moved beyond the suppressor grid, the high positive plate voltage quickly draws them to the plate.

Chapter 2

R-C COUPLED AF VOLTAGE AMPLIFIERS

The R-C coupled AF voltage amplifier circuit is one of the simplest amplifier circuits available. It is widely used for amplification of signals in the audio range, up to 10,000 or 20,000 cycles per second. The circuit goes by the name of RC amplifier, which refers to the combination of resistive load and coupling capacitor. It also is frequently referred to as a resistance-coupled amplifier.

CIRCUIT DESCRIPTION

When a signal voltage of a given amplitude (strength) is impressed on the control grid (input circuit), a signal voltage of larger amplitude will be delivered in the plate circuit, or output circuit. The accompanying diagrams portray the essential circuit actions occurring in two successive half-cycles. Fig. 2-1 depicts current (electron) flow conditions *during* an entire half-cycle of the signal which will be referred to here as a negative half-cycle; and also the instantaneous-voltage conditions at the midpoint of that same half-cycle.

Fig. 2-2 depicts the same current flow for the *entire* second half-cycle, and the voltage conditions at the midpoint of the second half-cycle. This, we will call the positive half-cycle.

The circuit components for the resistance-coupled AF voltage amplifier are:

R1—Grid load resistor for V1.
R2—Cathode biasing resistor.
R3—Plate load resistor.
R4—Grid load resistor for following stage.
C1—Cathode bypass capacitor.
C2—Coupling capacitor to following stage.
V1—Triode amplifier tube.
M1—Power supply.

There are three main currents at work in the circuit. Each has been shown in a separate color in Figs. 2-1 and 2-2. They are:

1. Grid-driving current for stage (blue).
2. Plate currert of the tube (red).
3. Grid-driving current for following stage (green).

The first current, flows in the input circuit and is called the grid-driving current (blue). It is directly associated with the *grid-driving voltage* (also shown in blue), a more common term than *grid-driving current* in discussing tube operation.

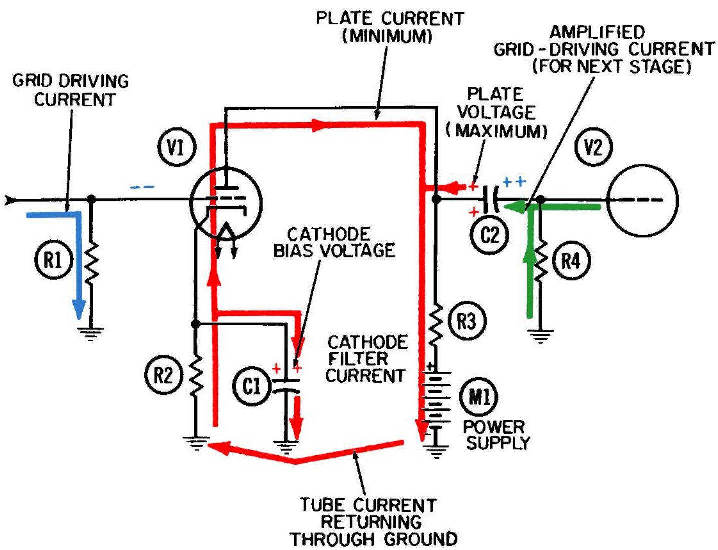


Fig. 2-1. The R-C coupled audio amplifier—negative half-cycle.

The second current is the unidirectional tube current, shown in red and called the *plate current.* The current which flows into and out of output coupling capacitor C2 and the cathode filtering current are also shown in red because of their dependence on the unidirectional tube current.

The final current, which is actually flowing in the next tube circuit and is not intrinsically a part of the RC amplifier, is the grid-driving current for the next tube stage. It is shown here (in green) to make easier the comparison between input and output voltages and thereby further clarify the term *amplification.*

Undoubtedly the most important single characteristic of vacuum tubes having control grids is their ability to amplify voltages. The valving, or throttling, action of the control grid within the tube makes it possible for small voltage changes impressed on the control grid to cause fairly large changes in the amount of electron current flowing through the tube. These large changes in tube current can then be made to generate larger voltage changes in the plate circuit. The output voltage should faithfully reproduce

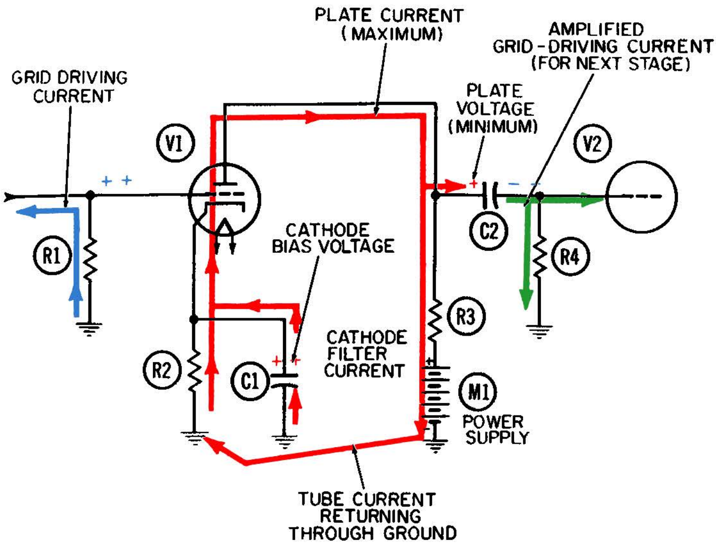


Fig. 2-2. The R-C coupled audio amplifier—positive half-cycle.

the waveshape of the input voltage, with no distortion. However, this goal is not always attained. The degree to which this is achieved determines the fidelity of the circuit.

CURRENT FLOWS

In Fig. 2-1, a small electron current is shown, in blue, flowing downward through the grid resistor R1. The control grid will be at its maximum negative voltage when maximum current is flowing downward through the grid resistor. Since Fig. 2-1 represents an entire half-cycle, the moment of maximum negative grid voltage occurs roughly near the midpoint of this half-cycle. The unidirectional tube current, shown in red, will be throttled down to its minimum value by this negative grid voltage.

The second diagram shows this grid-driving current flowing upward through resistor R1, in response to the positive voltage impressed from the external circuit. The maximum flow rate, and the resultant maximum positive voltage at the grid, will occur roughly at the midpoint of the second half-cycle. The unidirectional tube current will then flow at its maximum value.

If no signal voltage were applied to the grid, the tube current (plate current) would flow in a steady stream through the path indicated—that is, up from ground through cathode resistor R2, through the tube, downward through plate-load resistor R3 and the power supply to ground, then back to the cathode resistor. This is the *quiescent,* or static, operation of the tube. When a small signal voltage imposes fluctuations on the electron stream through the tube, these fluctuations develop larger voltage variations in the plate circuit, and the input signal is considered to be amplified.

This amplified signal voltage can perhaps best be explained by referring to Fig. 2-2. The increase in plate current (due to the positive grid voltage) is causing electrons to be dammed up at the entrance to plate-load resistor R3. These electrons are shown pouring onto the left-hand plate of the coupling capacitor C2, thereby reducing the positive voltage stored on that plate. At the same time, on the other side of this coupling capacitor, electrons are being driven away from the capacitor and downward through R4, the grid resistor for the next tube stage. (This is the current shown in green). Thus, we can see that a *phase shift* has occurred in this amplifier stage, for when the first grid is at maximum positive voltage, the second grid is at its maximum negative voltage.

The voltage on the left side of coupling capacitor C2 does not actually become negative, but varies between low and high values of positive voltage. To indicate this, the two red plus signs at this point in Fig. 2-1 have not been replaced by minus signs, but are merely changed to a single plus sign to signify the reduction in voltage caused by the additional electrons from the plate-current stream.

Simultaneously with this action, more electrons will flow through plate-load resistor R3 toward the power supply, causing an increased voltage drop across this resistor. Since the voltage at the lower end is fixed (being connected directly to the power-supply voltage), this increased voltage drop across the load will be evidenced by a decrease in the positive voltage at the top of resistor R3.

Thus we have two means of associating a drop in plate voltage with an increase in plate current. One is by the inflow of electrons into coupling capacitor C2, neutralizing an equal number of positive ions there. The second is by the increased electron flow through load resistor R3.

Fig. 2-1 depicts the half-cycle when the tube current is restricted by the negative grid voltage. Minimum plate current is indicated during this period. This decrease in current affords an opportunity for the low positive voltage on the left plate of C2 to build up again. Electrons will now be drawn out of this capacitor and toward the power-supply voltage. As they depart, there is an attendant increase in the number of positive ions remaining at this point and the voltage increases to a higher positive value.

This departure of electrons from the left plate of the coupling capacitor draws an equal number of electrons upwards through the grid resistor and onto the right plate (shown in green).

Thus, we have two means of visualizing that the voltage changes imparted to the grid of the next tube will duplicate, or *follow*, the voltage changes in the plate circuit of the amplifier stage. When electrons flow downward through R4 (green in Fig. 2-2), we know that the top of R4 is more negative than the bottom, or ground. This action coincides with the period of increased tube current which, as mentioned, has reduced the positive plate voltage.

CATHODE CIRCUIT

In the cathode circuit, capacitor C1 functions as a filter to prevent degeneration. The resulting filtering current is being driven by the fluctuations in demand for electrons at the cathode. In the Fig. 2-1, the control grid is negative, so the demand for electrons to enter the tube is not great. However, since the upper plate of the capacitor is already charged to a positive voltage, this voltage will draw electrons upward through cathode resistor R2. During the first half-cycle they are shown flowing onto the upper plate of the capacitor and of course neutralizing some of the positive ions there which make up the positive voltage on the cathode.

During the second half-cycle (Fig. 2-2) when the control grid is positive, the demand for electrons in the plate current stream is greatly increased. This bigger demand is supplied by free electrons from the upper plate of the capacitor. The departure of these electrons naturally creates additional positive ions on the capacitor plate.

These changes in the quantity of positive ions naturally would indicate a change in the positive voltage at the cathode. However, normal amplifier operation requires an unchanging cathode voltage. The answer to this apparent paradox lies in the *amount* of voltage change which occurs because of this regular inflow and outflow of electrons. To determine the amount of voltage change, a factor known as the time constant must be considered.

Time Constant

The time constant of a circuit is the time required by a resistance-capacitance combination to complete 63.2% of its charging or discharging action. Numerically, the time constant is equal to:

$$T = R \times C$$

where,

T is the time in seconds,
R is the resistance in ohms,
C is the capacitance in farads.

Any RC combination is defined as a "long time-constant" circuit when the value of T is "long" (five or ten times as long), compared with the time which elapses during one cycle of the frequency under consideration, and as a "short-time constant" circuit if significantly (five or ten times) shorter than the frequency under consideration.

Thus, if we make the time constant of the resistor-capacitor combination in the cathode circuit (C1 and R2 in Figs. 2-1 and 2-2) long, it will provide a relatively constant voltage at the cathode. If the signal frequency is 1,000 cycles per second, then the time required for one cycle is .001 second. Thus the time constant of this combination should be at least .005 seconds. Any combination of resistor and capacitor values whose product exceeds .005 second would theoretically meet this requirement. However, one additional consideration, which virtually dictates the size of the resistor, is the amount of positive voltage wanted at the cathode (cathode biasing voltage). Since all the tube current is going to pass through the cathode resistor, we can calculate by Ohm's law what size of resistor we would need, with a given optimum tube current, to achieve the desired cathode bias voltage.

Ohm's Law

Ohm's law states that the voltage developed across a resistor is proportional to the current through it, or:

$$E = I \times R$$

where,

E is the voltage developed, in volts,
I is the current in amperes,
R is the resistance in ohms.

Any capacitor plate which is charged to a negative voltage can be looked upon as an electron pool, since electrons in concentration constitute a negative voltage. Likewise, when charged to a positive voltage (as is the upper plate of C1 in this example), a capacitor plate can be considered an ion pool.

The amount of voltage in any such charge is directly proportional to the quantity of electrons or ions which are so concentrated. This is expressed by Coulomb's law, which states that:

$$Q = C \times E$$

where,

Q is the quantity of charge in coulombs,
C is the capacitor size in farads,
E is the voltage.

One coulomb equals slightly more than half a trillion *trillion* electrons (6.25×10^{18}, to be exact!). A coulomb of positive charge equals the same number of positive ions.

Filter Action

As indicated before, the actual number of electrons entering the tube is determined primarily by the construction of the tube, as is the size of the variations in this electron stream which are imposed by the alternating signal voltage. The size of the tube-current variations determines the quantity of electrons which actually flow onto the upper plate of capacitor C1 during the first half-cycle and off it during the second. If the quantity of positive ions already stored there (which represent the positive cathode voltage) is substantially greater than the number of electrons which flow in during the first half-cycle, the positive cathode voltage will not be appreciably affected. But if the electrons flowing in and out of the capacitor during each cycle is a significant fraction of the total number of ions stored there, the ion level will rise and fall, and the positive cathode voltage, being dependent on the ion level, will rise and fall too.

As an example, suppose the desired cathode voltage is +10 volts and the number of electrons flowing in during the first half-cycle is exactly 1% of the number of positive ions stored there. Then the cathode voltage would be reduced by 1%, or 0.1 volt, thereby making its value 9.9 volts on this half-cycle. On the second half-cycle, with the same number of electrons leaving the capacitor, the stored voltage would again increase to the full 10 volts.

Filtering is completed by allowing current to flow between the lower plate of the filtering capacitor and ground. This current, shown in red, is driven downward during the first half-cycle by the inflow of electrons to the top plate, and upward during the second half-cycle by the outflow of electrons going toward

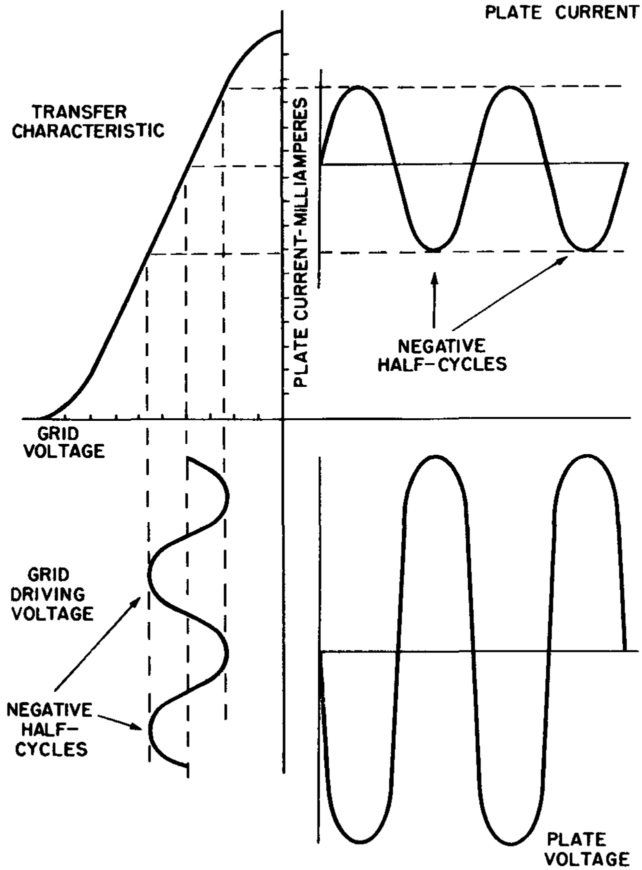


Fig. 2-3. Grid and plate waveforms for an R-C coupled audio amplifier.

the cathode. The electrons flowing along this path will always equal in quantity the electrons flowing to or from the other side of the capacitor. If this current were restricted somehow from flowing, filtering could not be done.

The variation in cathode voltage, as a result of the changes in tube current, is a measure of the degeneration which occurs. In other words, degeneration reduces the total amplification the tube can deliver.

WAVEFORM ANALYSIS

Fig. 2-3 is the conventional waveform diagram for relating the grid-driving voltage, the biasing or reference voltage, and the

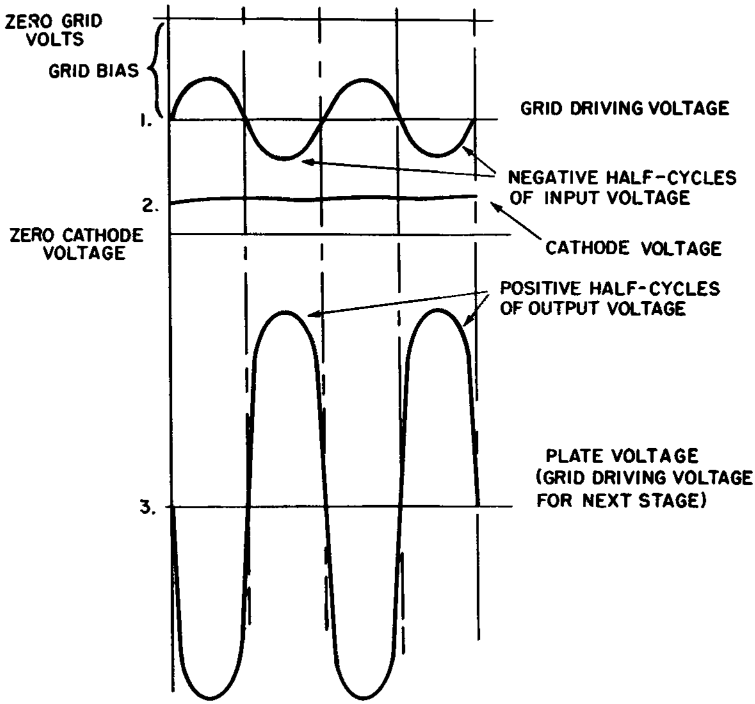


Fig. 2-4. Relationship between grid, cathode, and plate voltages in an R-C coupled audio amplifier.

plate current. This relationship is achieved by means of the transfer characteristic curve of the tube.

For any instantaneous grid voltage, a line projected vertically to the transfer characteristic curve and thence horizontally to the plate-current scale will indicate in milliamperes the resulting plate-current flow.

The plate-voltage sine wave is given below the one for the plate-current. Of special interest is the fact that when plate current is maximum, plate voltage is minimum, and vice versa. This illustrates the phase shift which occurs between grid and plate voltages in most vacuum tubes. When the grid voltage is most negative, the plate voltage is most positive; when the grid voltage is least negative, the plate voltage is least positive.

Fig. 2-4 shows this phase relationship between input and output voltages more clearly. The cathode voltage has also been shown in Fig. 2-4. Notice that it is essentially a flat line, increasing very slightly during those half-cycles when the tube conducts most heavily.

Response Curve

Fig. 2-5 shows a conventional frequency-response curve for a resistance-coupled amplifier. Below 100 cycles per second (cps). the response of the amplifier falls off because the signal is attenuated, or "consumed," by coupling capacitor C2. Capacitive reactance varies inversely with the frequency of the applied signal, in accordance with the standard formula:

$$X_C = \frac{1}{2\pi fC}$$

where,

X_C is the capacitive reactance in ohms,
f is the frequency in cycles per second,
C is the capacitance in farads.

Thus, at very low frequencies the coupling capacitor will couple, or "pass," only a small portion of the available signal from the plate circuit of the tube to the grid circuit of the next tube, and will attenuate most of the signal as it passes through.

The response of an amplifier circuit is a measure of how well it amplifies a voltage at any particular frequency. The response

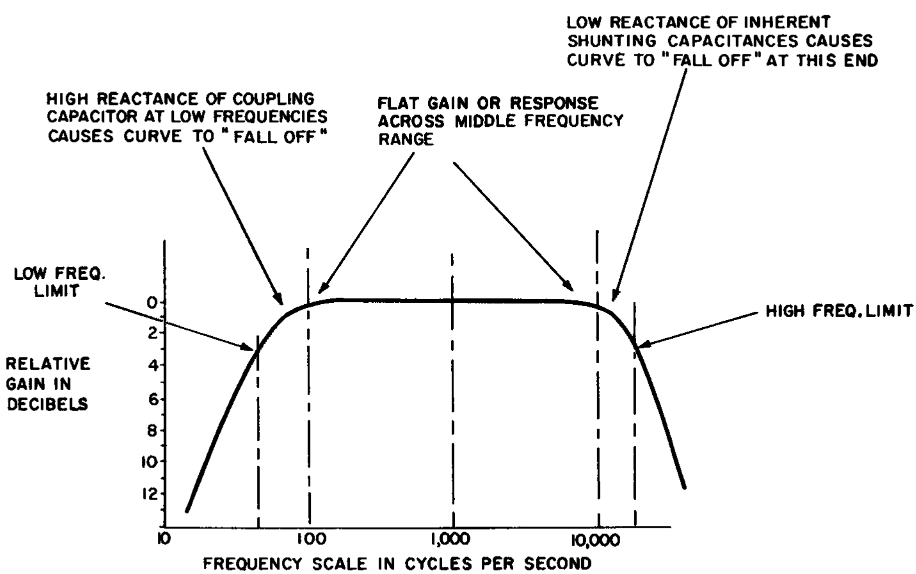


Fig. 2-5. An R-C coupled audio amplifier response curve.

curve is a means of comparing how well it responds to, or amplifies, voltages at any frequency within the range of the amplifier. The curve will also indicate the frequency limits within which the amplifier is designed to operate. It is very important in design consideration that an amplifier response curve be flat and that the sides be as steep as possible. A flat response curve indicates that the circuit will provide equal amplification for applied voltages of any frequency within its range. An amplifier which did otherwise would provide very poor sound reproduction indeed.

The high-frequency limit of operation for a resistance-coupled amplifier is determined by the interelectrode capacitances of both tubes and by the distributed or wiring capacitances of the entire circuit. Fig. 2-6 shows the equivalent circuit of the RC amplifier in Figs. 2-1 and 2-2. The cathode, grid, and plate of the next succeeding triode stage have been added in Fig. 2-6 because they have a definite bearing on the high-frequency limit of operation.

Three different currents are shown passing simultaneously through the amplifier tube:

1. Low-frequency current, (green)
2. Medium-frequency current, (red)
3. High-frequency current, (blue)

Let us define these terms. The low-frequency current is one having a frequency *lower* than the low-frequency limit of the

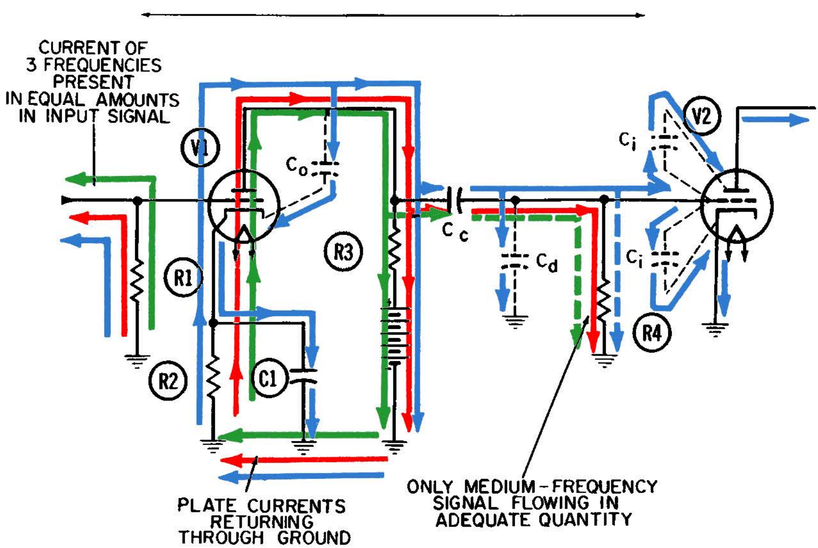


Fig. 2-6. Current flow at low, medium, and high frequencies in the R-C coupled audio amplifier—positive half-cycle.

response curve in Fig. 2-5, and the high-frequency current is one having a frequency *higher* than the high-frequency limit. Each of these limiting points is defined as being the point at which the amplifier response has fallen 3 decibels from the response achieved across the flat area of the curve.

It should be assumed that equal amplitudes or amounts of each of these three frequency components are applied at the input point, meaning the control grid of the first tube, V1. These three components of current are all shown as flowing upward through grid driving resistor R1 in Fig. 2-6. Since the frequencies of these three currents are drastically different, the time durations, or "periods," for single cycles at the three frequencies will differ greatly from each other. Consequently, the actual condition depicted in Fig. 2-6, where the three currents appear to be flowing in phase with each other through the grid resistor, would be achieved only rarely. There is an infinite variety of combinations when three such currents of three widely separated and variable frequencies can be somewhat out of phase with each other. But there is only one combination when they can all reach their maximum amplitude, in the same flow direction, at the same instant, thereby being truly in phase with each other as depicted in Fig. 2-6.

As an example, consider the following possible frequencies and resulting periods for one cycle of each of the three currents. The period of a sine wave is related to the frequency by the formula:

$$T = \frac{1}{F}$$

where,

T is the time for one cycle in seconds,
F is the frequency in cycles per second.

Current	*Frequency, F*	*Time for One Cycle, T*
Low Frequency	50 cps	.02 sec.
Middle Frequency	1,000 cps	.001 sec.
High Frequency	20,000 cps	.00005 sec.

In addition to the normal "manufactured" circuit components in Fig. 2-6, there are inherent characteristics which place the upper limit on the frequency response of a resistance-coupled amplifier like this one. These inherent characteristics include:

1. The output capacitance of amplifier tube V1. This is shown in dashed lines between the plate of V1 and its cathode, and is labeled C_o.

2. The distributed capacitance between all the wiring of the circuit and the nearest ground points. This is normally shown in equivalent circuits as a single, or "lumped," capacitance and is labeled C_d.
3. The input capacitance of the next amplifier stage. This consists of the inherent interelectrode capacitance between the control grid, and the cathode and plate of the next amplifier stage (designated C_i in Fig. 2-6).

Let us consider now what effects these inherent capacitances may have on the passage of currents at the three chosen frequencies—low, intermediate, and high.

Low-Frequency Limitation

The primary limitation on the passage of low-frequency currents is the reactance of the main coupling capacitor, labeled C_c in Fig. 2-6. Because of the excessive reactance which all capacitors exhibit at low frequencies, only a very small portion of the available low-frequency current can enter this capacitor. An equally small portion of current, at the same low frequency, will be driven out of the opposite plate and be available to flow downward through the grid-driving resistor for the next stage labeled as R4 in Fig. 2-6).

The amount of grid-driving voltage developed at any frequency depends on the amount of current, at this same frequency, which can be made to flow through the grid-driving resistor. In Fig. 2-6 the low-frequency current flowing in the circuit to the right of capacitor C_c is in dashed green lines to indicate the severe attenuation it suffered in getting through the coupling capacitor.

The classical method of verifying the extent of this attenuation is to calculate the reactance of the capacitor at the particular frequency, and to compare it with the resistance of the grid driving resistor, since these two components comprise the complete path of this current. At the low frequency of fifty cycles per second, the reactance of capacitor C_c will be *twenty times as great* as it is at 1,000 cps, and *two hundred times as great* as it is at 10,000 cps. (Reactance, of course, is the measure of a capacitor's *opposition to electron flow.*) At 50 cps the coupling reactance so greatly exceeds the grid resistance that most of the low-frequency signal is lost in the capacitor.

Middle-Frequency Current Passage

The middle-frequency current, shown in red in Fig. 2-6, can have any frequency in the entire middle range between the low- and high-frequency limitations shown in Fig. 2-5. In passing through the coupling capacitor, the current has only insignificant losses. Most of it is available to flow up and down through R4 (on alternate half-cycles, of course) and develop grid-driving voltage for tube V2. The inherent capacitances (C_d and C_i) have small values, on the order of 10 micromicrofarads each; consequently, their reactances are prohibitively large throughout the entire range of low and middle frequencies, and little or none of the signal currents bleed off at these frequencies.

High-Frequency Limitations

The range of higher audio frequencies is where the inherent capacitances of vacuum tubes and their circuitry limit the operation of audio-frequency amplifiers. The reason is that excessive quantities of the available current are bled off, leaving little or none to flow through grid resistor R4 and develop driving voltage for the next stage. The high-frequency currents are indicated in blue in Fig. 2-6. We see that some portion of the high-frequency currents are bypassed back to the cathode of tube V1 by the output capacitance, C_o, of the tube. At the high frequencies this action reduces the amount of signal current available for coupling across C_c to the next stage.

The signals suffer no intrinsic loss at the higher frequencies as they pass through coupling capacitor C_c, since the reactance of all capacitors decreases as the frequency increases. It is thus possible to say that there is negligible voltage drop, or only slight attenuation of its voltage, as the signal is passed through the coupling capacitor.

That portion of higher-frequency current which succeeds in getting through coupling capacitor C_c, finds four alternate paths available to it, all in parallel. Consequently the current will divide into four parts, the amount going to each part being inversely proportional to the impedance offered by each particular path. Only the current which manages to flow up and down through grid resistor R4 will develop driving voltage for the next stage; the other three are losses.

The distributed, or wiring, capacitance of the circuit has been represented by the simulated capacitor C_d. In Fig. 2-6 we see the high-frequency current flowing freely into this simulated capacitor and thus being bypassed to ground. This is the first of the three loss currents referred to in the previous paragraph.

The second loss current flows directly into the interelectrode capacitance between the control grid and cathode of tube V2. In Fig. 2-6 a component of high-frequency current is shown flowing between the cathode and the ground connection. This component is driven by the current flowing toward the control grid from the coupling capacitor, but contributes nothing to the operation of amplifier V2.

The third loss current associated with this amplifier stage flows in the interelectrode capacitance between control grid and plate. In Fig. 2-6 a component of this loss current is shown flowing *away* from the plate, since it is being driven by the electrons flowing toward the grid from the coupling capacitor. This current also contributes nothing to the operation of the amplifier stage.

Fig. 2-7 shows the equivalent circuit of Fig. 2-6, but redrawn with only the high-frequency currents flowing, since the inherent

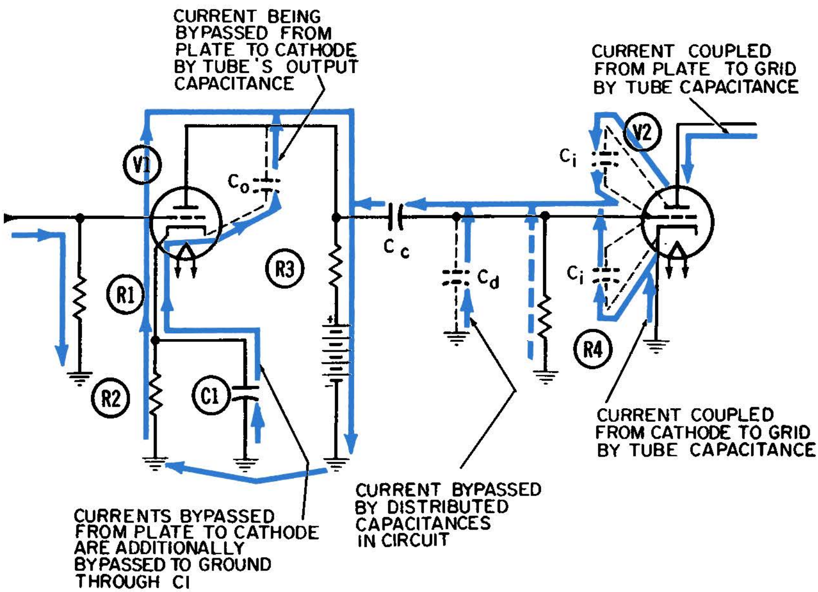


Fig. 2-7. Equivalent circuit at high frequencies in the R-C coupled audio amplifier—negative half-cycle.

capacitances discussed earlier are significant at the higher frequencies only. The flow directions of currents in Fig. 2-7 are the reverse of those in Fig. 2-6. Fig. 2-6 represents conditions during a positive half-cycle of operation, and Fig. 2-7 represents a negative half-cycle.

Therefore, in Fig. 2-7 the high-frequency signal current is flowing *downward* through resistor R1, making the control grid of tube V1 negative. As a result, the plate current through tube

V1 is reduced and the plate voltage rises. Some portion of the high plate-voltage peak, which would otherwise have been obtainable, will be lost. The reason is that the shunting effect of output capacitance of the tube permits some instantaneous electron current to be drawn *upward* from the upper plate of C_0. These additional electrons reduce the positive plate-voltage peak somewhat, and consequently are another loss current when the circuit is operated at high frequencies.

As the plate voltage rises (Fig. 2-7) and falls (Fig. 2-6), this loss current flows alternately up and down fairly freely, bypassing some of the high-frequency voltage back to the cathode. From here it has an easy bypass path through cathode filter capacitor C1 to ground.

The rise in plate voltage in Fig. 2-7 also draws current onto the right plate of coupling capacitor C_c. If there were no shunting capacitances to worry about, all of this current would be drawn upward through grid resistor R4 and a maximum positive voltage peak for application to the control grid of tube V2 would be developed across R4. In reality, some current will be drawn through each of the inherent capacitances and only a small remainder will flow upward through the grid resistor. This explains why all three loss currents are now flowing *toward* coupling capacitor C_c, instead of away from it as in Fig. 2-6.

FEEDBACK

Often, the output waveform will be distorted, that is, it will not be an accurate reproduction of the input waveform. Feedback is often employed to compensate for any distortion introduced by the circuit and to extend the frequency response of the amplifier.

Figs. 2-8 and 2-9 depict two successive half-cycles in the operation of a two-stage resistance-coupled amplifier which utilizes both negative and positive feedback. The positive feedback is achieved by coupling the plate voltage from the second stage back to the control grid of the first stage. The negative feedback is achieved through the degeneration process, by leaving the cathode resistor for the tube unfiltered, or unbypassed. Let us examine these two important actions in more detail. In order to do so, it will prove desirable to review the actions occurring in the entire circuit.

The essential components of this two-stage amplifier are:

R1—Grid input resistor for V1.
R2—Grid input and feedback resistor.
R3—Voltage-divider resistor used in feedback path.

R4—Cathode resistor used for developing negative feedback.
R5—Plate-load resistor for tube V1.
R6—Grid driving, or input, resistor for V2.
R7—Cathode biasing resistor for V2.
R8—Plate-load resistor for V2.
R9—Grid-driving, or input, resistor for next stage.
C1—Coupling capacitor between stages.
C2—Cathode filter capacitor for V2.
C3—Feedback capacitor.
C4—Output coupling capacitor to next stage.
V1 and V2—Triode amplifier tubes.
M1—Common power supply for both tubes.

There are seven electron currents operating in this circuit:

1. Three grid driving currents (green).
2. Two plate currents (solid red).
3. One positive feedback current (blue).
4. One cathode filter current (dotted red).

Analysis of Operation

By inspection of Fig. 2-8 we see that at the end of the first half-cycle, the control grid of V1 is positive, the control grid of V2 is negative, and the control grid of the next succeeding amplifier stage is positive. These voltage polarities reflect the normal 180° phase shift between the control-grid and plate voltages in an R-C vacuum-tube stage. Since the control grid of the second tube, V2, reaches its most negative value at the end of the first half-cycle, the plate current through this tube will be reduced to its minimum value and its plate voltage will rise to its maximum positive value. This rise in plate voltage is coupled into the feedback network by drawing electrons off the right plate of feedback capacitor C3. As these electrons flow out of the capacitor, toward the power supply, they draw an equal number upward from ground and through voltage divider R2-R3.

This upward flow of electrons makes the voltage at the bottom of resistor R1 positive with respect to ground; this instantaneous feedback polarity is indicated by a blue plus sign. The instantaneous grid voltage for the first tube, V1, is also positive as a result of the grid driving current. Consequently, the sum of these two positive voltages will be a higher voltage at the grid than the input-signal voltage can provide by itself. Because these two voltages are in phase, the feedback voltage (in blue) *reinforces* the signal voltage (in green) and the feedback is said to be positive.

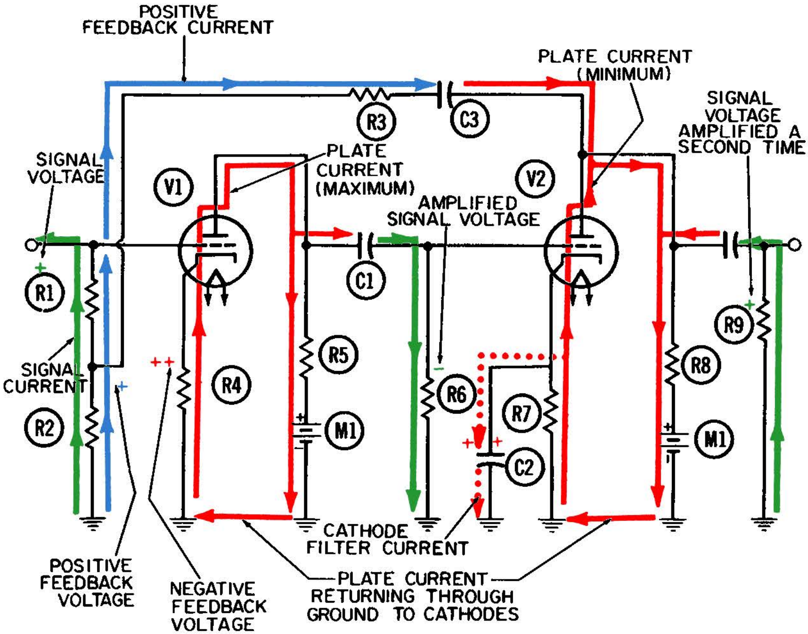


Fig. 2-8. An R-C coupled audio amplifier utilizing both positive and negative feedback—positive half-cycle.

This type of feedback is called voltage feedback, since it is in parallel with the plate voltage and in effect is driven by changes in the latter.

During the second half-cycle (Fig. 2-9), the control grid of V2 becomes positive, releasing a large amount of plate current through that tube and thus lowering its plate voltage. This reduction in plate voltage is coupled into the feedback network. It is convenient to visualize this action as consisting of the excess plate-current electrons pouring *onto* the right plate of capacitor C3, until they can be drawn through load resistor R8 to the power supply. As the electrons enter C3 they drive an equal number off the left plate of the capacitor, and downward through voltage-divider network (R3-R2) to ground. This downward flow of electrons tells us the resulting voltage at the top of resistor R2 must be negative with respect to ground, since electrons will always flow *away* from a negative voltage, to a less negative or a more positive voltage. This instantaneous feedback-voltage polarity has been indicated by a blue minus sign.

The alternating grid voltage for V1 is also negative at this instant, as a result of the downward flow of grid driving current

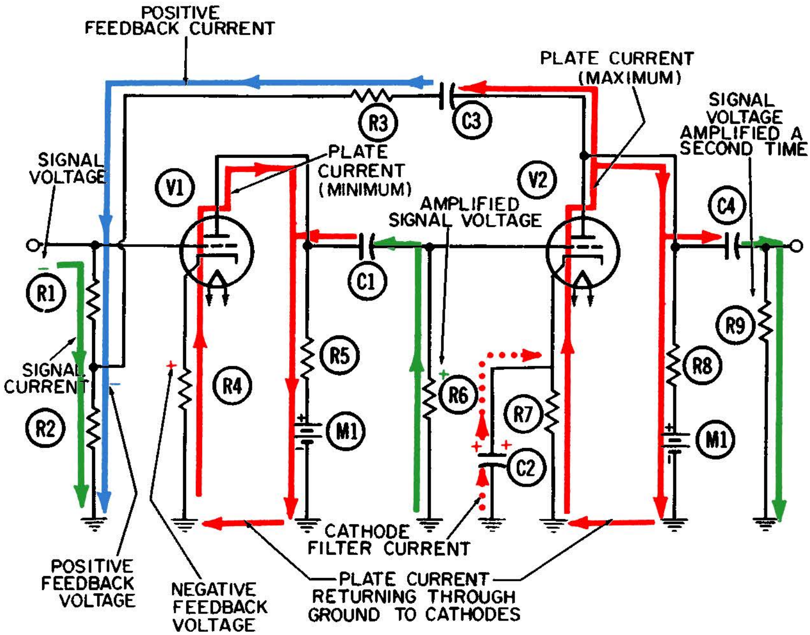


Fig. 2-9. An R-C coupled audio amplifier utilizing both positive and negative feedback—negative half-cycle.

through resistors R1 and R2. Since these two voltages are now both negative, their sum is a higher negative voltage at the grid than the driving signal can achieve alone. Looking at the results from both half-cycles, we see that the feedback voltage reinforces the signal voltage during the whole cycle. This logically gives rise to its designation as *positive feedback*.

Current Feedback

During the first half-cycle in Fig. 2-8, the positive grid voltage on V1 releases a large amount of plate current through this tube. This plate current flowing upward through resistor R4 to the cathode produces positive voltage (indicated by the plus signs) at the cathode.

When the control grid V1 is negative (Fig. 2-9) the plate current through the tube decreases. This causes a smaller voltage drop to be produced across the cathode resistor, and thereby lowers the positive voltage at the cathode. The result of these two actions is a continual *fluctuation* in the cathode voltage—rising when the grid voltage goes positive, and falling when it goes negative.

An *increase* in the positive voltage at a cathode has the same effect as a *decrease* in grid voltage—namely, the amount of plate current flowing across the tube is restricted. The reason for this behavior is that the cathode "recaptures" some of its own electrons after initial emission occurs. This recapturing process comes about in the following manner: When an electron is first emitted into the tube, it "sees" or "feels" (is subject to) whatever voltage exists on any electrode. The high positive plate voltage will try to attract the electron across the tube. A positive voltage at the grid, indicated in Fig. 2-8, will encourage this process, by allowing a large number of electrons to flow from cathode to plate, resulting in a heavy plate current. However, as the cathode voltage becomes more positive, it will tend to reattract the emitted electrons after emission. The cathode has two advantages over the other electrodes—(1) the instant after emission, the electron is *closer* to the cathode than to any of the other electrodes, and (2) the electron has not yet had the opportunity to build up any velocity as it travels away from the cathode. Consequently, even a slight increase in positive voltage at the cathode causes many of the emitted electrons to fall back onto the cathode, making fewer electrons available for plate current.

In the example of Fig. 2-8, the increase in the cathode voltage nullifies part of the effect of the positive voltage applied to the control grid by the input signal. Recall that the definition of instantaneous grid bias is the instantaneous *difference* in voltage between the grid and cathode of a tube. It is this difference between the two voltages that determines what portion of the emitted electrons will be permitted to cross the tube and become plate current.

In Fig. 2-9 we find an opposite set of conditions. The negative voltage at the grid of a tube will tend to repel most of the emitted electrons back to the cathode. However, since the positive cathode voltage has now been reduced, the cathode exerts less attraction for these electrons and so partially counteracts the negative grid voltage.

This is classified as a form of negative feedback since these continuing changes in the voltages at grid and cathode are "out of phase" with each other. Here the term "out of phase" refers to the *effects* of changing each of the two voltages, rather than to changing their polarities. Viewed in this light, a rise in the positive grid voltage is *out of phase* with a rise in the positive cathode voltage.

This type of negative feedback has the more familiar title of *degeneration.* The obvious result of degeneration is some loss in the amplifying capability of the circuit. Degeneration is usually avoided by the addition of a filter capacitor of suitable size across the cathode resistor, to make a long time-constant combination. This is why capacitor C2 and resistor R7 are in this circuit.

This type of feedback is also classified as *current feedback,* because the feedback voltage is developed directly by the plate-current stream flowing through the cathode resistor. It is an interesting anomaly, and one which may provide some confusion, that a separate "feedback current" does not exist as such. In the voltage-feedback example discussed previously, a feedback current has to flow through the voltage-divider network (R2-R3) in order for the necessary feedback voltage to be developed. Often, voltage feedback is used for the negative feedback circuit, too. Such a feedback circuit is discussed in the next chapter in conjunction with the transformer-coupled AF amplifier and could be used equally well in an R-C coupled circuit.

There is nothing unique about the remaining operations in the circuit. Each of the grid driving currents (shown in green) develops a larger, or more amplified, version of the signal voltage than the one at the preceding stage. That is, the alternating voltage across resistor R9 is greater than the voltage across R6, and the latter in turn is greater than the voltage developed across R1 and R2.

AMPLITUDE DISTORTION

Fig. 2-10 is the transfer characteristic curve of a typical triode tube. Note that it is similar to the curve of Fig. 2-3. Two cycles of input (grid) voltage are shown, along with the resulting two cycles of output (plate) current. Cycle A, which is similar to the grid driving cycle of Fig. 2-3, causes the tube to operate along the linear portion of the curve. Being a fairly faithful reproduction of the input waveshape, the resulting plate current is considered to be distortionless.

Cycle B is large enough to make the tube operate at *both* ends of the transfer characteristic curve. Because the curve is nonlinear at both ends, each half-cycle of Cycle B is badly distorted. Likewise, if *either* half-cycle of grid voltage drives the tube into one of the nonlinear portions of the curve, the resulting distortion would occur on that half-cycle only, but would still be unacceptable. This could happen if the grid-bias voltage were too small for Cycle A. Then, the grid-bias line would shift to the right, and the positive half cycles of plate current would be distorted. Alternatively, the negative half-cycles would be distorted if the grid-bias voltage were too large (shifting the grid-bias voltage line to the left).

PHASE DISTORTION

Fig. 2-11 shows two voltage sine waves of different frequencies, both before and after passing through an amplifier (such as the resistance-capacitance amplifier of Fig. 2-9). The purpose in showing these sine waves is to demonstrate the meaning of phase distortion.

Recall that for each stage of amplification, the signal should be inverted; that is, the output waveform should be 180° out-of-phase with the input. Therefore, in the two-stage amplifier of Fig. 2-9, the signal should be inverted twice or shifted 360°—a complete cycle. Hence, the output voltage waveform should be exactly in phase with the input waveform. Often, in passing through an amplifier, some frequencies will not be shifted exactly 180° in phase.

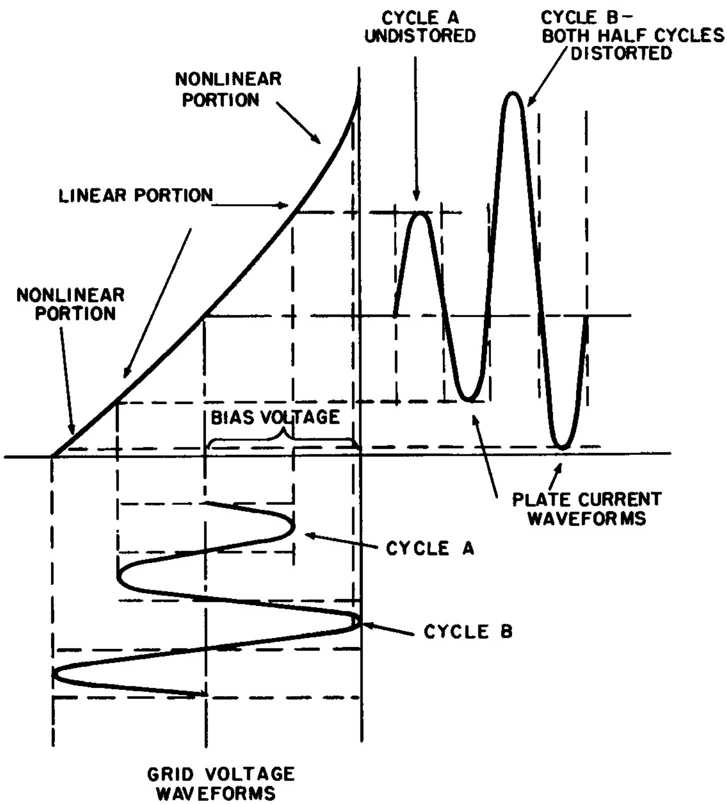


Fig. 2-10. How amplitude distortion is introduced when tube is operated on nonlinear portion of transfer characteristic curve.

Phase distortion occurs in an amplifier when currents or voltages of some frequencies suffer only a negligible variation from the normal phase inversion, whereas currents or voltages of other frequencies suffer a somewhat greater shift in phase.

In lines 1 and 3 of Fig. 2-11, the high-frequency voltage "in" has the same phase as the high-frequency voltage "out." This means the two voltages achieve their peak values, pass through zero, etc., at the same moment. These conditions tell us that no phase shift has occurred in this particular voltage during amplification. However, lines 2 and 4 show that the low-frequency voltage "in" is not in phase with the low-frequency voltage "out"; the latter has been shifted 90°, or a quarter of a cycle, in phase. This means the output voltage achieves its peak value a quarter of a cycle later than the input voltage.

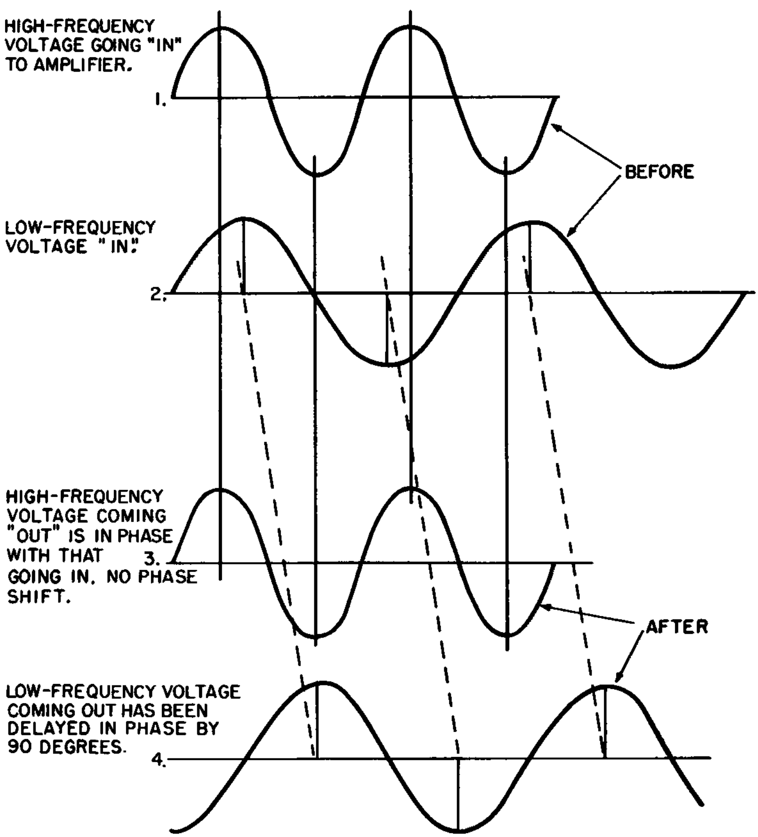


Fig. 2-11. The effect of phase distortion on a waveform.

Phase distortion normally is not a serious problem in the reproduction of sound because the ear cannot detect it. A moment's reflection will clarify why this is so. When we listen to a sustained chord of music we are listening to several tones of different pitches, each of a different frequency. Assume the low-frequency sound represented by the voltage waveforms of lines 2 and 4 is middle *C*, which has a frequency of 256 cycles per second. A 90° shift in phase means we will now hear each peak *about a thousandth of a second later*. Obviously, much greater phase differences, amounting to many whole cycles, can be created by the artist without noticeably degrading the over-all result.

Phase distortion is a more serious problem in the amplification of complex waveshapes. These usually represent the algebraic sum of many simple shapes, such as sine waves of many frequencies. If some (but not all) of these subordinate waveshapes have undergone shifts in phase, the resultant waveshape in the output is likely to look entirely different from the input waveshape.

Chapter 3

TRANSFORMER-COUPLED AF VOLTAGE AMPLIFIERS

Transformer coupling, while not as popular as R-C coupling discussed in the previous chapter, is sometimes used between AF voltage amplifiers. The chief disadvantage of transformer coupling is the high cost of a transformer which will provide the required frequency response.

CIRCUIT DESCRIPTION

Figs. 3-1 and 3-2 show two successive half-cycles in the operation of an audio voltage amplifier, in which two adjacent amplifier stages are linked together by means of an audio frequency transformer. The components which make up this circuit are as follows:

R1—Grid-driving and grid-return resistor.
R2—Cathode biasing resistor for V1.
R3—Cathode biasing resistor for V2.
C1—Cathode filter capacitor for V1.
C2—Cathode filter capacitor for V2.
T1—Audio-frequency coupling transformer.
V1 and V2—Triode amplifier tubes.
M1—Power Supply.

This is essentially a simple circuit. The relatively few currents involved and the colors they are shown in are:

1. Grid-driving current for tube V1 (green).
2. Plate current for each tube (red).
3. Transformer secondary current (blue).
4. Cathode filter current for each tube (dotted red).

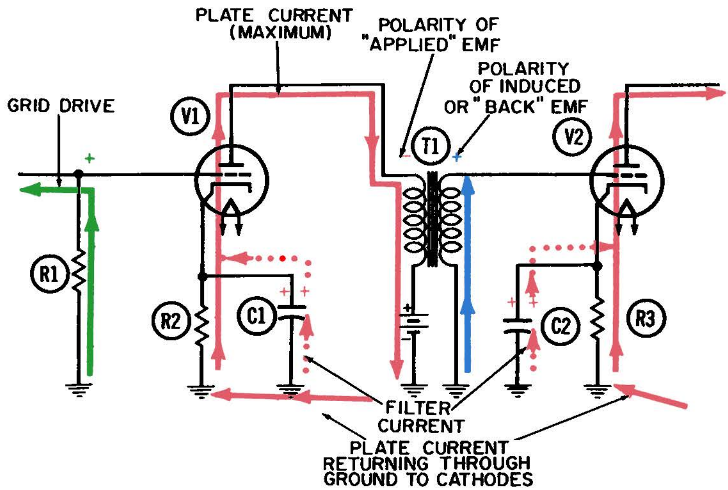


Fig. 3-1. The transformer-coupled AF amplifier—first half-cycle.

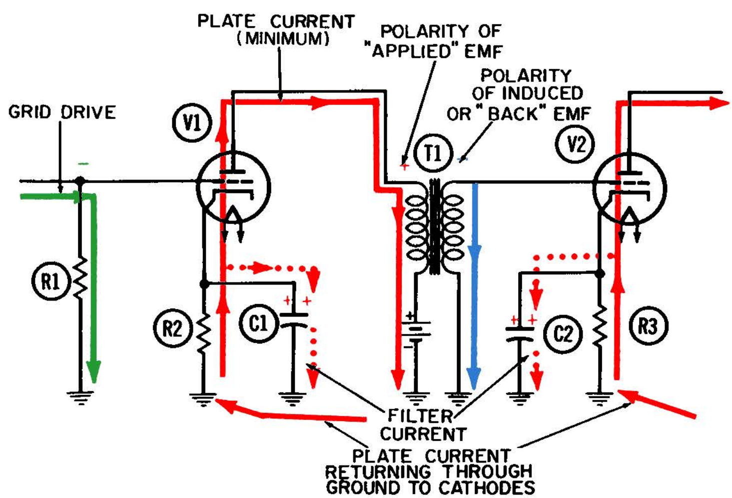


Fig. 3-2. The transformer-coupled AF amplifier—second half-cycle.

Fig. 3-1 is termed a positive half-cycle of operation because the control grid of V1 is being driven positive. The plus sign at the top of resistor R1 represents the instantaneous value of applied grid voltage and is consistent with the upward flow of grid-driving current through the resistor. The movements of this current, and the resulting instantaneous voltages at the grid, are controlled by preceding circuitry such as another voltage amplifier. It is this resulting grid-drive voltage we are seeking to amplify.

Maximum plate current through tube V1 coincides with maximum positive grid voltage. This heavy flow of plate current is indicated by the red line traversing the conventional plate-current path from cathode to plate within the tube and downward through the transformer primary. From here it can be drawn into the positive terminal of the power supply. The plate current completes its round trip by passing through the power supply to common ground. From here, it travels upward through cathode resistor R2 to the tube.

TRANSFORMER ACTION

Fig. 3-3 shows the graphical relationships between grid current and voltage, plate current and voltage, and transformer secondary voltage. Line 1 of this figure can be used to represent both the grid-driving current and the grid-driving voltage, since the current through a pure resistance is always in phase with the voltage across it. The reference line in the center of line 1 thus represents zero conditions for both current and voltage. When the current waveform crosses the reference line, this means no current is flowing *at that instant* and no voltage is developed across R1. These conditions occur midway during each half-cycle depicted in Figs. 3-1 and 3-2.

Whenever the current sine wave of Fig. 3-3 is below the reference line, the current it represents is flowing *downward* through R2. This occurs during the last half of the second half-cycle and the first half of the first one. Or we could say that it occurs during the fourth and first quarter-cycles of operation, and that during these same periods the grid voltage has to be negative. The latter is indicated by the portion of the voltage sine wave below the zero reference line during these periods.

Sine-wave Symbology

The use of voltage and current sine waves raises an interesting point. No other symbology available can present as much detailed information on a single cycle or on many cycles of operation as the sinusoidal, or sine-wave, symbology can. However, there are two important discrepancies in the way they are used which are traps for the unwary, as we shall soon see.

The definition of a sine wave is "a graphical representation, along a time reference line, *of simple harmonic motion.*" The world is full of voltage sine waves, but the interesting fact is that voltage does not have motion . . . voltage does not move. Only the current has motion, and the simplest and broadest

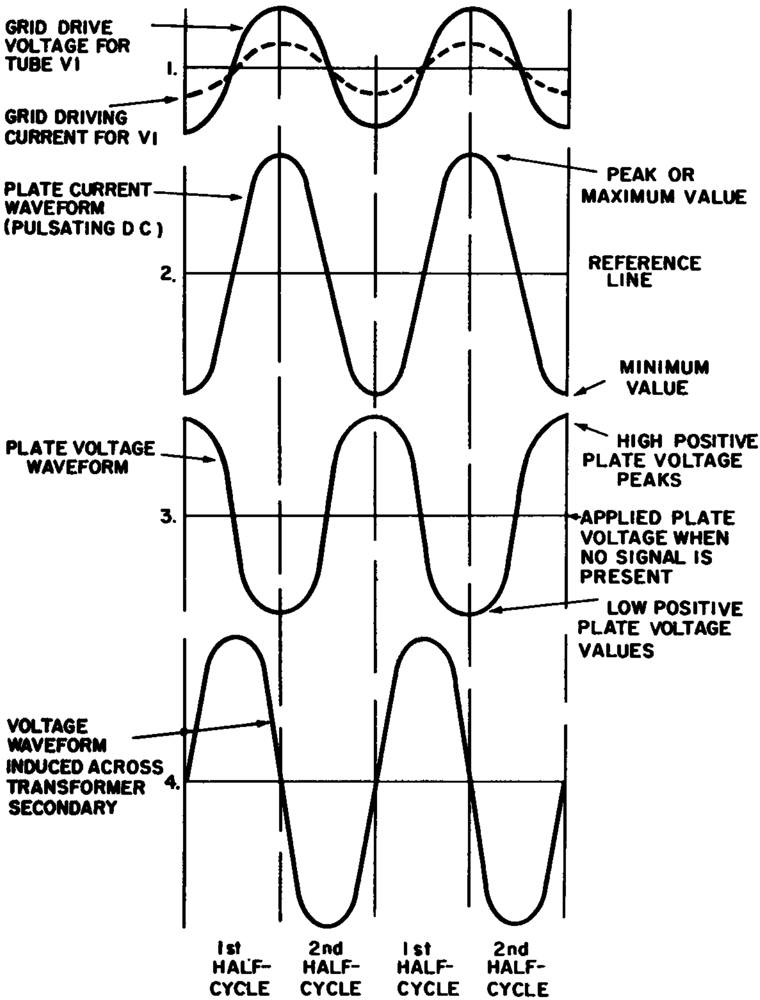


Fig. 3-3. Voltage and current waveforms in the transformer-coupled AF amplifier.

definition of electric current is that it consists of *electrons in motion*. A negative voltage is defined as *electrons in concentration*. Concentrations of electrons do not move around in a circuit; rather, the electrons flow from point to point. While electrons are moving they constitute a current. when they *accumulate* at any point, they constitute a negative voltage. When there is *deficiency* of electrons at any point, it constitutes a positive voltage.

So the discrepancy in a voltage sine wave is the implication, based on the definition of the sine wave, that all voltages have some kind of mysterious wave motion. For this reason, any time you see a voltage sine wave, remember that you are looking at a sine wave of quantity rather than motion. With this firmly in mind, you will be much better qualified to use the invaluable tool of sine-wave graphical representations of alternating voltages.

Since currents have motion, it is entirely proper to represent an alternating current by a simple harmonic-motion since wave. However, currents do not have polarity in the sense that a voltage has. Rather, they have directions of flow. All too frequently there is the tacit implication that any portion of a current sine wave above the reference or center line is "positive," whereas any portion below the line is "negative." The assignment of such polarities to current may have mathematical significance but is otherwise meaningless, particularly to the neophyte. Since current is always made up of electrons in motion, its flow direction during any portion of a cycle is important because it reveals (1) the points toward which electrons are being delivered to build up negative voltages, or (2) the points from which electrons are being depleted to build up positive voltages.

There has also been a tendency to refer to current as *negative* when we know it is composed of electrons flowing indisputably in one certain direction (such as the plate current of vacuum tubes). This is a holdover from olden days when negative electrons were not yet recognized as the prime current carriers in electric and electronic circuits. Current was universally assumed to flow from a positive to a negative voltage source. Later with the recognition of negative electrons as the current carriers, the term "negative current" was coined to describe them, the "positive-to-negative" or "conventional" current came to be known as "positive current" and this terminology still persists today.

There can be little genuine hope that this convention of "positive current" will ever disappear, since early researchers constructed much of the mathematics of electronics under the mistaken assumption that current flowed from positive to negative rather than vice versa. In fact, millions of words have been written, based on this early assumption. When you get right down to it, though, it is easier for *you* to remember to "change the sign" that to rewrite all that literature!

The alternating current in the primary winding is really a pulsating direct current. Changes in this primary current will induce a voltage in the secondary winding of the transformer, and the induced voltage will be maximum when the primary current is changing at its maximum rate. Referring to the plate-current sine wave in line 2 of Fig. 3-3, you can see that the plate current is not changing whenever it is passing through its maximum and minimum values (at the end of the first and second half-cycles respectively).

A true alternating current is changing at its maximum rate whenever it is changing direction—in other words, whenever its graphical representation is crossing the reference line. Since plate current is a pulsating direct current, it always flows in the same direction (clockwise in the usual circuit diagram), unlike a true alternating current which flows in both directions. For this reason it is necessary to treat pulsating direct current *as an alternating* current. The additional convention devised to accomplish this is to look upon the plate current as consisting of two separate but related currents—a pure direct current (the value of which is indicated by the reference line in line 2), and an *alternating component superimposed on the direct current.*

The *reference value* of plate current is the amount which will flow through the tube when no signal voltage is applied to the grid. This occurs only twice each cycle. Midway in the first half-cycle, the application of a positive voltage to the grid will increase the plate current. A negative voltage will decrease the plate current, midway in the second half-cycle.

The voltage polarities shown at the tops of the primary and secondary windings in Fig. 3-1 are chosen to coincide with that instant when the plate current is *increasing at its maximum rate*—midway in the first half-cycle. We see from line 4 of Fig. 3-3 that the voltage induced across the secondary winding has its maximum positive value at this instant. This voltage is applied to the control grid of vacuum tube V2. As a result, maximum plate current flows from cathode to plate in V2.

These voltage polarities are normally referred to as *applied emf* or *back emf.* In Fig. 3-2 these polarities are reversed—because the plate current is *decreasing* at its maximum rate—in the middle of the second half-cycle. The plate voltage is considered to be *increasing* in the positive direction, also at its maximum rate. This is the reason for the plus sign at the top of the primary winding in Fig. 3-2; it indicates the positive polarity of the applied emf across the primary winding *at this instant.*

Both tubes in this circuit employ the type of self-bias known as cathode biasing. Note the small resistor in series between the cathode and ground; plate current must flow through it before reaching the tube. When cathode-biasing is used, the plate current must flow at all times. Otherwise the positive cathode bais voltage would fall toward zero. This would change the grid-to-cathode voltage difference (called *grid bias*) in such a direction that more plate current would flow. Consequently, the use of cathode biasing automatically signifies that a tube is being operated under Class-A conditions—by definition, a tube in which plate current is flowing throughout the entire cycle.

The process of bypassing the cathodes with filter capacitors C1 and C2 has been indicated on the circuit diagrams of Figs. 3-1 and 3-2. The filter currents which flow in and out of ground below these capacitors are indicated in dotted red lines. Since there is absolutely no difference between these filtering processes and the ones in the resistance-capacitance coupled amplifiers of the previous chapters, the cathode filtering process will not be redescribed here.

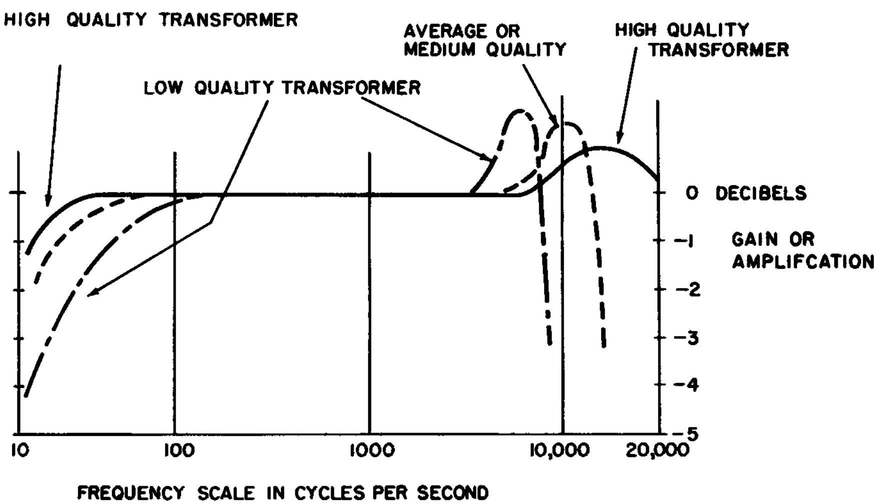


Fig. 3-4. Response curves of transformer-coupled AF amplifiers.

FREQUENCY RESPONSE

Fig. 3-4 shows some conventional frequency-response curves for an audio-frequency voltage amplifier using transformer coupling. The horizontal scale indicates that its range of usefulness is approximately the same as for the resistance-capacitance coupled amplifier previously discussed. Low-frequency operation is limited here by the extremely low inductive reactance which the transformer primary winding presents to the changing plate current. The applied emf developed across the primary winding is proportional to the inductive reactance of the primary winding through which the plate current must flow; inductive reactance is of course proportional to the frequency. Voltage, current, inductive reactance, and frequency are related by these two common formulas:

$$E = I \times X_L$$

where,

E is the applied emf in volts,
I is the AC component of plate current in amperes,
X_L is the inductive reactance in ohms;

and:

$$X_L = 2\pi fL$$

where,

X_L is the inductive reactance in ohms,
f is the frequency of the applied AC component of plate current in cycles per second,
L is the inductance of the primary winding, *plus* any inductance coupled from the secondary, in henrys.

The average voltage amplifier using transformer coupling will have a good frequency response down to about 50 cycles per second. Below 50 cps the response deteriorates rapidly.

The high-frequency response of a transformer-coupled amplifier is limited by many inherent circuit capacitances. Figs. 3-5, 3-6, and 3-7 are adaptations of the equivalent circuit normally used in arriving at mathematical solutions for a transformer-coupled amplifier. In addition to the inherent capacitances, an equivalent circuit also indicates the presence of such other inherent circuit constants as resistances and inductances.

A combined listing of the actual, or manufactured, circuit components, along with the inherent characteristics *which act like components,* would read as follows (refer to Figs. 3-5, 3-6 and 3-7):

C1—Output capacitance of tube (inherent).
C2—Shunting effect of capacitance between adjacent turns of primary winding (inherent).

C3—Capacitance between primary and secondary windings (inherent).
C4—Shunting effect of capacitance between adjacent turns of secondary winding (inherent).
C5—Input capacitance of next tube (inherent).
R1—Theoretical plate resistance of tube (inherent).
R2—DC resistance of primary winding (inherent).
R3—Resistance representing eddy-current losses in primary winding (inherent).
R4—Resistance representing hysteresis losses in primary (inherent).
R5—Resistance representing direct-current losses in secondary winding (inherent).
R6—Input resistance of next stage (inherent).
L1—Leakage inductance of primary winding (inherent).
L2—Actual primary-winding inductance (manufactured).
L3—Actual secondary-winding inductance (manufactured).
L4—Leakage inductance of secondary winding (inherent).
V1—Triode amplifier tube (manufactured).

Fig. 3-5 shows the currents in the three audio-frequency ranges —low (green), middle (red), and high (blue)—in their passage through the amplifier circuitry. All currents are drawn as if they are momentarily in phase. Of course three currents of such widely different frequencies will rarely be in phase even momentarily. This has been done for illustrative purposes only; in general, the amplifier reacts independently to each current.

The plate current of medium frequencies (red) passes through the amplifier and receives maximum amplification. Like all others, this current must flow through all inherent circuit constants in its series path before passing through the power supply and back to ground. This path includes the theoretical plate resistance of the tube, the inherent DC resistance of the primary winding, the inherent leakage current of the primary, the theoretical resistance associated with hysteresis losses, and the primary winding of the transformer. In passing through the transformer primary, the plate current induces another current (also in red) in the secondary winding. This secondary current also must flow through the three inherent circuit characteristics which lie in its series path—the secondary leakage inductance, the DC resistance of the secondary winding, and the theoretical input resistance of the next amplifier stage.

Note that no significant portion of this middle-frequency current flows into any of the four inherent shunting capacitances which lead to ground; nor into the capacitance C3, which would

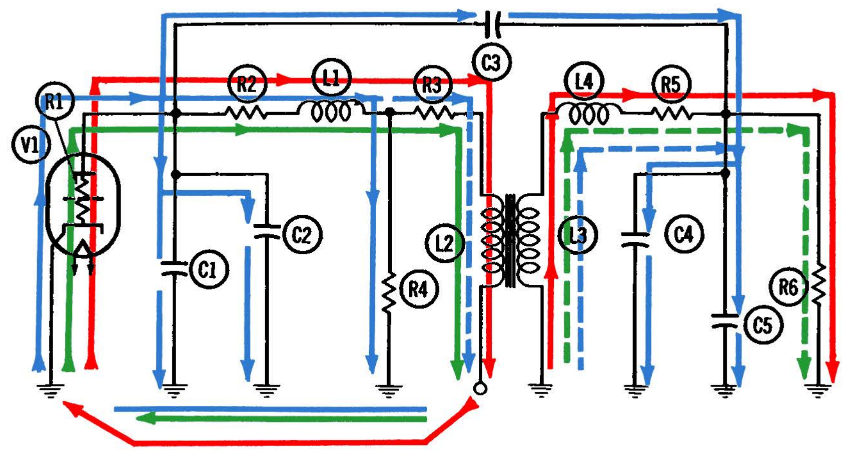


Fig. 3-5. Equivalent circuit of transformer-coupled AF amplifier—first half-cycle.

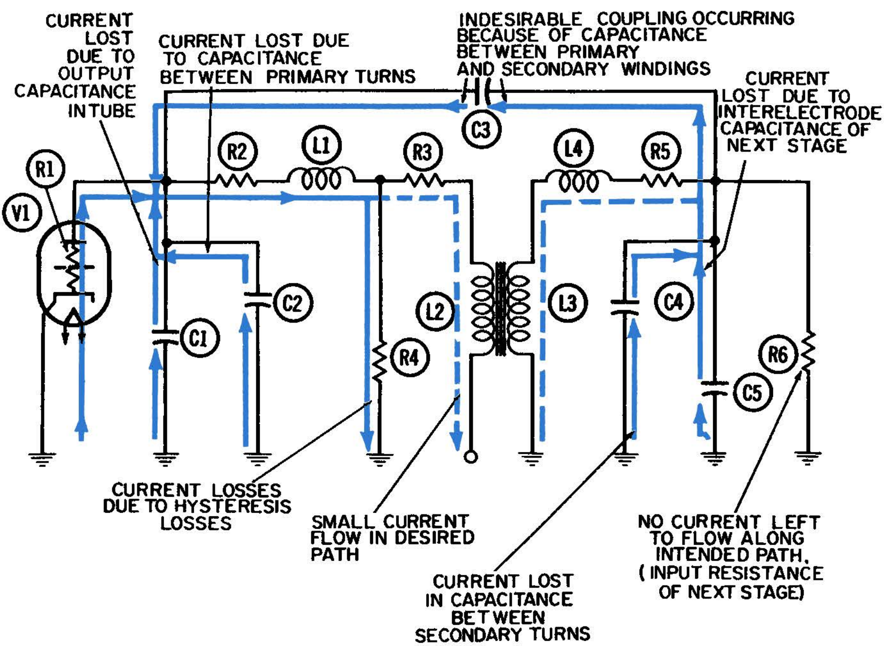


Fig. 3-6. Equivalent circuit of transformer-coupled AF amplifier at high frequencies—second half-cycle.

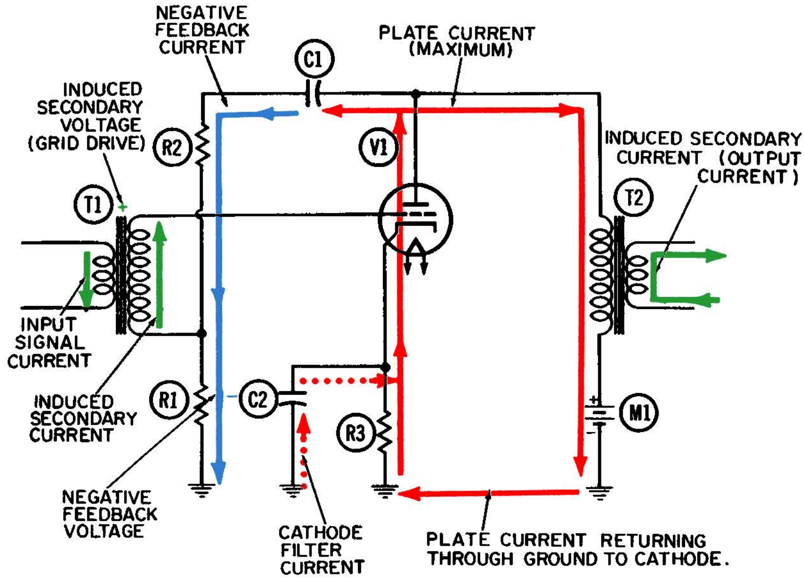


Fig. 3-7. Negative feedback amplifier circuit—first half-cycle.

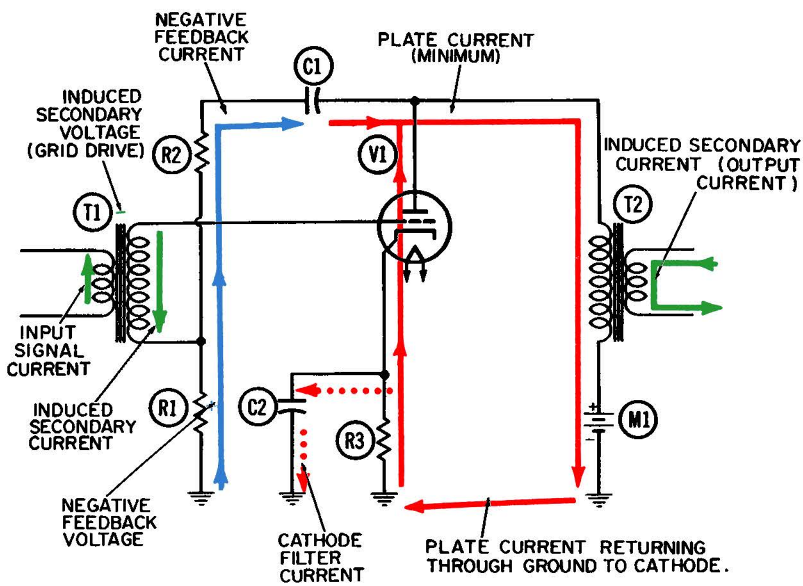


Fig. 3-8. Negative feedback amplifier circuit—second half-cycle.

couple it directly to the next stage rather than via normal transformer action. All these inherent capacitances are so small in value (10 or 20 micromicrofarads) that they have an extremely high reactance at low and middle frequencies. For this reason they do not bleed off any currents at these frequencies and consequently have no adverse effect on circuit operation.

The low-frequency current (in green) follows the same path through the amplifier as the middle-frequency current. Because transformer action is inadequate at very low frequencies, the low-frequency current induced in the secondary winding is seriously weakened. Therefore, it is drawn as a dashed rather than a solid line, to indicate this attenuated condition.

Like the middle-frequency current, none of this low-frequency current flows into any of the inherent shunting capacitances, again because of their small size, and hence, high reactance at the low frequencies. As stated previously, the sole limitation on low-frequency operation of a transformer-coupled amplifier is the inability of the transformer, *unless especially designed for the task,* to induce sufficient secondary current at extremely low frequencies.

The high-frequency current, shown in blue in Fig. 3-5, has a rough time getting through the transformer-coupled amplifier. Portions of it flow into every one of the inherent shunting paths. These shunted portions must be counted as losses, since they no longer are available to flow into the primary winding of the transformer and induce a current in the secondary winding.

Fig. 3-5 is considered a positive half-cycle; at this time, the control grid (not shown) becomes positive and maximum plate current is released into the tube and external plate circuit. This accounts for the flow directions shown. The excess electrons in the plate current are driving electron current away from the plate and along the three unwanted shunt paths available to them. These paths are downward into C1, (the output capacitance of the tube), downward into C2 (the capacitance between adjacent turns of the primary winding), and to the right into C3 (the inherent capacitance between adjacent turns in the primary and secondary windings of the transformer). None of these current components are available to do their primary task of flowing through the primary winding and inducing a current in the secondary-winding.

The high-frequency current in Fig. 3-5 is also shown flowing downward through R3 which represents the eddy-current losses in the primary winding. There will be some eddy currents induced in the transformer core at all frequencies; consequently, currents of all frequencies will incur some eddy-current losses. However, the amount of eddy-current losses increases as the *square* of the frequency. Hence, losses become most significant at the higher frequencies.

The small portion of current which succeeds in flowing through the primary winding is shown as a dashed line, to indicate the seriousness of the reduction. This small current induces a small current and voltage combination in the secondary winding—also shown as a dashed line. This secondary current is further reduced by the two inherent shunting capacitances, C4 and C5, and practically nothing is left to flow into input resistance R6.

Fig. 3-6 represents a negative half-cycle of the same high-frequency current. During this half-cycle the currents previously driven downward in the four shunting capacitances—C1, C2, C4, and C5—are now being drawn upward from ground. These currents all flow very freely over these unwanted capacitive paths to ground as the frequency increases, leaving less and less current to do the necessary work.

The current coupled directly to the secondary via the inherent capacitance (C3) between adjacent turns of the two windings also reverses its direction each half-cycle. In Fig. 3-6 we see it flowing to the left, attracted of course by the inevitable rise in plate voltage whenever the plate current falls.

At first thought, this current does not really appear to be "lost" —after all, it *is* coupled to the secondary circuit and is therefore available to drive the control grid of the next amplifier stage, despite its unorthodox journey up to that point. This assumption is fallacious for several reasons, including the important one that current which reaches the control grid via this path will be *out of phase* with a current of the same frequency which traveled over the conventional path. Consequently, there would be two components of what was originally a single current, each attempting to drive the control grid independently of the other. As a result, the two would reach their peaks at different moments in the same cycle and partially cancel each other.

FREQUENCY DISTORTION

Of the three broad types of distortion—amplitude (nonlinear), frequency, and phase distortion—encountered in tube operation, it is possible to visualize at least one of them by reference to Fig. 3-5. Frequency distortion occurs when an amplifier provides unequal amplification of currents at different frequencies.

All currents whose frequencies fall within the band covered by the flat portion of the response curve (Fig. 3-4) will be amplified equally and passed equally by the coupling network. Hence, no frequency distortion occurs within this frequency band which is shown in red in Fig. 3-5. However, the low-frequency currents (in green) are amplified very poorly because of transformer limitations, and the high-frequency currents suffer because of all the losses caused by undesired capacitances. Thus, the low, medium, and high-frequency components are not equally amplified. This is defined as frequency distortion.

Examples of amplitude and phase distortion were discussed in Chapter 2 and will not be repeated here since they are the same for all amplifiers.

NEGATIVE VOLTAGE FEEDBACK

Figs. 3-7 and 3-8 illustrate two half-cycles in the operation of a commonly used feedback circuit. In this circuit a portion of the plate voltage is coupled, or fed back, to the input (grid circuit). Since the plate voltage is normally out of phase with the grid voltage, this type of feedback is considered to be negative.

The circuit used here is a simple transformer-coupled voltage amplifier for audio frequencies. The only difference between this circuit and the preceding one (other than the feedback connection from plate to grid, of course) is that the control grid is driven by a transformer rather than a resistor.

The necessary components of this circuit include:

R1—Portion of voltage-divider network used for developing feedback voltage.
R2—Remaining portion of voltage-divider network.
R3—Cathode biasing resistor.
C1—Blocking and coupling capacitor.
C2—Cathode filter capacitor.
T1—Input transformer of the voltage step-up type.
T2—Output transformer of current step-up type.
V1—Triode voltage amplifier tube.
M1—Power Supply.

Identification of Currents

The operating currents in this circuit which need to be identified include:

1. Input transformer primary and secondary currents (both in green).
2. Plate current of tube (red).
3. Feedback current (blue).

4. Output current in output-transformer secondary (green)
5. Cathode filter current (dotted red).

Details of Operation

Fig. 3-7 shows what is called a positive half-cycle, because the driving signal delivered through the input transformer to the control grid becomes progressively more positive throughout the half-cycle. The polarity of this voltage is indicated by the plus sign at the top of the secondary winding of input transformer T1. This is the voltage induced in the secondary by the input current flowing in the primary winding. The *directions* of current flow in the primary and secondary are at all times related to each other and to the instantaneous polarity of the induced voltage. This is in accordance with the normal principles of transformer action.

The positive-going signal on the control grid in Fig. 3-7 releases a large surge of plate current into the tube. The normal path of plate current is from cathode to plate, then downward through the primary winding of output transformer T2 and into the positive terminal of power supply M1, through the power supply to ground and through it to the bottom of cathode resistor R3. From here the plate current flows upward and returns to the cathode.

With the feedback network (consisting of C1, R2, and R1) in the circuit, a portion of this surge of plate current electrons flows onto the right plate of capacitor C1. An equal amount of electrons are driven off the left plate of C1 and downward through R2 and R1; this is the current shown in blue. When electrons are flowing downward through this path, we know that the instantaneous voltage at any point along the path will be more negative than the voltage at any other point farther down the path, since electrons always flow from negative to positive. Hence we can infer that the voltage at the junction of R1 and R2 will be negative with respect to the ground at the bottom of R1.

Since the bottom of the secondary winding of input transformer T1 is also connected to the junction of R1 and R2, the positive control-grid voltage resulting from the transformer action will be reduced by the amount of this negative voltage developed across R1. Since the driving and feedback voltages are out of phase, the feedback is considered negative.

The total voltage developed across R1 and R2 by the flow of feedback current is divided between the two in proportion to their resistances. This is a straight Ohm's-law relationship:

$$\begin{aligned} E_T &= I \times R_T \\ &= I\,(R1 + R2) \end{aligned}$$

or,

$$E_T = E_1 + E_2$$

also,

$$E_1 = I \times R1$$
$$E_2 = I \times R2$$

where,

E_T is the total voltage drop across R1 and R2,
E_1 is the voltage drop across R1,
E_2 is the voltage drop across R2,
R_T is the sum of resistances R1 and R2, in ohms,
I is the effective value of the alternating current, in amperes.

Let,

$$R1 = 10{,}000 \text{ ohms.}$$
$$R2 = 90{,}000 \text{ ohms.}$$
$$I = 1 \text{ milliampere.}$$

Then,

$$E_1 = .001 \times 10{,}000$$
$$= 10 \text{ volts,}$$
$$E_2 = .001 \times 90{,}000$$
$$= 90 \text{ volts,}$$

and,

$$E_T = 10V + 90V$$
$$= 100 \text{ volts}$$

Thus, the total voltage across network R1 – R2 is divided in the ratio of 9 to 1, which is the ratio between the two resistances. The effective value of the feedback voltage is 10 volts.

Fig. 3-9 shows a simplification of the voltage waveforms in this circuit. Line 1 is the alternating voltage, which is normally applied to the control grid via the input transformer. During the first half-cycle, this voltage increases continuously in the positive direction. Because the cathode is biased positive by the R3 – C2 filter combination, the grid is automatically biased an equal amount in the negative direction (since the true definition of grid bias is "the *difference* in voltage between grid and cathode").

Under the conditions indicated, the peak voltage swing at the control grid is slightly less than this bias value. Hence, the control grid never becomes positive with respect to the cathode and no significant amount of grid-leakage electrons will flow.

Line 2 shows the sinusoidal waveforms for plate current and plate voltage. Note that they are 180° out of phase with each other; when the plate current reaches its maximum value, at the end of the first half-cycle, the plate voltage will be at its minimum value.

This alternating component of plate voltage can all be considered as being coupled into the feedback network. This coupling is accomplished by means of the feedback current (shown in blue in Figs. 3-7 and 3-8), which works in and out of feedback capacitor C1. This current suffers negligible losses and phase shift;

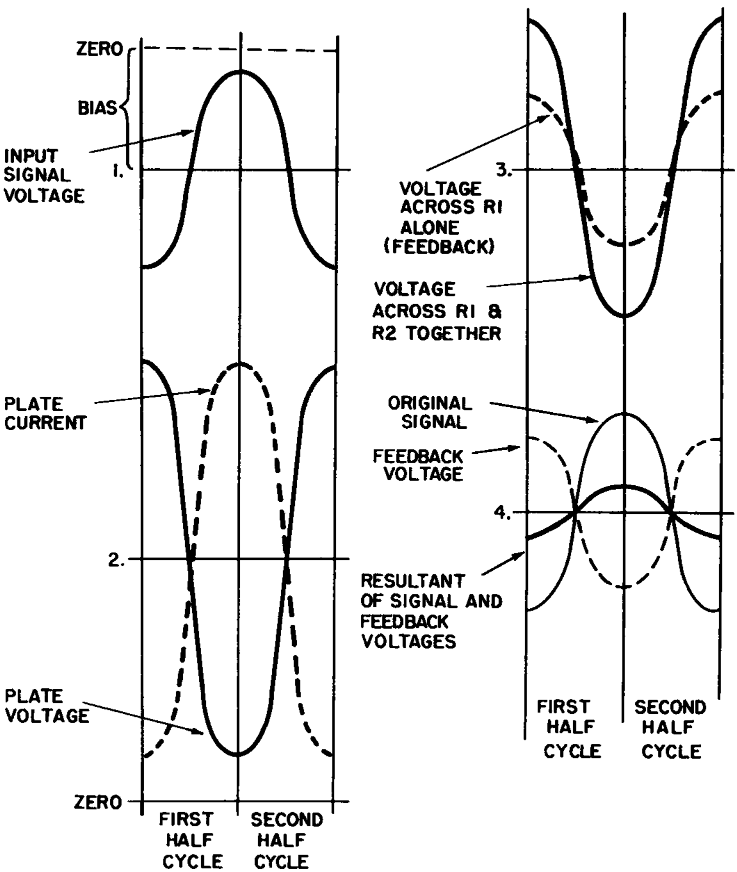


Fig. 3-9. Voltage and current waveforms in negative-feedback amplifier circuit.

so the alternating voltage developed across the two series resistors (line 3 of Fig. 3-9) is an exact replica of the alternating component of plate voltage. The reduced portion in dashed lines represents the amplitude and phase of the voltage developed across feedback resistor R1 and fed back to the grid from the plate.

Line 4 is the control-grid voltage redrawn with the feedback voltage superimposed on the same axis. Because the two voltages are exactly out of phase, they tend to cancel each other out. The values of the resistors must be so adjusted that the alternating voltage applied through the transformer to the control grid is at least slightly larger than the feedback voltage. Otherwise, the resultant voltage will not have sufficient amplitude to provide the necessary excitation.

It will be apparent that the grid is actually being driven by the smaller voltage indicated in line 4 as the "resultant grid voltage," rather than by the original alternating voltage indicated in line 1. This implies that *smaller* pulsations of plate current will occur. This will result in smaller swings of plate voltage, and also less feedback current through the two resistors. Hence, the feedback voltage will likewise be smaller. Thus, the indicated amplitudes of the four voltage waveforms must be considered gross approximations only.

During the second half-cycle (Fig. 3-8), the grid driving voltage goes negative. The greatly reduced plate current which results is accompanied by a rise in the plate voltage, as indicated by the waveforms in line 2 of Fig. 3-9. This is the opportunity for electrons to flow *off* the right plate of capacitor C1. An equal number of electrons are drawn *upward* through the voltage-divider network, making the feedback voltage *positive* at the junction of R1 and R2. Since this is also the same half-cycle the input transformer is trying to make the grid *negative,* we see that these two voltages still oppose each other. As indicated in line 4 of Fig. 3-9, the algebraic sum of these two voltages, at the end of the second half-cycle, is a small negative voltage.

This is called *voltage feedback* because it in effect is "tapped off" from the voltage changes occurring at the plate, even though the feedback voltage across the voltage divider owes its existence to the feedback current (shown in blue).

Although we have shown the feedback loop from the plate to the grid of the same tube, the feedback voltage can be (and often is) taken from other points. The only requirement is that the feedback voltage be 180° out-of-phase with the signal voltage. For example, the feedback voltage could be taken from the plate of the last tube in a three-stage amplifier and applied to the grid of the first stage. Thus, any variations introduced by any of the three tubes would be cancelled out.

Also, the two forms of feedback discussed in the previous chapter (positive voltage and negative current) can also be used with the transformer-coupled amplifier. Since operation is the same, they will not be discussed again here.

Cathode-Filter Circuit

The cathode filtering current, shown in dotted red, reflects *withdrawals of electrons from* the ion pool, on the upper plate of C2 during each first half-cycle or *additions of electrons to* the pool during the second half. As electrons are added to or withdrawn from the plate of C2 an equal number flows to or from ground to the bottom plate.

Thus, capacitor C2 aids in keeping the cathode voltage constant, by supplying electrons when the tube current is maximum, and storing them when it is minimum.

Chapter 4

AUDIO-FREQUENCY POWER AMPLIFIERS

Audio-frequency power amplifiers are used in all public-address systems, radio and television receivers, record players, recorders, etc., to provide sufficient audio power to drive the speakers or other devices connected to its output. Speakers are usually *current-operated* devices requiring a fairly heavy electron current to flow at the audio frequencies. The power developed across any resistive load varies as to the square of the current flowing through that load, in accordance with the power formula which states that:

$$P \text{ (or W)} = I^2 \times R$$

where,

P is the power in watts,
I is the current in amperes,
R is the resistance of the load in ohms.

A tube used as a power amplifier is designed to deliver a large quantity of cathode-plate current. The current is normally delivered to a transformer in the load circuit. This enables the particular speaker load to be matched in impedance with that of the plate circuit. An exact match between the two impedances is necessary for optimum, or maximum, transfer of power from the plate circuit to the load circuit.

Since the impedance of the average speaker is fairly small (on the order of a few ohms), and since the plate-circuit impedance will be much larger, the impedance-matching process takes advantage of the turns ratio (which is a manufactured characteristic of transformers). The impedance-matching characteristic of a transformer varies in accordance with the *square* of the turns ratio between the primary and secondary windings. If a primary winding has twice as many turns as the secondary, the turns ratio—normally expressed as N1 ÷ N2—will be 2, or 2-to-1, and the transformer can match two impedances in the ratio of 4-to-1.

If a turns ratio is 20-to-1, the transformer can match two impedances which differ from each other by a factor of 400-to-1. Thus, if a speaker has an impedance of 8 ohms and the plate circuit an impedance of 3,200 ohms, the two impedances can be matched to each other by using a transformer having a 20-to-1 turns ratio between the primary and secondary.

Sample circuits have been chosen to depict circuit conditions and problems during audio-frequency power amplification. The first circuit uses a single power-amplifier triode. All use output transformers of the current step-up type. In the first example, the movement of the output current through the speaker coil, and the resultant movements of the speaker diaphragm, will be discussed in detail. The later examples represent typical push-pull circuits. This portion of the discussion has not been repeated here, since the principles are identical for all circuits.

TRANSFORMER-COUPLED POWER AMPLIFIER

Figs. 4-1 and 4-2 show two successive half-cycles in the operation of a conventional audio-frequency power amplifier. A transformer couples the plate circuit to the load, which is shown as a speaker. This type of circuit must be operated under Class-A conditions, meaning the plate current must not be cut off, or interrupted, during any portion of an individual cycle. Self-biasing is accomplished by using a cathode resistor and bypass capacitor. The power-amplifier tube is driven by the output from the preceding voltage amplifier.

The components which make up this complete circuit are as follows:

R1—Grid driving and grid-return resistor.
R2—Cathode biasing resistor.
C1—Cathode filter capacitor.
T1—Audio-frequency output transformer.
V1—Power-amplifier triode.
M1—Power supply.

Identification of Currents

The currents at work in this circuit include:

1. Grid driving current (green).
2. Plate current (pulsating DC), (solid red).

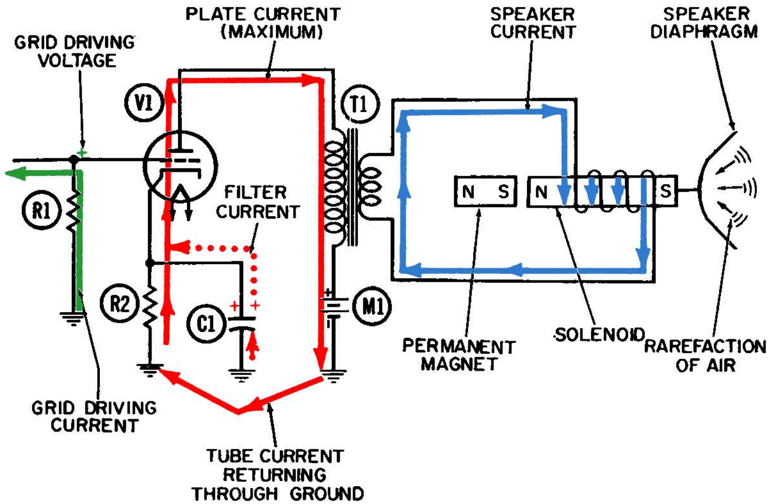


Fig. 4-1. Operation of an AF power amplifier—first half-cycle.

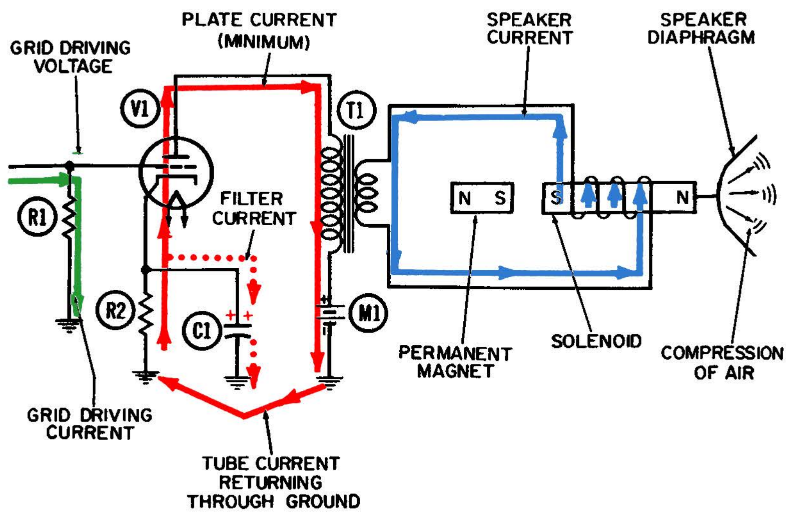


Fig. 4-2. Operation of an AF power amplifier—second half-cycle.

3. Speaker or output current (blue).
4. Cathode filter current (dotted red).

In addition to these currents, provision is always made for the possibility of grid-leakage current flowing out of the tube, and for the necessity of furnishing it a return path to the cathode. Resistor R1 provides this return path. Since the circuit operation as a whole does not depend on grid-leakage current, however, it is not shown in Figs. 4-1 and 4-2.

Details of Operation

Fig. 3-1 is considered the positive half-cycle of operation because the voltage at the grid is increasing in the positive direction throughout the entire half-cycle. The upward flow of grid driving current through R1 during this first half-cycle exists because electrons will always flow toward areas of more positive voltage.

As the grid voltage becomes more positive, more and more plate current will be released through the tube. Throughout the ranges of grid voltage and plate current in which this operation is carried out, it is desirable that the *amount* of plate current bear the same proportion to the amount of grid-cathode voltage at all times. When this condition is achieved, the tube is considered to be a linear amplifier. This term is derived from the characteristic curve for a triode (shown in Fig. 2-3).

The complete path for plate current (shown in solid red) is of course from cathode to plate, downward through the primary winding of the output transformer, through the power supply, and into the common ground. From here it flows through resistor R2 to the cathode. During that portion of a cycle when this current is *increasing* as it flows down through the primary winding, it will induce more and more current to flow in the opposite direction in the secondary winding. This secondary current, shown in blue, is the one which actually drives the speaker diaphragm.

During the second, or negative, half-cycle in Fig. 4-2, the direction of grid driving current and resultant grid voltage are reversed from that shown in Fig. 4-1. The gradual reduction in grid voltage causes a continual reduction in the plate current through the tube. As this decreasing plate current flows downward through the primary winding, it will simultaneously cause the current in the secondary winding to *decrease* in the opposite direction from the plate current, which is actually an *increase* in the same direction (downward) as shown by the blue line in Fig. 4-1. This is how a pulsating direct current in one winding can actually cause an alternating current to flow in the other winding. Thus, from one half-cycle to the next, the output currents in the secondary winding and speaker coil alternately flow in the opposite direction.

Speaker Action

A transducer is broadly defined as a device for converting energy from one form into another. A speaker qualifies as a transducer because it converts the electrical energy represented by the output current into sound energy which can be heard. As shown in Fig. 4-1 and 4-2, this is accomplished with the aid of a permanent magnet, a movable solenoid, and a diaphragm which is connected to the solenoid and moves with it to set up the air vibrations we know as sound waves.

The solenoid operates on the same principle as the electromagnet. When electron current flows through a coil of wire, magnetic lines of force are established which pass through the coil in an axial direction. Furthermore, the direction (polarity) of these lines of force depends on the direction of the electron flow through the coil. The polarity of these or any magnetic lines of force is either north or south.

The magnetic lines of force (also called *lines of flux*) are greatly strengthened by placing an easily magnetized material, such as soft iron, within the coil. This has been done in the speaker of Figs. 4-1 and 4-2. The *polarity* of the magnetic field created, as a result of the electron current through the moving coil, has a north pole at the left end and a south pole at the right end of the coil, as shown in Fig. 4-1.

This combination of a coil of wire and a movable iron core becomes a solenoid with the addition of a permanent magnetic field to the temporary one. This permanent magnetic field is provided by the magnet in Fig. 4-1 and 4-2. Its permanent south pole is on the right, adjacent to the left end of the movable iron core. When the core is magnetized, as shown in Fig. 4-1, it will be drawn to the left, closer to the permanent magnet, since a south and a north magnetic pole will always be attracted to each other. The core pulls the flexible diaphragm with it, creating a "rarefaction" of the air in front of the speaker, which becomes one half of a single cycle of a sound wave.

When the direction of the output current in Fig. 3-2 has been reversed (Fig. 4-2) the resulting magnetic lines of force change direction. The movable iron core now has a south magnetic pole at its left end and a north magnetic pole at its right end. Since the two south poles repel each other, the entire core moves to the right, pushing the flexible diaphragm ahead of it. This diaphragm movement compresses the air in front of the speaker which becomes the other half of a single cycle of a sound wave.

A sound wave consists of these alternate compressions and rarefactions of air traveling through the atmosphere. When these air vibrations strike another transducer such as the human ear, they are "transduced" to appropriate nerve vibrations, bringing pleasure (presumably!) to the listener.

The frequency of the output current determines the frequency, or pitch, of the sound produced. As an example, if the current frequency is 400 cycles per second, the iron core will move back and forth 400 cycles each second and thus accurately reproduce the desired pitch.

The *volume* of sound produced depends on the distance the diaphragm travels back and forth each cycle. This will be the same distance as the one traveled by the iron core, since the two are rigidly joined together. The strength of the alternating current through the secondary winding determines the strength of the temporary magnetic field, which in turn regulates the movements of the iron core.

The Permanent Magnet

The permanent magnet shown in Figs. 4-1 and 4-2 to attract or repel the solenoid is used in the majority of speakers. However, in some speakers, a coil of wire is wound around an iron core and connected to a source of direct current. Thus we have a second electromagnet. Unlike the solenoid electromagnet, however, the magnetic field for this second electromagnet will remain constant and the poles unchanged because it is connected to a *DC source* instead of the AC through the solenoid coil.

How do we tell which pole is which in an electromagnet? It's simple! Just grasp the coil with the left-hand so that your fingers point in the direction the electrons are flowing through the coil. Then extend your thumb, and it will point toward the north magnetic pole.

Speakers employing permanent magnets are called permanent-magnet, or PM, speakers, while those with electromagnets are called electromagnetic or EM speakers. Operation of both types is the same—the only difference is the added connections for the extra coil, usually called the *field*. In practice, the field is usually connected to a DC source in the equipment's power supply, but sometimes a separate power supply is used.

Cathode Filtering

The cathode filter or bypass current, shown in dotted red, flows back and forth into and out of capacitor C1. Its only purpose is to keep the voltage at the cathode constant. Remember that the grid bias of any tube is the instantaneous *difference* in voltage between grid and cathode. The actual voltage at the grid is changed by the flow of grid driving current up and down through the grid driving resistor, and it is desirable that the amount of plate current, at any instant throughout the cycle, always be proportional to the grid driving voltage. If we were measuring grid driving voltage with respect to a fixed value such as ground, this condition would be relatively simple to attain. However, we are really measuring the grid driving voltage with respect to the *cathode,* since the total instantaneous grid bias (which really determines how much plate current will flow) is the difference between the cathode and grid voltages. Therefore, the cathode should, insofar as possible, be held at some fixed value of positive voltage.

It is obvious that the cathode voltage is subject to fluctuation, since it is produced by the flow of plate current through cathode biasing resistor R2 and the plate current is varying over a fairly wide range. The addition of a filtering capacitor stabilizes this cathode voltage and thereby prevents such voltage fluctuations. The combination of resistor R2 and capacitor C1 is a familiar example of a long time-constant RC filter. A positive voltage builds up on the upper plate of capacitor C1. When the demand for plate current is very low (the condition depicted in Fig. 3-2), this positive cathode voltage continues to draw electron current upward through the cathode resistor. During these negative half-cycles the excess electron current "spills over" onto the capacitor rather than entering the tube. This action drives an equal number of electrons off the lower plate and into common ground.

During the positive half-cycles depicted by Fig. 3-1, the control grid is positive; hence the demand for the cathode to emit more electrons into the tube increases. If there were no cathode bypass capacitor, the additional plate current would have to be supplied directly from ground, below the cathode resistor. In flowing upwards through R2 this current would cause an increased voltage drop across the resistor, in accordance with Ohm's low. The larger drop would result in a higher positive voltage at the cathode.

When a suitable bypass capacitor is connected across the resistor, the additional demand for plate-current electrons will be supplied directly from the positive ion pool on the upper plate of the capacitor. *If the capacitor is large enough in value,* the ion pool will be large enough that an insignificant number of extra electrons will be given up into the tube, in comparison with the number of positive ions stored there. Hence the positive voltage of the ion pool will not be changed noticeably by the departure of the electrons.

The filtering current which flows between the lower plate of the capacitor and ground will flow *upward* during the positive half-cycle of Fig. 3-1, drawn by the departure of the extra electrons into the tube.

Thus we see that the filtering current flows up and down between the capacitor and ground at the frequency of the applied voltage.

ADVANTAGES OF PUSH-PULL OPERATION

Several important advantages accrue from using two power-amplifier tubes in push-pull connection. As discussed in earlier chapters, it is normally desirable to operate a tube on the linear portion of its transfer characteristic curve in order to avoid distortion. The distortion arising from operating a tube along nonlinear portions of this curve is classified as second-harmonic distortion. In the push-pull connection, the second-harmonic distortion caused by one tube is canceled out, in the output transformer, by second-harmonic distortion caused by the second tube. Consequently, the output is essentially distortionless. The fact that these two distortions can be canceled out permits each tube to be driven harder—in fact, into the nonlinear portions of the characteristic curve. The power output achieved from two tubes in push-pull is more than double the power that can be achieved with a single tube of the same type. This feature permits the use of two lower power tubes in push-pull, instead of one high power tube, to achieve the desired power outputs.

Another advantage of the push-pull circuit is that DC magnetization of the output-transformer primary winding is avoided. In the circuit just discussed, some plate current is flowing downward through the primary winding at all times. (This can be verified by examination of Figs. 4-1 and 4-2.) As a result of the continuous current through one winding, the iron core becomes magnetized and this detracts from its ability to operate efficiently as a transformer. This undesirable effect is eliminated in all the other circuits of this chapter, since any permanent magnetism which might otherwise be acquired as one plate current flows downward through part of the primary winding will be canceled out (neutralized) by the other plate current flowing upward through the other portion of the primary.

Still another advantage of a push-pull connection is that the sum of the two currents entering the power supply is very nearly constant, particularly when the tubes are being operated under Class-A conditions. This eliminates the necessity of decoupling the power supply with an additional filter capacitor to bypass small surges in current around the power supply to ground. Because a single power supply is normally used to supply many circuits, it is essential that no voltage or current surges be permitted to momentarily raise or lower the power-supply voltage, since the operating conditions of all other tubes connected to the power supply would be immediately affected.

Because of the symmetrical relationship between the two grid voltages and the resulting plate currents, a push-pull circuit is sometimes referred to as a balanced amplifier.

PUSH-PULL AMPLIFIER USING GRID-LEAK BIAS

Figs. 4-3 and 4-4 show two successive half-cycles of operation of a push-pull power amplifier for audio frequencies. A transformer is used in the input circuit to supply driving voltages to the two tubes. These driving voltages must be equal in amplitude but 180° out of phase with each other. There are several methods of meeting the two conditions. The transformer input is one.

This circuit has the following components:

R1—Grid-leak biasing resistor for both tubes.
C1—Grid-leak biasing capacitor for both tubes.
T1—Input transformer.
T2—Output transformer.
V1—First power-amplifier triode.
V2—Second power-amplifier triode.
M1—Common power supply for both tubes.

There are seven different electron currents at work in this circuit:

1. Input-signal current flowing in primary of transformer T1, (blue).
2. Grid driving current flowing in secondary of transformer T1, (solid green).
3. Grid-leakage current for V1 (dotted green).
4. Grid-leakage current for V2 (also in dotted green).
5. Plate current for V1 (red).
6. Plate current for V2 (also in red).
7. Output current flowing in secondary winding of transformer T2 (blue).

Circuit Description

As indicated in Figs. 4-3 and 4-4, the secondary winding of transformer T1 has more turns than the primary. This indicates the transformer is a voltage step-up and current step-down type. This transformer is being driven by the input signal current, shown in blue in Fig. 4-3. The primary current is shown flowing downward through the primary winding.

The action of any transformer or inductor is to oppose any change in the total current flowing in the two windings. Thus, if we consider that fraction of the first half-cycle when the input-signal current is *building up* as it flows downward through the primary winding of T1, we can immediately visualize a different current being caused to flow upward in the secondary winding. The latter also is increasing, so that the *total* current flowing in the two windings (the algebraic sum of the two currents) will be considerably less than if the secondary current did not flow.

This induced current, shown in solid green in Fig. 4-3, flows upward in the secondary winding. Associated with this secondary current is the back emf or counter emf. Its polarity during this portion of the first half-cycle is indicated by the plus sign at the top and the minus sign at the bottom of the secondary winding. (It is easy to correlate these polarities with the upward flow of secondary current, since electrons will always flow *toward* a positive voltage and *away* from a negative one.)

The positive polarity also exists at the control grid of V1 during the first half-cycle. This positive grid voltage releases a large amount of plate current through V1. The complete path of the plate current (in red) is from cathode to plate, downward through the upper half of output transformer T2 to its center tap, then through common power supply M1 to ground, and back to the cathode.

Since the control grid of tube V2 is connected to the lower end of the secondary winding of input transformer T1, its grid voltage will always be 180° out of phase with the voltage applied to the grid of V1. This condition is indicated in Fig. 4-3 by the minus sign at the bottom of the secondary winding. The negative voltage at the grid of V2 drastically restricts the flow of plate current through V2 during this half-cycle. The complete path of plate current for V2 is from cathode to plate within the tube, upward through the lower half of the primary winding of output transformer T2, then through the common power supply to ground, and back to the cathode of V2.

Capacitor C1 and resistor R1 serve as a common grid-leak bias combination for both tubes. Leakage electrons which strike the grid of either tube must flow back to ground through the appropriate half of the secondary winding of transformer T1, and then through resistor R1. If R1 has a sufficiently high resistance, all grid-leakage electrons from both tubes will accumulate on the left plate of capacitor C1, and a negative voltage will build up and be applied equally to the control grid of each tube. This negative voltage, known as a *grid-leak bias voltage,* is characterized by an *intermittent* input of new electrons from each tube once each cycle, and by a continuous drain of electrons from the capacitor, through resistor R1 and back to ground.

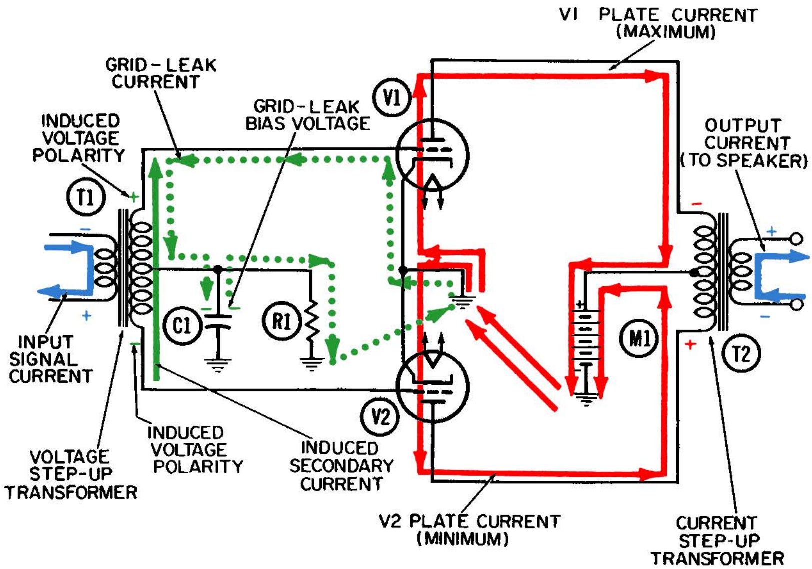


Fig. 4-3. Operation of a push-pull AF power amplifier using grid-leak bias—first half-cycle.

A circuit constructed in this manner—with a transformer in the input portion—will normally be operated Class-A, which means each tube is conducting some plate current during the entire audio-frequency cycle. Thus, in Fig. 4-3, when V1 conducts heavily, V2 will conduct lightly. During the second half-cycle, V2 will have a more positive grid voltage and will conduct heavily while tube V1 will have a negative grid voltage and consequently conduct only a small amount of plate current. The plate current in each tube is a pulsating direct current, and the pulsation from each tube will cause transformer action between the primary and secondary windings of T2. These two separate transformer actions will fortunately be in the appropriate phase to aid, or reinforce, each other. As a result, a very heavy secondary current (in blue) will flow in the output circuit. This output current is a greatly amplified version of the small input-signal current, also shown in blue, which flows up and down in the primary winding of T1.

Notice, transformer T1 has more turns in its secondary than in the primary. Therefore, it steps-up the voltage (and steps-down the current) before applying it to the two control grids, since vacuum tubes are voltage controlled devices. Transformer T2, on the other hand, has more turns of wire in its primary than in its secondary winding. So it will act as a current step-up (and volt-

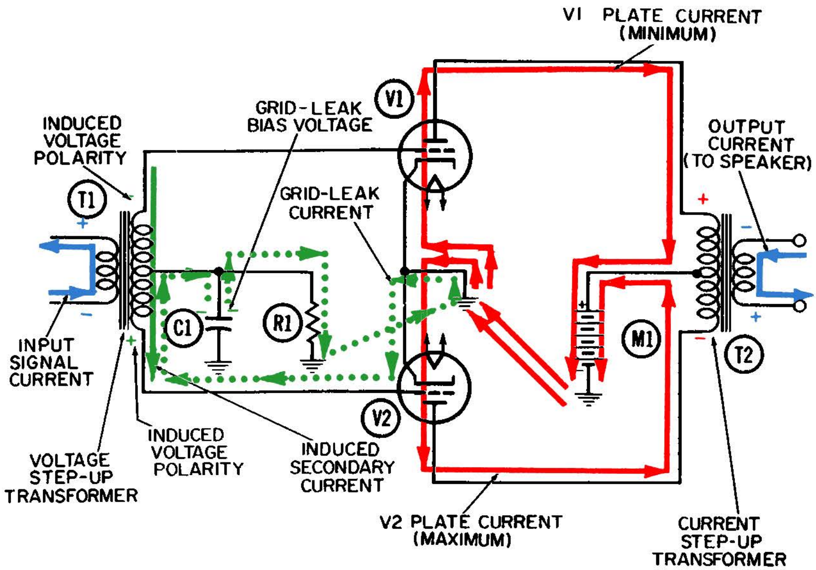


Fig. 4-4. Operation of a push-pull AF power amplifier using grid-leak bias—second half-cycle.

age step-down) transformer. This is advantageous for this reason—the transducer (speaker) to which the secondary winding of the output transformer is connected will usually be a current-operated device. Hence, the volume of sound available will depend directly on the strength, or amplitude, of the *current* pulsations flowing through the speaker coil. The speaker current, and the current through the secondary winding of transformer T2, are of course one and the same.

Transformer Action

Let us consider the transformer actions as a result of the two plate currents in Fig. 4-3. During the first half-cycle the plate current starts at its minimum value and *increases* continuously until it reaches its maximum value at the end. As this current flows *downward* through the upper half of the primary winding of T2 at an increasing rate, another current will be induced to flow *upward* in the secondary winding (also at an increasing rate) because the natural tendency of any transformer is to *oppose* any change in the total current flowing through the windings. Associated with these two currents are appropriate voltage polarities, the signs of which are indicated at the tops of the primary and secondary windings. An increase in plate current is normally associated with a reduction in plate voltage, because of the greater number of electrons in the plate area. This is the meaning of the minus sign at the top of the primary winding in Fig. 4-3.

By definition, a back emf always has a polarity opposite that of the applied emf, or voltage. Consequently, in Fig. 4-3, the resulting back emf in the secondary winding of T2 will have a positive polarity at the top. It is possible to correlate both voltage polarities with the directions of current flow indicated—more electrons flow *away* from the minus sign in the primary winding, and more electrons flows *toward* the plus sign in the secondary winding.

During the same first half-cycle (Fig. 4-3), current through V2 starts out at its maximum value and decreases to minimum at the end of the half-cycle. Associated with this decrease in plate current is the conventional rise in plate voltage. The latter can be symbolized by the plus sign at the bottom of the primary winding, which also designates the polarity of the applied emf across the lower half of the primary.

The resulting back emf across the secondary winding will have a negative polarity at the bottom of the winding, as indicated by the minus sign. Associated with this polarity will be a flow of electron current away from the negative region and *upward* through the winding.

Hence, during the first half-cycle two different components of secondary current are made to flow *in phase* with each other by the two streams of plate current, thus making a very heavy current available for operating the speaker.

During the second half-cycle (Fig. 4-4) most of the previous conditions are reversed. The direction of signal current in the primary of the input transformer T1 is upward, and the resulting back emf in the secondary winding is positive at the bottom. This causes a steady *increase* in the plate current through tube V2, with the resultant lowering in plate voltage and a negative polarity sign for the applied emf across T2. The resulting back emf across the secondary winding will have a positive polarity at the bottom, indicated by the plus sign, and during this half-cycle electron current will of course be flowing *downward* in the secondary winding at an increasing rate.

As the control grid of tube V1 becomes progressively more negative during this second half-cycle, the plate current through V1 decreases. This causes a rise in plate voltage, as indicated by the plus sign at the top of the primary winding of T2. The transformer action across T2 gives a back emf of negative polarity at the top of the secondary winding, as indicated by the minus sign. Therefore, electron current flows *downward* through the secondary winding.

Thus, the two transformer actions resulting from the two plate currents will drive currents in the secondary winding, which are in phase during each half-cycle of operation. This feature is of course the special attractiveness of the push-pull circuit.

Plate and Grid-Leak Currents

For the newcomer to electronics, the complete path of plate and grid-leakage currents will now be briefly reviewed.

Electrons which leave the cathode and reach the plate of tube V1 will flow through the upper half *only* of the primary winding of transformer T2 before being drawn into the positive terminal of power supply M1 and delivered through the power supply to ground and back to the cathode. It is of course the high positive voltage of the power supply which causes this entire sequence to occur, since this voltage provides the positive plate voltage which draws the electrons across the tube.

By similar reasoning, the plate-current path for tube V2 is from cathode to plate, upward through the lower half *only* of the primary winding of transformer T2 to the positive terminal of the power supply, through the power supply to ground, and back to the cathode.

Grid-leakage electrons will flow out of the tubes via the control grids whenever a control-grid voltage is more positive than the cathode voltage. In tube V1 this will occur near the middle of the first half-cycle, and in V2, near the middle of the second half-cycle.

Grid-leakage electrons from both tubes must flow back to their respective cathodes *through* half of the secondary winding of T1 and through resistor R1. Prior to entering R1, the electrons will accumulate on the top plate of capacitor C1 and form a reservoir of negative voltage (known as the grid-leak bias voltage). This voltage biases the control grids of both tubes to the same negative value.

Fig. 4-5 gives the time relationship between the voltages at the two control grids, the two plate currents, and the output current flowing in the secondary winding of transformer T2 in graphical form.

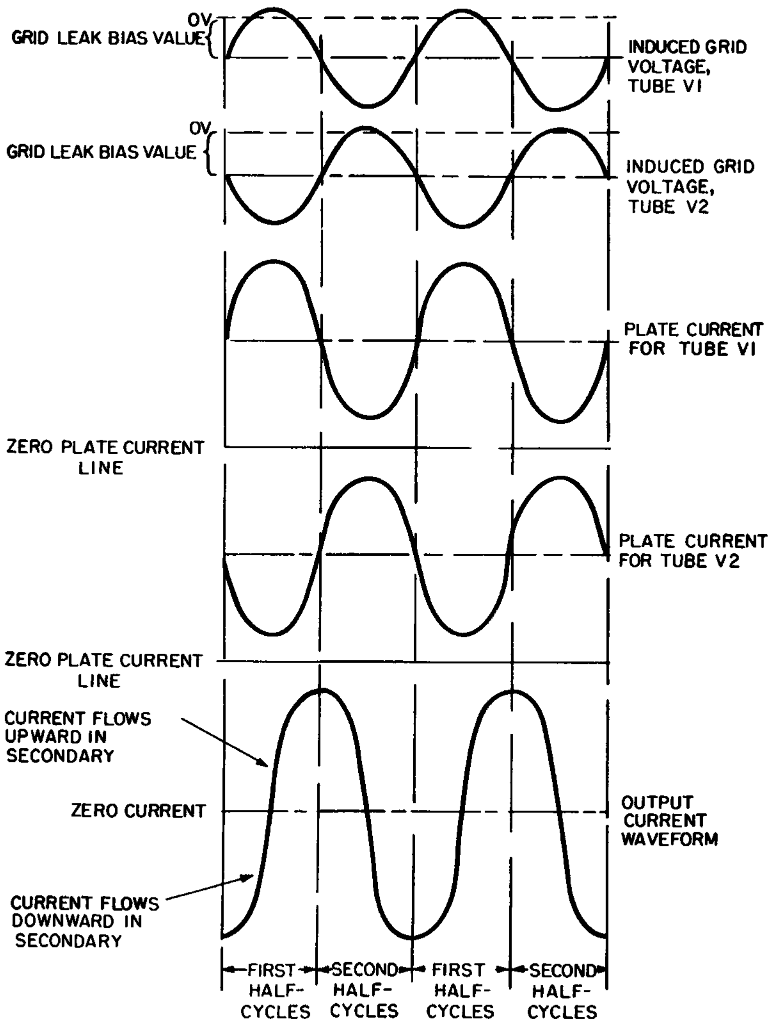


Fig. 4-5. Voltage and current waveforms in the amplifier of Figs. 4-3 and 4-4.

PUSH-PULL AMPLIFIER USING CATHODE BIAS

Another common type of push-pull power amplifier is given in Figs. 4-6 and 4-7. Notice that here two signals, each 180° out of phase, drive the grids of the push-pull amplifier tubes. (How these two 180° out of phase signals are obtained is explained in

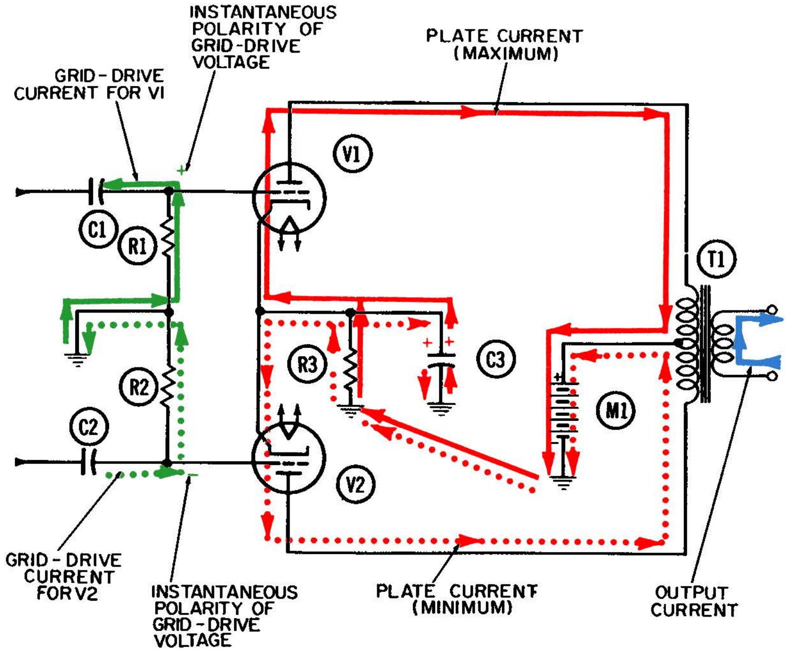


Fig. 4-6. Operation of a push-pull AF power amplifier using cathode bias—first half-cycle.

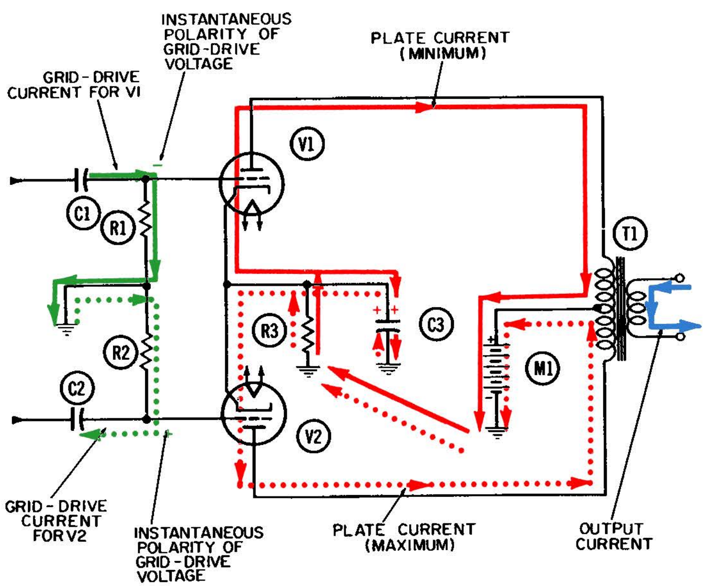


Fig. 4-7. Operation of a push-pull AF power amplifier using cathode bias—second half-cycle.

the next chapter. For now, just assume that two signals of opposite polarity are applied to the two inputs.)

The components of the circuit are:

R1—Grid-driving and grid-return resistor for V1.
R2—Grid-driving and grid-return resistor for V2.
R3—Cathode biasing resistor for both tubes.
C1—Grid-coupling capacitor to V1.
C2—Grid-coupling capacitor to V2.
C3—Cathode filter capacitor.
T1—Output transformer.
V1 and V2—Triode power-amplifier tubes.
M1—Common power supply for both tubes.

There are five currents at work in this circuit which must be identified and analyzed to understand the operation of the circuit. The currents and colors representing them in Figs. 4-6 and 4-7 are:

1. Grid-drive current for V1 (solid green).
2. Grid-drive current for V2 (dotted green).
3. Plate current for V1 (solid red).
4. Plate current for V2 (dotted red).
5. Output current to speaker (blue).

Circuit Operation

During the first half-cycle (Fig. 4-6) electrons are being drawn upward through R1 to the right plate of C1 as shown in solid green. This electron flow indicates that the polarity of the signal voltage applied to the left plate of C1 is becoming more positive. At the same time, electrons (shown in dotted green) are flowing upward through R2, indicating that the signal voltage applied to the left plate of C2 is becoming less positive (more negative). The polarities of the grid-driving voltages resulting from the electron flows through R1 and R2 are indicated by the green plus sign at the grid of V1 and the green minus sign at the grid of V2. During the second half-cycle (Fig. 4-7), the conditions are reversed, the grid-driving currents are reversed and the grid of V1 is driven negative and the grid of V2 positive. Thus, the conditions are essentially the same as in Figs. 4-3 and 4-4. That is, when the grid of one tube is driven positive, the other is driven negative.

Operation of the two push-pull tubes is practically identical to that of the push-pull amplifier with transformer input discussed previously. The plate current for each push-pull tube must flow out of ground and through cathode biasing resistor R3, so that both plate currents will contribute to the total bias voltage developed across R3.

The path for the plate current in tube V1 includes a journey through R3, then upward through the tube from cathode to plate, and downward through the upper half of the output-transformer primary winding. The current exits from the transformer at the center top and is drawn onto the positive terminal of the power supply for delivery back to the common ground. Through the upper portion of the transformer primary, the V1 plate current will flow in pulses, reaching its maximum during the half-cycle shown in Fig. 4-6 and minimum during the half-cycle in Fig. 4-7. The flow of pulsating DC through the primary winding of the transformer will produce an alternating current (shown in blue) in the secondary winding. This action is identical to the transformer action of the push-pull amplifier discussed previously.

Whenever the plate current in tube V1 is *increasing* (Fig. 4-6), the secondary current (blue) will flow *upward*. By the same token, it will flow *downward* whenever the plate current is *decreasing*, as shown by the second half-cycle of Fig. 4-7.

The plate current for the lower push-pull tube, V2, is shown in dotted red. It originates at the cathode, flows to the plate and upward through the lower half of the primary winding, then goes through the power supply to ground. From ground the current flows up through resistor R3. This completes its journey back to the cathode. V2's current, which is also a pulsating DC, is 180° out of phase with the pulsations going through the upper tube. Thus, the resulting transformer action between primary and secondary will drive additional secondary current in the transformer, the two components of which will be in phase with each other.

As with the previous push-pull amplifier circuit, the secondary current will be twice as heavy as for a single tube. Because the secondary winding has fewer turns of wire than either half of the primary, the secondary current is increased. This step-up action is desirable, because the secondary current normally drives some type of transducer—such as a speaker—which requires a low voltage but a high current.

Cathode Filtering

Filter capacitor C3 performs two filtering actions simultaneously. If they could be looked at separately, each would appear as shown in Figs. 4-6 and 4-7. For instance, when excess electrons flow *onto* **the top plate of C3 in Fig. 4-6 (because tube V2 re-**

fuses to accept them), an equal number would flow off the bottom plate. Both components of filter current will reverse their direction when V2 conducts heavily (see Fig. 4-7).

The filtering current associated with the fluctuations of plate current through the upper tube, V1, is also shown. At all times it is flowing 180° out of phase with the filtering current associated with tube V2. During *ideal* operating conditions, these two filter currents will at all times be equal in amount but opposite in flow direction. They would cancel each other out completely and the filter capacitor could be dispensed with entirely, with no fear of degeneration.

In actuality such an ideal condition can never be achieved. For one thing, the grid driving voltage developed for each tube will vary slightly. Further, it is highly unlikely the emission characteristics of two identical tubes would remain the same throughout the operating life of the tubes—or even after their first day in service. Consequently, if both grid-driving voltages are equal, and both push-pull tubes have exactly the same emission characteristics, the current shown flowing between the bottom plate of C3 and ground will not exist. However, in any practical circuit a certain amount of current will flow here. The important idea is to visualize the two filtering actions separately. Once this is done, the exact degree to which they may be canceling each other out is of small concern.

CLASS-B PUSH-PULL AMPLIFIER

Often, the bias and plate voltages are selected so that, when no driving signal is present, each of the push-pull tubes will be exactly at the point of conduction. By proper selection of components, the bias voltage is made to exactly equal the grid cutoff value, as determined by the characteristic curves of the tube. Thus, each tube will conduct from cathode to plate whenever an applied signal voltage makes its grid voltage more positive than its cutoff value as shown in Fig. 4-8. Obviously, each tube will not conduct electrons whenever an applied signal voltage makes its grid voltage more negative than its cutoff value. This is illustrated by the plate-current curves in Fig. 4-8.

The net result is that when two equal amplitude–opposite-phase sinusoidal voltages drive the two push-pull tubes, each tube will conduct electrons during half of a cycle but will be cut off during the other half. This is what is known as Class-B operation of the tubes.

The output, or speaker current, which flows in the secondary winding of the output transformer is alternately driven by each plate current as it flows through its half of the transformer primary winding. This is the same as for the two previous push-pull

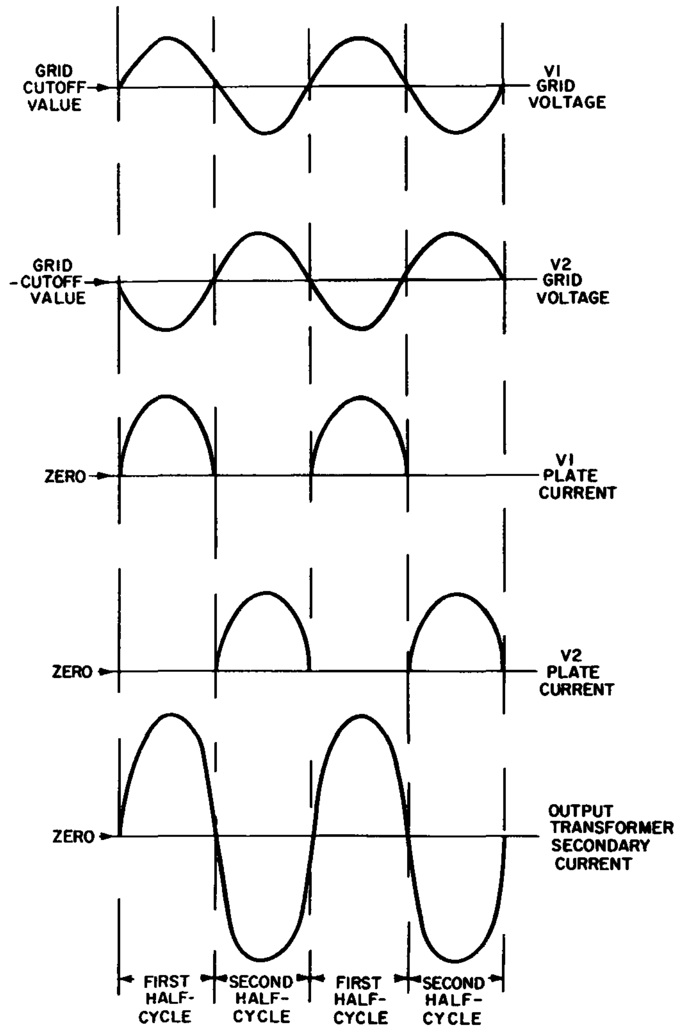


Fig. 4-8. Voltage and current waveforms in a Class-B power amplifier.

amplifier examples, except that current is flowing through only half of the output transformer at a time.

Class-B amplifiers have a much higher efficiency than Class-A amplifiers. Therefore, even though only half of the output transformer has current flowing through it at a given instant, approximately *twelve* times as much audio power can be delivered by two tubes operating Class-B than by their Class-A counter-parts.

Chapter 5

AUDIO PHASE-INVERSION CIRCUITS

In the previous chapter, the need for two signals equal in amplitude but opposite in phase to drive the push-pull audio amplifiers was discussed. One method of obtaining the required signal (using a center-tapped transformer) was given in Figs. 4-3 and 4-4. In this chapter two methods of obtaining the required signal using R-C coupling will be given.

SINGLE-TRIODE PHASE INVERTER

Figs. 5-1 and 5-2 show common phase inversion circuit. This circuit provides the two 180° out of phase output signals necessary to drive the control grids of the two push-pull power amplifier tubes.

The components of this circuit are:

C1—Input capacitor from previous voltage-amplifier stage.
C2—Cathode bypass or filter capacitor.
C3—Plate coupling capacitor.
C4—Cathode coupling capacitor.
R1—Grid driving and grid return resistor.
R2—Cathode biasing resistor.
R3—Cathode "following" resistor.
R4—Plate load resistor.
R5—Grid driving and grid return resistor for V2.
R6—Grid driving and grid return resistor for V3.
V1—Triode tube used for phase-inversion purposes.
V2 and V3—Power-amplifier tubes.
M1—Power supply.

The currents, and the colors indicating them, in this circuit are:

1. Grid-driving current for V1 (green).
2. Plate current (solid red).
3. Grid-driving current for V2 (solid blue).
4. Grid-driving current for V3 (dotted blue).
5. Cathode filter current (dotted red).

In addition to these currents, it is always possible, and sometimes inevitable, that grid leakage current will flow from any vacuum tube. Because the grid-leakage phenomenon is not used in this particular circuit, grid-leak currents have not been shown in the diagrams of Figs. 5-1 and 5-2. However, all tube circuits invariably take care of any grid-leakage electrons by having *a closed path back to ground and the cathode* from the grid. This path may consist of a single resistor or any number of such components in combination, as long as grid-leakage electrons have a path available through which they can return to the cathode of the tube from which they were emitted. In Figs. 5-1 and 5-2, this path is provided by R1 between the grid and ground, then through R3 and R2 to the cathode.

Also not shown, nor seldom referred to in discussions of circuit operation, are the cathode *heating* currents. These current,

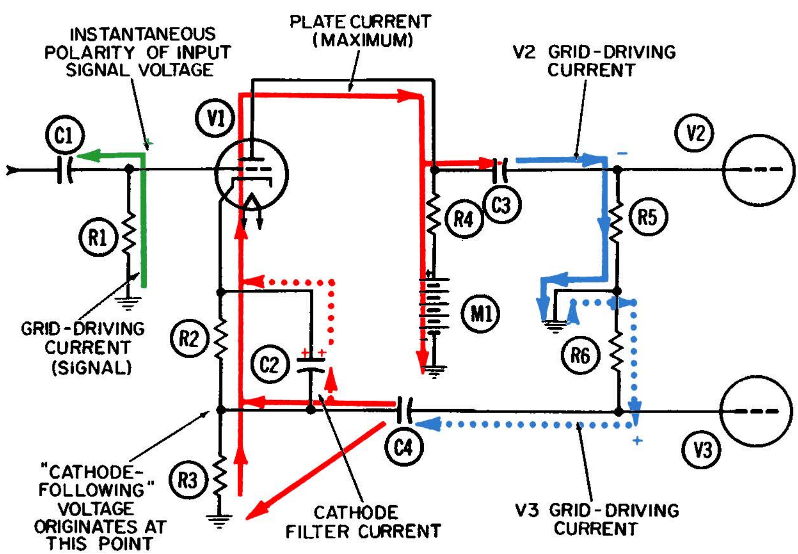


Fig. 5-1. Operation of a cathode-follower phase-inverter circuit—first half-cycle.

which frequently go by the name of filament (or filament heating) currents, were discussed more fully in the opening chapter. They perform the essential function of heating the tube cathodes so that electron emission can occur.

The remaining currents, which might be termed "operating" ones, are shown in Figs. 5-1 and 5-2. The initial, or input, function in this circuit is that of driving the grid of tube V1. This action is provided by the electron current (in green) as it flows upward through grid resistor R1 during the first half-cycle depicted by

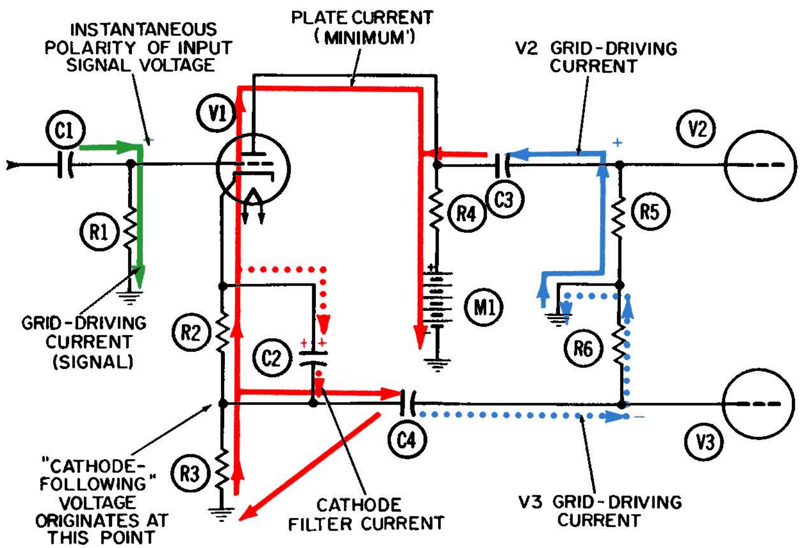


Fig. 5-2. Operation of a cathode-follower phase-inverter circuit—second half-cycle.

Fig. 5-1. The current here is, in all probability, being driven by the plate-current and -voltage combination of a preceding voltage-amplifier stage.

When current is being drawn upward and onto the right plate of capacitor C1, this indicates a positive voltage at the top of resistor R1. The voltage, indicated by a plus sign, is also applied to the control grid of tube V1, releasing a large pulsation of electron current into the plate circuit of the tube. This plate current (in solid red) flows onto the left plate of coupling capacitor C3, driving another current *downward* through grid resistor R5. This is the grid driving current for tube V2, and is shown in solid blue. Its complete path lies between coupling capacitor C3 and the ground connection at the bottom of R5. Its downward direction during this first half-cycle tells us the voltage at the top of resistor R5 has to be negative. This negative voltage is indicated by a minus sign, to show the instantaneous polarity of the grid voltage.

Since the polarity at the grid of tube V1 is *positive* during this first half-cycle, we see that the signal has experienced the normal phase reversal in its passage from the first to the second tube.

The Cathode-Follower Principle

The complete path of the plate current, shown by the solid red lines, is from cathode to plate, downward through load resistor R4, through power supply M1 and into the common ground connection. The plate current then has free access to the cathode by being drawn *upward* through cathode biasing resistors R3 and R2.

By virtue of the electrons which have left the cathode and gone across the tube to the plate, the voltage at the top of these two resistors will be positive with respect to ground, and it is this positive voltage which draws electrons up from ground and completes the plate-current path. If no bypass capacitor were present, this positive cathode voltage would increase as the plate current increased during the positive half-cycles, and would decrease during the negative half-cycles as the plate current decreased. This phenomenon is known as degeneration.

Capacitor C2 is used for filtering purposes across R2 in order to keep the voltage drop across R2 constant and thereby prevent degeneration across this resistor. A certain amount of degeneration will occur across remaining cathode resistor R3, however, for the following reason. As the plate current through V1 increases, the positive voltage at the top of resistor R3 will rise accordingly, because of the Ohm's law relationship between the value of the resistor, the amount of current, and the resulting voltage across the resistor.

Capacitor C4 couples this rise in positive voltage to the control grid of the lower push-pull tube, V3. This action can be visualized by looking at the currents flowing in and out of C4. As the positive voltage at the top of R3 *increases,* it will tend to draw electrons *away* from the left plate of C4. Their departure draws an equal number of electrons onto the right plate of C4. This electron flow, shown in dotted blue, constitutes the grid driving current for the lower push-pull tube, V3. Their downward flow through grid resistor R6 indicates that the voltage at the bottom of R6 will have a positive polarity (indicated by the blue plus sign) since electrons will always flow away from an area of negative voltage and toward an area of positive voltage. This is the positive grid voltage for tube V3.

When an alternating voltage is taken, or "coupled," from it, the cathode will have the same polarity as the input or driving voltage. In the example of Fig. 5-1, the moment the grid voltage reaches its most positive value, the voltage across the lower cathode resistor, R3, will also reach its most positive value and be coupled to the grid of the next tube, making the grid positive. This function is known as cathode following which means the voltage coupled out of the cathode circuit has the same polarity as the voltage at the grid of the same tube. In that sense the cathode voltage "follows" the input voltage.

In the second half-cycle, depicted by Fig. 5-2, most of these conditions are reversed. The grid-drive current flows *downward* through resistor R1, making the control grid of tube V1 negative. As a result, the plate current through tube V1 is reduced and its plate voltage rises. This rise in plate voltage draws electron away from the left plate of C3 and causes an equal number to flow upward through R5 to the right plate of C3. The resulting voltage drop across R5 makes the grid of V2 positive as indicated by the blue plus sign.

This reduction in the current flowing upward through R3 and into the tube causes a *smaller* voltage drop across this resistor than occurred during the first half-cycle. This means the positive voltage at the top of resistor R3 will fall and thus permit electrons to return toward the left plate of capacitor C4. This return flow will be accompanied by (1) a reversal in the direction of the grid driving current flowing through resistor R6, and (2) a change in polarity, of the grid drive voltage for tube V3, from plus to minus.

Hence, it is evident that the phase of the driving signal has now been inverted—when one push-pull tube is driven positive, the other is driven negative and vice versa.

Cathode Filtering

Capacitor C2 is bridged across resistor R2 to bypass the plate-current pulses around R2. It does this by alternately *receiving* some electrons onto its top plate during negative half-cycles such as the one in Fig. 5-2 and *relinquishing* them into the tube during positive half-cycles (Fig. 5-1). When electrons are given up into the tube, an equal number will be drawn onto the lower plate of the capacitor; this current is shown in dotted red. Fig. 5-2 shows what happens when the tube refuses to take the electrons coming up through the cathode resistors. The excess electrons flow onto the upper plate of capacitor C2 and drive an equal number away from the lower plate.

The small current flowing in and out of the capacitor is the cathode filter current. Its action is somewhat analogous to that

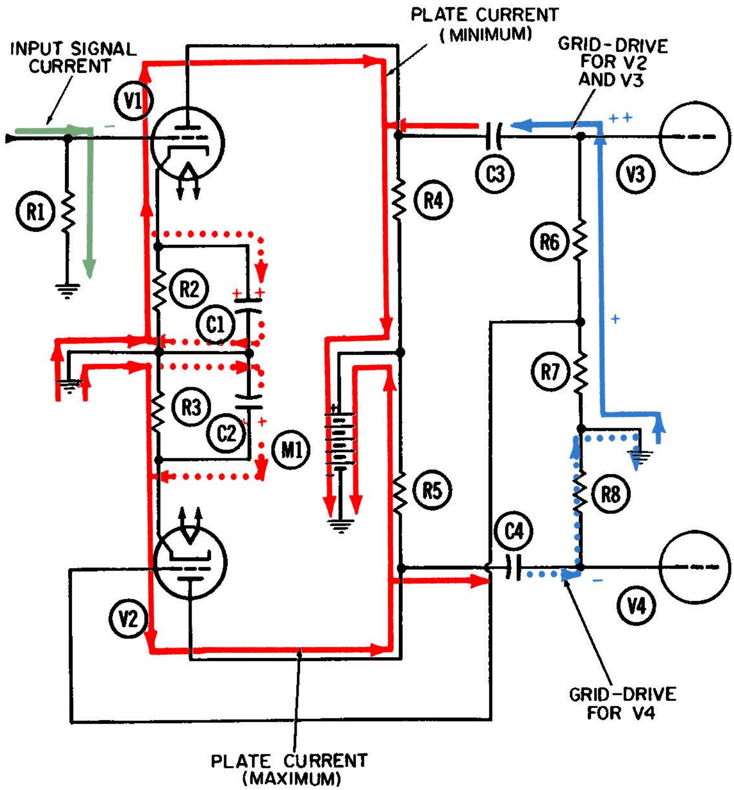


Fig. 5-3. Operation of a two-tube phase-inverter circuit—first half-cycle.

of a shock absorber on an automobile—it keeps the voltage at the cathode from fluctuating with the current going into the tube.

TWO-TRIODE PHASE INVERTER

Figs. 5-3 and 5-4 depict another common type of circuit arrangement for achieving push-pull amplification at audio frequencies. An additional driving tube is utilized, its purpose being to invert the phase of the input signal.

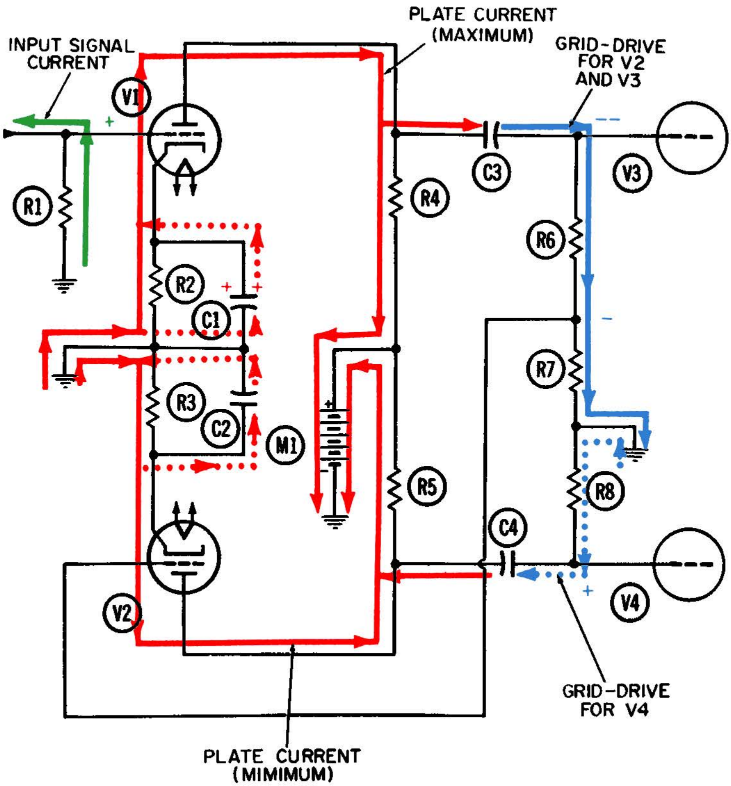


Fig. 5-4. Operation of a two-tube phase-inverter circuit—second half-cycle.

The components which make up this circuit are:

R1—Input grid drive resistor.
R2—Cathode bias resistor for V1.
R3—Cathode bias resistor for V2.
R4—Plate load or coupling resistor for V1.
R5—Plate load or coupling resistor for V2.
R6—Grid drive resistor for V3.
R7—Grid drive resistor for V2 (the phase-inverting resistor).
R8—Grid drive resistor for V4.
C1—Cathode bypass capacitor for V1.
C2—Cathode bypass capacitor for V2.
C3—Coupling and blocking capacitor between V1 and V3.
C4—Coupling and blocking capacitor between V2 and V4.
V1—Input driving tube.

V2—Input phase-inverting tube.
V3 and V4—Push-pull amplifier tubes.
M1—Power supply.

The currents, and the colors they are shown in are:

1. Input-signal current flowing through R1 (green).
2. Plate current for V1 (solid red).
3. Plate current for V2 (also in solid red).
4. Cathode filter currents for V1 and V2 (dotted red).
5. Grid driving current for tubes V2 and V3 (solid blue).
6. Grid driving current for tube V4 (dotted blue).

Analysis of Operation

The grid driving current (in green) flowing through resistor R1 would in all probability be the output current of a preceding voltage-amplifier stage. During the first half-cycle depicted by Fig. 5-3, this current is flowing downward through R1. This tells us the top of the resistor must be more negative than the bottom, since electrons (being negative themselves) will *always* flow away from a more negative voltage and toward a more positive one. This negative grid voltage is depicted by a minus sign at the top of the resistor in Fig. 5-3.

Throughout the entire first quarter-cycle, the grid voltage is becoming progressively more negative. Likewise, the plate current through V1 is being progressively reduced. The result is that the plate current (in solid red) will have dropped to its minimum value by the *end* of the first quarter-cycle. Since this current must flow downward through plate load and coupling resistor R4, the voltage drop across R4 will be smaller and the plate voltage higher than at any other moment during the entire cycle.

Ordinarily, any fluctuations in plate voltage will be coupled, across capacitor C3, to the grid driving resistor for the next stage. The change in plate voltage just described, which occurs during the first half-cycle, can only come about if more electrons are taken away from the plate than are delivered onto it. This means the positive terminal of the power supply draws more electrons downwards through plate load resistor R4 than the plate current of tube V1 is delivering. These extra electrons can only come from the left plate of capacitor C3. An equal number must then be drawn onto the right plate of the same capacitor, to compensate for the loss.

The electrons being drawn onto the right plate of C3 can only come upward through resistors R6 and R7 from the common ground connection at the bottom of R7. In flowing through R6 and

R7, these electrons comprise the grid driving current for both tubes V3 and V2 and the voltage at the top of R6 becomes progressively more positive throughout the first quarter-cycle.

Recall that the grid voltage for tube V1 became progressively more *negative* during this same quarter-cycle. So it should be obvious the conventional phase shift or inversion from grid to plate of tube V1 has occurred. A *small portion* of this V3 grid driving voltage is now used to drive the grid of V2. This was the purpose in putting low-resistance R7 in series with high-resistance R6. By selecting the proper values for R6 and R7, the voltage developed across R7 by the grid driving current can be made *equal in value* but *opposite in polarity* to the voltage being developed across resistor R1 by the original input-signal current. Thus, if the voltage amplification achieved by V1 has a value of 100 (not unusual for voltage amplifiers), resistor R7 would need to be only 1/100th the value of resistor R6.

Since the control grid of V2 is connected directly to the junction of R6 and R7, the voltage at this point becomes the grid drive voltage for the tube. Thus, during the first half-cycle shown in Fig. 5-3, the control grid of V2 becomes progressively more positive throughout the half-cycle, causing a steady increase in the current through the tube.

We associate an increase in plate current with a *decrease* in the positive plate voltage applied to the plate. This decrease in voltage can only come about if more electrons are delivered into the plate area *at any instant during the entire half-cycle* than the power supply is drawing away. If a temporary surplus of electrons is created on the plate during this half-cycle, the only place they can accumulate is on the left plate of capacitor C4. Moreover, they cannot flow onto the left plate of C4 unless an equal number are permitted to flow away from the right plate. The electrons which flow away (actually, they are "pushed" away) from the right plate of C4 have only one path available to them, and that is upward through resistor R8 to the common ground connection.

These electrons become the grid driving current for push-pull tube V4. Their amount increases steadily, or sinusoidally (since all grid driving voltages in this circuit have the same sinewave shape as the input-signal voltage), throughout the entire first quarter-cycle of Fig. 5-3. Consequently the grid voltage for tube V4 increases sinusoidally in the *negative direction,* causing the plate current through tube V4 to decrease from its maximum to its minimum value.

During the second half-cycle, the grid-driving currents and the resulting voltages will be reversed, as shown in Fig. 5-4. Current will flow upward through R1, driving the grid of V1 progressively more positive during the third quarter cycle. This increase in plate current results in a greater voltage drop across R4; hence the plate voltage for V1 will be reduced. Electrons flow onto the left plate of C3 driving an equal number off the right plate of C3 and down through R6 and R7 as shown by the solid blue line.

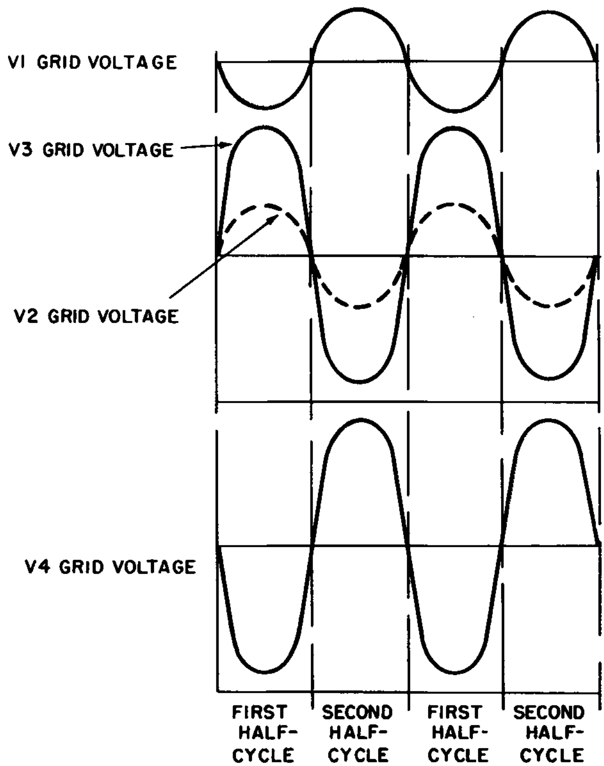


Fig. 5-5. Grid-voltage waveforms for the circuit in Figs. 5-3 and 5-4.

This electron flow drives the grid of V3 negative and the voltage at the junction of R6 and R7 will be a negative polarity but equal in value to the voltage at the grid of V1.

The negative voltage at the grid of V2 reduces the plate current through this tube; hence, its plate voltage increases. This increase in the V2 plate voltage draws electrons away from the left plate of C4 and an equal number of electrons (indicated by the dotted blue line) flow from ground, through R8, and onto the right plate of the capacitor. The flow of electrons onto the right plate of C4 becomes the grid-driving current for V4. The grid-driving voltage produced by this current through R8 is indicated by the plus sign at the grid of V4.

Thus, we have established that two sinusoidal voltages, both equal in amplitude, but 180° out of phase, are driving the two push-pull tubes. Fig. 5-5 shows the relationship between the four grid voltages.

The cathode filter current, indicated by the dotted red lines in Figs. 5-3 and 5-4, smooth out the fluctuations in the cathode voltages that would normally exist because of the pulsations in current through the cathode resistors. This is the same as was explained for Figs. 5-1 and 5-2, except that now we have two capacitors, and two filter currents.

Chapter 6

IMPEDANCE-COUPLED RF VOLTAGE AMPLIFIER

The prime function of the radio-frequency (RF) voltage amplifier is to amplify the radio-frequency voltage which is already in existence in the grid portion of the circuit—in other words, to get a higher voltage at the same radio frequency in the plate circuit.

The radio-frequency band includes those frequencies lying within the broadcast band which extends from 540 to 1600 kilocycles per second. In addition, frequencies up to several hundred megacycles per second are also considered radio frequencies.

Pentode tubes are usually employed for RF amplifiers operating in the broadcast band and the simplest type of coupling between stages is impedance coupling. That is, a single coil is used, instead of a transformer between stages.

Sometimes the coupling circuit is made adjustable and tuned to an exact frequency. Then, signals at the desired frequency will receive most of the amplification and all other frequencies will be rejected. In other words, the RF amplifier *selects* a certain frequency for amplification. The degree to which this is accomplished is termed the *selectivity* of the circuit.

Often, it is more desirable to amplify all RF signals present at the grid. The gain and selectivity will not be as great, but the *bandwidth,* or range of frequencies amplified, will be greater in the untuned circuit used in this application.

UNTUNED IMPEDANCE-COUPLED AMPLIFIER

Figs. 6-1 and 6-2 show two half-cycles in the operation of a radio-frequency voltage amplifier using untuned impedance coupling.

The load circuit consists of radio-frequency choke coil L1. The various components of this circuit are:

R1—Grid driving and grid leakage resistor.
R2—Cathode biasing resistor.
R3—Screen-grid dropping resistor.
R4—Grid driving resistor for next stage.
C1—Cathode filter capacitor.
C2—Screen-grid filter capacitor.
C3—Coupling and blocking capacitor.
L1—Radio-frequency choke coil.
V1—Pentode amplifier tube.
V2—Next amplifier tube.
M1—Power supply.

The following currents are at work in this circuit:

1. Grid driving current (solid green).
2. Plate current (solid red).
3. Screen-grid current (solid blue).
4. Screen-grid filtering current (dotted blue).
5. Cathode filtering current (dotted red).
6. Amplified grid driving current for next stage (dotted green).

Basically, this circuit and the ones discussed previously are alike in principle and function. As before, the grid is driven by causing an alternating current to flow up and down through the grid resistor. This grid driving current, usually called the signal current, flows at a radio-frequency rate in this example.

At an assumed frequency of 1,000 kilocycles per second, this grid driving current would make one million complete journeys down and up through the grid resistor, causing the grid voltage to change from negative to positive and back to negative this many times each second.

This varying control-grid voltage turns the plate-current stream through the tube down and up a million times a second. The resulting plate current flowing into radio-frequency choke L1 is a pulsating DC. The impedance of this choke coil is high enough that the *pulsations* of plate current cannot pass through the coil. Instead most of them flow onto the left plate of coupling capacitor C3, driving electrons away from its right plate and downward through resistor R4. This situation, depicted in Fig. 6-2, is called the second half-cycle of operation.

During those periods *between* the pulses of plate current, this grid drive current for the next stage flows back upward through R4. The purpose of the tube stage is to *amplify* the input-signal voltage applied across resistor R1. This amplification cannot be

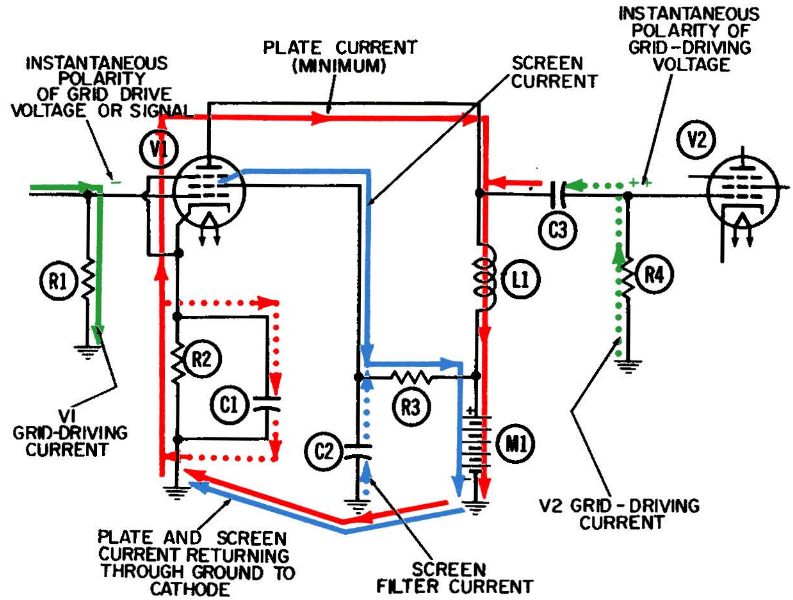


Fig. 6-1. Operation of the untuned impedance-coupled amplifier—first half-cycle.

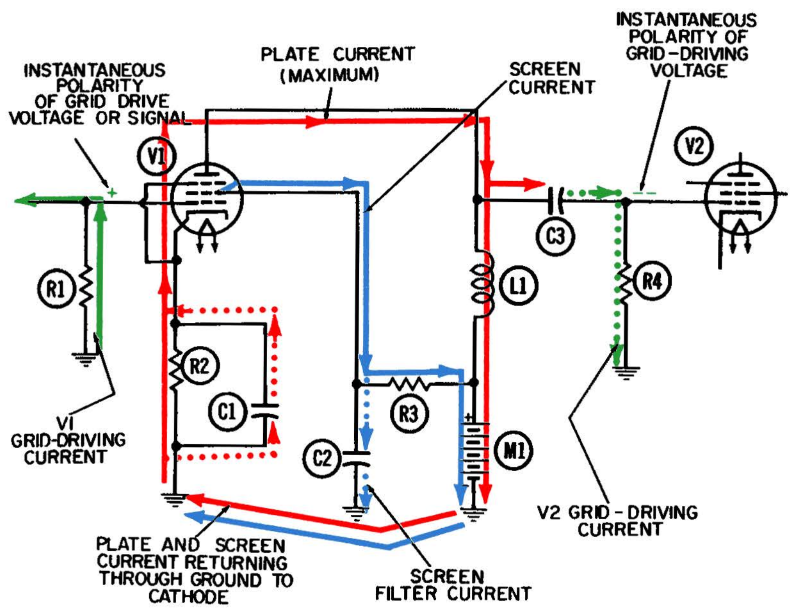


Fig. 6-2. Operation of the untuned impedance-coupled amplifier—second half-cycle.

accomplished unless the alternating voltage developed across R4 is significantly larger than the voltage across R1. If the voltage amplification (gain) achieved by this amplifier is equal to 50, then 50 times more alternating voltage will be developed across R4 than across R1. Should the two resistors have the same ohmic value, then the current flowing through R4 would also be 50 times greater than the current through R1.

The filtering of the pulses out of the plate current at the cathode, and out of the screen current by means of capacitor C2, are routine actions. Cathode filtering has already been adequately described. Screen-grid filtering is of course required only with tetrodes or pentodes, which have the extra grid. On the second half-cycle (Fig. 6-2), when the number of electrons in the plate-current stream increases, the number exiting from the tube via the screen grid will increase accordingly. If filter capacitor C2 were missing, this increase in screen current would cause a corresponding increase in the voltage drop across screen resistor R3. As a result, the voltage at the screen would be lowered during these positive half-cycles.

During the negative half-cycles (Fig. 6-1), when the negative control grid reduces the number of electrons in the plate-current stream, the number exiting from the tube at the screen grid will be reduced accordingly. Without filter capacitor C2, this reduction in screen-grid current would cause a corresponding *decrease* in the voltage drop across resistor R3, and a resultant *rise* in the positive voltage applied to the screen grid.

These voltage changes at the screen grid are undesirable because they constitute a form of degeneration which reduces the available amplification from the circuit as a whole. The reason is that the screen-grid voltage has a definite effect on the amount of plate current through the tube. With this type of degeneration present, the voltages at the screen and control grids will be working at cross-purposes: As the control grid tries to *increase* the plate current, the screen grid will act to reduce it, and vice versa.

The resulting loss in amplification can be avoided by the addition of C2. This filter capacitor absorbs the pulses of screen current during the positive half-cycles. The filter current (shown in dotted blue) is now driven from the lower plate of C2 to ground and permitted to return upward on the negative half-cycles.

With the audio circuits discussed in earlier chapters, filter connections were usually made directly to ground. When radio-frequency currents are being handled, cathode and screen filter capacitors should normally be connected to the lower end of the cathode resistor rather than directly to ground. Once the radio-frequency currents are permitted to enter the common ground (usually the chassis), they could be coupled through it to some other point and introduce undesirable feedback there.

As is true with all vacuum-tube circuits, the plate and screen currents must eventually return to the cathode after passing through the load and power supply M1. This return path has been indicated beneath the diagrams.

As mentioned previously, a circuit using an untuned impedance as a load lacks the high selectivity of circuits with tuned loads (discussed later). It is this feature which gives rise to the use of this circuit, for there are applications where radio-frequency amplifiers in series can become *too* selective and pass too narrow a band of frequencies to carry the desired intelligence, or modulation. By using an occasional untuned impedance load like this one, the selectivity is broadened somewhat, but at the expense of gain.

TUNED IMPEDANCE-COUPLED AMPLIFIER

This pentode radio-frequency amplifier has a tuned circuit connected to the grid and another one in the plate circuit. These circuits are normally tuned to be resonant at the same radio frequency.

Figs. 6-3 and 6-4 depict the two half-cycles of the tuned impedance-coupled RF voltage amplifier. The various functions of this circuit, and the manner in which they are accomplished, will be discussed in detail in this section. The circuit components include:

R1—Grid resistor.
R2—Cathode biasing resistor.
R3—Screen-grid dropping resistor.
R4—Grid resistor for next tube.
C1—Grid tank capacitor.
C2—Grid coupling capacitor.
C3—Cathode filter capacitor.
C4—Screen-grid filter capacitor.
C5—Plate tank capacitor.
C6—Grid coupling capacitor for next tube.
L1—Grid tank coil.
L2—Plate tank coil.
V1—Pentode tube.
M1—Power supply.

There are three different groups, or "families," of currents at work in this circuit during normal operation. The first of these includes the radio-frequency alternating currents in the two tank circuits, together with their output currents and voltages. These have been shown in solid green in the grid circuit, and in blue in the plate circuit. The second family is made up of the unidirectional currents, shown in solid red, which flow primarily in one direction only; their paths are through the vacuum tube, and also through the power supply.

The third family consists of filtering currents (one is shown in dotted red and the other in blue) flowing into and out of capacitors C3 and C4.

All these currents will have radio-frequency components—it should not be inferred that the ones labeled "radio-frequency alternating currents" are the only currents with RF components.

Fig. 6-3 shows the current flow and voltage polarities during the first half-cycle. It is labeled a "negative half-cycle" because the grid driving voltage becomes progressively more negative during this half-cycle, until at the end it reaches its most negative value.

Fig. 6-4 shows the current flow and voltage polarities during the second, "positive," half-cycle. During this half-cycle, the grid-driving voltage becomes progressively more positive and at the end reaches its most positive value.

Fig. 6-5 shows the significant current and voltage waveforms which occur during circuit operation. Vertical lines have been drawn on the diagram to separate the half-cycles.

RADIO-FREQUENCY ALTERNATING CURRENTS

Fig. 6-3, which depicts current conditions during an entire half-cycle of radio frequency and the voltage conditions at the *end* of the half-cycle, shows electron current (in solid green) flowing upward through grid tank inductor L1 and charging the upper plate of grid tank capacitor C1 with electrons. The negative voltage created at this point causes electrons to flow onto one plate of coupling capacitor C2. An equal number are driven off the opposite plate and flow downward through grid resistor R1. This electron flow is also shown in solid green.

The grid will have its maximum negative voltage at the same time this current is flowing downward through the grid resistor at its maximum rate. It will always help, in determining whether a grid is negative or positive, to remember that electrons always flow *from* negative *to* positive. Since they are flowing downward through the resistor, toward ground, this tells us the ground voltage is more positive than the voltage at the top of the resistor, which is connected to the grid.

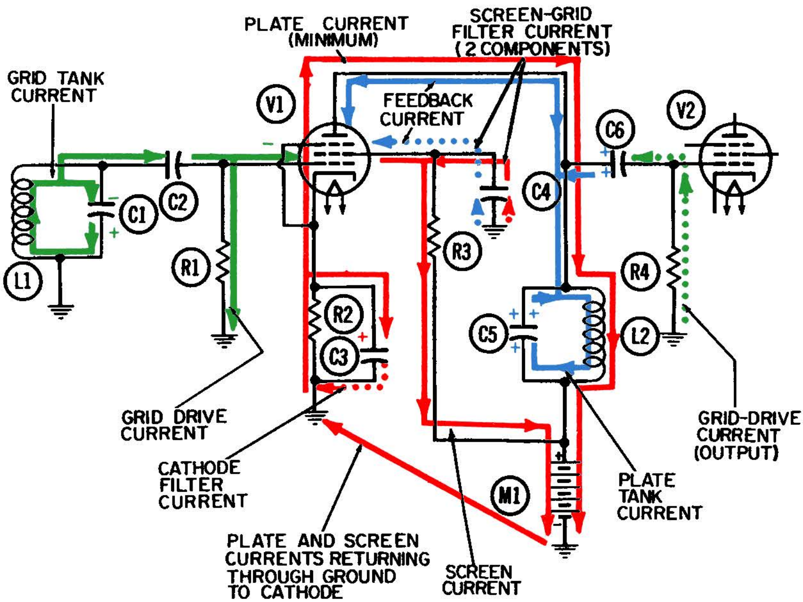


Fig. 6-3. Operation of the tuned impedance-coupled amplifier—first half-cycle.

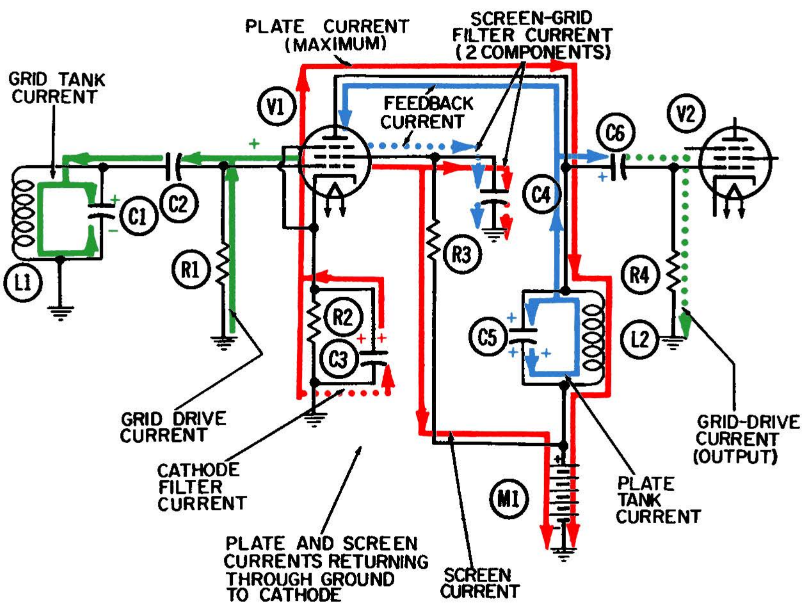


Fig. 6-4. Operation of the tuned impedance-coupled amplifier—second half-cycle.

Special attention should now be given to the waveforms for this circuit, in order that phase relationships between the various currents and voltages can be understood.

Grid tank current flows from the bottom plate to the top plate of capacitor C1 during the entire negative half-cycle and stops at the end of the half-cycle. In the waveform representing grid tank current in Fig. 6-5, that portion of the waveform *below* the center, or reference, line represents electrons flowing *upward* through tank inductor L1. Conversely, that portion *above* the reference line represents electron current flowing *downward* through L1.

At those points where the current waveform actually *crosses* the reference line—at the beginning and end of each half-cycle—*zero* current in flowing. That is, electrons have stopped flowing in one direction, and have not yet started in the opposite direction.

In Fig. 6-5 we see that at the end of the negative half-cycle, when the upward electron flow through the tank inductor has been completed, the grid tank voltage shown in line 2 has reached its *negative* peak value. The reason is that the tank current has delivered the maximum concentration of electrons to the upper plate of capacitor C1.

Line 3 of Fig. 6-5 shows the direction and amount of the grid drive current, which is caused to flow by the tank voltage of line 2 and is "in phase" with this voltage. The grid drive current, in Fig. 6-3, flows downward through grid resistor R1. This current is also known as the tank circuit's "external current." As long as there is a negative charge, meaning negative voltage, on the upper plate of C1, this electron current will flow *away* from the negative charge (or downward through the grid resistor). When there is a positive charge, meaning positive voltage, on the upper plate of the tank capacitor, these electrons will be drawn *toward* this positive voltage and consequently, *upward* through the grid resistor.

The voltage developed *across* any resistor is always in phase with and proportional to the current *through* it.

Thus, the voltage developed across resistor R1 (the grid driving voltage) will have its maximum negative value at the end of the negative half-cycle, when the tank's external current reaches its maximum downward flow. At the end of the positive half-cycle, when the external current achieves its maximum upward flow, the grid driving voltage will attain its maximum positive value. Thus, the tank voltage and the grid driving voltage will be in phase with each other at all times.

V1 is being operated under what are called Class-A conditions. That is, the tube conducts electrons during the entire cycle, as shown by the plate current waveform (line 4) of Fig. 6-5.

Another RF alternating current is shown in the plate tank circuit—this time in solid blue. This plate tank current (which is oscillating continuously between capacitor C5 and inductor L2) consists of considerably *more* electrons than does the grid tank current. The plate tank current is actually an "amplified" version of the grid tank current.

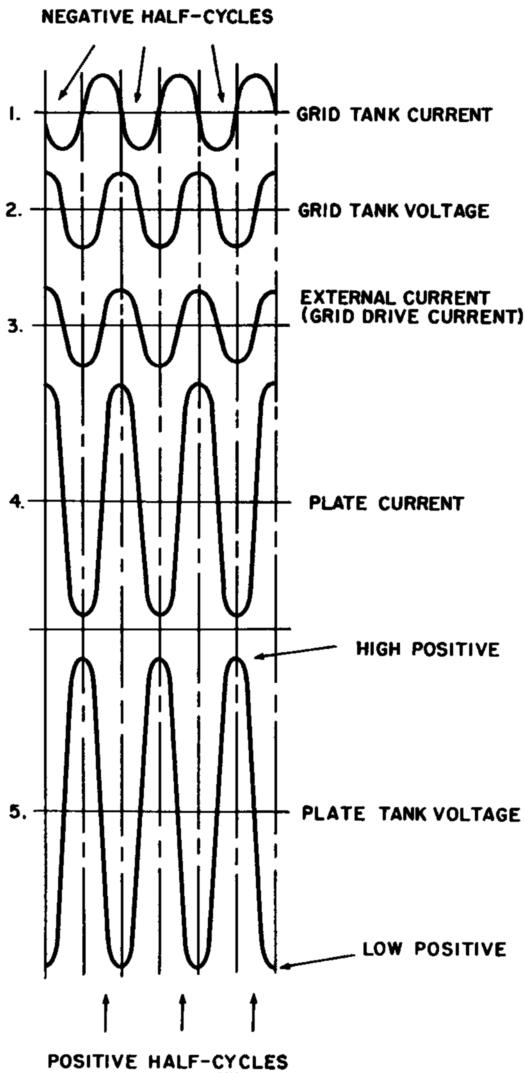
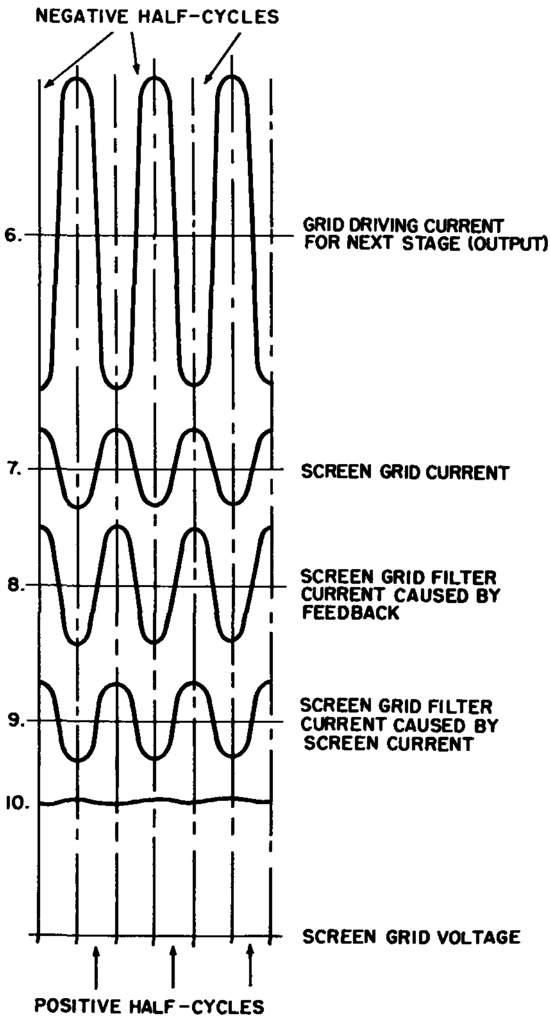


Fig. 6-5. Voltage and current waveforms

The plate tank voltage, which is measured at the top of coil L2 and capacitor C5, is also an amplified version of the grid tank voltage.

This plate tank current supports two other currents, both shown in solid blue. One is the output current flowing in and out of capacitor C6. The other is the feedback current, which flows



in the tuned impedance-coupled amplifier.

between the tank and the plate of the tube. Both act as "loads" on the electrons which are oscillating in the tank. During the last portion of the negative half-cycle and the first portion of the positive half-cycle, when the plate tank voltage is most positive, electrons are being drawn from the left plate of C6 and from the plate of the vacuum tube. This action draws electrons upward through grid-resistor R4 of the next tube and onto the right plate of C6. This flow of electrons (shown in dotted green), is the grid-driving current for the next tube. It will produce a positive voltage, with respect to ground, at the top of R4.

FILTERING CURRENTS

The function of the screen-grid, in helping to prevent a circuit from going into self-sustained oscillations, can now be explained by reference to the feedback current.

The feedback current, shown in solid blue, is separate from the unidirectional plate current, shown in solid red. During the last portion of the first half-cycle, the electrons which make up the feedback current are being drawn *away* from the tube plate and *toward* tank circuit inductor L2. Their movement away from the tube plate draws electrons *toward* the screen grid from its external circuit. A filtering current (dotted blue) therefore flows in the screen grid circuit. During the latter portion of the negative half-cycle and the first portion of the positive half-cycle, this filtering current is flowing upward from the top plate of C4 to the screen grid, and upward from ground to the lower plate of C4.

The screen grid and the plate of the tube act like two plates of a capacitor. The feedback current, which is driven by the oscillating plate tank voltage, in turn drives the filtering current along its path to ground through capacitor C4. If this screen grid were not in the tube, the feedback current would drive an unwanted current in the control grid circuit and the entire circuit could go into self-sustained oscillation. Both the control grid and the screen grid have interelectrode capacitance with respect to the plate of the tube. However, the screen grid is much closer to the plate, and therefore has much more capacitance to the plate, than does the control grid. Consequently, most of the energy represented by the feedback current is diverted harmlessly to ground, through filter capacitor C4 by means of the filtering current.

Additionally the wire mesh, which makes up the screen grid, shields the control-grid wires from the plate of the tube and thus greatly reduces the amount of interelectrode capacitance between control grid and plate.

C4 must do an additional filtering job—it must bypass to ground the fluctuations in the unidirectional screen grid current. The electron stream which flows through the vacuum tube consists of the part which goes to the plate and its external circuit, and the part which exists at the screen grid. The number of electrons in this stream is being continually varied by the changing voltage on the control grid. During the positive half-cycle (represented by Fig. 6-4), the control grid is made positive and a heavy surge of current goes through the tube. That portion which exists at the screen grid finds two alternate paths—it can flow directly into the screen-grid resistor, which is a comparatively high impedance; or it can flow momentarily onto the upper plate of capacitor C4. A size of capacitor is chosen that will act as a comparatively low reactance (impedance) at the particular frequency. Consequently, the surge of electrons in the screen-grid current during the positive half-cycle flows into C4, driving an equal number of electrons from the lower plate of C4 as shown by the dotted-red lines. A half-cycle later, during the conditions depicted by Fig. 6-3, the screen-grid current is reduced considerably, and the excess electrons resting on C4 from the previous half-cycle will now be drawn off through the screen-grid resistor R3 and to the power supply. At the same time, electrons will flow upward from ground to the lower plate of C4. These electrons, shown in dotted red, are the filtering component for the unidirectional screen-grid current. They of course are independent of the filtering current for the feedback energy previously described, even though they flow along the same path.

Resistor R2 and capacitor C3 function as an RC filter in much the same fashion as R3 and C4. All the unidirectional current which passes through V1 must first flow upward through R2 to reach the cathode. Since this current is constantly fluctuating (because of the voltage variations at the control grid), the amount of current through the resistor would also fluctuate if it were not for filter capacitor C3. If the current were allowed to fluctuate the voltage across R2 would also fluctuate, causing a normally undesirable condition known as *degeneration.*

During the period depicted by Fig. 6-3, the control-grid voltage has been made negative and the flow of electrons through the tube is thus restricted. The cathode is being held at a positive voltage by the deficiency of electrons (indicated by the red plus sign) on the upper plate of C3. This positive voltage will continue to attract electrons upward through resistor R2, and if the negative control grid prevents them from entering the tube, they will flow directly onto the upper plate of C3, as indicated by the red arrow. This action would *tend* to reduce the positive voltage in storage on the capacitor, and such reduction would be equivalent to a half-cycle of degeneration.

Fig. 6-4 indicates that the positive control grid increases the amount of electron current through the tube. This increased demand for electrons to leave the cathode may be supplied either through resistor R2 or capacitor C3. A size of capacitor is chosen that will have a reactance of a very few ohms at the operating frequency. Consequently, a sudden surge of electrons will be drawn into the tube from the upper plate of C3. This action will *tend* to increase the positive voltage on C3 (and at the cathode of the tube) and thereby constitute another half-cycle of degeneration.

The size of a capacitor (meaning its amount of capacitance) is paramount in determining whether such degeneration will occur, or whether it will be held within acceptable limits if it does. As long as the "pool" of positive ions on the upper plate of capacitor C3 is overwhelmingly large, in comparison with the number of electrons coming into or going out of capacitor C3 on successive half-cycles, then the "pool" voltage will not change significantly from one half-cycle to another and degeneration will not occur.

The cathode filtering current is shown in dotted red between the lower plate of C3 and ground. It is moving downward during the first half-cycle, being driven by the influx of electrons onto the top plate of C3. During the second half-cycle, as electrons surge away from the upper plate and into the tube, the filtering current is drawn upward from ground and toward the lower plate. The free movement of this filtering current is essential to the filter function. If something prevented this current from flowing (say, a broken connection), then the fluctuations of current onto and away from the top plate of C3 (shown in solid red) cannot occur. The electron flow through resistor R2 will then vary in unison with the variations in electron flow through the tube, and the resulting voltage across the resistor will also vary. In other words, we would have degeneration.

The most obvious effect of degeneration is a decrease in the over-all amplification achieved by the circuit. This amplification is a comparison between the input and output voltages. The amount of output voltage in this figure is proportional to the number of electrons (shown in solid blue) oscillating in the plate tank circuit. The size of any plate tank oscillation will depend on the size, or strength, of the current or voltage which replenishes it each cycle. This oscillation is replenished by the *variations in amount* of unidirectional current which reaches the tank from the tube.

Fig. 6-3 shows a negative voltage on the control grid, with the resulting *decrease* in the number of electrons through the tube. If degeneration were occurring, this decrease in tube current through cathode resistor R2 would also decrease the positive voltage at the cathode. The *difference* in voltage between cathode and grid would not then be as great as desired, and the *reduction* in tube current from its normal value would not be as great as desired.

Fig. 6-4 shows a positive voltage on the control grid, with the resulting *increase* in the number of electrons going through the tube. If degeneration were occurring, this increase in tube current through the cathode resistor would increase the positive voltage at the cathode. The difference in voltage between control grid and cathode again would not be as great as desired, and the *increase* in tube current flowing would not be as great as desired.

The plate tank oscillation is sustained by the surges in the unidirectional plate current. The size, or strength, of each surge is determined by the difference in the number of electrons flowing through the tube at these two moments (namely, at the grid-voltage negative and positive peaks). Larger surges of electrons will sustain larger oscillations. As the surges become smaller, so will the oscillations. When degeneration is occurring, the minimum current through the tube will not be low enough and the maximum current will not be great enough. As a result, their *differences* will be reduced and the plate tank oscillation will be smaller accordingly. The output voltage, which is directly proportional to the size of this oscillation, will also be reduced accordingly.

The total path of the unidirectional plate current (solid red) is a closed circuit which can be considered to originate and terminate at the ground connection below the cathode resistor. Normal vacuum-tube action includes a heated cathode which will emit electrons into the tube, and a positive voltage on the plate (anode) to attract the electrons across the tube. Once across the tube, they continue flowing toward the point of highest positive voltage —the point known as B+, or the power supply. Plate current flows through the power supply, entering at its positive terminal and exiting at its negative terminal, or ground. Once this current is returned to a common ground, the condition of having a closed path for the plate current has been met.

When a varying grid voltage imposes fluctuations in the quantity of the current, as is done in this example, these fluctuations are available for sustaining the oscillation in the plate tank circuit.

The size of the current fluctuation determines the size of the tank oscillation which will be supported, each individual fluctuation replenishing and thus reinforcing an individual cycle of oscillation.

The ability of a vacuum tube to act as an amplifier stems from the fact that small changes in control-grid voltage will cause much larger changes in the amount of current which flows through the tube (plate current). These large fluctuations in plate current can then give the oscillations much greater voltage swings than they had in the grid circuit.

The second member of the "unidirectional tube-current family" is the current which exits from the tube via the screen-grid electrode (also shown in solid red). Going by the name of *screen-grid current,* it flows (in unison with the unidirectional plate current) upward through the cathode resistor and into the tube via the cathode. Because the screen grid is maintained at a high positive voltage, a substantial portion of the electrons passing through the tube are attracted to it. After striking the screen-grid wires, these electrons exit from the tube and are drawn through screen-grid resistor R3, toward the point of highest positive voltage in the circuit (the entrance to the power supply). Their closed path is through the power supply and back to common ground.

If there were no fluctuations in the amount of over-all tube current, there would be no significant fluctuations in the amount of screen-grid current. (Such a condition is referred to as static operation of the tube.) The plate tank oscillation would not be sustained under these conditions. However, when the signal voltage is impressed at the grid circuit, the electron stream through the tube does fluctuate in quantity and the tube is said to be operating under dynamic conditions. The control-grid wires, through which this stream must pass, act like a control valve on this stream. A positive voltage at the grid turns the stream "up," by increasing the number of electrons that flow. This condition is depicted by Fig. 6-4, where plate current is maximum. A less positive (more negative) voltage at the control grid turns this stream "down," by reducing the number of electrons passing through the tube. This condition is depicted by Fig. 6-3, where plate current is minimum.

The manner in which capacitor C4 filters out these fluctuations in screen-grid current was described in the discussion on filtering currents, and will not be repeated here. The RC combination of R3 and C4 must be a "long time-constant" combination to the radio frequency in question, and the combination of R3 and C4 operates in much the same fashion as R2 and C3 in the cathode circuit. The filtering action assures that a steady rather than a fluctuating flow of electrons occurs in screen-grid resistor R3. If this current were allowed to fluctuate, then the voltage across R3 would also fluctuate and vary the voltage at the screen grid accordingly, whereas the latter voltage should be constant. In other words, the screen-grid voltage would decrease whenever the tube current increased and vice versa. Thus, degeneration would be occurring, and the end result would be the same as when degeneration occurs in the cathode circuit—namely, a decrease in amplification.

This circuit is called a *voltage amplifier*. We are seeking to amplify the driving voltage applied to the control grid of the amplifier tube. This is the voltage developed across grid resistor R1 by the flow of grid driving current through R1. This grid drive voltage has the same value and phase as the grid tank voltage shown in line 2 of Fig. 6-5.

The plate tank voltage, represented by the plus signs on the upper plate of capacitor C5 in Fig. 6-3 and 6-4, alternates at the same frequency as the grid tank voltage, but its amplitude is much larger. The voltage value is, of course, directly related to the number of electrons in oscillation in the plate tank circuit. For these reasons, it is an "amplified" version of the grid tank and grid driving voltages.

Chapter 7

TRANSFORMER-COUPLED RF VOLTAGE AMPLIFIERS

There are three methods of using transformer coupling to amplify voltages at radio frequencies. They are:

Untuned primary—tuned secondary.
Tuned primary—untuned secondary.
Tuned primary—tuned secondary (frequently called bandpass amplification).

In the discussions that follow, the operation of these circuits will be explained in detail.

UNTUNED-PRIMARY-TUNED-SECONDARY COUPLING

Between the first two variations given in the foregoing, the untuned primary—tuned secondary offers more advantages and hence enjoys wider usage. Figs. 7-1 and 7-2 show two successive half-cycles of such a circuit. Any tuned transformer coupling will introduce the problem of *coupled impedance*. The principles of coupled impedance apply equally to the first two examples given previously. In other words, it matters not which winding is tuned and which is not, as far as explaining the principles is concerned.

The elements for the circuit in Figs. 7-1 and 7-2 include:

R1—Grid driving and grid return resistor for V1.
R2—Cathode biasing resistor for V1.
R3—Cathode biasing resistor for V2.
C1—Cathode filter capacitor for V1.
C2—Tuning capacitor for secondary winding.
C3—Cathode filter capacitor for V2.
T1—Radio-frequency transformer.

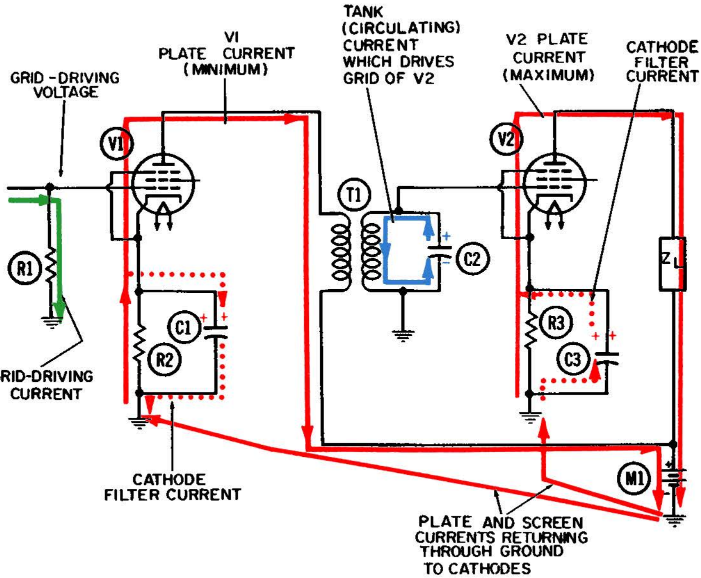


Fig. 7-1. Operation of the untuned-primary—tuned-secondary RF amplifier—first half-cycle.

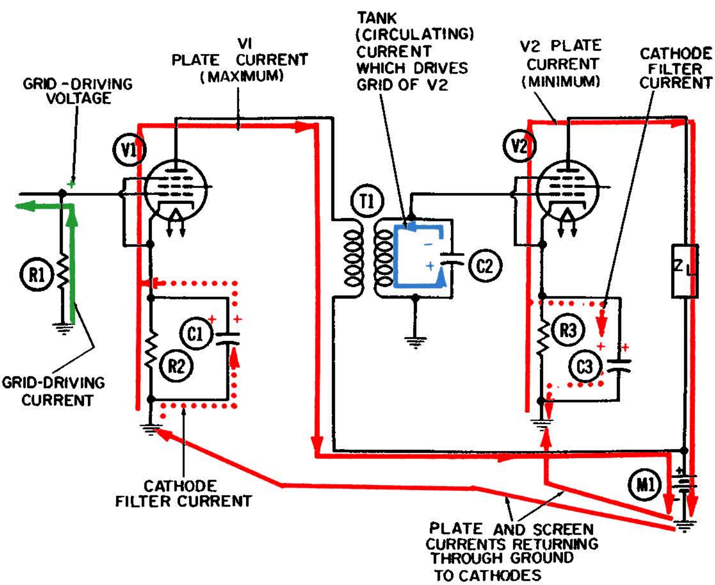


Fig. 7-2. Operation of the untuned-primary—tuned-secondary RF amplifier—second half-cycle.

Z_L—Load circuit for second stage.
V1 and V2—Pentode amplifier tubes.
M1—Common power supply for both stages.

Additionally, a screen-grid resistor and its filter capacitor are required for each pentode tube. Since screen-grid biasing and filtering were covered in the previous chapter, these components and the currents which flow through them have been omitted from the circuit diagrams and also from the discussion which follows.

The remaining currents at work in this circuit appear in Figs. 7-1 and 7-2. They include:

1. Initial grid driving current or signal (green).
2. Plate current through both tubes (solid red).
3. Cathode filter currents for both tubes (dotted red).
4. Oscillating tank current (blue).

Notice, both tubes for this circuit are served by a common power supply, M1. In actual practice, a single power supply normally supplies the B+ voltage to all tubes in the radio or television set. A B+ line is run through the set and every plate and screen grid requiring high positive voltage is tapped into it. If we could look inside the B+ line, we would see a vast stream of electrons moving steadily toward the high-voltage terminal of the power supply. This electron stream is composed of all the plate currents and all the screen currents from all the tubes. It is drawn into the positive terminal of the power supply and through the power supply to common ground.

When the tank circuit, consisting of capacitor C2 and the transformer secondary winding, is tuned to the frequency of the pulsations in the plate current, the tank is said to be resonant at that frequency. In flowing through the primary winding, the pulses will induce a secondary current that lags the current through the primary winding by exactly 90°. The voltage produced by the secondary current will be in phase with the current when the tank is resonant at the applied frequency.

The secondary current will also induce a current in the primary winding. This current will lag the "inducing" current by another 90°; so it will be 180° out of phase with the original applied voltage in the primary. Also, this current induced by the secondary into the primary will have a companion voltage, also induced in the primary winding. These two, the primary induced current and voltage, will be in phase with each other but 180° out of phase with the original applied voltage and current.

Currents which are out of phase *oppose* each other and subtract from each other. Voltages do likewise.

In the example of an untuned primary winding and a tuned secondary winding that is exactly resonant at the frequency of applied current and voltage, the coupling between the two windings *reduces* the strength of the original applied current and voltage. In turn, the induced secondary current and voltage suffer the same fate.

Mathematically, the reduction in applied current and voltage in the primary is the result of *coupled impedance*—in other words, the impedance from the secondary is coupled back to the primary.

This sequence can be understood by relating the two currents and voltages to the tank current *circulating* in the tuned tank, and also to the tank voltage associated with this tank current. We are in reality talking about *four* currents and four voltages on the two sides of the transformer.

Fig. 7-3 shows four successive quarter-cycles in this type of coupling circuit. The four currents are identified as follows:

1. Primary plate current (solid red).
2. Secondary induced current (dotted red).
3. Secondary tank current (solid blue).
4. Primary induced current (dotted blue).

The four voltage polarities are:

"Applied" voltage in primary (red).
Induced voltage in secondary (red).
Secondary tank voltage (blue).
Primary induced voltage (also known as counter emf), (blue).

By inspection of the four parts of Fig. 7-3, we see that at the end of each quarter-cycle, the applied plate current in the primary winding goes through its characteristic motions as follows:

1. It is *decreasing* at its maximum rate (Fig. 7-3A).
2. It has its *minimum* value (Fig. 7-3B).
3. It is increasing at its maximum rate (Fig. 7-3C).
4. It achieves its maximum value (Fig. 7-3D).

We know that whenever pulsating DC (like this one) flows through one winding of a transformer, a current will be induced in the secondary winding, and this current will lag the primary current by 90°. We can observe this phenomenon in Fig. 4-11. The primary current (plate current) reaches its minimum value at the end of the second quarter-cycle, but the induced voltage does not reach its maximum value until the end of the third quarter-cycle.

In Fig. 7-3D the plate current has reached its maximum value, whereas the voltage induced in the secondary winding does not reach its peak until 90° later, or at the end of the first quarter-cycle shown in Fig. 7-3A.

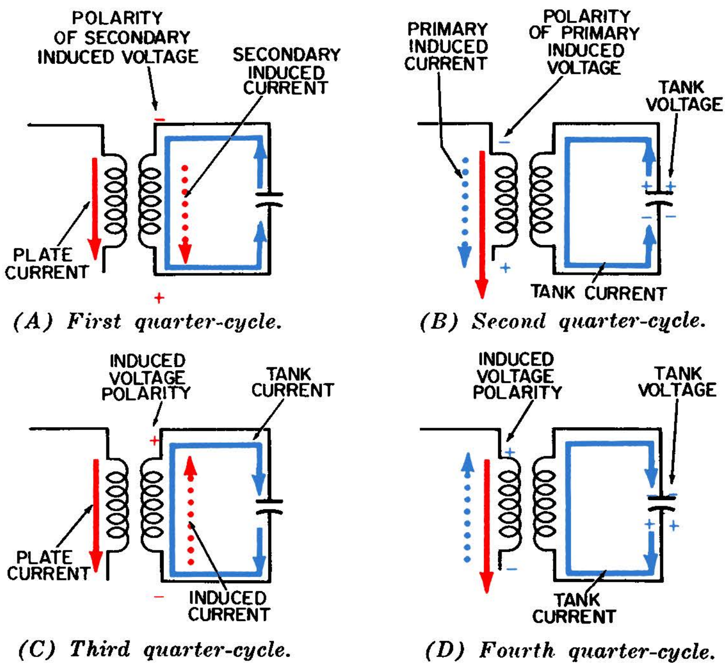


Fig. 7-3. The four quarter-cycles of operation of the tuned secondary circuit at resonance.

On the other hand, the induced secondary voltage and current are in phase with each other. This means they achieve their peak values at the same instant as indicated in Figs. 7-3A and C.

It is worth taking the time to understand *why* the induced voltage and current within the secondary winding are in phase with each other. One of our initial assumptions was that the tank circuit was tuned so it would be resonant at the frequency of the applied current. Part of the definition of resonance includes the stipulation that the inductive reactance and the capacitive reactance must be equal in value but opposite in polarity, so that they cancel each other. This means they "add up to zero" and the only remaining impedance is the insignificant resistance in the wire of the coil. Consequently, the induced current 'sees" only a low-resistance path within the tank and the current and voltage will be in phase.

Although the tank circuit, consisting of capacitor C2 and the secondary winding of transformer T1 in Fig. 7-1 and 7-2, is an example of *parallel* resonance as far as delivering an output voltage to the grid is concerned, the capacitor and secondary winding are in *series* to the induced current. This anomaly occurs frequently and can easily confuse you. However, the true criterion in determining whether components are in series or in parallel with each other is not the manner in which they are connected, but the path they present to certain currents. The tank circuit in this example is parallel-resonant to the external circuit to which it is connected, and series-resonant to currents flowing within the tank (the induced and circulating currents.) This point will be discussed further in the later example involving both a tuned primary and secondary winding.

We see from inspection of Fig. 7-3 that the induced current in the secondary winding is flowing in phase with the circulating current. The circulating current (also called the tank current) is in reality an *oscillation* of electrons sustained by the induced current. With a tuned circuit having a reasonably high value of Q, a fairly substantial oscillation can be built up from a fairly small amount of sustaining energy.

The tank voltage and current are of course 90° out of phase with each other. A *downward* current peak is achieved at the end of the first quarter-cycle in Fig. 7-3A, but another quarter-cycle is required before this current flow can deliver enough electrons to the lower plate of capacitor C2 to create a voltage peak. There will be a negative polarity on the bottom plate of C2, and a positive polarity (deficiency of electrons) on the upper plate. By this time the induced current has come to a halt. Likewise, an *upward* peak of electron current is achieved through the secondary winding at the end of the third quarter-cycle; but another quarter-cycle is required before this current flow can deliver enough electrons to the upper plate of C2 to create a negative voltage peak here.

It is a characteristic of a coupling transformer that its coupling works both ways—the primary current will induce a current and a companion voltage in the secondary winding; at the same time, the induced secondary current will itself induce a second current and companion voltage in the primary winding. In our example (Fig. 7-1 and 7-2) the pentode has a "plate resistance" of several hundred thousand ohms, which is very high. The total impedance of the primary circuit is essentially resistive, so the current and voltage induced in the primary winding will be in phase with each other. This means they will reach their peak maximum and minimum values at the same moment. These induced current and voltage peaks occur at the end of the second and fourth quarter-cycles. This happens to be 90°, or a quarter of a cycle, later than the peak values of the *inducing* current (the tank current). Thus, the voltage reinduced in the primary winding is essentially 180°, or half a cycle, out of phase with the original (applied) voltage and thus reduces the effectiveness of the applied voltage. Accordingly, less current and voltage will be induced in the secondary winding than would be possible if the reinduced voltage did not exist.

Fig. 7-4 graphically illustrates the currents and voltages of Fig. 7-3. The currents shown above their reference lines are flowing upward through the coil, except for the plate current, which always flows downward as a pulsating DC.

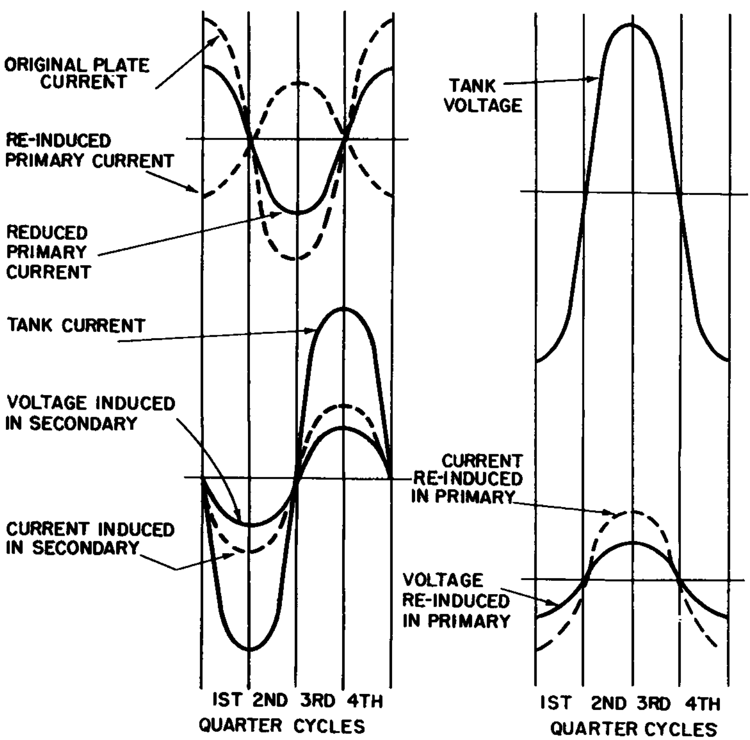


Fig. 7-4. Voltage and current waveforms in the tuned secondary circuit at resonance.

The total current flowing in the primary winding is of course the sum of the primary plate current, plus the current induced in this winding by the circulating tank current. Since they are out of phase, the primary plate current is reduced by the amount of the induced current. It is convenient to think of this reduction in primary current as being caused by an additional impedance "coupled" into the primary winding from the secondary circuit, because impedances always change the amount of current flowing in a circuit (usually they *reduce* it—but not always, as we shall see in the following example).

The amount of impedance coupled from one winding to the other, and the amounts of current and voltage induced in one winding by current in the other one, can be precisely calculated. However, these calculations will not be elaborated upon here. Instead, we will take the opportunity to grasp some of the important terminology of coupled circuits—the degree of coupling, tight or loose coupling, coefficient of coupling, mutual coupling, and coupled impedance.

In an iron-core transformer like the one in audio-output or low-frequency power circuits, practically all the magnetic lines of force set up by a current through one winding will flow through the iron core and encircle or "link" the other winding. Under these circumstances, the degree, or *coefficient* of coupling between the two windings is practically unity.

Higher frequencies force us to use very small values of inductance, because inductive reactance increases as the frequency does. A coil designed for radio frequencies will consist of only a few turns of wire wound around an air core, and its inductance will be 100 to 200 microhenrys. Two such coils constitute a radio-frequency transformer, and the coefficient of coupling between coils (represented by the symbol k) will be extremely low—perhaps one or two per cent. With an air-core transformer, it is almost impossible to avoid a great amount of leakage flux (the term applied to magnetic lines of force which are set up by a current through one winding and which do not link the other winding).

The mutual inductance between two coils, L1 and L2, and their coefficient of coupling, k, are related to each other by the following formula:

$$M = k\sqrt{L1 \times L2}$$

where,

M is the mutual inductance in henrys,
k is the coefficient of coupling,
L1 is the primary inductance in henrys,
L2 is the secondary inductance in henrys.

As an example, if we assumed a perfect iron-core transformer, the coefficient of coupling would be unity, or 1. If we assumed also that L1 is equal to L2, then the mutual inductance, M, would be found by:

$$M = 1 \times \sqrt{L1 \times L1}$$
$$= L1.$$

In other words, whenever two windings have the same inductance, and the coefficient of coupling is unity, the mutual inductance between them is equal to the inductance of either winding.

It is re-emphasized that this is an unusual example and that two assumptions had to be made:

1. The tank circuit must be tuned to the frequency of the applied current, so that the induced secondary voltage and current will be in phase with each other, and
2. The total resistance of the primary winding and its circuit must be much greater than the inductive reactance of the primary, so that the current and voltage induced in the primary will be in phase with each other, and also that the applied primary plate current and applied primary voltage will be in phase with each other.

Either of these assumptions is easily invalidated by changing components—and hence, conditions—in the circuit. A slight change in frequency of the applied current would have the same result. Or the use of a triode tube (which has a lower plate resistance than a pentode does) would invalidate the second assumption.

TUNED-PRIMARY-TUNED-SECONDARY COUPLING

Figs. 7-5 and 7-6 show two successive half-cycles in the operation of a radio-frequency voltage amplifier that has a tuned primary circuit on the plate (input) side and a tuned secondary circuit on the output side leading to the next grid. This is the second of the two most widely-used adaptations of transformer coupling at radio frequencies, the first being the untuned-primary—tuned-secondary one just considered.

A pentode tube again is used. It is not impossible to use specially-designed triodes at radio frequencies, but the pentode has several natural characteristics which make it much more suitable at radio frequencies.

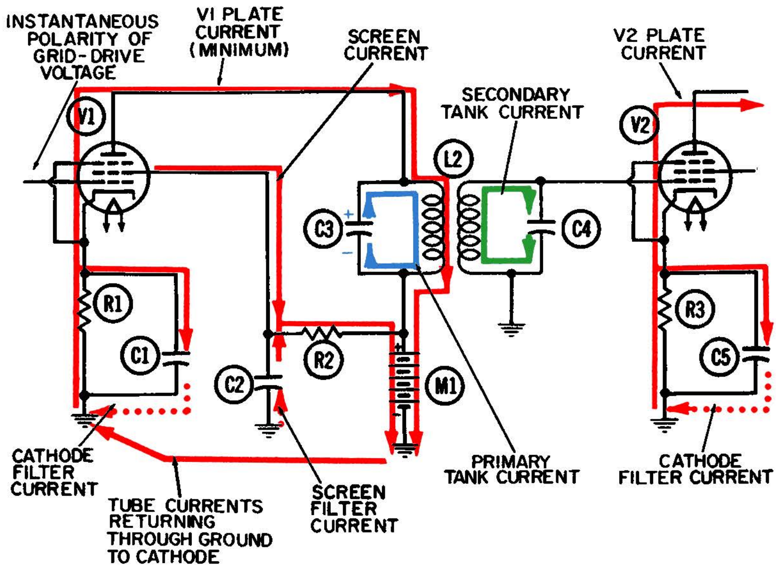


Fig. 7-5. Operation of the tuned-primary—tuned-secondary RF amplifier —first half-cycle at resonance.

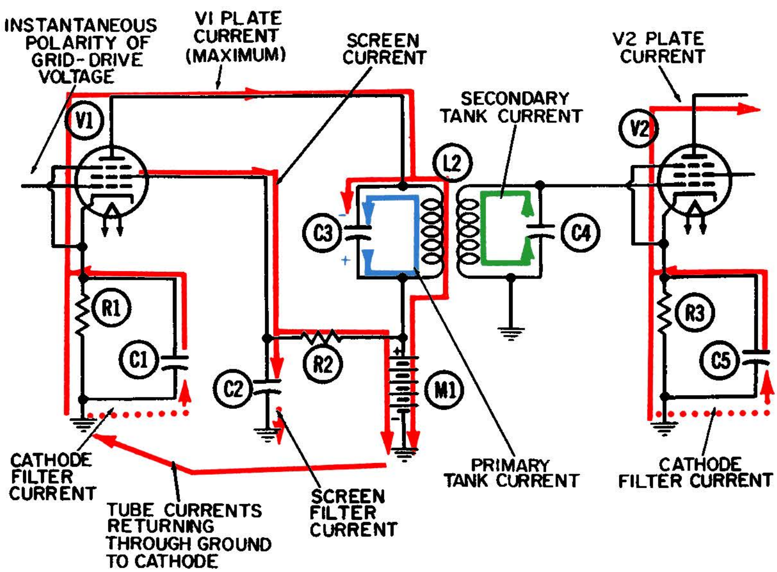


Fig. 7-6. Operation of the tuned-primary—tuned-secondary RF amplifier —second half-cycle at resonance.

One of these important characteristics is the *shielding* which the screen grid provides between the plate and control grid. As explained in Chapter 1, such shielding does much toward reducing or even eliminating interelectrode capacitance between plate and grid, and thus prevents feedback of energy from output to input. In Fig. 6-3 and 6-4 for the tuned-impedance-coupled amplifier, a feedback current was shown flowing from the tuned plate circuit back to the plate. Then by interelectrode capacitance it was coupled to the screen grid, from where it was bypassed to ground by the screen-grid filter capacitor.

Although this undesired feedback current is not shown in the radio-frequency circuits of this chapter, it is always present, and it is a major consideration in the choice of a pentode tube.

Another important characteristic of the pentode is its shorter *transit time*. An electron will always require a finite amount of time, however small, to cross over to the plate after being emitted from the cathode. To the tube, this transit time becomes more and more of a limiting factor as the applied frequency rises and each cycle becomes correspondingly shorter. Here is a simple formula which relates the frequency to the duration of each cycle:

$$f = \frac{1}{T}$$

where,

f is the frequency of applied current in cycles per second,
T is the duration of an individual cycle in seconds.

If a half-cycle of applied voltage is nearly equal in duration to the transit time, electrons will still be in transit within the tube (as a result of the positive grid voltage) after the advent of the next half-cycle has now made the grid voltage negative. The resultant phase shift between output and input usually limits or even destroys the utility of the tube.

A third and very important characteristic of the pentode tube is its high plate resistance. Recall from the first chapter that the plate resistance is the *ratio* between a small change in plate voltage and the resultant small change in plate current when the grid voltage is maintained constant.

The several electron currents at work in this circuit include:

1. Grid driving current (not shown), the voltage polarity of which is negative on the first half-cycle and positive on the second.
2. Plate current through both pentodes (red).
3. Screen-grid current (also in red).
4. Cathode and screen-grid filter currents (dotted red).

5. Plate tank current (blue).
6. Grid tank current for next stage (green).

Both of the amplifier stages indicated in Figs. 7-5 and 7-6 are using cathode biasing. Since the existence of a cathode biasing voltage depends on the continuing flow of plate current through the tube, we have come to identify cathode biasing with Class-A operation of the tube—meaning that some plate current flows at all times throughout the entire cycle.

The details of grid driving, cathode biasing and filtering, screen-grid filtering, etc., have been covered in many prior examples and will not be rediscussed here. The following discussion will be oriented around the phase relationships between the plate current, plate tank current, and grid tank current for the next stage. Once these currents and their phase relationships can be visualized for the condition of resonance and critical coupling, it becomes relatively simple to understand the small but important variations from this special case. These variations arise first from small changes in the signal or carrier frequency; as a result, the tuned circuits operate either above or below the natural frequency of the circuit. The second important variation arises from the degree of coupling.

The current diagrams of Fig. 7-3 can be adapted to the two tuned circuits (plate and grid tanks) of Figs. 7-5 and 7-6, but only where the latter circuits are being operated *exactly* at resonance. The five individual currents which should be identified separately would include:

1. Plate current.
2. Circulating current in plate tank. This is the primary *inducing* current, which function was performed by the primary plate current.
3. Secondary induced current.
4. Circulating current in grid tank.
5. Current reinduced in the primary by the circulating current in the grid tank.

The circulating current in the plate tank and the secondary induced currents are identical, as they were in the untuned example, and for the same reason. The circulating, or oscillating, current is in reality sustained or built up by this continual inducing of a current in the secondary winding.

The circulating current in the grid tank and the current reinduced in the primary by this current are exactly *out of phase* with each other. As a result, the reinduced current opposes the

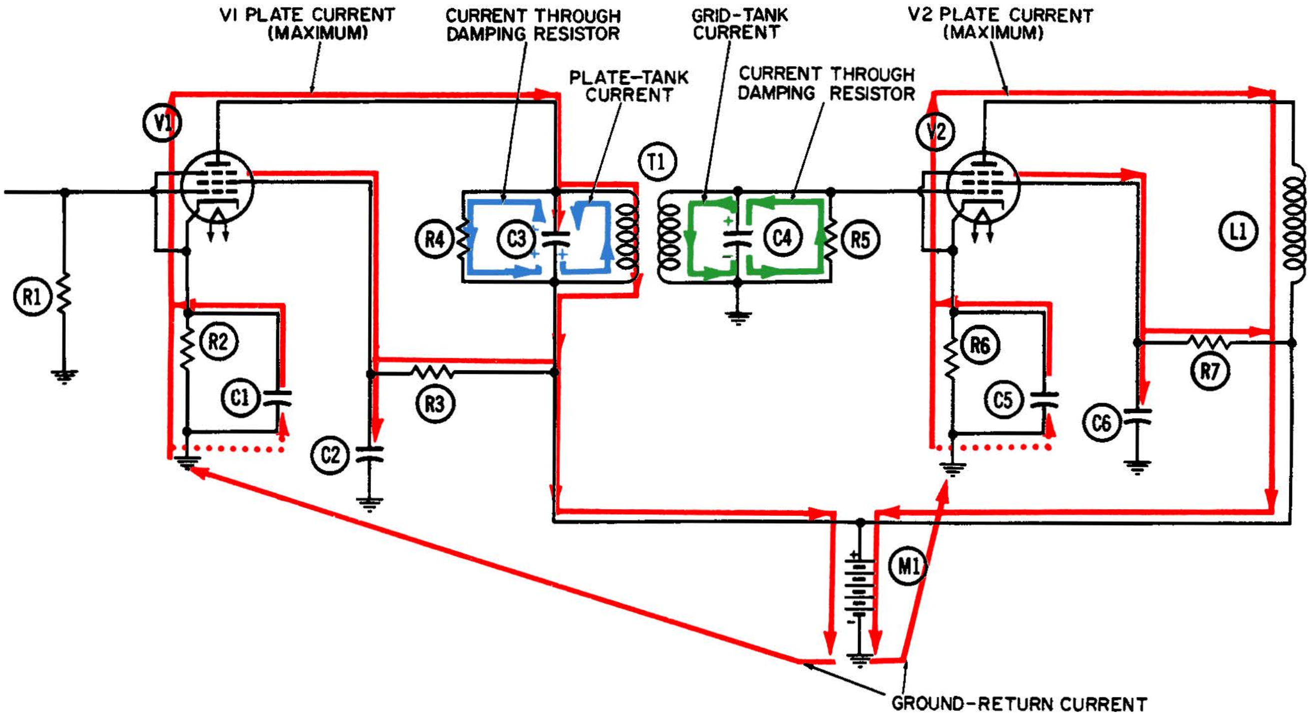


Fig. 7-7. Operation of the bandpass RF amplifier—first half-cycle.

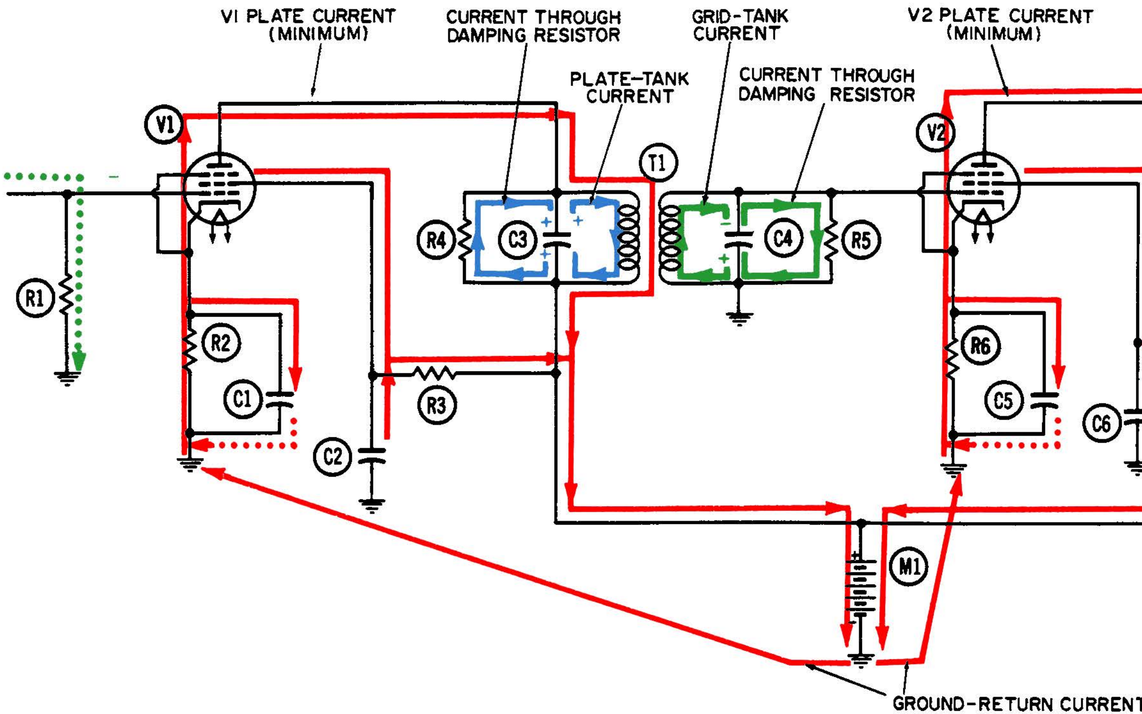


Fig. 7-8. Operation of the bandpass RF amplifier—second half-cycle.

primary tank current and thereby reduces the amount of current circulating there. This is similar to the untuned example discussed previously, where the current reinduced in the primary winding was opposite in phase to the applied plate current through this winding.

In this tuned example, the plate current supports or replenishes the oscillation of electrons in the plate tank, whereas the reinduced current opposes this oscillation. Obviously, the plate current is strong enough to overcome this opposition and support the circulating currents in the two tuned tanks.

As in the untuned example, the reduction in primary tank current is due to the impedance coupled back from the secondary to the primary winding. When the opposing current is out of phase with the primary circulating current (as in this resonant example), the coupled impedance acts like a pure resistance inserted within the tuned circuit with a size that would reduce the primary current the same amount as it is in fact reduced by the out-of-phase induced current. If the flow directions of the tuned tank currents and induced currents are related to the polarities of the tank voltages and induced voltages, we will find that at resonance the two tank votlages will be 90° out of phase with each other.

THE BANDPASS AMPLIFIER

Figs. 7-7 and 7-8 show two half-cycles in the operation of a radio-frequency voltage amplifier being used as a bandpass amplifier. This type of circuit differs from the preceding example of a tuned-primary—tuned-secondary circuit only in the addition of the two resistors across the two tuned tank circuits. Their purpose is to *reduce* the response of the particular tank circuit at resonance. Fig. 7-9 shows a typical response curve for a highly selective, or high-Q, resonant circuit. It is obvious that the closer the current being amplified is to the resonant frequency of the tuned circuit, the larger the gain (response).

Should we desire to amplify only a single frequency, the amplifier circuit could be tuned to that frequency and maximum amplification or gain would be realized. More frequently than not, however, we face the problem of amplifying not a single frequency, but a *band* of frequencies. The reason being that radio frequencies are usually carriers of intelligence superimposed at the transmitter by one of several processes of modulation. Whenever a carrier signal is modulated by an audio signal, new radio frequencies—known as side frequencies or *sidebands*—are introduced.

As a simple example of what this means, assume we desire to amplitude-modulate a 1,000-kilocycle carrier signal with a 5,000-cycle audio signal. The radio-frequency signal would then consist of these three components:

1. The original carrier of 1,000 kc.
2. The carrier *plus* the modulating frequency, or 1,005 kc.
3. The carrier *minus* the modulating frequency, or 995 kc.

The 1,005-kilocycle signal is known as the *upper* sideband, and the 995-kilocycle signal is the *lower* sideband. To be acceptable, an amplifier must provide fairly equal amplification of all three. It must "pass" a band of frequencies 10 kilocycles wide and centered at the 1,000-kilocycle point. An "ideal" response curve would look like a rectangle standing on end as shown by the dashed line in Fig. 7-9. Its response would be equal or flat over the 10-kilocycle band, and it would not respond whatsoever to any frequencies above or below this band. A more practical and realizable response curve is shown as a broader curve superimposed on the ideal curve. It is characterized by a rounded rather than a flat top, indicating reasonably uniform application over the passband. It also has sloping rather than vertical sides, indicating an acceptable (if not complete) attenuation of any frequencies above or below the passband.

Use of Damping Resistor

If a resistor is placed across a tuned tank, the tank voltage will be prevented from building up as high as it would otherwise. The resistor acts as a "load" on the oscillation of electrons—any unbalance in voltage across the tank capacitor will begin redistributing itself through the resistor. From Fig. 7-7, we see electron current flowing from the upper plate of tank capacitor C3, to the lower plate, through resistor R4. This direction of flow will persist as long as the positive voltage on the lower plate of C3 is higher than the positive voltage on the upper plate. Also, in Fig. 7-7 we see electron current flowing out of the bottom plate of grid tank capacitor C4 and upward through resistor R5 to the top plate. This flow will persist as long as the voltage is more negative on the lower than on the upper plate.

In both tanks in Fig. 7-7, the tank currents flow *onto* the respective plate of each capacitor, trying to build up a high peak voltage; at the same time, electrons are being drained off through the resistors. It is this continual drainage that prevents the achievement of high peak voltages and sharp response curves at resonance. A resistor of high ohmic value drains off only a small amount of current and so constitutes a "light" load on the tank circuit. Conversely, a low-value resistor will drain off much current and constitute a "heavy" load.

In Fig. 7-8, the polarities of the two tank voltages have been reversed, and so have the directions of electron flow through the two bandpass resistors. The tank-voltage polarities, tank-current directions, and flow directions of the resistor currents will be discussed later for each quarter-cycle.

Critical Coupling

Two tuned circuits are said to be "critically" coupled whenever they give a single response peak at their resonant frequency. Either one of the response curves in Fig. 7-9 could result from critically coupled tuned circuits. However, a damping resistor such as R4 or R5 (Figs. 7-7 and 7-8) is not normally used with critical coupling. When it is desired to pass a band of frequencies, the tuned circuits would be "overcoupled." Fig. 7-10 shows three response curves for three degrees of overcoupling. Contributing to the width of these double-humped response curves are the size of the resistors across the tuned circuits, their *Q* (quality), and finally the degree of overcoupling between them. Overcoupling is the opposite of "loose" coupling.

The value of critical coupling can be determined by the formula:

$$K = \frac{1}{\sqrt{Q_1 \times Q_2}}$$

where,

K is the value of critical coupling,
Q_1 is the *Q* of the plate tank circuit,
Q_2 is the *Q* of the grid-tank circuit.

As an example, if each tuned circuit has a *Q* of 100 (which is not unreasonable), the value of critical coupling, K, would be .01 and a single-peaked response curve similar to those in Fig. 7-9 could be achieved.

Overcoupling

If the two inductor windings are wound closer together, or if the coupling between them is increased by adjustment of a variable core, the coefficient of coupling will be greater than .01 and the circuits will be overcoupled—the objective in the design of bandpass amplifiers. The double humps in the response curves of Fig. 7-10 are the result of resonances occurring at frequencies on either side of the natural frequency. Fig. 7-11 has been drawn to represent four successive quarter-cycles in the operation of the two tank circuits of Fig. 7-7, *when these circuits are being operated above the resonant frequency.*

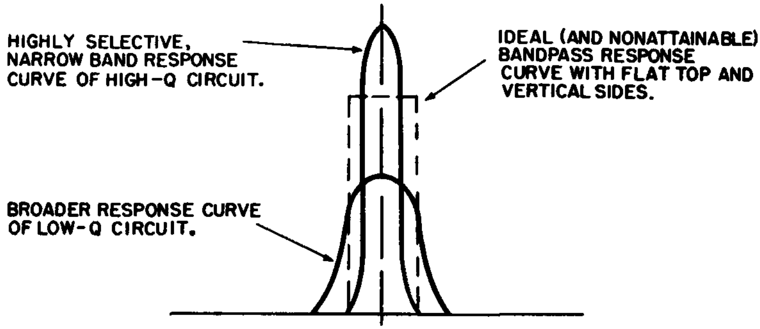


Fig. 7-9. Response curves of high- and low-Q circuits at resonance.

It was previously stated that when two tuned circuits are coupled together at their resonant frequency, the two resulting tank voltages are 90°, or a quarter of a cycle, out of phase with each other. However, as soon as the frequency being amplified deviates even slightly from the resonant frequency of the tanks, the phase difference will increase to a maximum of 180°, or half a cycle. With very high-Q circuits, this 180° phase difference between the two tank voltages will occur fairly close to the resonant frequency. The inside curve of Fig. 7-10, with its two resonant peaks fairly close together, represents the response of a high-Q circuit and the outer curve, with its resonant peaks far apart, the response of a lower-Q circuit.

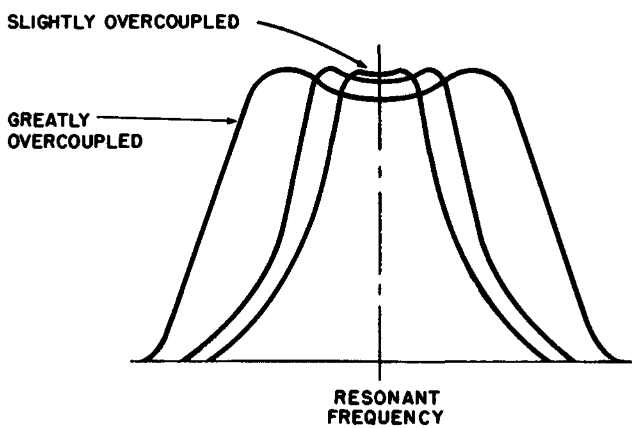


Fig. 7-10. Response curves of over-coupled tuned circuits.

Thus we see that either the Q of the tank circuits, or their degree of overcoupling, can have an effect on where these resonant peaks occur and consequently on the width of the passband.

Operating Above Resonance

Let us assume in Fig. 7-11 that the current being amplified is *higher* than the resonant frequency of the tank circuits. Then each tank circuit will appear to be *inductive* to these currents. The reason is that the inductor and capacitor are in series with each other (as far as the circulating current is concerned), and whenever the frequency rises, the inductive reactance *increases* and the capacitive reactance *decreases*. Either tank circuit will appear to be completely inductive to its circulating current as soon as the internal resistance of the tank becomes negligible (compared with the inductive reactance). Since capacitors and connecting wires have minute amounts of resistance, most of the internal resistance of a tank is due to the resistance of the wire composing the coil.

In a high-Q coil this resistance is of course very small, as illustrated by the formula for the Q of a coil:

$$Q = \frac{\omega L}{R}$$

where,

ω equals 2π times the frequency of operation (called omega),
L is the inductance of the coil in henrys,
R is the resistance of the coil in ohms.

The quantity, ωL, is also the inductive reactance of the coil at the frequency of operation.

Phase Relationships

In the previous example of two tuned circuits operated at resonance, the primary tank current induced a secondary tank current. Along with this secondary tank current was an induced secondary voltage, and the two were *in phase* with each other, since the inductive and capacitive reactances had equal but opposite values and canceled each other. So the series impedance of the secondary tank circuit was purely resistive.

In the example we are considering here, when the secondary tank circuit is operated at some frequency higher than resonance, the capacitive reactance is opposite but *not equal* to the inductive reactance. Only part of the latter is canceled, and the circuit is inductive rather than purely resistive. Therefore, the primary tank current still induces a secondary tank voltage which lags the primary tank current by 90°. However, instead of being in phase with the induced secondary voltage, the secondary induced current *lags it by another 90°*, because in an inductive circuit the current always lags the voltage by 90°.

During the first quarter-cycle, in Fig. 7-11A, the primary tank current is flowing *upward* through its inductor at its maximum rate. However, the induced secondary current is flowing *downward* through *its* inductor at its maximum rate. This denotes that the two are 180°, or half a cycle, out of phase. Both currents, the inducing and the induced, are shown in blue so they can be more easily related to each other.

The secondary tank current, shown in green, is an oscillation of electrons supported by the secondary induced current (in fact, these two currents are normally indistinguishable). Like all electron oscillations in tuned L-C circuits, energy is stored alternately in magnetic and in electric fields. The magnetic field is maximum when the tank current reaches maximum, at the end of the first and third quarter-cycles. The electric field is maximum when the voltage across the tank capacitor is maximum, at the end of the second and fourth quarter-cycles.

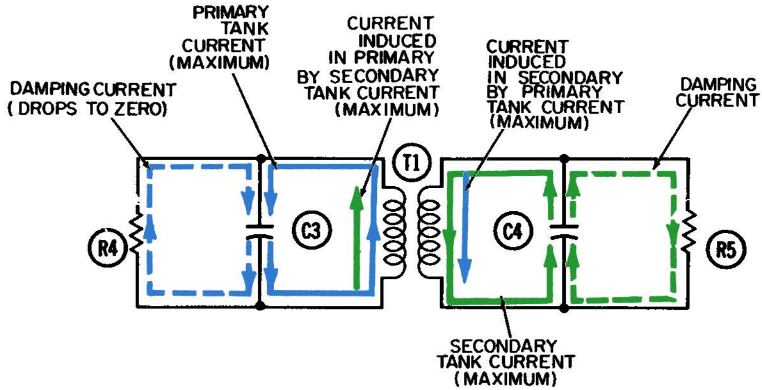
The secondary tank current also reinduces a new voltage in the primary circuit, which lags the secondary current by 90°. The primary circuit is inductive for the same reason the secondary is. When the operating frequency is higher than the natural frequency of the circuit, all capacitive reactance is canceled but some inductive reactance is left over. When this inductive reactance becomes significantly larger than the winding resistance the primary tank circuit will appear as a pure inductance to the induced primary current. This current will thus lag the induced primary voltage by another 90°, and consequently be 180° (or half a cycle) behind the phase of the original tank current in the primary circuit.

Two events which are a whole cycle out of phase with each other are actually "in phase," so that the primary induced current adds to and thus strengthens the primary tank current. Thus, the response curve is peaked at a frequency higher than the resonant frequency and the primary tank appears to be operating at resonance, when we know this cannot be true.

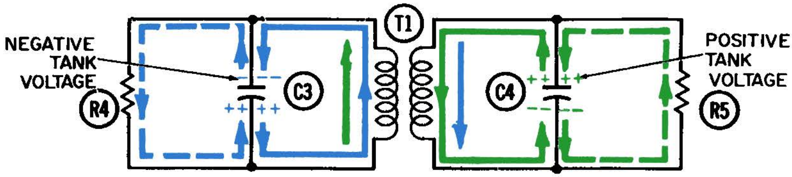
In each of the four quarter-cycles shown in Fig. 7-11 we see an induced primary current flowing in phase with the primary tank current. There is also an induced secondary current flowing in phase with the secondary tank current.

Operating Below Resonance

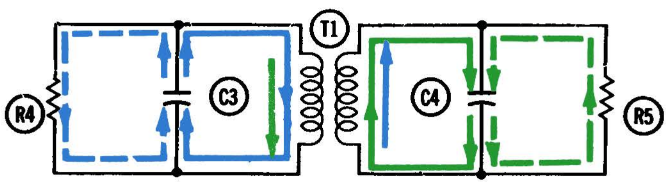
The diagrams of Fig. 7-11 cannot be applied equally well to two tuned circuits operating *below* their resonant frequency.



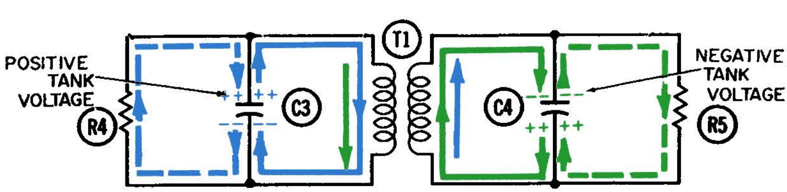
(A) First quarter-cycle.



(B) Second quarter-cycle.

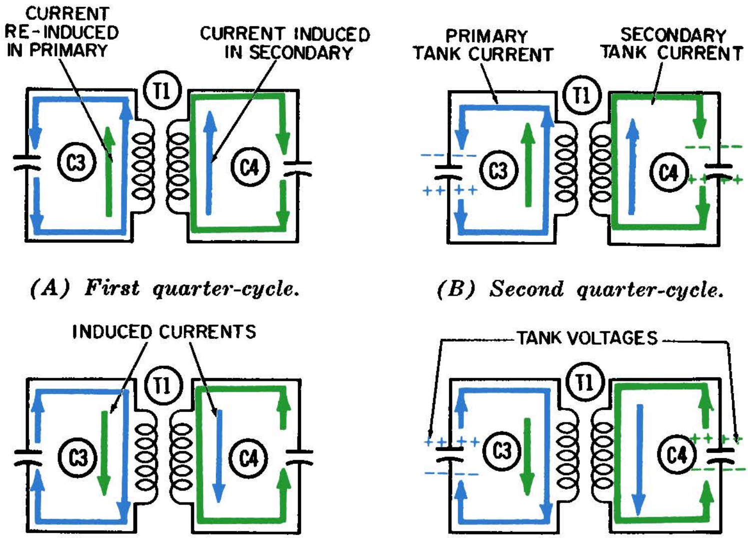


(C) Third quarter-cycle.



(D) Fourth quarter-cycle.

Fig. 7-11. The four quarter-cycles of operation of the bandpass tank circuit at a frequency above resonance.



(A) First quarter-cycle.

(B) Second quarter-cycle.

(C) Third quarter-cycle.

(D) Fourth quarter-cycle.

Fig. 7-12. The four quarter-cycles of operation of the bandpass tank circuit at a frequency below resonance.

When this happens, each of the inductive reactances of the two windings will decrease and the capacitive reactances of the two tank capacitors will increase, in accordance with the standard reactance formulas. To a current circulating within either tank circuit, the over-all impedance of its series path will be capacitive, since all inductive reactance in each path will be canceled but some capacitive reactance will be left over. Now it becomes interesting to analyze the phase relationships between the two tank currents and their voltages, and between the two induced voltages and their currents.

In Fig. 7-12A, the primary tank current is flowing *upward* through the primary winding and again induces a voltage in the secondary winding which lags the primary current by 90°. Therefore, the secondary voltage is zero at the end of the first quarter-cycle. This induced voltage will have an induced current flowing with it; but since this current is flowing in a circuit that is capacitive, it will *lead the voltage*. This means maximum current occurs 90°, or a quarter of cycle, in advance of the maximum voltage or exactly in phase with the inducing current. In the four quarter-cycles of Fig. 7-12 we see the induced secondary current, shown in blue, flowing in phase with the inducing primary current, also shown in blue. As in the previous example, the induced secondary current supports the oscillation of electrons in the second tank and these two currents are indistinguishable. Both the primary and the secondary tank currents cause tank-voltage peaks at the end of the second and fourth quarter-cycles. Unlike the previous example, these tank voltages are in phase with each other—that is, their positive and negative peaks each occur simultaneously.

The secondary current also induces a voltage in the primary which lags the secondary current by a quarter of a cycle. The induced primary current associated with this induced voltage *leads* the voltage by a quarter of a cycle, because of the capacitive reactance exhibited by the primary circuit when operated below resonance. Thus, the induced primary current turns out to be exactly in phase with the original inducing current, or primary tank current.

Consequently, when operated below resonance, both induced currents will reinforce their respective oscillating tank currents, causing them to build up in a manner similar to a current build-up at resonance.

The damping resistors of Fig. 7-11 have been omitted from Fig. 7-12 for clarity. However, they would be required in the normal bandpass amplifier, whether it is being operated above or below resonance. During the first and third quarter-cycles, electrons flow through these resistors in unison with the electrons which flow through the respective inductors. During the entire first quarter-cycle, some excess electrons are amassed on the lower plate of capacitor C3, and they flow from this plate upward through the inductor and resistor. During the entire third quarter-cycle, some electrons are amassed on the upper plate of capacitor C3, and they flow from this plate downward through the resistor and inductor.

During the second and fourth quarter-cycles, the currents through the resistor and inductor do not appear to be flowing in unison with each other. During the second quarter-cycle, while the oscillating tank current is delivering electrons to the upper plate of C3 and trying to build up a tank-voltage peak, the resistor is letting electrons drain off. During the fourth quarter-cycle, a similar situation is occurring at the bottom plate of C3.

Resistor R5, bridged across the secondary tank circuit, acts in a similar manner to prevent the attainment of a high peak voltage across the secondary tank.

SERIES *VERSUS* PARALLEL IMPEDANCE

One of the hallmarks of a *parallel*-resonant tank circuit is the high impedance it presents to an external circuit. At the same time, the tank circuit presents an extremely low impedance to a current circulating within it. The reason is that the inductive and capacitive components are in *series resonance* to the circulating or oscillating current, so their respective reactances cancel each other.

When we say that a parallel-resonant tank circuit offers high impedance to an external circuit, we are referring to its opposition to the passage of an external current. A tuned tank in the plate circuit of an amplifier tube, as discussed earlier, offers a good example from which to explain the meaning of the term, *high parallel impedance.* Whenever any of these tuned plate tanks is operated at resonance, the *ratio* between tank voltage and line current (plate current) will reach its highest value. This ratio, called the tank impedance, is derived from the fundamental Ohm's-law relationship which states that the voltage *across* a resistor (or network) is proportional to the current through it.

In a pentode tube, as we tune a tank towards resonance the tank voltage rises, meaning a large number of electrons are in oscillation, whereas the plate current is virtually unchanged. This gives a high ratio of tank voltage to line current, and consequently a high resonant impedance. When the circuit is operating off-resonance, the amount of circulating or oscillating current is greatly decreased. This leads to a lowered tank voltage and tank impedance.

In a triode amplifier using a tuned plate tank, the amount of plate current will be greatly reduced when the tank is at resonance, because the negative (or low-positive) voltage peak at the plate occurs simultanously with the positive grid-voltage peak. The latter is trying to release maximum current through the tube, whereas the low plate voltage restricts the plate current. A simple operating test for resonance is to tune the tank slowly near the resonant frequency and observe the amount of plate or line current with an ammeter. The point where minimum plate current is achieved indicates the tank is resonant and its tank voltage is maximum. Obviously, the ratio between maximum tank voltage and minimum line current indicates the highest attainable value of tank impedance, or resonant impedance.

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