Operational Amplifiers and Linear ICs

THIRD EDITION

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CHAPTER 1

Introduction to Operational Amplifiers

Objectives

After studying this chapter, you will be able to

1. Sketch the circuit symbol for an operational amplifier (op-amp) and identify all terminals.
2. Draw a basic (three bipolar junction transistor) op-amp internal circuit diagram. Identify all terminals, and explain the circuit operation.
3. Sketch an op-amp voltage follower circuit. Explain its operation.
4. Draw the diagram for an op-amp noninverting amplifier. Explain the circuit operation, and calculate the voltage gain for given resistor values.
5. Draw the diagram for an op-amp inverting amplifier. Explain the circuit operation, and calculate the voltage gain for given resistor values.

INTRODUCTION

Operational amplifiers (op-amps) are very high gain amplifier circuits with two high-impedance input terminals and one low-impedance output. The input terminals are identified as *inverting input and noninverting input*. The basic op-amp circuit consists of a differential amplifier input stage, a level shifting intermediate stage, and an emitter-follower output stage. Operational amplifiers can be employed for a great many circuit applications by using various combinations of externally connected components. The simplest of these are the voltage follower, the noninverting amplifier, and the inverting amplifier.

1-1 IC OPERATIONAL AMPLIFIER

Circuit Symbol and Terminals

The circuit symbol for an op-amp, illustrated in Fig. 1-1, shows that there are two input terminals, one output terminal, and two supply terminals. Plus–minus supply voltages ($+V_{CC}$ and $-V_{EE}$) are normally used and these typically range from ±5 to ±22 V. The input terminals are designated as *inverting input* (minus sign) and *noninverting input* (plus sign). A positive-going voltage applied to the inverting input produces a negative-going (inverted)

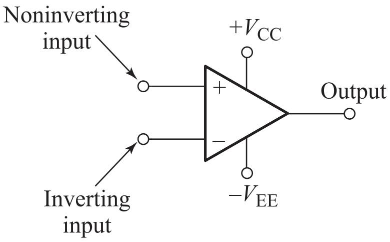


Figure 1-1 Operational amplifier circuit symbol. There are two supply terminals ($+V_{CC}$ and $-V_{EE}$), two input terminals (inverting and noninverting), and one output.

output, and a positive-going signal at the noninverting input generates a positive-going (noninverted) output.

Basic Op-amp Circuit

The basic circuit of an IC op-amp consists of a bipolar junction transistor (BJT) differential amplifier input stage combined with an emitter follower output. This is illustrated in Fig. 1-2. Note the plus—minus supply ($+V_{CC}$ and $-V_{EE}$), which is normally used. Transistors Q_1 and Q_2 together with resistors R_E and R_C constitute a differential amplifier, which produces a voltage change at the collector of Q_2 when a voltage difference is applied to the bases of Q_1 and Q_2. The Q_2 collector voltage is passed to the voltage divider (R_a and R_b), which shifts the dc voltage level down to approximately half-way between $+V_{CC}$ and $-V_{EE}$. This voltage is then applied to the output via the emitter follower consisting of transistor Q_3 and emitter resistor R_{E3}.

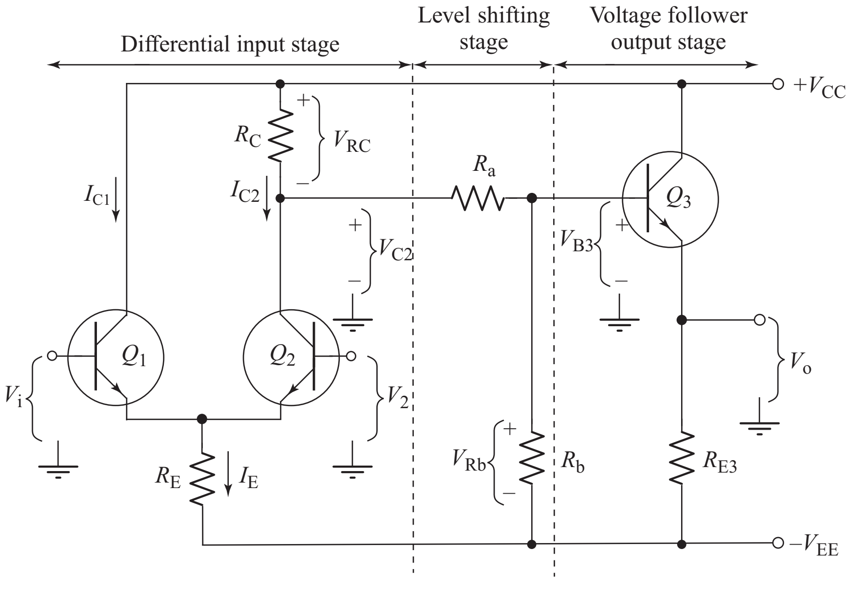


Figure 1-2 An op-amp circuit consists basically of a differential amplifier input stage, a level shifting intermediate stage, and an emitter follower output.

Example 1-1

Calculate the voltage and current levels for the circuit shown in Fig. 1-2 if $V_{CC} = \pm 10$ V, $V_i = V_2 = 0$, and the components are $R_a = 47$ kΩ, $R_b = 100$ kΩ, and $R_C = R_E = R_{E3} = 4.7$ kΩ. For simplicity, assume that Q_1 and Q_2 are perfectly matched, that the current through R_a and R_b has no effect on the voltage drop across R_C, and that the Q_3 base current has no effect on the voltage divider.

Solution

$$\begin{aligned} V_{RE} &= V_{B1} - V_{BE} - V_{EE} \\ &= 0 - 0.7\text{ V} - (-10\text{ V}) \\ &= 9.3\text{ V} \end{aligned}$$

$$\begin{aligned} I_E &= \frac{V_{RE}}{R_E} = \frac{9.3\text{ V}}{4.7\text{ k}\Omega} \\ &= 1.98\text{ mA} \end{aligned}$$

$$I_{C1} = I_{C2} = \frac{I_E}{2} = 0.99\text{ mA}$$

$$\begin{aligned} V_{RC} &= I_{C2} \times R_C \\ &= 0.99\text{ mA} \times 4.7\text{ k}\Omega \\ &= 4.65\text{ V} \end{aligned}$$

$$\begin{aligned} V_{RaRb} &= V_{CC} - V_{EE} - V_{RC} \\ &= 10\text{ V} - (-10\text{ V}) - 4.65\text{ V} \\ &= 15.35\text{ V} \end{aligned}$$

$$\begin{aligned} V_{Rb} &= \frac{V_{RaRb} \times R_b}{R_a + R_b} \\ &= \frac{15.53\text{ V} \times 100\text{ k}\Omega}{100\text{ k}\Omega + 4.7\text{ k}\Omega} \\ &= 10.4\text{ V} \end{aligned}$$

$$\begin{aligned} V_o &= V_{EE} + V_{Rb} - V_{BE} \\ &= -10\text{ V} + 10.4\text{ V} - 0.7\text{ V} \\ &= -0.3\text{ V} \end{aligned}$$

To further investigate the operation of the circuit in Fig. 1-2, suppose that a positive input ($+V_i$) is applied to the base of Q_1 and that the Q_2 base is held at ground level. This produces an increase in I_{C1} and a decrease in I_{C2}, resulting in a decreased voltage drop across resistor R_C. Consequently, V_{C2} and V_{B3} are increased, producing a positive-going output voltage. If the input to Q_1 base is negative ($-V_i$) instead of positive, I_{C1} is decreased and I_{C2} is increased, resulting in an increase in V_{RC}, a decrease in V_{B3}, and a consequent negative-going output.

It is seen that a positive-going input at the base of Q_1 produces a positive-going output at the Q_3 emitter, and that a negative-going input to Q_1 gives a negative-going output. This means that an input voltage applied to Q_1 base results in an output having the same polarity as the input (a noninverted output). Thus, the terminal at the base of Q_1 is the *noninverting input*.

Now assume that Q_1 base is maintained at ground level while a positive input ($+V_2$) is applied to the base of Q_2. In this case I_{C1} is decreased and I_{C2} is increased, producing an increased voltage drop across R_C and a consequent negative-going output. When the input to Q_2 base is negative ($-V_2$) instead of positive, I_{C2} is decreased, I_{C1} is increased, V_{RC} is decreased, and the output is positive-going. So, an input voltage to Q_2 base results in an output having the opposite polarity to the input (an inverted output). So, the terminal at the base of Q_2 is the *inverting input*.

The differential amplifier stage offers high input impedance (Z_i) at the BJT bases. The emitter follower output stage gives a low output impedance (Z_o). The input stage also provides voltage gain, and the more complex circuitry of a practical IC op-amp produces much higher gain than would be available from the simple differential amplifier stage illustrated. As with all amplifiers, the voltage gain is the output voltage divided by the input voltage. In this case, the input voltage is the difference between the two input terminal voltages (V_D). Where no negative feedback is involved, the voltage gain is termed the *open-loop voltage gain* (A_{OL}) (or $A_{v(OL)}$). When negative feedback is employed, the voltage gain becomes the *closed-loop gain* (A_{CL}). The high input impedance and the low output impedance are also enhanced by the practical op-amp circuitry, and they are both very much improved by the use of negative feedback in typical op-amp applications.

Section Review

1-1.1 Sketch the graphic symbol for an op-amp and identify all of the terminals.

1-1.2 Sketch the basic (three BJT) internal circuit for an op-amp. Identify the inverting and noninverting terminals and briefly explain the circuit operation.

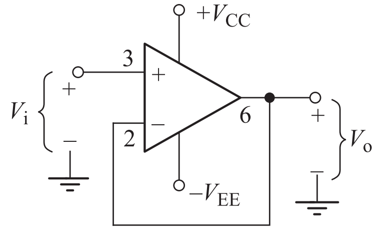
Practice Problem

1-1.1 Calculate V_o for the circuit in Example 1-1 when the supply is $V_{CC} = \pm 15$ V and R_C and R_E are changed to 5.6 kΩ.

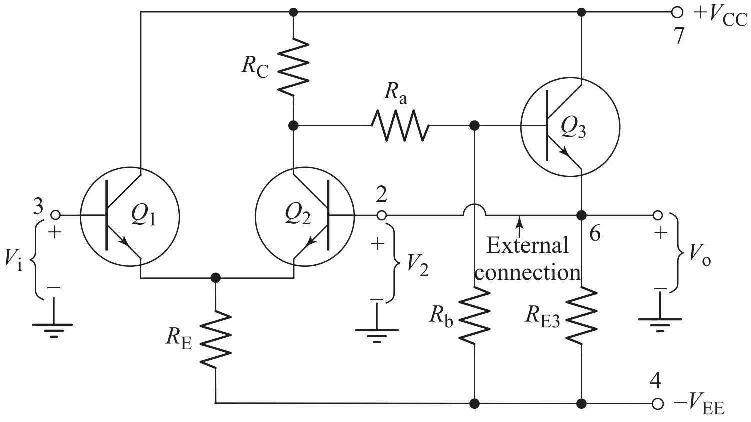
1-2 THE VOLTAGE FOLLOWER CIRCUIT

The IC op-amp lends itself to a wide variety of applications. The very simplest of these is the *voltage follower* shown in Fig. 1-3(a). The output terminal is connected directly to the inverting input terminal, the signal is applied to the noninverting input, and the load is directly coupled to the output. The output voltage now follows the input, giving the circuit a voltage gain of 1, a very high input impedance, and a very low output impedance.

To understand how the voltage follower operates, consider the basic op-amp circuit reproduced in Fig. 1-3(b). As in Fig. 1-3(a), the output (terminal 6) is connected to the inverting input terminal (terminal 2). With terminal 3 grounded, terminal 2 and the output must also be at ground level. If the input voltage (V_i) is increased above ground level, I_{C1} is increased and I_{C2} is decreased, causing V_{C2} to be decreased and thus producing an increase in V_o, which brings V_2 back to equality with V_i. If V_2 were somehow to go above the level of V_i, I_{C2} would be increased to produce a drop in V_o, which would



(a) Voltage follower circuit



(b) Basic op-amp circuit connected as a voltage follower

Figure 1-3 **In a voltage follower circuit, the op-amp output is connected directly back to the inverting input terminal. When the input voltage changes, the output changes to keep the inverting input terminal voltage equal to the voltage at the noninverting input.**

drive V_2 back to equality with V_i. It is seen that there is 100% negative feedback (NFB), which maintains the output voltage equal to the input. The output always *follows* the input; hence the name *voltage follower*.

The output of a voltage follower does not perfectly follow the input, because there has to be a very small difference between the two input terminals (a *differential input*, V_D) to produce the output voltage change. This depends on the op-amp amplification without feedback, known as the *open-loop voltage gain* (A_{OL} or $A_{v(OL)}$). When negative feedback is employed, the voltage gain becomes *closed-loop gain* (A_{CL}).

The voltage follower has a high input impedance, a low output impedance, and a closed-loop voltage gain of 1. This is similar to a BJT emitter follower. However, the difference between the dc input and output voltages with a voltage follower is typically less than 50 µV compared to 0.7 V for an emitter follower. As will be demonstrated, the voltage follower also has a much higher input impedance and a much lower output impedance than the emitter follower.

Example 1-2

Calculate the difference between the input and output voltages for a voltage follower with a 3 V input if the op-amp has A_{OL} = 200 000.

Solution

$$V_D = \frac{V_o}{A_{OL}} = \frac{3\ \text{V}}{200\,000} = 15\ \mu\text{V}$$

Practice Problems

1-2.1 Calculate the precise peak output voltage levels when a ±100 mV signal is applied as input to a voltage follower that uses an op-amp with $A_{OL} = 100\,000$.

1-2.2 The output of a voltage follower is to follow the input within 20 μV. Determine the minimum open-loop gain of the amplifier if the maximum input is ±5 V.

1-3 THE NONINVERTING AMPLIFIER

The *noninverting amplifier* circuit shown in Figs. 1-4(a) and (b) behaves in a similar way to a voltage follower, except that the output voltage is divided by resistors R_1 and R_2 before being fed back to the inverting terminal. Consider the conditions that exist when the noninverting input is grounded. As is the case of the voltage follower, the inverting input terminal must also be at (or very close to) ground, and thus the junction of R_1 and R_2 is also at ground level. With both ends of resistor R_2 at ground level, there is no current flow through R_2, and so (neglecting the very small bias current into terminal 2) there is no current through R_1 and no voltage drop across R_1. Consequently, the circuit output voltage equals the input, which is at ground level.

Now suppose that a +100 mV input is applied to terminal 3. As explained, the output will move to a level that makes the feedback voltage (to terminal 2) equal to the voltage at terminal 3. The feedback voltage is developed across resistor R_2, and the output appears across $R_1 + R_2$. So,

$$V_{R2} = V_i = I_1 R_2$$

and

$$V_o = I_1(R_1 + R_2)$$

giving a *closed-loop voltage gain*

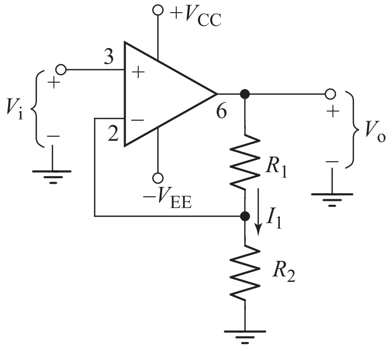
$$A_{CL} = \frac{V_o}{V_i} = \frac{I_1(R_1 + R_2)}{I_1 R_2}$$

or,

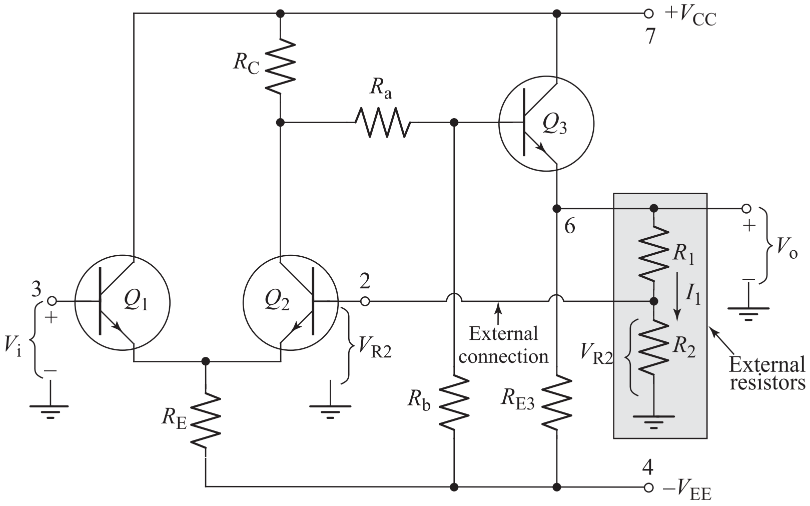
$$A_{CL} = \frac{R_1 + R_2}{R_2} \tag{1-1}$$

Example 1-3

A noninverting amplifier, as in Fig. 1-4, has $R_1 = 8.2\ \text{k}\Omega$ and $R_2 = 150\ \Omega$. (a) Calculate the voltage gain. (b) Determine a new resistance for R_2 to give $A_{CL} = 75$.



(a) Noninverting amplifier circuit



(c) Basic op-amp circuit connected as a noninverting amplifier

Figure 1-4 A noninverting amplifier operates in the same way as a voltage follower except that the output voltage is divided before it is fed back to the inverting input terminal. The circuit closed-loop voltage gain is $A_{CL} = (R_1 + R_2)/R_2$.

Solution

(a) From Eq. 1-1

$$A_{CL} = \frac{R_1 + R_2}{R_2} = \frac{8.2\ \text{k}\Omega\ +\ 150\ \Omega}{150\ \Omega}$$

$$= 55.7$$

(b) Again from Eq. 1-1

$$A_{CL} = \frac{R_1 + R_2}{R_2} = \frac{R_1}{R_2} + 1$$

giving

$$R_2 = \frac{R_1}{A_{CL} - 1} = \frac{8.2\ \text{k}\Omega}{75 - 1}$$

$$= 111\ \Omega$$

Practice Problems

1-3.1 For cases (a) and (b) in the circuit in Example 1-3, calculate the voltages across resistors R_1 and R_2 when a +50 mV signal is applied as input.

1-3.2 A noninverting amplifier, as in Fig. 1-4, has $R_1 = 4.7\ \text{k}\Omega$ and $R_2 = 220\ \Omega$. (a) Determine the closed-loop voltage gain. (b) Calculate the difference between the two input terminal voltages for a 300 mV input if the op-amp has $A_{\text{OL}} = 100\,000$.

1-4 THE INVERTING AMPLIFIER

The circuit shown in Fig. 1-5(a) is essentially the same as the noninverting amplifier in Fig. 1-4(a) with the important exception that the noninverting terminal is grounded and the input voltage is applied to resistor R_2. In this case, a positive-going input voltage produces a negative-going output and vice versa. So, the circuit is an *inverting amplifier*. Figure 1-5(b) shows the way the circuit is usually drawn. Note that the junction of the two resistors is connected to the op-amp inverting input terminal, the noninverting terminal is grounded, and the input is applied between R_2 and ground, exactly as in Fig. 1-5(a).

Figure 1-5(c) shows the basic op-amp circuit connected as an inverting amplifier. When a positive-going input is applied to R_2, I_{C2} is increased, thus increasing the voltage drop across R_C and driving the output voltage down. Because the base of Q_1 is grounded, the base of Q_2 will always be maintained at ground level (by negative feedback) regardless of the level of V_i. Thus, when V_i is applied, the output voltage moves to the level that keeps the inverting input terminal at ground. For this reason, the inverting input terminal in this type of circuit is referred to as a *virtual ground* or *virtual earth*.

Note from the above explanation that V_o is moved in a negative direction when V_i is positive. Similarly, when V_i is negative, V_o has to move in a positive direction to keep the op-amp inverting input terminal at ground level.

Now return to Fig. 1-5(b) and recall that the voltage at the inverting input terminal always remains close to ground because the noninverting terminal is grounded. Thus, the junction of R_1 and R_2 always remains at ground level. With V_i at one of R_2 and ground at the other end, V_i appears across R_2, as illustrated. Also, with V_o at one end of R_1 and ground at the other end, V_o is seen to be developed across R_1. Ignoring the very small bias current flowing into the op-amp inverting input terminal, the current I_1 effectively flows through both R_1 and R_2. The input and output voltages can now be expressed as

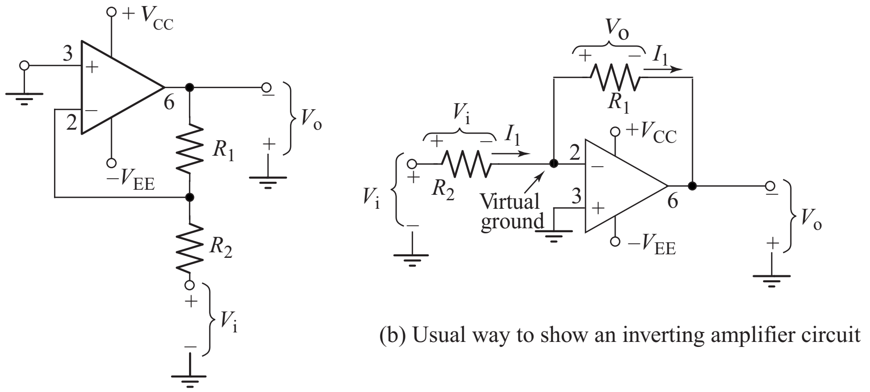
$$V_i = I_1 R_2$$

and

$$V_o = -I_1 R_1$$

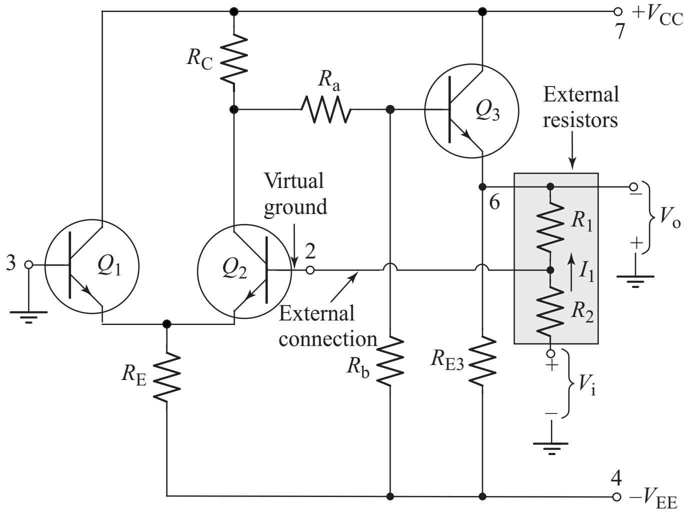
The closed-loop voltage gain is

$$A_{\text{CL}} = \frac{V_o}{V_i} = \frac{-I_1 R_1}{I_1 R_2}$$



(b) Usual way to show an inverting amplifier circuit

(a) Inverting amplifier circuit



(c) Basic op-amp circuit connected as an inverting amplifier

Figure 1-5 In an inverting amplifier the input is applied via resistor R_2 to the inverting input. This is essentially the same as a noninverting amplifier with the noninverting terminal grounded and the signal applied to the voltage divider. The circuit closed-loop voltage gain is $A_{CL} = -R_1/R_2$.

or,

$$A_{CL} = -\frac{R_1}{R_2} \tag{1-2}$$

The minus sign in Eq. 1-2 indicates that the output is inverted with respect to the input.

Example 1-4

An inverting amplifier, as in Fig. 1-5, has $R_1 = 8.2\ \text{k}\Omega$ and $R_2 = 270\ \Omega$. (a) Determine the voltage gain. (b) Calculate a new resistance for R_2 to give $A_{CL} = 60$.

Solution

(a) From Eq. 1-2

$$A_{CL} = -\frac{R_1}{R_2} = -\frac{8.2\ \text{k}\Omega}{270\ \Omega}$$
$$= -30.4$$

(b) From Eq. 1-2

$$R_2 = \frac{R_1}{A_{CL}} = \frac{8.2\ \text{k}\Omega}{60}$$
$$= 137\ \Omega$$

Practice Problems

1-4.1 For cases (a) and (b) in the circuit in Example 1-4, calculate the current through resistors R_1 and R_2 when a +100 mV signal is applied as input.

1-4-2 An inverting amplifier, as in Fig. 1-5, has $R_1 = 3.9\ \text{k}\Omega$ and $R_2 = 180\ \Omega$. (a) Determine the voltage gain. (b) If the op-amp has $A_{OL} = 200\ 000$, calculate the voltage difference between the op-amp input terminals when a 200 mV input is applied.

Review Questions

Section 1-1

1-1 Sketch the circuit symbol for an op-amp and identify all terminals.

1-2 Draw a basic (three BJT) op-amp internal circuit diagram. Identify the inverting input, noninverting input, and output terminals. Explain the circuit operation.

Section 1-2

1-3 Draw a circuit diagram for a voltage follower (a) using an op-amp graphic symbol and (b) using the basic three BJT op-amp circuit. Discuss the voltage follower operation.

Section 1-3

1-4 Draw a circuit diagram for a noninverting amplifier (a) using an op-amp graphic symbol and (b) using the basic three BJT op-amp circuit. Explain the circuit operation, and write the equation for the closed-loop voltage gain.

Section 1-4

1-5 Draw a circuit diagram for an inverting amplifier (a) using an op-amp graphic symbol and (b) using the basic three BJT op-amp circuit. Explain the circuit operation, and write the equation for the closed-loop voltage gain. Explain the term virtual ground.

Problems

Section 1-1

1-1 Recalculate the circuit current and voltage levels for the basic three BJT op-amp circuit in Example 1-1 when the output is directly connected to the inverting input terminal.

1-2 A basic op-amp circuit as in Fig. 1-2 has the following components: $R_C = R_E = R_{E3} = 6.8\ \text{k}\Omega$, $R_a = 56\ \text{k}\Omega$, and $R_b = 120\ \text{k}\Omega$. The supply is $V_{CC} = \pm 12$ V. Calculate the circuit current and voltage levels when the output is directly connected to the inverting input terminal. Assume that Q_1 and Q_2 are perfectly matched and that I_{B3} has no effect on the voltage divider.

Section 1-2

1-3 A 741 op-amp (Data Sheet A-1 in Appendix A) is connected as a voltage follower. If $V_i = 750$ mV and the amplifier open-loop gain is the only error source, calculate the precise level of V_o for (a) the specified minimum voltage gain and (b) for the specified typical gain.

1-4 An LM308 op-amp (Data Sheet A-3 in Appendix A) is substituted in place of the 741 in Problem 1-3. Calculate the output voltages for cases (a) and (b) once again.

1-5 An op-amp voltage follower with a 200 mV minimum input signal is to have 0.005% maximum output error. Determine the amplifier minimum open-loop gain.

1-6 A voltage follower using an LM308 op-amp is to reproduce the input with a maximum error of 10 μV due to the op-amp open-loop gain. Calculate the acceptable minimum input voltage.

Section 1-3

1-7 An op-amp noninverting amplifier, as in Fig. 1-4, has $R_1 = 22\ \text{k}\Omega$ and $R_2 = 120\ \Omega$. Calculate the output voltage produced by a 75 mV input.

1-8 An op-amp noninverting amplifier is to have a voltage gain of 101. If $R_2 = 180\ \Omega$ in Fig 1-4, determine a suitable resistance value for R_1.

1-9 A 120 mV signal is to produce a 12 V output from an op-amp noninverting amplifier. If a 15 kΩ resistor is to be used for R_1 (as in Fig. 1-4), determine a suitable resistance value for R_2.

1-10 Calculate the closed-loop gain for a noninverting amplifier, as in Fig. 1-4, with $R_1 = 27\ \text{k}\Omega$ and $R_2 = 390\ \Omega$. Determine the voltage gain that results if the resistor positions are reversed.

Section 1-4

1-11 An op-amp inverting amplifier, as in Fig. 1-5(b), has $R_2 = 120\ \Omega$ and $R_1 = 22\ \text{k}\Omega$. Calculate the output voltage produced by a 50 mV input.

1-12 An op-amp inverting amplifier is to have a voltage gain of 150. If $R_1 = 33\ \text{k}\Omega$ in Fig 1-5(b), determine a suitable resistance value for R_2.

1-13 Calculate the closed-loop voltage gain for an inverting amplifier, as in Fig. 1-5(b), which has $R_1 = 39\ \text{k}\Omega$ and $R_2 = 680\ \Omega$. Determine the new voltage gain if the resistor positions are reversed.

1-14 An op-amp inverting amplifier, as in Fig. 1-5(b), is to have a 0.5 V input signal and a 9 V output. Determine a suitable resistance value for R_2 if $R_1 = 12\ \text{k}\Omega$.

Practice Problem Answers

1-1.1	–0.2 V
1-2.1	±(100 mV – 0.1 µV)
1-2.2	250 000
1-3.1	(50 mV, 2.7 V), (50 mV, 3.69 V)
1-3.2	22.4, 67 µV
1-4.1	370 µV, 730 µA
1-4.2	–21.7, 21.7 µV