APPLICATIONS OF ELECTRONICS

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PREFACE

It is the aim of the authors to bring together in one volume a discussion of the principles and equipment covering the many specialized fields of electronics and communications. Circuits and equipment are described for essentially all modern applications. These include amplifier and rectifier circuits, low- and high-frequency oscillators, communications receivers and transmitters, industrial electronic devices, electronic navigational aids, test instruments, and electronics in military applications.

The book is so arranged that equipment circuitry is not discussed until the necessary foundation material (amplifiers, tubes, transistors, etc.) has been fully covered. This enables the reader to deal easily and logically with such diverse subjects as superheterodyne receivers and industrial control circuits. Once the reader has fully mastered the fundamental principles underlying all electronic circuits, he will be capable of shifting from subject to subject with confidence and understanding.

A practical approach is employed in this book designed specifically for technicians and servicemen. Mathematics is kept to a minimum and is brought in only where it is essential to an understanding of the particular subject matter. However, knowledge of elementary electricity and electronics, as covered in *Basic Electronics* by Bernard Grob, is assumed.

Special self-examination questions are given at the end of each chapter, together with longer, essay-type questions for classroom use or for those who wish to test themselves more extensively. Summaries are placed at the ends of chapters and related chapter groups. Bibliographies are included, too, together with an extensive appendix of supplemental material. The answer key for self-examination questions is in the back of the book.

Special acknowledgment of assistance is due to M. Goldstein, American Institute of Engineering and Technology; Jerome R. Balton and Nathan Buch, RCA Institutes, Inc.; Edwin J. Williamson, RCA Communications, Inc.; and Melvin Whitmer. The authors are also indebted to the many organizations which provided photographs, operating manuals, and charts. Special acknowledgment in each instance is made with the appropriate illustration.

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1

VACUUM-TUBE AMPLIFIERS

Introduction. This unit explains how any vacuum tube with a control grid can amplify its input signal. The tube and its circuit components then form an amplifier stage. Triodes, tetrodes, or pentodes can be used. Furthermore, we can have d-c amplifiers or a-c amplifiers for either r-f or a-f signal variations. Figure 1-1 shows a typical audio-amplifier chassis with its power supply. The topics are as follows:

- 1-1 Amplifier Requirements
- 1-2 Voltage Gain
- 1-3 Types of Amplifiers
- 1-4 Methods of Coupling
- 1-5 Classes of Operation
- 1-6 Methods of Bias
- 1-7 Fixed Bias
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- 1-14 Direct and Alternating Voltages in the Amplifier
- 1-15 Load Line
- 1-16 Troubles in Amplifier Circuits

1-1 Amplifier Requirements. The amplifier is the foundation on which the entire science of electronics is built. Without this ability, vacuum tubes and electronic devices would have only limited application. Communications as we now know it would not exist, and industrial control would have to rely on mechanical, pneumatic, and hydraulic systems for its operation. Because the amplifier is so important, a careful study will be made of it in its most common forms. The primary function of an amplifier is to receive a small signal at its input and provide a much larger version of it at the output. In the voltage amplifier shown in Fig. 1-2, an input signal of 1 volt, applied to the grid circuit, is amplified to provide a 40-volt signal in the plate circuit. Therefore the amplitude of the signal voltage has been multiplied by the factor of 40. The same amplification applies to rms (root-mean-square), peak, or peak-to-peak values of the signal. A typical circuit to provide this amplification is shown in Fig. 1-3. The principal component of the stage is the vacuum tube itself, which is the amplifier. A triode, a tetrode, or a pentode can be used.

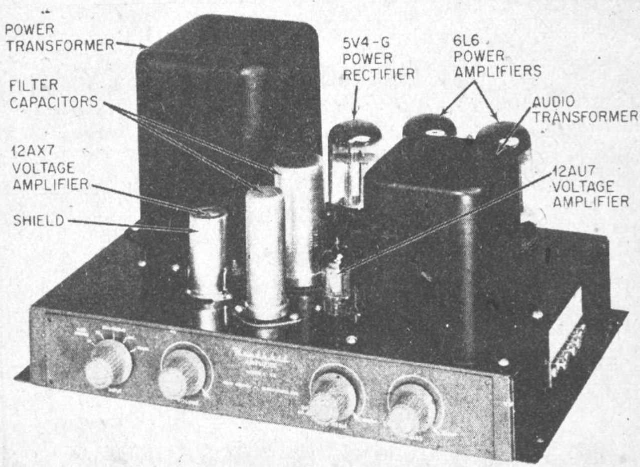


FIG. 1-1. Audio-amplifier chassis, with power supply. (*Heathkit Corp.*)

Plate Load. Resistor R_L is placed in the plate circuit so that the plate current can produce a voltage drop outside the tube. When the voltage across the resistor (i_bR_L) varies, the net plate-cathode voltage also varies, since this equals the fixed B+ voltage minus the i_bR_L drop. For this reason, the amplified signal-voltage output from plate to chassis ground has a polarity opposite the grid-signal voltage input. Capacitor C_c transfers the a-c component of the fluctuating d-c plate voltage, which is the amplified signal-voltage output, to the next stage while blocking the steady d-c component. Note that without this load resistance, the plate current can be varied by the grid voltage, but no amplified output voltage will be obtained.

B+ Voltage. The B supply is required to produce plate current. The B+ voltage, applied between the plate and cathode, enables plate current to flow from the cathode to the plate, then through R_L and the B supply, and finally back to the cathode again. This current can flow only in one direction. In essence, it is a fluctuating direct current, containing a strong d-c component on which is superimposed a smaller a-c (that is, signal) component. It is this a-c component which produces the signal-voltage drop across R_L.

Grid Bias. A low-voltage battery (commonly called a C battery) is inserted between the control grid and cathode. Its purpose is to bias the control grid negative with respect to the cathode. The bias is negative because the minus terminal of the C battery connects to the control grid, while the positive terminal reaches the cathode through the chassis

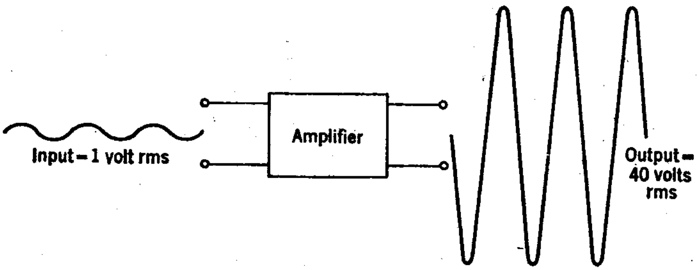


FIG. 1-2. The amplifier increases the amplitude of the 1-volt input signal to provide 40 volts output signal.

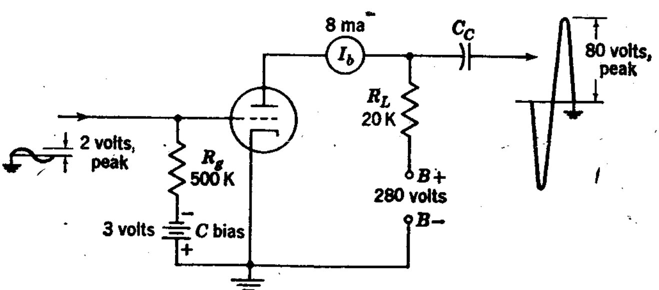


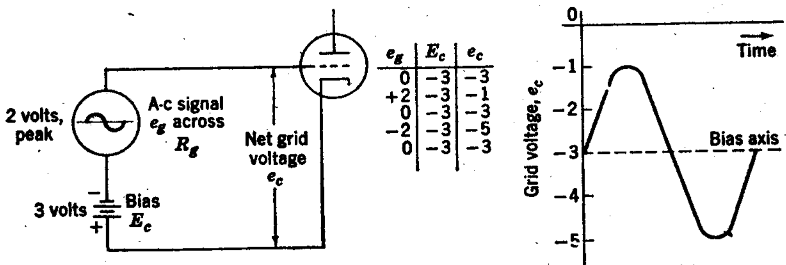
FIG. 1-3. Circuit of a triode amplifier stage.

ground. With the control grid biased negative, there is no grid current and no d-c voltage drop across the grid resistor R_g.

The bias voltage is large enough so that the input signal cannot make the net grid voltage positive, even during the positive half cycle of the a-c voltage. As a result, equal variations of the a-c grid-signal voltage produce equal increases and decreases in the plate current. A grid resistor is inserted in the circuit in order to present a load to the incoming signal and to place this signal in series with the d-c grid bias.

How the Control-grid D-c Bias and A-c Signal Combine. The a-c signal voltage applied to the control grid is developed across the grid load resistor R_g. The C bias supply has a negligibly small impedance.

Therefore the d-c bias voltage of the C supply and the a-c signal voltage across R_g are in series with each other between grid and cathode (Fig. 1-4*a*). The resultant net grid-cathode voltage e_c, then, is the combination of the d-c grid voltage E_c and the a-c grid signal e_g. The bias is negative all the time. When the signal voltage is negative, it adds to the bias; when the signal is positive, it bucks the bias. In Fig. 1-4*b*, the net values of e_c are tabulated for the zero and peak values of the a-c signal. Note



e_g	E_c	e_c
0	−3	−3
+2	−3	−1
0	−3	−3
−2	−3	−5
0	−3	−3

(*a*) (*b*) (*c*)

FIG. 1-4. How the bias and signal combine in the grid-cathode circuit. (*a*) D-c bias E_c in series with a-c signal e_g. (*b*) Tabulation of peak and average values for net grid voltage e_c. (*c*) Graph of e_c values.

that at no time does the combined grid voltage become positive with respect to the cathode.

Grid Drive. The a-c signal input is called the ***grid-drive voltage***, since it makes e_c vary about its bias axis.

Plate Current. With B+ voltage applied, plate current flows.* When the signal drives the net grid voltage less negative, the plate current increases; when it drives the net grid voltage more negative, the plate current decreases. It is important to note, however, that the plate current itself is *not* the output-signal voltage. The plate-load resistor R_L is needed to provide the amplified output-signal voltage.

1-2 Voltage Gain. How the amplifier produces an output voltage greater than the input voltage is illustrated by the waveshapes in Fig. 1-5, corresponding to the current and voltage values listed in Table 1-1. These are calculated for the amplifier circuit in Fig. 1-3. In Table 1-1, the vertical columns list the values of grid-signal voltage e_g, d-c bias E_c, and the combined grid voltage e_c. The corresponding values of plate current are listed also, together with the resultant voltage drop i_bR_L across the 20,000-ohm plate-load resistor. Finally, the net plate-cathode voltage e_b is given. This is equal to the B+ value of 280 volts minus the

* The instantaneous values of total plate current are generally indicated by the letter symbol i_b; the symbol i_p is for the a-c signal variations in plate current.

i_bR_L voltage drop. This is subtracted from B+ because the voltage drop across R_L reduces the plate voltage.

The signal voltage e_g, given in the first column, has a peak voltage swing of 2 volts, positive and negative, from its zero axis. The d-c bias voltage E_c stays steady at -3 volts. The combined grid voltage then varies between -1 volt and -5 volts. In the next column are the corresponding values of plate current. The average value is 8 ma, set by the -3 volts bias. When the grid voltage varies 2 volts, the plate current changes by 4 ma, in this example. A grid-signal swing from -3 volts to -1 volt increases i_b from 8 to 12 ma; a grid-voltage change from -3 to -5 volts lowers i_b from 8 to 4 ma. The column of voltage-drop values across R_L simply equals the product i_bR_L. For the average i_b value of 8 ma, determined by the bias, the voltage drop across the 20,000-ohm R_L is 160 volts. These voltage values vary as i_b is varied by the grid voltage. Finally, the net plate-cathode voltages in the last column are calculated by subtracting each i_bR_L voltage drop from the

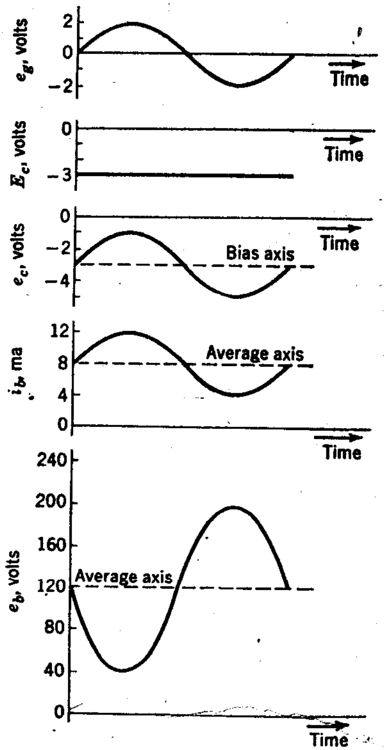


FIG. 1-5. Voltage and current waveforms for amplifier circuit in Fig. 1-3. From top to bottom: a-c signal voltage input to grid e_g; d-c grid-bias voltage E_c; instantaneous grid voltage e_c; instantaneous plate current i_b; net plate-cathode voltage e_b.

Table 1-1 Voltage and Current Values for Amplifier in Fig. 1-3*

e_g, volts	E_c, volts	e_c, volts	i_b, ma	i_bR_L, volts	e_b, volts $= 280 - i_bR_L$
0	−3	−3	8	160	120
+2	−3	−1	12	240	40
0	−3	−3	8	160	120
−2	−3	−5	4	80	200
0	−3	−3	8	160	120

* B+ = 280 volts, R_L = 20,000 ohms.

fixed B+ value of 280 volts. For the average $i_b R_L$ drop of 160 volts, as determined by the grid bias, the net plate-cathode voltage equals 280 − 160 volts, or 120 volts.

As the a-c signal drives the grid voltage e_c ±2 volts about the bias axis, the plate current swings ±4 ma about the 8-ma axis. The plate-current variations follow the grid signal, increasing when e_c becomes less negative and decreasing when e_c becomes more negative. Because this is a variation of current, however, its amplitude cannot be compared with the input voltage. It is the varying net plate-cathode voltage e_b that is the amplified output-signal voltage. The plate voltage has peak variations of 80 volts from its average axis. From 120 volts, e_b swings down to 40 volts and up to 200 volts, corresponding to a swing of ±80 volts.

Gain of the Stage. Compared with the grid-input swing of ±2 volts, the plate-voltage swing of ±80 volts is 40 times as great. This is the voltage gain of the stage. Its symbol is A:

$$A = \text{voltage gain} = \frac{\text{signal-voltage output}}{\text{signal-voltage input}} \tag{1-1}$$

The output and input voltage amplitudes can be compared in rms, average, peak, or peak-to-peak values as long as the same measure is used for both. In this example,

$$A = \frac{\text{output}}{\text{input}} = \frac{\text{80 volts, peak}}{\text{2 volts, peak}} = 40$$

There is no unit for A, since it is a ratio of two voltages. It should be noted that the voltage gain A is not the same as the amplification factor μ. The gain depends on the circuit, while the μ is a characteristic of the tube. These two factors are related, however, by the formula

$$\text{Gain} = \mu \frac{R_L}{R_L + R_p} \tag{1-2}$$

where R_L is the external plate-load resistance of the circuit, and R_p is the internal plate resistance of the tube. The gain can be equal to μ or smaller but never greater. For example, with a tube having a μ of 80 and R_p of 20,000 ohms when it is used in the circuit of Fig. 1-3 with an R_L of 20,000 ohms,

$$A = \mu \frac{R_L}{R_L + R_p} = 80\left(\frac{20{,}000}{20{,}000 + 20{,}000}\right) = 80\left(\frac{20{,}000}{40{,}000}\right) = 80 \times \frac{1}{2} = 40$$

The higher the value of R_L compared with R_p, the higher is the gain as it approaches the value of μ for the tube.

Phase Inversion. The plate-voltage variations of e_b in Fig. 1-5 have opposite polarity from the grid-voltage signal e_s. This phase inversion stems from the fact that the amplified output signal is produced by the varying voltage drop across R_L. As the i_bR_L drop becomes greater with more current, the net plate-cathode voltage is smaller; when less plate current produces a smaller i_bR_L voltage, the plate voltage rises. With a sine-wave signal, the amplified output voltage in the plate circuit can be considered 180° out of phase with the input voltage in the grid circuit.

Fluctuating D-c Plate Voltage. The amplifier plate voltage e_b is a fluctuating d-c voltage with a steady d-c average value and an a-c component varying about this axis. If you measure from plate to cathode with a d-c voltmeter, it will read the average d-c value of 120 volts. An a-c voltmeter connected across the same two points reads the rms value of the a-c component. This value equals 0.707 × 80, or 56.56 volts here. All values of plate voltage are positive, but the variations below the average can be considered negative with respect to the axis. When the steady d-c component is blocked by the coupling capacitor C_c, these variations below the axis provide the negative half cycle of the a-c component coupled to the next circuit, while the variations above the axis correspond to the positive half cycle. The a-c component is the desired output voltage, but there cannot be any signal output unless direct current flows to produce the fluctuating d-c plate voltage.

Summary of Amplifier Operation. The amplification can be considered in the following steps:

1. The grid signal varies the instantaneous values of grid voltage above and below the negative bias voltage axis.
2. The variations in grid voltage produce corresponding changes in plate current.
3. The plate-current variations vary the voltage drop across the plate-load resistor R_L.
4. The net plate-cathode voltage is equal to the B+ voltage minus the voltage drop across R_L.
5. Therefore the plate-cathode voltage varies. This varying voltage is the amplified output signal.

The output-signal voltage is an amplified duplicate of the grid-signal voltage, but with opposite polarity. For the one cycle illustrated in Fig. 1-5, every variation in grid voltage, whether at the peak or intermediate values, has a corresponding variation in plate voltage. The same variations are repeated every cycle. Therefore the variations in plate voltage provide an output signal with the same frequency as the input signal.

Before we continue with the discussion, mention should be made of the common practice of using the term *amplifier* to mean both a single stage and a complete system, containing a number of amplifier stages. Thus, when you speak of a high-fidelity system as consisting of an amplifier, a record changer, and a loudspeaker, you mean an amplifier system where there are several amplifier stages. On the other hand, in this chapter, the term amplifier is meant to mean a single stage. Surprisingly enough, this practice does not lead to ambiguity, and the reader will have very little difficulty understanding what is meant when he meets the word. However, he should be aware of this dual usage.

1-3 Types of Amplifiers. Different names are assigned to amplifiers in order to describe a feature of the circuit or to indicate its function. For instance, an audio amplifier amplifies a-c signal voltages in the a-f range. An r-f stage amplifies r-f signal voltages. Because they deal with higher a-c signal frequencies, r-f amplifiers generally use pentodes instead of triodes. With their lower grid-plate capacitance, pentodes can provide more stable r-f gain. Pentodes can also be used for audio amplifiers. Triodes are preferable, however, for either a-f or r-f amplifiers where reduction of tube noise is important.

R-f amplifiers practically always employ tuned circuits. In the control-grid circuit, a tuned circuit can provide maximum r-f signal voltage at the resonant frequency; in the output circuit, parallel resonance allows maximum plate-load impedance at the desired frequency. As a result, the circuits are generally different for a-f and r-f amplifiers because the a-f stage must amplify a broad range of audio frequencies, while the r-f stage amplifies a band of frequencies centered about the resonant frequency of its tuned circuit.

For either r-f or a-f circuits, a stage can be considered a voltage amplifier or a power amplifier. Both amplify the input-signal voltage, but a power amplifier is required to supply appreciable signal current in the output rather than high voltage. A good illustration is the final audio amplifier that supplies signal to drive a loudspeaker. A speaker requires high current. Therefore the audio-output stage is a power amplifier. High values of output current are obtained by using a power tube, which is physically larger than a voltage amplifier tube, and by using a relatively low plate-load impedance. For example, where an a-f voltage amplifier may have a plate-load resistor of 0.5 meg, an audio-output stage generally has an external plate-load impedance of 4,000 ohms. A comparison of tube sizes can be seen in Fig. 1-1.

1-4 Methods of Coupling. Several methods may be used to transfer or couple a signal from one circuit to another. These are: resistance-capacitance, or RC, coupling with a plate-load resistor R_L; impedance coupling, where a choke replaces R_L; and transformer coupling. R-f amplifiers generally have tuned coupling circuits. Such tuned amplifiers may be impedance-coupled or transformer-coupled. With any type of circuit, triodes or pentodes can be used.

RC Coupling. This method of coupling is generally used with a-f voltage amplifiers because it provides the same amount of gain for a wide range of audio frequencies. In Fig. 1-6*a*, R_L is the plate load in series with the plate and the B+ supply. Since R_L presents the same resistance to all audio frequencies, the *RC* amplifier provides equal gain for different frequencies. This is called *uniform*, or *flat*, frequency response. As indicated in Fig. 1.6*b*, this a-f amplifier has a flat response from 100 to 5,000 cps.

Amplifier response is limited at low frequencies by coupling capacitor C_{c_2}. Capacitive reactance rises as the signal frequency drops, causing more of the output-signal voltage to appear across the coupling capacitor

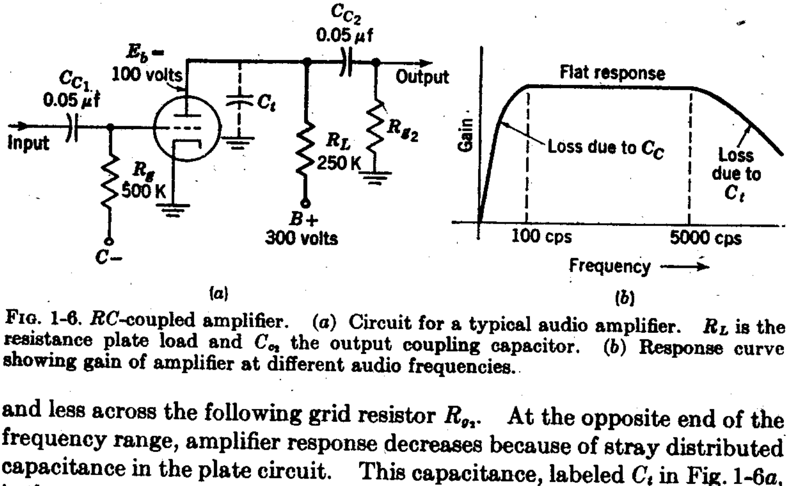


FIG. 1-6. *RC*-coupled amplifier. (*a*) Circuit for a typical audio amplifier. R_L is the resistance plate load and C_{c_2} the output coupling capacitor. (*b*) Response curve showing gain of amplifier at different audio frequencies.

and less across the following grid resistor R_{g_2}. At the opposite end of the frequency range, amplifier response decreases because of stray distributed capacitance in the plate circuit. This capacitance, labeled C_t in Fig. 1-6*a*, is the total capacitance shunted across the plate-cathode circuit. Typical values for C_t are 20 to 40 μμf, but at high frequencies even this small amount of capacitance can effectively bypass signals around a high-valued R_L.*

One disadvantage of the *RC* amplifier is the fact that the I_bR_L voltage drop reduces the average plate voltage available for the tube. The amount of plate current that flows is determined by the voltage actually at the plate, with respect to cathode. In an *RC* amplifier, this average plate-cathode voltage is much less than the B-supply voltage. For example, if the average plate current in Fig. 1-6*a* is 0.8 ma with a 250,000-ohm R_L, the average I_bR_L voltage drop equals 200 volts. The average plate-

* As a matter of fact, when a circuit designer wishes to extend the frequency range of an amplifier, one of the first things he does is lower R_L. This makes the shunt capacitance C_t less effective until the frequency rises to a higher value.

cathode voltage is then only 100 volts, equal to 300 volts minus the 200-volt I_bR_L drop. Thus, R_L cannot be made too high. Note the low wattage rating required for R_L. With an average voltage drop of 200 volts and an average current of 0.8 ma, its *EI* product equals 0.16 watt dissipated in heat. Typically, a ⅓- to 1-watt carbon resistor would be used here.

The function of the coupling capacitor is illustrated in Fig. 1-7, where *C* corresponds to C_c, and *R* is equivalent to R_g in the *RC* amplifier. The voltage applied to this *RC* circuit is the fluctuating d-c plate voltage e_b. In this example, e_b has an average value of 100 volts, varying from 150 to 50 volts as the signal varies.

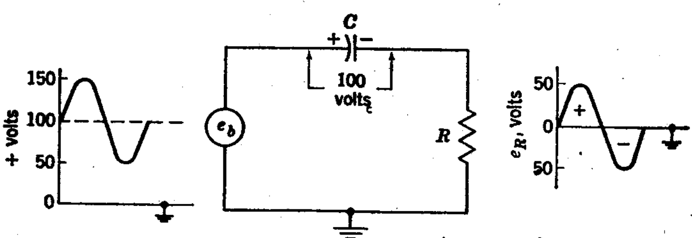


FIG. 1-7. How an *RC* circuit couples the a-c component of e_b across R_g, while the d-c component is blocked by C_c.

Since the charge or discharge path is the same for the *RC* circuit, *C* soon charges to the average value of the applied voltage, which equals 100 volts here. With *C* charged to 100 volts, when the applied voltage e_b increases, it produces a charging current that develops a positive voltage across *R*; when e_b decreases below 100 volts, *C* discharges, and its discharge current produces a negative voltage across *R*. As a result, as e_b varies from 50 volts above to 50 volts below the 100-volt axis, the increases produce the positive half cycle of voltage e_R, while the decreases produce the negative half cycle. The voltage across *R* is an a-c voltage varying above and below zero, which is the chassis ground reference. The average d-c level of the fluctuating d-c input is the 100 volts across *C*. Therefore the steady d-c component is blocked as the voltage across *C*, while the a-c component is passed as the a-c voltage across *R*. This voltage is the amplified a-c signal to the control grid of the next stage.

Impedance Coupling. The circuit shown in Fig. 1-8 uses an inductance as a choke for the plate-load impedance, instead of R_L in the *RC* amplifier. The coupling capacitor C_c is still needed, however, to block the steady d-c component of plate voltage. Either an iron-core choke can be used for an audio amplifier or an air-core choke for an r-f amplifier. The advantage of a choke for the plate load is that it has low d-c resistance but can provide the high value of an a-c impedance required for high voltage gain.

Single-tuned Stage. The r-f amplifier in Fig. 1-9 uses a single parallel-resonant circuit to provide the required plate-load impedance for the a-c signal. The d-c resistance of the r-f coil L is negligible, and the average d-c plate voltage is practically equal to B+. However, the parallel LC circuit provides a high impedance at the resonant frequency.

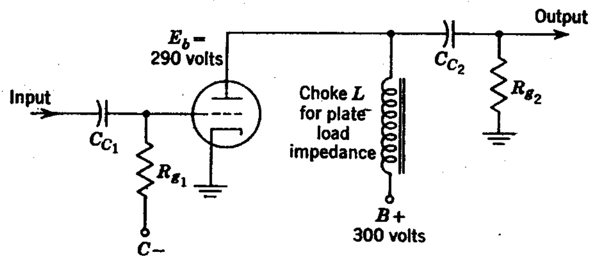


FIG. 1-8. Impedance-coupled amplifier with audio choke as plate-load impedance. An r-f choke can be used instead for an r-f amplifier.

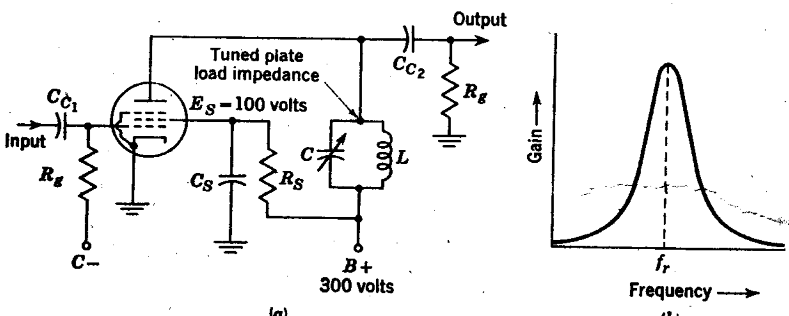


FIG. 1-9. Single-tuned r-f amplifier. (*a*) Circuit. (*b*) Frequency response.

The response curve in *b* is the same as the resonance curve of the tuned circuit. For parallel resonance, the impedance is maximum at f_r, decreasing to very low values at frequencies far off resonance. Since the gain of the amplifier is proportional to the amount of plate-load impedance, the response of the amplifier for different frequencies corresponds to the response of the parallel-resonant circuit. That is, the tuned amplifier can provide gain only for frequencies at and near the resonant frequency. The bandwidth of the resonant response depends on the Q of the LC circuit.

Pentodes are generally used for r-f amplifiers The only additional need of the pentode circuit is a positive d-c screen-grid voltage. In Fig. 1-9, R_s is the screen-dropping resistor. The screen voltage is equal to the

B+ voltage minus the I_sR_s voltage drop, where I_s is the screen-grid current. Assuming 4-ma screen current, the dropping resistor must be 50,000 ohms for a 200-volt I_sR_s drop, with 100 volts left for the screen grid. C_s is the screen-bypass capacitor. Its reactance must be low enough to bypass R_s for the lowest frequency amplified in the stage.

Transformer Coupling. Figure 1-10 shows a typical audio power-output-stage transformer coupled to a loudspeaker. The primary winding

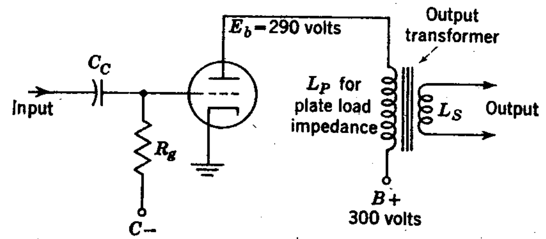


FIG. 1-10. Transformer-coupled amplifier with audio transformer. An r-f transformer would be used instead for an r-f amplifier.

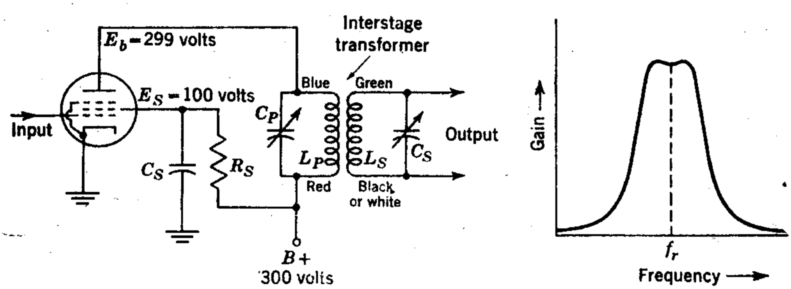


FIG. 1-11. Double-tuned r-f amplifier. (*a*) Circuit. (*b*) Frequency response.

L_p is the plate-load impedance. This arrangement has the advantage of low d-c resistance, resulting in a high value of E_b, which is important for maximum power output. The a-c impedance of the primary is usually 2,000 to 5,000 ohms, this value being high enough because the requirement is power output rather than voltage gain. The a-c component of the signal current in the primary L_p induces the desired signal voltage in the secondary winding L_s by transformer action. Since the secondary is isolated, the steady d-c component of the primary current is blocked. Therefore the secondary has a-c signal only.

Double-tuned Stage. The circuit in Fig. 1-11*a* is a transformer-coupled amplifier, but both the primary and secondary of the r-f transformer are tuned. Because of the isolated secondary winding, no blocking capacitor is needed. The primary-tuned circuit L_pC_p is the plate-load impedance