

CHAPTER I

BACKGROUND AND OBJECTIVES

1.1 INTRODUCTION

An operational amplifier is a high-gain direct-coupled amplifier that is normally used in feedback connections. If the amplifier characteristics are satisfactory, the transfer function of the amplifier with feedback can often be controlled primarily by the stable and well-known values of passive feedback elements.

The term operational amplifier evolved from original applications in analog computation where these circuits were used to perform various mathematical operations such as summation and integration. Because of the performance and economic advantages of available units, present applications extend far beyond the original ones, and modern operational amplifiers are used as general purpose analog data-processing elements.

High-quality operational amplifiers¹ were available in the early 1950s. These amplifiers were generally committed to use with analog computers and were not used with the flexibility of modern units. The range of operational-amplifier usage began to expand toward the present spectrum of applications in the early 1960s as various manufacturers developed modular, solid-state circuits. These amplifiers were smaller, much more rugged, less expensive, and had less demanding power-supply requirements than their predecessors. A variety of these discrete-component circuits are currently available, and their performance characteristics are spectacular when compared with older units.

A quantum jump in usage occurred in the late 1960s, as monolithic integrated-circuit amplifiers with respectable performance characteristics evolved. While certain performance characteristics of these units still do not compare with those of the better discrete-component circuits, the integrated types have an undeniable cost advantage, with several designs available at prices of approximately \$0.50. This availability frequently justifies the replacement of two- or three-transistor circuits with operational

¹ An excellent description of the technology of this era is available in G. A. Korn and T. M. Korn, *Electronic Analog Computers*, 2nd Ed., McGraw-Hill, New York, 1956.

amplifiers on economic grounds alone, independent of associated performance advantages. As processing and designs improve, the integrated circuit will invade more areas once considered exclusively the domain of the discrete design, and it is probable that the days of the discrete-component circuit, except for specials with limited production requirements, are numbered.

There are several reasons for pursuing a detailed study of operational amplifiers. We must discuss both the theoretical and the practical aspects of these versatile devices rather than simply listing a representative sample of their applications. Since virtually all operational-amplifier connections involve some form of feedback, a thorough understanding of this process is central to the intelligent application of the devices. While partially understood rules of thumb may suffice for routine requirements, this design method fails as performance objectives approach the maximum possible use from the amplifier in question.

Similarly, an appreciation of the internal structure and function of operational amplifiers is imperative for the serious user, since such information is necessary to determine various limitations and to indicate how a unit may be modified (via, for example, appropriate connections to its compensation terminals) or connected for optimum performance in a given application. The modern analog circuit designer thus needs to understand the internal function of an operational amplifier (even though he may never design one) for much the same reason that his counterpart of 10 years ago required a knowledge of semiconductor physics. Furthermore, this is an area where good design practice has evolved to a remarkable degree, and many of the circuit techniques that are described in following chapters can be applied to other types of electronic circuit and system design.

1.2 THE CLOSED-LOOP GAIN OF AN OPERATIONAL AMPLIFIER

As mentioned in the introduction, most operational-amplifier connections involve feedback. Therefore the user is normally interested in determining the *closed-loop gain* or *closed-loop transfer function* of the amplifier, which results when feedback is included. As we shall see, this quantity can be made primarily dependent on the characteristics of the feedback elements in many cases of interest.

A prerequisite for the material presented in the remainder of this book is the ability to determine the gain of the amplifier-feedback network combination in simple connections. The techniques used to evaluate closed-loop gain are outlined in this section.

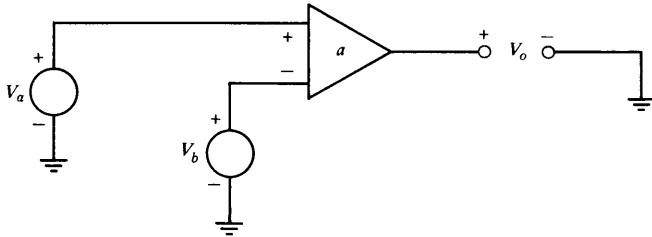


Figure 1.1 Symbol for an operational amplifier.

1.2.1 Closed-Loop Gain Calculation

The symbol used to designate an operational amplifier is shown in Fig. 1.1. The amplifier shown has a differential input and a single output. The input terminals marked $-$ and $+$ are called the *inverting* and the *non-inverting* input terminals respectively. The implied linear-region relationship among input and output variables² is

$$V_o = a(V_a - V_b) \quad (1.1)$$

The quantity a in this equation is the *open-loop gain* or *open-loop transfer function* of the amplifier. (Note that a gain of a is assumed, even if it is not explicitly indicated inside the amplifier symbol.) The dynamics normally associated with this transfer function are frequently emphasized by writing $a(s)$.

It is also necessary to provide operating power to the operational amplifier via power-supply terminals. Many operational amplifiers use balanced (equal positive and negative) supply voltages. The various signals are usually referenced to the common ground connection of these power sup-

² The notation used to designate system variables consists of a symbol and a subscript. This combination serves not only as a label, but also to identify the nature of the quantity as follows:

Total instantaneous variables:

lower-case symbols with upper-case subscripts.

Quiescent or operating-point variables:

upper-case symbols with upper-case subscripts.

Incremental instantaneous variables:

lower-case symbols with lower-case subscripts.

Complex amplitudes or Laplace transforms of incremental variables:

upper-case symbols with lower-case subscripts.

Using this notation we would write $v_I = V_I + v_i$, indicating that the instantaneous value of v_I consists of a quiescent plus an incremental component. The transform of v_i is V_i . The notation $V_i(s)$ is often used to reinforce the fact that V_i is a function of the complex variable s .

plies. The power connections are normally not included in diagrams intended only to indicate relationships among signal variables, since eliminating these connections simplifies the diagram.

Although operational amplifiers are used in a myriad of configurations, many applications are variations of either the inverting connection (Fig. 1.2a) or the noninverting connection (Fig. 1.2b). These connections combine the amplifier with impedances that provide feedback.

The closed-loop transfer function is calculated as follows for the inverting connection. Because of the reference polarity chosen for the intermediate variable V_a ,

$$V_o = -aV_a \quad (1.2)$$

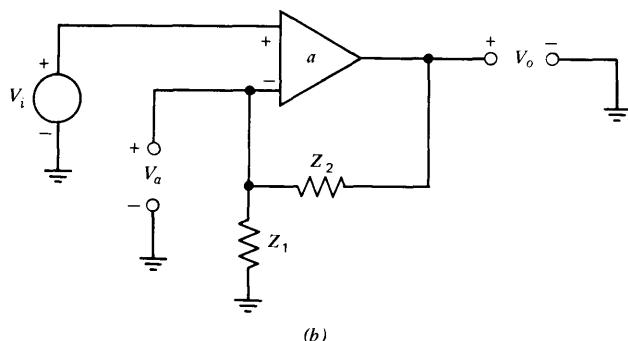
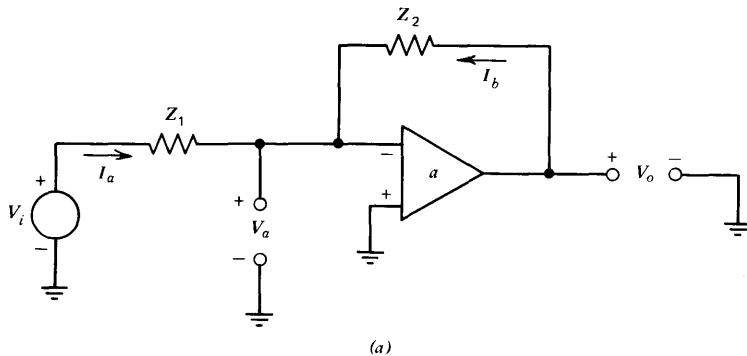


Figure 1.2 Operational-amplifier connections. (a) Inverting. (b) Noninverting.

where it has been assumed that the output voltage of the amplifier is not modified by the loading of the Z_1 - Z_2 network. If the input impedance of the amplifier itself is high enough so that the Z_1 - Z_2 network is not loaded significantly, the voltage V_a is

$$V_a = \left(\frac{Z_2}{Z_1 + Z_2} \right) V_i + \left(\frac{Z_1}{Z_1 + Z_2} \right) V_o \quad (1.3)$$

Combining Eqns. 1.2 and 1.3 yields

$$V_o = -\left(\frac{aZ_2}{Z_1 + Z_2} \right) V_i - \left(\frac{aZ_1}{Z_1 + Z_2} \right) V_o \quad (1.4)$$

or, solving for the closed-loop gain,

$$\frac{V_o}{V_i} = \frac{-aZ_2/(Z_1 + Z_2)}{1 + [aZ_1/(Z_1 + Z_2)]} \quad (1.5)$$

The condition that is necessary to have the closed-loop gain depend primarily on the characteristics of the Z_1 - Z_2 network rather than on the performance of the amplifier itself is easily determined from Eqn. 1.5. At any frequency ω where the inequality $|a(j\omega)Z_1(j\omega)/[Z_1(j\omega) + Z_2(j\omega)]| \gg 1$ is satisfied, Eqn. 1.5 reduces to

$$\frac{V_o(j\omega)}{V_i(j\omega)} \simeq -\frac{Z_2(j\omega)}{Z_1(j\omega)} \quad (1.6)$$

The closed-loop gain calculation for the noninverting connection is similar. If we assume negligible loading at the amplifier input and output,

$$V_o = a(V_i - V_a) = aV_i - \left(\frac{aZ_1}{Z_1 + Z_2} \right) V_o \quad (1.7)$$

or

$$\frac{V_o}{V_i} = \frac{a}{1 + [aZ_1/(Z_1 + Z_2)]} \quad (1.8)$$

This expression reduces to

$$\frac{V_o(j\omega)}{V_i(j\omega)} \simeq \frac{Z_1(j\omega) + Z_2(j\omega)}{Z_1(j\omega)} \quad (1.9)$$

when $|a(j\omega)Z_1(j\omega)/[Z_1(j\omega) + Z_2(j\omega)]| \gg 1$.

The quantity

$$L = \frac{-aZ_1}{Z_1 + Z_2} \quad (1.10)$$

is the *loop transmission* for either of the connections of Fig. 1.2. The loop transmission is of fundamental importance in any feedback system because it influences virtually all closed-loop parameters of the system. For example, the preceding discussion shows that if the magnitude of loop transmission is large, the closed-loop gain of either the inverting or the non-inverting amplifier connection becomes virtually independent of a . This relationship is valuable, since the passive feedback components that determine closed-loop gain for large loop-transmission magnitude are normally considerably more stable with time and environmental changes than is the open-loop gain a .

The loop transmission can be determined by setting the inputs of a feedback system to zero and breaking the signal path at any point inside the feedback loop.³ The loop transmission is the ratio of the signal returned by the loop to a test applied at the point where the loop is opened. Figure 1.3 indicates one way to determine the loop transmission for the connections of Fig. 1.2. Note that the topology shown is common to both the inverting and the noninverting connection when input points are grounded.

It is important to emphasize the difference between the loop transmission, which is dependent on properties of both the feedback elements and the operational amplifier, and the open-loop gain of the operational amplifier itself.

1.2.2 The Ideal Closed-Loop Gain

Detailed gain calculations similar to those of the last section are always possible for operational-amplifier connections. However, operational amplifiers are frequently used in feedback connections where loop characteristics are such that the closed-loop gain is determined primarily by the feedback elements. Therefore, approximations that indicate the *ideal closed-loop gain* or the gain that results with perfect amplifier characteristics simplify the analysis or design of many practical connections.

It is possible to calculate the ideal closed-loop gain assuming only two conditions (in addition to the implied condition that the amplifier-feedback network combination is stable⁴) are satisfied.

1. A negligibly small differential voltage applied between the two input terminals of the amplifier is sufficient to produce any desired output voltage.

³ There are practical difficulties, such as insuring that the various elements in the loop remain in their linear operating regions and that loading is maintained. These difficulties complicate the determination of the loop transmission in physical systems. Therefore, the technique described here should be considered a conceptual experiment. Methods that are useful for actual hardware are introduced in later sections.

⁴ Stability is discussed in detail in Chapter 4.

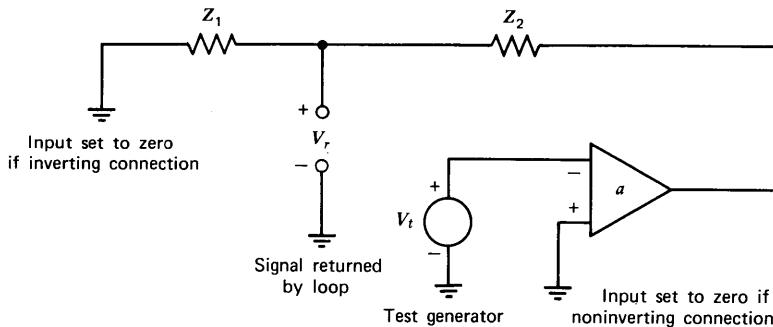


Figure 1.3 Loop transmission for connections of Fig. 1.2. Loop transmission is $V_r/V_t = -a Z_1/(Z_1 + Z_2)$.

2. The current required at either amplifier terminal is negligibly small.

The use of these assumptions to calculate the ideal closed-loop gain is first illustrated for the inverting amplifier connection (Fig. 1.2a). Since the noninverting amplifier input terminal is grounded in this connection, condition 1 implies that

$$V_a \simeq 0 \quad (1.11)$$

Kirchhoff's current law combined with condition 2 shows that

$$I_a + I_b \simeq 0 \quad (1.12)$$

With Eqn. 1.11 satisfied, the currents I_a and I_b are readily determined in terms of the input and output voltages.

$$I_a \simeq \frac{V_i}{Z_1} \quad (1.13)$$

$$I_b \simeq \frac{V_o}{Z_2} \quad (1.14)$$

Combining Eqns. 1.12, 1.13, and 1.14 and solving for the ratio of V_o to V_i yields the ideal closed-loop gain

$$\frac{V_o}{V_i} = -\frac{Z_2}{Z_1} \quad (1.15)$$

The technique used to determine the ideal closed-loop gain is called the *virtual-ground* method when applied to the inverting connection, since in this case the inverting input terminal of the operational amplifier is assumed to be at ground potential.

The noninverting amplifier (Fig. 1.2*b*) provides a second example of ideal-gain determination. Condition 2 insures that the voltage V_a is not influenced by current at the inverting input. Thus,

$$V_a \simeq \frac{Z_1}{Z_1 + Z_2} V_o \quad (1.16)$$

Since condition 1 requires equality between V_a and V_i , the ideal closed-loop gain is

$$\frac{V_o}{V_i} = \frac{Z_1 + Z_2}{Z_1} \quad (1.17)$$

The conditions can be used to determine ideal values for characteristics other than gain. Consider, for example, the input impedance of the two amplifier connections shown in Fig. 1.2. In Fig. 1.2*a*, the inverting input terminal and, consequently, the right-hand end of impedance Z_1 , is at ground potential if the amplifier characteristics are ideal. Thus the input impedance seen by the driving source is simply Z_1 . The input source is connected directly to the noninverting input of the operational amplifier in the topology of Fig. 1.2*b*. If the amplifier satisfies condition 2 and has negligible input current required at this terminal, the impedance loading the signal source will be very high. The noninverting connection is often used as a buffer amplifier for this reason.

The two conditions used to determine the ideal closed-loop gain are deceptively simple in that a complex combination of amplifier characteristics are required to insure satisfaction of these conditions. Consider the first condition. High open-loop voltage gain at anticipated operating frequencies is necessary but not sufficient to guarantee this condition. Note that gain at the frequency of interest is necessary, while the high open-loop gain specified by the manufacturer is normally measured at d-c. This specification is somewhat misleading, since the gain may start to decrease at a frequency on the order of one hertz or less.

In addition to high open-loop gain, the amplifier must have low voltage offset⁵ referred to the input to satisfy the first condition. This quantity, defined as the voltage that must be applied between the amplifier input terminals to make the output voltage zero, usually arises because of mismatches between various amplifier components.

Surprisingly, the incremental input impedance of an operational amplifier often has relatively little effect on its input current, since the voltage that appears across this impedance is very low if condition 1 is satisfied.

⁵ Offset and other problems with d-c amplifiers are discussed in Chapter 7.

A more important contribution to input current often results from the bias current that must be supplied to the amplifier input transistors.

Many of the design techniques that are used in an attempt to combine the two conditions necessary to approach the ideal gain are described in subsequent sections.

The reason that the satisfaction of the two conditions introduced earlier guarantees that the actual closed-loop gain of the amplifier approaches the ideal value is because of the negative feedback associated with operational-amplifier connections. Assume, for example, that the actual voltage out of the inverting-amplifier connection shown in Fig. 1.2a is more positive than the value predicted by the ideal-gain relationship for a particular input signal level. In this case, the voltage V_a will be positive, and this positive voltage applied to the inverting input terminal of the amplifier drives the output voltage negative until equilibrium is reached. This reasoning shows that it is actually the negative feedback that forces the voltage between the two input terminals to be very small.

Alternatively, consider the situation that results if positive feedback is used by interchanging the connections to the two input terminals of the

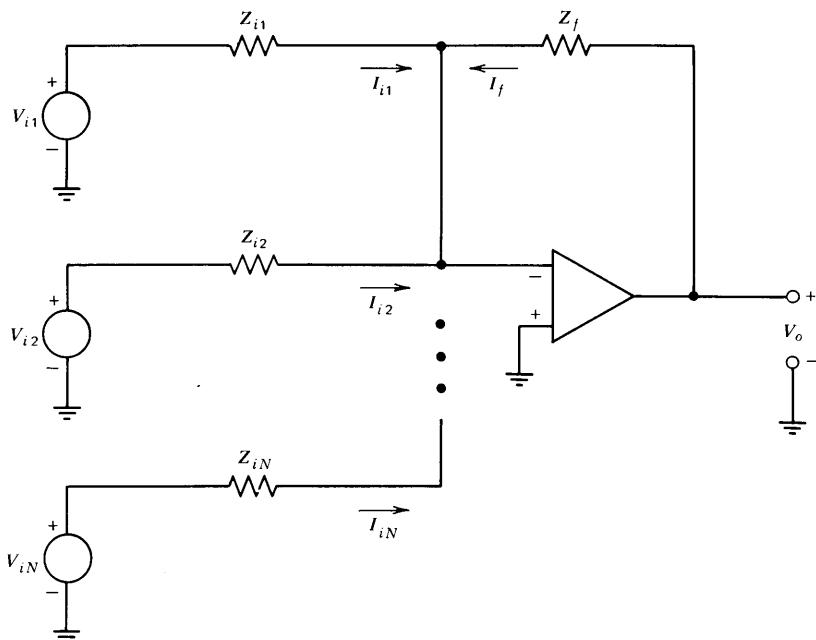


Figure 1.4 Summing amplifier.

amplifier. In this case, the voltage V_o is again zero when V_o and V_i are related by the ideal closed-loop gain expression. However, the resulting equilibrium is unstable, and a small perturbation from the ideal output voltage results in this voltage being driven further from the ideal value until the amplifier saturates. The ideal gain is not achieved in this case in spite of perfect amplifier characteristics because the connection is unstable. As we shall see, negative feedback connections can also be unstable. The ideal gain of these unstable systems is meaningless because they oscillate, producing an output signal that is often nearly independent of the input signal.

1.2.3 Examples

The technique introduced in the last section can be used to determine the ideal closed-loop transfer function of any operational-amplifier connection. The summing amplifier shown in Fig. 1.4 illustrates the use of this technique for a connection slightly more complex than the two basic amplifiers discussed earlier.

Since the inverting input terminal of the amplifier is a virtual ground, the currents can be determined as

$$\begin{aligned} I_{i1} &= \frac{V_{i1}}{Z_{i1}} \\ I_{i2} &= \frac{V_{i2}}{Z_{i2}} \\ &\vdots \\ I_{iN} &= \frac{V_{iN}}{Z_{iN}} \\ I_f &= \frac{V_o}{Z_f} \end{aligned} \quad (1.18)$$

These currents must sum to zero in the absence of significant current at the inverting input terminal of the amplifier. Thus

$$I_{i1} + I_{i2} + \cdots + I_{iN} + I_f = 0 \quad (1.19)$$

Combining Eqns. 1.18 and 1.19 shows that

$$V_o = -\frac{Z_f}{Z_{i1}} V_{i1} - \frac{Z_f}{Z_{i2}} V_{i2} - \cdots - \frac{Z_f}{Z_{iN}} V_{iN} \quad (1.20)$$

We see that this amplifier, which is an extension of the basic inverting-amplifier connection, provides an output that is the weighted sum of several input voltages.

Summation is one of the “operations” that operational amplifiers perform in analog computation. A subsequent development (Section 12.3) will show that if the operations of gain, summation, and integration are combined, an electrical network that satisfies any linear, ordinary differential equation can be constructed. This technique is the basis for analog computation.

Integrators required for analog computation or for any other application can be constructed by using an operational amplifier in the inverting connection (Fig. 1.2a) and making impedance Z_2 a capacitor C and impedance Z_1 a resistor R . In this case, Eqn. 1.15 shows that the ideal closed-loop transfer function is

$$\frac{V_o(s)}{V_i(s)} = -\frac{Z_2(s)}{Z_1(s)} = -\frac{1}{RCs} \quad (1.21)$$

so that the connection functions as an inverting integrator.

It is also possible to construct noninverting integrators using an operational amplifier connected as shown in Fig. 1.5. This topology precedes a noninverting amplifier with a low-pass filter. The ideal transfer function from the noninverting input of the amplifier to its output is (see Eqn. 1.17)

$$\frac{V_o(s)}{V_a(s)} = \frac{RCs + 1}{RCs} \quad (1.22)$$

Since the conditions for an ideal operational amplifier preclude input cur-

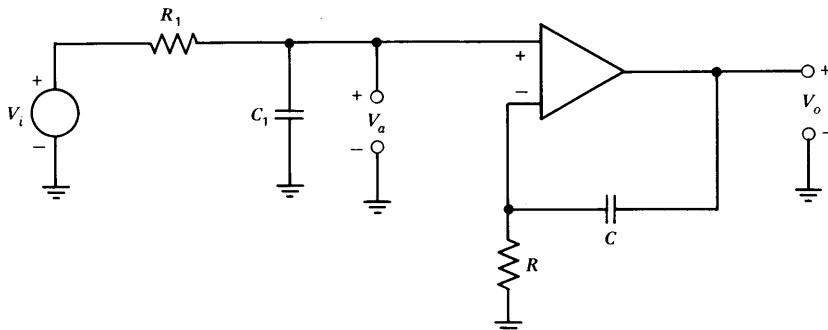


Figure 1.5 Noninverting integrator.

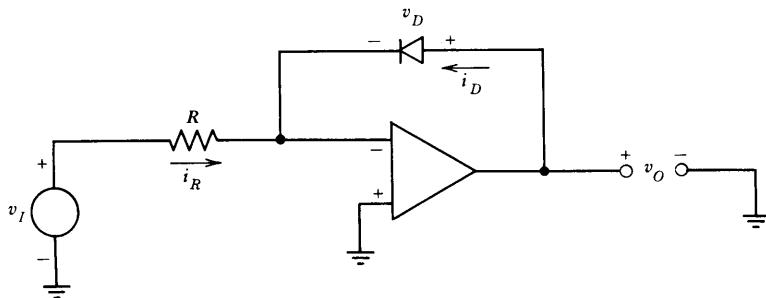


Figure 1.6 Log circuit.

rent, the transfer function from V_i to V_a can be calculated with no loading, and in this case

$$\frac{V_a(s)}{V_i(s)} = \frac{1}{R_1 C_1 s + 1} \quad (1.23)$$

Combining Eqns. 1.22 and 1.23 shows that the ideal closed-loop gain is

$$\frac{V_o(s)}{V_i(s)} = \left[\frac{1}{R_1 C_1 s + 1} \right] \left[\frac{R C s + 1}{R C s} \right] \quad (1.24)$$

If the two time constants in Eqn. 1.24 are made equal, noninverting integration results.

The comparison between the two integrator connections hints at the possibility of realizing most functions via either an inverting or a non-inverting connection. Practical considerations often recommend one approach in preference to the other. For example, the noninverting integrator requires more external components than does the inverting version. This difference is important because the high-quality capacitors required for accurate integration are often larger and more expensive than the operational amplifier that is used.

The examples considered up to now have involved only linear elements, at least if it is assumed that the operational amplifier remains in its linear operating region. Operational amplifiers are also frequently used in intentionally nonlinear connections. One possibility is the circuit shown in Fig. 1.6.⁶ It is assumed that the diode current-voltage relationship is

$$i_D = I_S(e^{q v_D/kT} - 1) \quad (1.25)$$

⁶ Note that the notation for the variables used in this case combines lower-case variables with upper-case subscripts, indicating the total instantaneous signals necessary to describe the anticipated nonlinear relationships.

where I_S is a constant dependent on diode construction, q is the charge of an electron, k is Boltzmann's constant, and T is the absolute temperature.

If the voltage at the inverting input of the amplifier is negligibly small, the diode voltage is equal to the output voltage. If the input current is negligibly small, the diode current and the current i_R sum to zero. Thus, if these two conditions are satisfied,

$$-\frac{v_I}{R} = I_S(e^{qv_o/kT} - 1) \quad (1.26)$$

Consider operation with a positive input voltage. The maximum negative value of the diode current is limited to $-I_S$. If $v_I/R > I_S$, the current through the reverse-biased diode cannot balance the current i_R . Accordingly, the amplifier output voltage is driven negative until the amplifier saturates. In this case, the feedback loop cannot keep the voltage at the inverting amplifier input near ground because of the limited current that the diode can conduct in the reverse direction. The problem is clearly not with the amplifier, since no solution exists to Eqn. 1.26 for sufficiently positive values of v_I .

This problem does not exist with negative values for v_I . If the magnitude of i_R is considerably larger than I_S (typical values for I_S are less than 10^{-9} A), Eqn. 1.26 reduces to

$$-\frac{v_I}{R} \simeq I_S e^{qv_o/kT} \quad (1.27)$$

or

$$v_o \simeq \frac{kT}{q} \ln \left(\frac{-v_I}{RI_S} \right) \quad (1.28)$$

Thus the circuit provides an output voltage proportional to the log of the magnitude of the input voltage for negative inputs.

1.3 OVERVIEW

The operational amplifier is a powerful, multifaceted analog data-processing element, and the optimum exploitation of this versatile building block requires a background in several different areas. The primary objective of this book is to help the reader apply operational amplifiers to his own problems. While the use of a "handbook" approach that basically tabulates a number of configurations that others have found useful is attractive because of its simplicity, this approach has definite limitations. Superior results are invariably obtained when the designer tailors the circuit

he uses to his own specific, detailed requirements, and to the particular operational amplifier he chooses.

A balanced presentation that combines practical circuit and system design concepts with applicable theory is essential background for the type of creative approach that results in optimum operational-amplifier systems. The following chapters provide the necessary concepts. A second advantage of this presentation is that many of the techniques are readily applied to a wide spectrum of circuit and system design problems, and the material is structured to encourage this type of transfer.

Feedback is central to virtually all operational-amplifier applications, and a thorough understanding of this important topic is necessary in any challenging design situation. Chapters 2 through 6 are devoted to feedback concepts, with emphasis placed on examples drawn from operational-amplifier connections. However, the presentation in these chapters is kept general enough to allow its application to a wide variety of feedback systems. Topics covered include modeling, a detailed study of the advantages and limitations of feedback, determination of responses, stability, and compensation techniques intended to improve stability. Simple methods for the analysis of certain types of nonlinear systems are also included. This in-depth approach is included at least in part because I am convinced that a detailed understanding of feedback is the single most important prerequisite to successful electronic circuit and system design.

Several interesting and widely applicable circuit-design techniques are used to realize operational amplifiers. The design of operational-amplifier circuits is complicated by the requirement of obtaining gain at zero frequency with low drift and input current. Chapter 7 discusses the design of the necessary d-c amplifiers. The implications of topology on the dynamics of operational-amplifier circuits are discussed in Chapter 8. The design of the high-gain stages used in most modern operational amplifiers and the factors which influence output-stage performance are also included. Chapter 9 illustrates how circuit design techniques and feedback-system concepts are combined in an illustrative operational-amplifier circuit.

The factors influencing the design of the modern integrated-circuit operational amplifiers that have dramatically increased amplifier usage are discussed in Chapter 10. Several examples of representative present-day designs are included.

A variety of operational-amplifier applications are sprinkled throughout the first 10 chapters to illustrate important concepts. Chapters 11 and 12 focus on further applications, with major emphasis given to clarifying important techniques and topologies rather than concentrating on minor details that are highly dependent on the specifics of a given application and the amplifier used.

Chapter 13 is devoted to the problem of compensating operational amplifiers for optimum dynamic performance in a variety of applications. Discussion of this material is deferred until the final chapter because only then is the feedback, circuit, and application background necessary to fully appreciate the subtleties of compensating modern operational amplifiers available. Compensation is probably the single most important aspect of effectively applying operational amplifiers, and often represents the difference between inadequate and superlative performance. Several examples of the way in which compensation influences the performance of a representative integrated-circuit operational amplifier are used to reinforce the theoretical discussion included in this chapter.

PROBLEMS

P1.1

Design a circuit using a single operational amplifier that provides an ideal input-output relationship

$$V_o = -V_{i1} - 2V_{i2} - 3V_{i3}$$

Keep the values of all resistors used between 10 and 100 kΩ.

Determine the loop transmission (assuming no loading) for your design.

P1.2

Note that it is possible to provide an ideal input-output relationship

$$V_o = V_{i1} + 2V_{i2} + 3V_{i3}$$

by following the design for Problem 1.1 with a unity-gain inverter. Find a more efficient design that produces this relationship using only a single operational amplifier.

P1.3

An operational amplifier is connected to provide an inverting gain with an ideal value of 10. At low frequencies, the open-loop gain of the amplifier is frequency independent and equal to a_0 . Assuming that the only source of error is the finite value of open-loop gain, how large should a_0 be so that the actual closed-loop gain of the amplifier differs from its ideal value by less than 0.1%?

P1.4

Design a single-amplifier connection that provides the ideal input-output relationship

$$v_o = -100 \int (v_{i1} + v_{i2}) dt$$

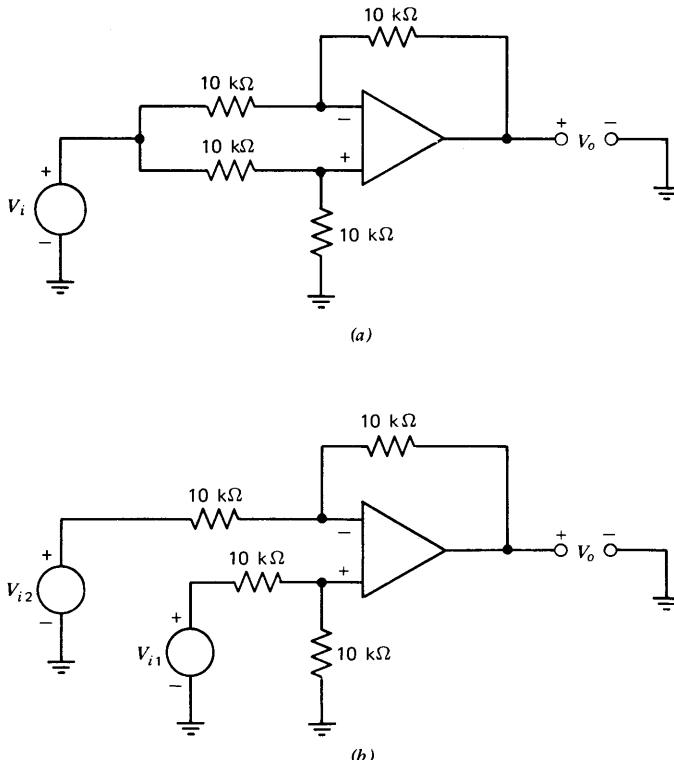


Figure 1.7 Differential-amplifier connections.

Keep the values of all resistors you use between 10 and 100 k Ω .

P1.5

Design a single-amplifier connection that provides the ideal input-output relationship

$$v_o = +100 \int (v_{i1} + v_{i2}) dt$$

using only resistor values between 10 and 100 k Ω . Determine the loop transmission of your configuration, assuming negligible loading.

P1.6

Determine the ideal input-output relationships for the two connections shown in Fig. 1.7.

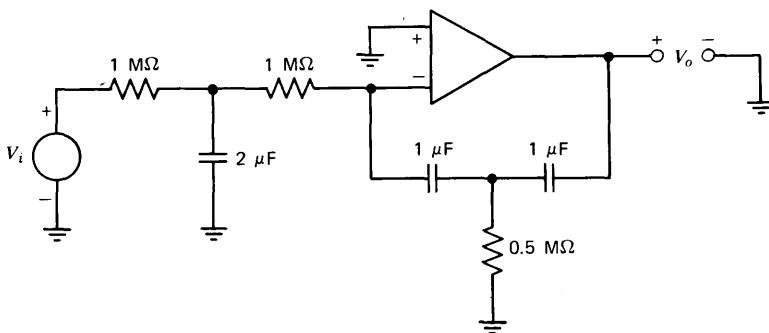


Figure 1.8 Two-pole system.

P1.7

Determine the ideal input-output transfer function for the operational-amplifier connection shown in Fig. 1.8. Estimate the value of open-loop gain required such that the actual closed-loop gain of the circuit approaches its ideal value at an input frequency of 0.01 radian per second. You may neglect loading.

P1.8

Assume that the operational-amplifier connection shown in Fig. 1.9 satisfies the two conditions stated in Section 1.2.2. Use these conditions to determine the output resistance of the connection (i.e., the resistance seen by the load).

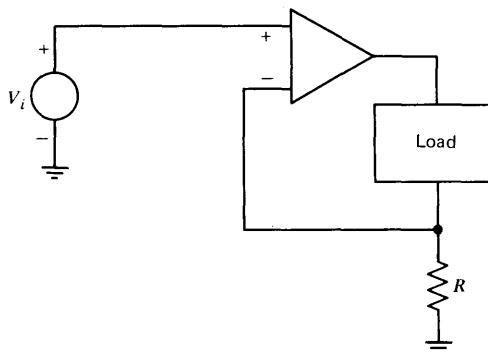


Figure 1.9 Circuit with controlled output resistance.

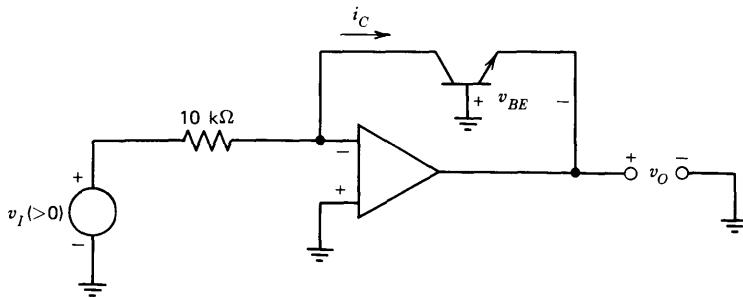


Figure 1.10 Log circuit.

P1.9

Determine the ideal input-output transfer relationship for the circuit shown in Fig. 1.10. Assume that transistor terminal variables are related as

$$i_C = 10^{-13} e^{40 v_{BE}}$$

where i_C is expressed in amperes and v_{BE} is expressed in volts.

P1.10

Plot the ideal input-output characteristics for the two circuits shown in Fig. 1.11. In part *a*, assume that the diode variables are related by $i_D = 10^{-13} e^{40 v_D}$, where i_D is expressed in amperes and v_D is expressed in volts. In part *b*, assume that $i_D = 0$, $v_D < 0$, and $v_D = 0$, $i_D > 0$.

P1.11

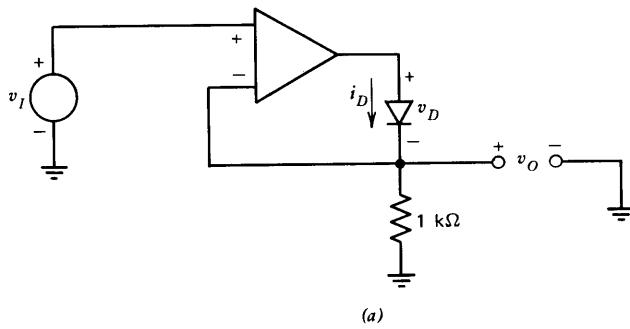
We have concentrated on operational-amplifier connections involving negative feedback. However, several useful connections, such as that shown in Fig. 1.12, use positive feedback around an amplifier. Assume that the linear-region open-loop gain of the amplifier is very high, but that its output voltage is limited to ± 10 volts because of saturation of the amplifier output stage. Approximate and plot the output signal for the circuit shown in Fig. 1.12 using these assumptions.

P1.12

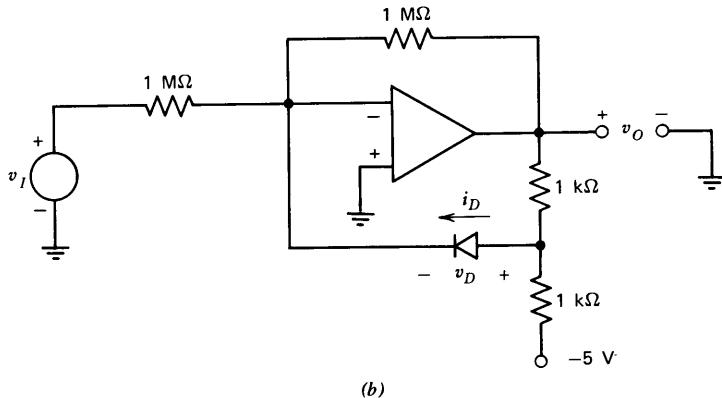
Design an operational-amplifier circuit that provides an ideal input-output relationship of the form

$$v_O = K_1 e^{v_I/K_2}$$

where K_1 and K_2 are constants dependent on parameter values used in your design.



(a)



(b)

Figure 1.11 Nonlinear circuits.

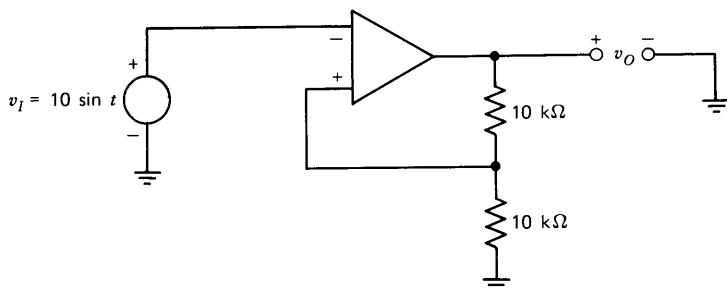


Figure 1.12 Schmitt trigger.

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