12 The Operational Amplifier

CHAPTER OUTLINE

CHAPTER OBJECTIVES

- Describe the basic operational amplifier and its characteristics
- Discuss op-amp modes and several parameters
- Explain negative feedback in op-amps
- Analyze op-amps with negative feedback
- Describe how negative feedback affects op-amp impedances
- Discuss bias current and offset voltage
- Analyze the open-loop frequency response of an op-amp
- Analyze the closed-loop frequency response of an op-amp
- Troubleshoot op-amp circuits

KEY TERMS

- Operational amplifier (op-amp)
- Differential amplifier
- Differential mode
- Common mode
- CMRR
- Open-loop voltage gain
- Slew rate
- Negative feedback
- Closed-loop voltage gain
- Noninverting amplifier
- Voltage-follower
- Inverting amplifier
- Phase shift
- Gain-bandwidth product

APPLICATION ACTIVITY PREVIEW

For the Application Activity in this chapter, the audio amplifier from the PA system in Chapter 7 is modified. The two-stage preamp portion of the amplifier is replaced by an op-amp circuit. The power amplifier portion is retained in its original configuration with the exception of the drive circuit so that the new design consists of an op-amp driving a push-pull power stage. In the original system there are two PC boards—one for the preamp and one for the power amplifier. The new design will allow both the preamp and the power amplifier to be on a single PC board.

VISIT THE COMPANION WEBSITE

Study aids and Multisim files for this chapter are available at http://www.pearsonhighered.com/electronics

INTRODUCTION

In the previous chapters, you have studied a number of important electronic devices. These devices, such as the diode and the transistor, are separate devices that are individually packaged and interconnected in a circuit with other devices to form a complete, functional unit. Such devices are referred to as *discrete components.*

Now you will begin the study of linear integrated circuits (ICs), where many transistors, diodes, resistors, and capacitors are fabricated on a single tiny chip of semiconductive material and packaged in a single case to form a functional circuit. An integrated circuit, such as an operational amplifier (op-amp), is treated as a single device. This means that you will be concerned with what the circuit does more from an external viewpoint than from an internal, component-level viewpoint.

In this chapter, you will learn the basics of op-amps, which are the most versatile and widely used of all linear integrated circuits. You will also learn about open-loop and closed-loop frequency responses, bandwidth, phase shift, and other frequency-related parameters. The effects of negative feedback will be examined.

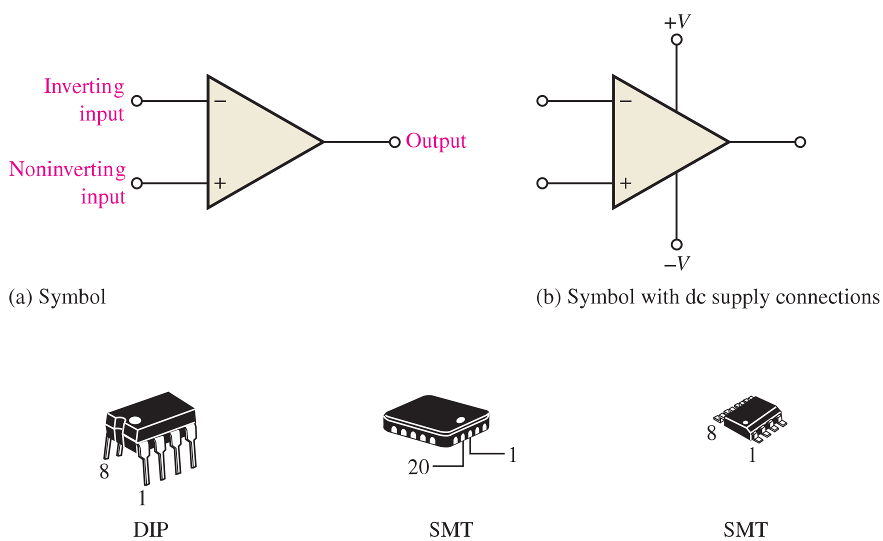
12–1 INTRODUCTION TO OPERATIONAL AMPLIFIERS

Early operational amplifiers (op-amps) were used primarily to perform mathematical operations such as addition, subtraction, integration, and differentiation—thus the term *operational.* These early devices were constructed with vacuum tubes and worked with high voltages. Today's op-amps are linear integrated circuits (ICs) that use relatively low dc supply voltages and are reliable and inexpensive.

After completing this section, you should be able to

- **Describe the basic operational amplifier and its characteristics**
  - Identify the schematic symbol and IC package terminals
- Discuss the ideal op-amp
- Discuss the practical op-amp
  - Draw the internal block diagram

The standard **operational amplifier (op-amp)** symbol is shown in Figure 12–1(a). It has two input terminals, the inverting (−) input and the noninverting (+) input, and one output terminal. Most op-amps operate with two dc supply voltages, one positive and the other negative, as shown in Figure 12–1(b), although some have a single dc supply. Usually these dc voltage terminals are left off the schematic symbol for simplicity but are understood to be there. Some typical op-amp IC packages are shown in Figure 12–1(c).



(c) Typical packages. Pin 1 is indicated by a notch or dot on dual in-line (DIP) and surface-mount technology (SMT) packages, as shown.

◀ **FIGURE 12–1**

Op-amp symbols and packages.

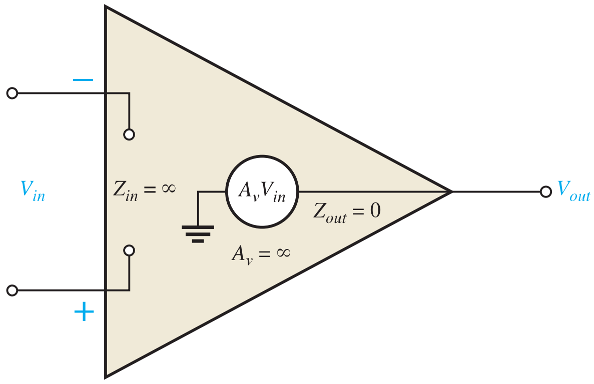
HISTORY NOTE

The operational amplifier concept originated around 1947. It was proposed that such a device would form an extremely useful analog building block. The first commercial op-amps used vacuum tubes, but it was not until the introduction of the integrated circuit did the op-amp start to fulfill its true potential. In 1964, the first integrated circuit op-amp, designated the 702, was developed by Fairchild Semiconductor. This was later followed by the 709 and eventually the 741, which has become an industry standard.

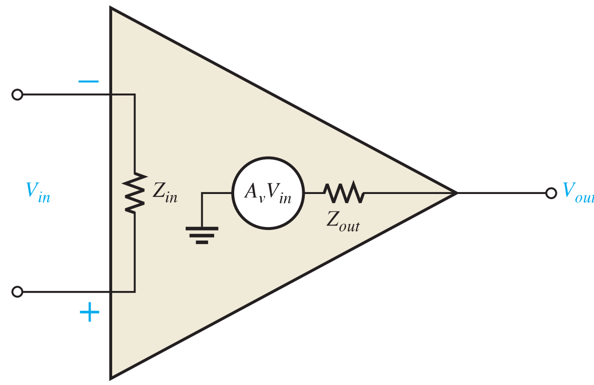
The Ideal Op-Amp

To illustrate what an op-amp is, let's consider its ideal characteristics. A practical op-amp, of course, falls short of these ideal standards, but it is much easier to understand and analyze the device from an ideal point of view.

First, the ideal op-amp has *infinite voltage gain* and *infinite bandwidth.* Also, it has an *infinite input impedance* (open) so that it does not load the driving source. Finally, it has a *zero output impedance.* Op-amp characteristics are illustrated in Figure 12–2(a). The input voltage, V_{in}, appears between the two input terminals, and the output voltage is A_vV_{in}, as indicated by the internal voltage source symbol. The concept of infinite input impedance is a particularly valuable analysis tool for the various op-amp configurations, which will be discussed in Section 12–4.



(a) Ideal op-amp representation



(b) Practical op-amp representation

▲ FIGURE 12–2

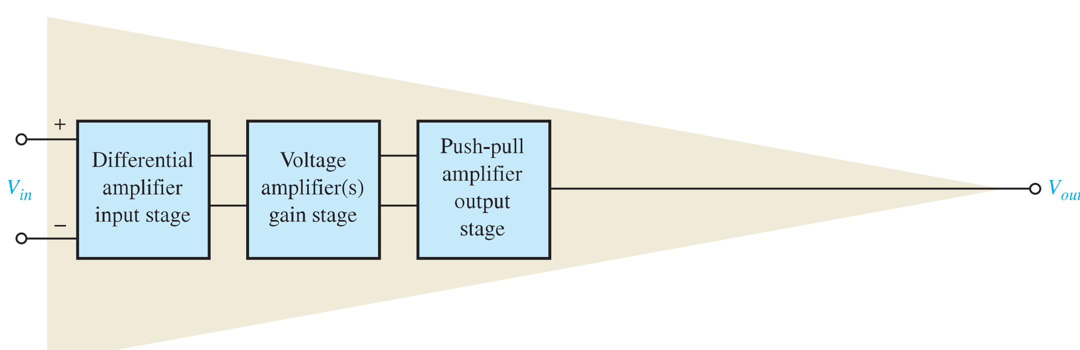
Basic op-amp representations.

The Practical Op-Amp

Although **integrated circuit (IC)** op-amps approach parameter values that can be treated as ideal in many cases, the ideal device can never be made. Any device has limitations, and the IC op-amp is no exception. Op-amps have both voltage and current limitations. Peak-to-peak output voltage, for example, is usually limited to slightly less than the two supply voltages. Output current is also limited by internal restrictions such as power dissipation and component ratings.

Characteristics of a practical op-amp are *very high voltage gain, very high input impedance, and very low output impedance.* These are labelled in Figure 12–2(b). Another practical consideration is that there is always noise generated within the op-amp. **Noise** is an undesired signal that affects the quality of a desired signal. Today, circuit designers are using smaller voltages that require high accuracy, so low-noise components are in greater demand. All circuits generate noise; op-amps are no exception, but the amount can be minimized.

Internal Block Diagram of an Op-Amp A typical op-amp is made up of three types of amplifier circuits: a differential amplifier, a voltage amplifier, and a push-pull amplifier, as shown in Figure 12–3. The **differential amplifier** is the input stage for the op-amp. It provides amplification of the difference voltage between the two inputs. The second stage is usually a class A amplifier that provides additional gain. Some op-amps may have more than one voltage amplifier stage. A push-pull class B amplifier is typically used for the output stage.



▲ FIGURE 12–3

Basic internal arrangement of an op-amp.

The differential amplifier was introduced in Chapter 6. The term *differential* comes from the amplifier's ability to amplify the difference of two input signals applied to its inputs. Only the difference in the two signals is amplified; if there is no difference, the output is zero. The differential amplifier exhibits two modes of operation based on the type of input signals. These modes are *differential* and *common,* which are described in the next section. Since the differential amplifier is the input stage of the op-amp, the op-amp exhibits the same modes.

SECTION 12–1 CHECKUP
Answers can be found at www.pearsonhighered.com/floyd.

1. What are the connections to a basic op-amp?
2. Describe some of the characteristics of a practical op-amp.
3. List the amplifier stages in a typical op-amp.
4. What does a differential amplifier amplify?

12–2 OP-AMP INPUT MODES AND PARAMETERS

In this section, important op-amp input modes and several parameters are defined. Also several common IC op-amps are compared in terms of these parameters.

After completing this section, you should be able to

- **Discuss op-amp modes and several parameters**
  - Identify the schematic symbol and IC package terminals
- Describe the input signal modes
  - Explain the differential mode ◆ Explain the common mode
- Define and discuss op-amp parameters
  - Define *common-mode rejection ratio (CMRR)* ◆ Calculate the CMRR
  - Express the CMRR in decibels ◆ Define open-loop voltage gain
  - Explain maximum output voltage swing ◆ Explain input offset voltage
  - Explain input bias current ◆ Explain input impedance ◆ Explain input offset current ◆ Explain output impedance ◆ Explain slew rate
  - Explain frequency response
- Compare op-amp parameters for several devices

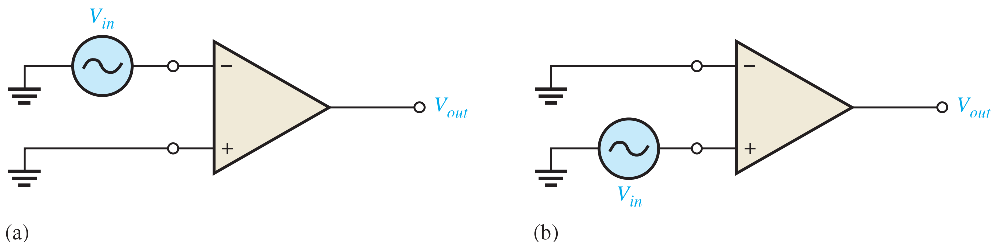
Input Signal Modes

Recall that the input signal modes are determined by the differential amplifier input stage of the op-amp.

Differential Mode In the **differential mode**, either one signal is applied to an input with the other input grounded or two opposite-polarity signals are applied to the inputs. When an op-amp is operated in the single-ended differential mode, one input is grounded and a signal voltage is applied to the other input, as shown in Figure 12–4. In the case where the signal voltage is applied to the inverting input as in part (a), an inverted, amplified signal voltage appears at the output. In the case where the signal is applied to the noninverting input with the inverting input grounded, as in Figure 12–4(b), a noninverted, amplified signal voltage appears at the output.

▶ FIGURE 12–4

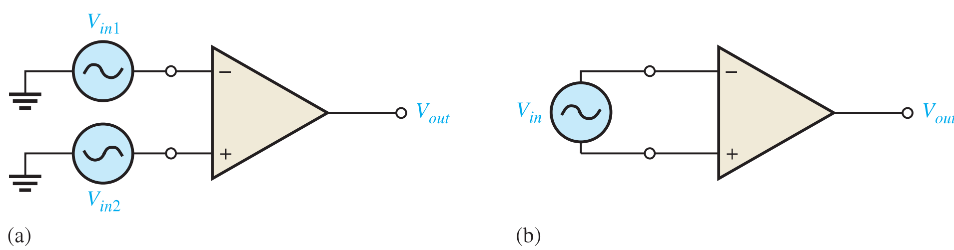
Single-ended differential mode.



In the double-ended differential mode, two opposite-polarity (out-of-phase) signals are applied to the inputs, as shown in Figure 12–5(a). The amplified difference between the two inputs appears on the output. Equivalently, the double-ended differential mode can be represented by a single source connected between the two inputs, as shown in Figure 12–5(b).

▶ FIGURE 12–5

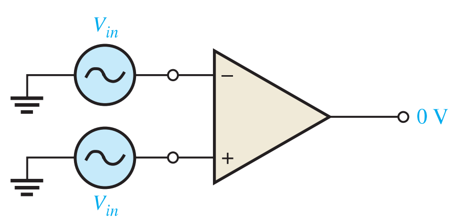
Double-ended differential mode.



Common Mode In the **common mode**, two signal voltages of the same phase, frequency, and amplitude are applied to the two inputs, as shown in Figure 12–6. When equal input signals are applied to both inputs, they tend to cancel, resulting in a zero output voltage.

▶ FIGURE 12–6

Common-mode operation.



This action is called *common-mode rejection*. Its importance lies in the situation where an unwanted signal appears commonly on both op-amp inputs. Common-mode rejection means that this unwanted signal will not appear on the output and distort the desired signal. Common-mode signals (noise) generally are the result of the pick-up of radiated energy on the input lines, from adjacent lines, the 60 Hz power line, or other sources.

Op-Amp Parameters

Common-Mode Rejection Ratio Desired signals can appear on only one input or with opposite polarities on both input lines. These desired signals are amplified and appear on the output as previously discussed. Unwanted signals (noise) appearing with the same polarity on both input lines are essentially cancelled by the op-amp and do not appear on the output. The measure of an amplifier's ability to reject common-mode signals is a parameter called the **CMRR (common-mode rejection ratio)**.

Ideally, an op-amp provides a very high gain for differential-mode signals and zero gain for common-mode signals. Practical op-amps, however, do exhibit a very small common-mode gain (usually much less than 1), while providing a high open-loop differential voltage gain (usually several thousand). The higher the open-loop gain with respect to the common-mode gain, the better the performance of the op-amp in terms of rejection of common-mode signals. This suggests that a good measure of the op-amp's performance in rejecting unwanted common-mode signals is the ratio of the open-loop differential voltage gain, A_{ol}, to the common-mode gain, A_{cm}. This ratio is the common-mode rejection ratio, CMRR.

$$\mathbf{CMRR} = \frac{A_{ol}}{A_{cm}}$$

Equation 12–1

The higher the CMRR, the better. A very high value of CMRR means that the open-loop gain, A_{ol}, is high and the common-mode gain, A_{cm}, is low.

The CMRR is often expressed in decibels (dB) as

$$\mathbf{CMRR} = 20 \log\left(\frac{A_{ol}}{A_{cm}}\right)$$

Equation 12–2

The **open-loop voltage gain**, A_{ol}, of an op-amp is the internal voltage gain of the device and represents the ratio of output voltage to input voltage when there are no external components. The open-loop voltage gain is set entirely by the internal design. Open-loop voltage gain can range up to 200,000 (106 dB) and is not a well-controlled parameter. Datasheets often refer to the open-loop voltage gain as the *large-signal voltage gain.*

A CMRR of 100,000, for example, means that the desired input signal (differential) is amplified 100,000 times more than the unwanted noise (common-mode). If the amplitudes of the differential input signal and the common-mode noise are equal, the desired signal will appear on the output 100,000 times greater in amplitude than the noise. Thus, the noise or interference has been essentially eliminated.

EXAMPLE 12–1

A certain op-amp has an open-loop differential voltage gain of 100,000 and a common-mode gain of 0.2. Determine the CMRR and express it in decibels.

Solution

$A_{ol} = 100{,}000$, and $A_{cm} = 0.2$. Therefore,

$$\text{CMRR} = \frac{A_{ol}}{A_{cm}} = \frac{100{,}000}{0.2} = \mathbf{500{,}000}$$

Expressed in decibels,

$$\text{CMRR} = 20 \log (500{,}000) = \mathbf{114\ dB}$$

*Related Problem**

Determine the CMRR and express it in dB for an op-amp with an open-loop differential voltage gain of 85,000 and a common-mode gain of 0.25.

***Answers can be found at www.pearsonhighered.com/floyd.**

Maximum Output Voltage Swing ($V_{O(p\text{-}p)}$) With no input signal, the output of an op-amp is ideally 0 V. This is called the *quiescent output voltage.* When an input signal is applied, the ideal limits of the peak-to-peak output signal are $\pm V_{CC}$. In practice, however, this ideal can be approached but never reached. $V_{O(p\text{-}p)}$ varies with the load connected to the op-amp and increases directly with load resistance. For example, the Fairchild KA741 datasheet shows a typical $V_{O(p\text{-}p)}$ of ± 13 V for $V_{CC} = \pm 15$ V when $R_L = 2\ \text{k}\Omega$. $V_{O(p\text{-}p)}$ increases to ± 14 V when $R_L = 10\ \text{k}\Omega$.

Some op-amps do not use both positive and negative supply voltages. One example is when a single dc voltage source is used to power an op-amp that drives an analog-to-digital converter (discussed in Chapter 14). In this case, the op-amp output is designed to operate between ground and a full scale output that is near (or at) the positive supply voltage. Op-amps that operate on a single supply use the terminology V_{OH} and V_{OL} to specify the maximum and minimum output voltage. (Note that these are not the same as the digital definitions of V_{OL} and V_{OH}.)

GREENTECH NOTE

Designers today are "going green" by reducing power in op-amps and applications. To reduce power dissipated by op-amps, lower voltage supplies can be used as well as greater reliance on CMOS. In some cases, CMOS requires only a few picoamps of bias current, which helps designers reduce current in the external circuit.

Input Offset Voltage The ideal op-amp produces zero volts out for zero volts in. In a practical op-amp, however, a small dc voltage, $V_{OUT(error)}$, appears at the output when no differential input voltage is applied. Its primary cause is a slight mismatch of the base-emitter voltages of the differential amplifier input stage of an op-amp.

As specified on an op-amp datasheet, the *input offset voltage,* V_{OS}, is the differential dc voltage required between the inputs to force the output to zero volts. Typical values of input offset voltage are in the range of 2 mV or less. In the ideal case, it is 0 V.

The *input offset voltage drift* is a parameter related to V_{OS} that specifies how much change occurs in the input offset voltage for each degree change in temperature. Typical values range anywhere from about 5 μV per degree Celsius to about 50 μV per degree Celsius. Usually, an op-amp with a higher nominal value of input offset voltage exhibits a higher drift.

Input Bias Current You have seen that the input terminals of a bipolar differential amplifier are the transistor bases and, therefore, the input currents are the base currents.

The *input bias current* is the dc current required by the inputs of the amplifier to properly operate the first stage. By definition, the input bias current is the *average* of both input currents and is calculated as follows:

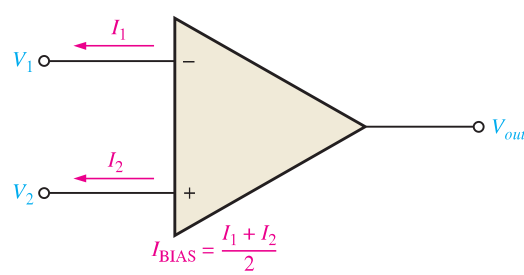
Equation 12–3

$$I_{BIAS} = \frac{I_1 + I_2}{2}$$

The concept of input bias current is illustrated in Figure 12–7.

▶ FIGURE 12–7

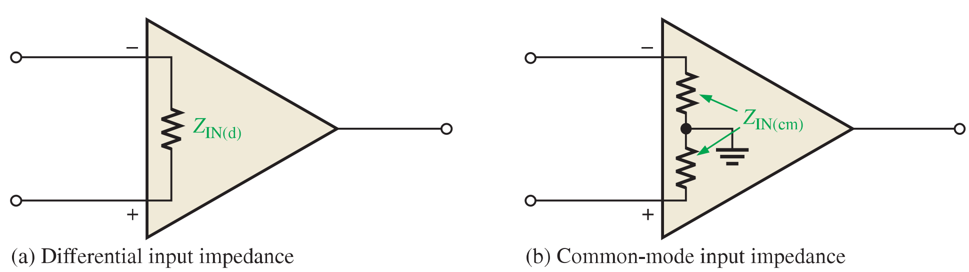
Input bias current is the average of the two op-amp input currents.



Input Impedance Two basic ways of specifying the input impedance of an op-amp are the differential and the common mode. The *differential input impedance* is the total resistance between the inverting and the noninverting inputs, as illustrated in Figure 12–8(a). Differential impedance is measured by determining the change in bias current for a given change in differential input voltage. The *common-mode input impedance* is the resistance between each input and ground and is measured by determining the change in bias current for a given change in common-mode input voltage. It is depicted in Figure 12–8(b).

▶ FIGURE 12–8

Op-amp input impedance.



Input Offset Current Ideally, the two input bias currents are equal, and thus their difference is zero. In a practical op-amp, however, the bias currents are not exactly equal.

The *input offset current,* I_{OS}, is the difference of the input bias currents, expressed as an absolute value.

$$I_{OS} = |I_1 - I_2|$$

Equation 12–4

Actual magnitudes of offset current are usually at least an order of magnitude (ten times) less than the bias current. In many applications, the offset current can be neglected. However, high-gain, high-input impedance amplifiers should have as little I_{OS} as possible because the difference in currents through large input resistances develops a substantial offset voltage, as shown in Figure 12–9.

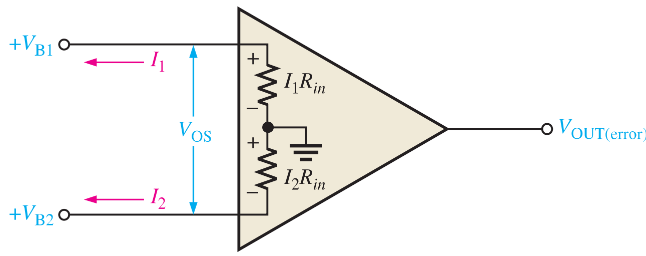


FIGURE 12–9

Effect of input offset current.

The offset voltage developed by the input offset current is

$$V_{OS} = I_1R_{in} - I_2R_{in} = (I_1 - I_2)R_{in}$$

$$V_{OS} = I_{OS}R_{in}$$

Equation 12–5

The error created by I_{OS} is amplified by the gain A_v of the op-amp and appears in the output as

$$V_{OUT(error)} = A_vI_{OS}R_{in}$$

Equation 12–6

A change in offset current with temperature affects the error voltage. Values of temperature coefficient for the offset current in the range of 0.5 nA per degree Celsius are common.

Output Impedance The *output impedance* is the resistance viewed from the output terminal of the op-amp, as indicated in Figure 12–10.

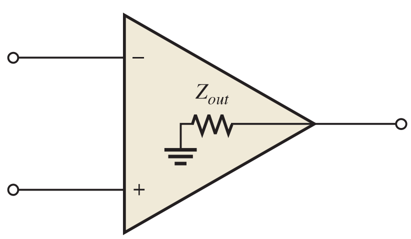


FIGURE 12–10

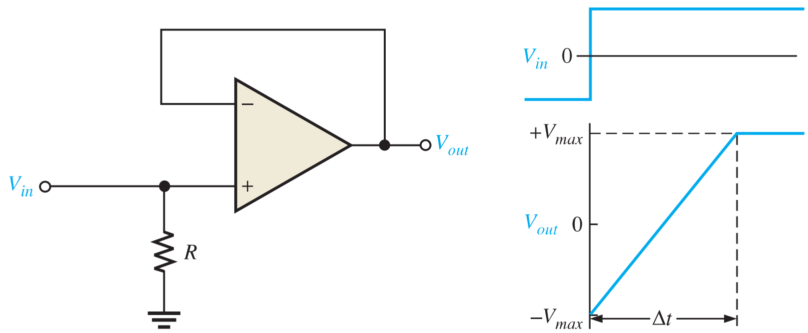
Op-amp output impedance.

Slew Rate The maximum rate of change of the output voltage in response to a step input voltage is the **slew rate** of an op-amp. The slew rate is dependent upon the high-frequency response of the amplifier stages within the op-amp.

Slew rate is measured with an op-amp connected as shown in Figure 12–11(a). This particular op-amp connection is a unity-gain, noninverting configuration that will be discussed in Section 12–4. It gives a worst-case (slowest) slew rate. Recall that the high-frequency components of a voltage step are contained in the rising edge and that the upper critical frequency of an amplifier limits its response to a step input. For a step input, the slope on the output is inversely proportional to the upper critical frequency. Slope increases as upper critical frequency decreases.

▶ FIGURE 12–11

Slew-rate measurement.



(a) Test circuit (b) Step input voltage and the resulting output voltage

A pulse is applied to the input and the resulting ideal output voltage is indicated in Figure 12–11(b). The width of the input pulse must be sufficient to allow the output to "slew" from its lower limit to its upper limit. A certain time interval, Δt, is required for the output voltage to go from its lower limit $-V_{max}$ to its upper limit $+V_{max}$, once the input step is applied. The slew rate is expressed as

Equation 12–7

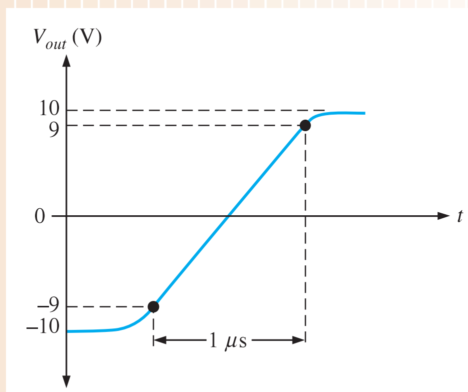
$$\textbf{Slew rate} = \frac{\Delta V_{out}}{\Delta t}$$

where $\Delta V_{out} = +V_{max} - (-V_{max})$. The unit of slew rate is volts per microsecond (V/μs).

EXAMPLE 12–2

The output voltage of a certain op-amp appears as shown in Figure 12–12 in response to a step input. Determine the slew rate.

▶ FIGURE 12–12



Solution The output goes from the lower to the upper limit in 1 μs. Since this response is not ideal, the limits are taken at the 90% points, as indicated. So, the upper limit is +9 V and the lower limit is −9 V. The slew rate is

$$\text{Slew rate} = \frac{\Delta V_{out}}{\Delta t} = \frac{+9\text{ V} - (-9\text{ V})}{1\ \mu\text{s}} = \mathbf{18\ V/\mu s}$$

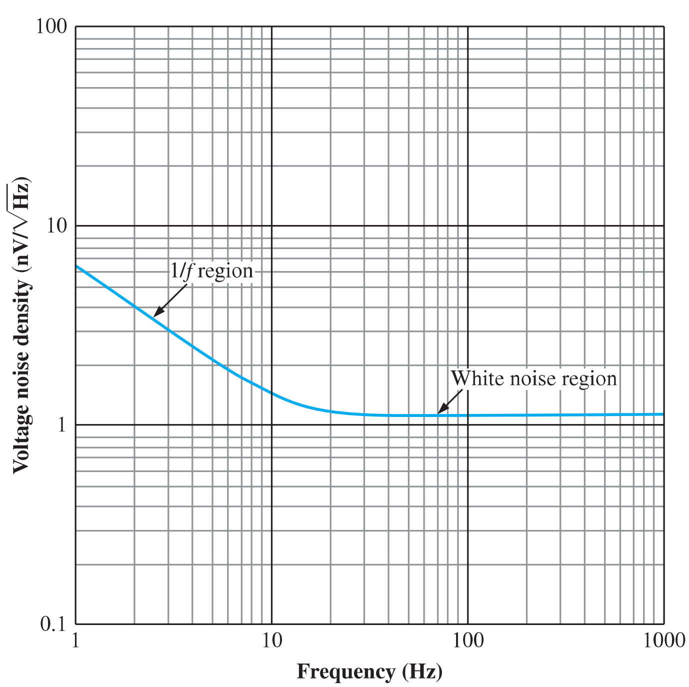
Related Problem When a pulse is applied to an op-amp, the output voltage goes from −8 V to +7 V in 0.75 μs. What is the slew rate?

Frequency Response The internal amplifier stages that make up an op-amp have voltage gains limited by junction capacitances, as discussed in Chapter 10. Although the differential amplifiers used in op-amps are somewhat different from the basic amplifiers discussed earlier, the same principles apply. An op-amp has no internal coupling capacitors, however; therefore, the low-frequency response extends down to dc (0 Hz).

Noise Specification Noise has become a more important issue in new circuit designs because of the requirement to run at lower voltages and with greater accuracy than in the past. As little as two or three microvolts can create errors in analog-to-digital conversion. Many sensors produce only tiny voltages that can be masked by noise. As a result, unwanted noise from op-amps and components can degrade the performance of circuits.

Noise is defined as an unwanted signal that affects the quality of a desired signal. While interference from an external source (such as a nearby power line) qualifies as noise, for the purpose of op-amp specifications, interference is not included. Only noise generated within the op-amp is considered in the noise specification. When the op-amp is added to a circuit, additional noise contributions are added from other circuit elements, such as the feedback resistors or any sensors. For example, all resistors generate thermal noise—even one sitting in the parts bin. The circuit designer must consider all sources within the circuit, but the concern here is the op-amp specification for noise, which only considers the op-amp.

There are two basic forms of noise. At low frequencies, noise is inversely proportional to the frequency; this is called $1/f$ noise or "pink noise". Above a critical noise frequency, the noise becomes flat and is spread out equally across the frequency spectrum; this is called "white noise". The power distribution of noise is measured in watts per hertz (W/Hz). Power is proportional to the square of the voltage, so noise voltage (density) is found by taking the square root of the noise power density, resulting in units of volts per square root hertz ($V/\sqrt{Hz}$). For operational amplifiers, noise level is normally shown with units of $nV/\sqrt{Hz}$ and is specified relative to the input at a specific frequency above the noise critical frequency. For example, a noise level graph for a very low-noise op-amp is shown in Figure 12–13; the specification for this op-amp will indicate that the input voltage noise density at 1 kHz is $1.1\ nV/\sqrt{Hz}$. At low frequencies, the noise level is higher than this due to the $1/f$ noise contribution as you can see from the graph.



◀ **FIGURE 12–13**

Noise as a function of frequency for a typical op-amp.

Comparison of Op-Amp Parameters

Table 12–1 provides a comparison of values showing selected parameters for some representative op-amps. As you can see from the table, there is a wide difference in certain specifications. All designs involve certain compromises, so in order for designers to optimize one parameter, they must often sacrifice another parameter. Choosing an op-amp for a particular application depends on which parameters are important to optimize. Parameters depend on the conditions for which they are measured. For details on any of these specifications, consult the datasheet.

Most available op-amps have three important features: short-circuit protection, no latch-up, and input offset nulling. Short-circuit protection keeps the circuit from being damaged if the output becomes shorted, and the no latch-up feature prevents the op-amp from hanging up in one output state (high or low voltage level) under certain input conditions. Input offset nulling is achieved by an external potentiometer that sets the output voltage at precisely zero with zero input.

▼ TABLE 12–1

OP-AMP	CMRR (dB) (TYP)	OPEN-LOOP GAIN (dB) (TYP)	GAIN-BANDWIDTH PRODUCT (MHz) (TYP)	INPUT OFFSET VOLTAGE (mV) (MAX)	INPUT BIAS CURRENT (nA) (MAX)	SLEW RATE (V/µs) (TYP)	COMMENT
AD8009	50	N/A	320[1]	5	150	5500	Extremely fast, low distortion, uses current feedback
AD8055	82	71		5	1200	1400	Low noise, fast, wide bandwidth, gain flatness 0.1 dB, video driver
ADA4891	68	90[2]		2500	0.002	170	CMOS-extremely low bias current, very fast, useful as video amplifier
ADA4092	85	118	1.3	0.2	50	0.4	Single supply (2.7 V to 36 V) or two supply operation, low power
FAN4931	73	102	4	6	0.005	3	Low cost CMOS, low power, output swings to within 10 mV of rail, extremely high input resistance
FHP3130	95	100	60	1	1800	110	High current output (to 100 mA)
FHP3350	90	55	190	1	50	800	High speed; useful as video amp
LM741C	70	106	1	6	500	0.5	General-purpose, overload protection, industry standard
LM7171	110	90	100	1.5	1000	3600	Very fast, high CMRR, useful as an instrumentation amplifier
LMH6629	87	79	800[3]	0.15	23000	530	Fast, ultra low noise, low voltage
OP177	130	142		0.01	1.5	0.3	Ultra-precision; very high CMRR and stability
OPA369	114	134	0.012	0.25	0.010	0.005	Extremely low power, low voltage, rail-to-rail.
OPA378	100	110	0.9	0.02	0.15	0.4	Precision, very low drift, low noise
OPA847	110	98	3900	0.1	42,000	950	Ultra low-noise, wide bandwidth amplifier, voltage feedback

[1]Depends on gain; gain = 10 is shown
[2]Depends on gain; gain = 2 is shown
[3]Small signal