CHAPTER

15

Basic Analog Electronics: Operational Amplifiers

15.1 GOALS OF THIS CHAPTER

Electronic circuits come in two basic varieties: analog and digital. Digital circuits feature electronic components that produce only two voltage levels, one high and the other low. This limits the signals they can handle to single bits that hold a 0 or 1. To transmit information, single bits are combined into groups; commonly an 8-bit binary number is called a "byte." Bytes can be combined to make larger binary numbers or can be used to encode alphanumeric characters, most often in a coding scheme known as ASCII code. Digital circuits form the basis of all modern computers and microprocessors. Although nearly all the medical instruments contain one or more small computers (i.e., microprocessors) along with related digital circuitry, bioengineers are not usually concerned with their design. They may be called upon to develop some, or all, of the software but not the actual electronics, except perhaps for interface circuits.

Analog circuit elements support a continuous range of voltages, and the information they carry is usually encoded as a time-varying continuous signal similar to those used throughout this text. All of the circuits described thus far have been analog circuits. Analog circuitry is a necessary part of most medical instrumentation because the biomedical sensors (biotransducers) usually produce analog electric signals. This includes devices that measure movement, pressure, bioelectric activity, sound and ultrasound, light, and other forms of electromagnetic energy. Bioelectric signals such as the EEG, ECG, and EMG are also analog signals.

Before analog signals are processed by a digital computer, some type of manipulation is usually required in the analog domain. This analog signal processing may not only consist of increasing the amplitude of the signal, but can also include filtering and other basic signal processing operations. Unlike digital circuitry, the design of analog circuits is often the responsibility of the biomedical engineer. After analog signal processing, the signal is usually converted to a digital signal using an analog-to-digital converter (ADC). The components of a typical biomedical instrument are summarized in Figure 15.1.

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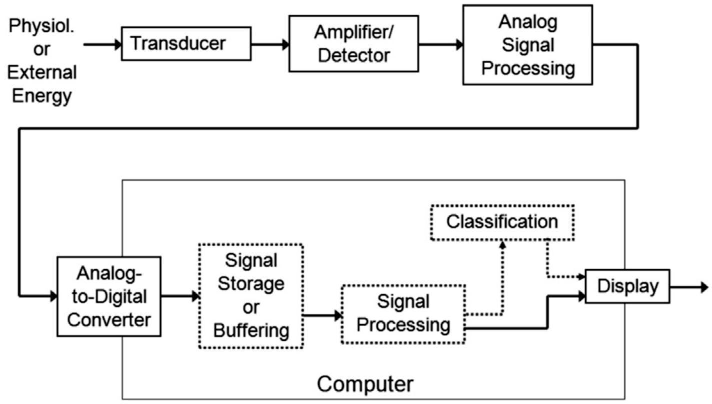


FIGURE 15.1 Basic elements of a typical biomedical instrument.

The goal of this chapter is to give you the basic tools to design commonly used analog circuits. In particular, you should understand when these circuits can be casually designed using an example circuit with standard off-the-shelf components or when special care must be taken to account for limitations in these real-world components.

Specific goals of this chapter include the following:

- Describing the concepts of an ideal amplifier
- Introducing the ideal op amp as a special case of an ideal amplifier
- Deriving the transfer function of inverting and noninverting amplifiers based on practical components known as operational amplifiers (op amps)
- Describing the limitations of practical (real-world) op amp components and determining when these become important in circuit design
- Describing the use of power supplies and potential noise sources
- Presenting and describing the most commonly used op amp circuits

15.2 THE AMPLIFIER

Increasing the amplitude or gain of an analog signal is termed “amplification” and is achieved using an electronic device known as an “amplifier.” The properties of an amplifier are commonly introduced using a simplification called the “ideal amplifier.” In this pedagogical scenario, the properties of a real amplifier are described as deviations from the idealization. In many practical situations, real amplifiers closely approximate the idealization; the limitations of real amplifiers and their deviations from the ideal become important only in more challenging applications. Nevertheless, the biomedical engineer involved in circuit design must know these limitations to understand when a typical amplifier circuit is being challenged.

An ideal amplifier is characterized by three properties:

1. It has a well-defined gain at all frequencies (or at least over a specific range of frequencies),

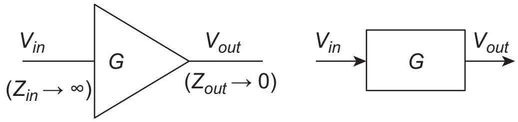


FIGURE 15.2 Schematic (left) and block diagram (right) of an ideal amplifier with a gain of G.

2. Its output is an ideal source ($Z_{out} = 0.0\ \Omega$), and
3. Its input is an ideal load ($Z_{in} \rightarrow \infty\ \Omega$).

An ideal amplifier is simply a pure gain term having ideal input (property 3) and output (property 2) characteristics. These properties make it the real-world embodiment of the systems gain element introduced in Section 6.5.1. The schematic and system representation of an ideal amplifier are shown in Figure 15.2.

The transfer function of this amplifier would be:

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{V_{out}(\omega)}{V_{in}(\omega)} = G \tag{15.1}$$

where G would usually be a constant, or a function of frequency.

Many amplifiers have a differential input configuration, that is, there are two separate inputs and the output is the gain constant times the difference between the two inputs. Stated mathematically:

$$V_{out} = G(V_{in2} - V_{in1}) \tag{15.2}$$

The schematic for such a "differential amplifier" is shown in Figure 15.3. Note that one of the inputs is labeled + and the other −, to indicate how the difference is taken: the minus terminal subtracts its voltage from the plus terminal. (It is common to draw the negative input above the positive input.) The + the terminal is also known as the "noninverting input," whereas the − terminal is also referred to as the "inverting input."

Some transducers, and a few amplifiers, produce a differential signal—actually two signals that move in opposite directions with respect to the information they represent. For such differential signals, a differential amplifier is ideal, since it takes advantage of both input signals. Moreover, the subtraction tends to cancel any signal that is common to both inputs and undesirable noise is often common to both inputs. However, most of the time only a single signal is available. In these cases, a differential amplifier may still be used, but one of the

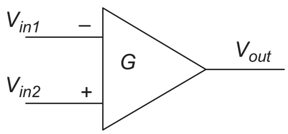


FIGURE 15.3 An amplifier with a "differential input" configuration. The output of this amplifier is G times $V_{in2} - V_{in1}$, i.e., $V_{out} = G(V_{in2} - V_{in1})$.

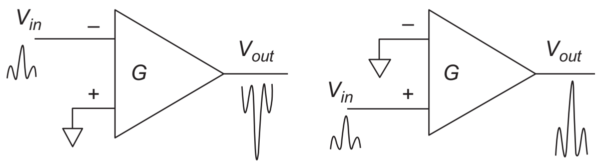


FIGURE 15.4 A differential amplifier configured as an inverting (left) and noninverting (right) amplifier.

inputs is set to zero by grounding. If the positive input is grounded and the signal is sent into the negative input, Figure 15.4 (left side), then the output will be the inverse of the input:

$$V_{out} = G(-V_{in}) \tag{15.3}$$

In this case the amplifier may be called an "inverting amplifier" for obvious reasons. If the opposite strategy is used and the signal is sent to the positive input while the negative input is grounded as in Figure 15.4 (right side), the output will have the same direction as the input. This amplifier is termed a "noninverting amplifier" (sort of a double negative).

15.3 THE OPERATIONAL AMPLIFIER

The "operational amplifier," or "op amp," is a basic building block for a wide variety of analog circuits. One of its first uses was to perform mathematical operations, such as addition and integration, in analog computers, hence the name operational amplifier. Although the functions provided by analog computers are now performed by digital computers, the op amp remains a valuable, perhaps the most valuable, tool in analog circuit design.

In its idealized form, the op amp has the same properties as the ideal amplifier described previously except for one curious departure: it has infinite gain. Thus an ideal op amp has infinite input impedance (ideal load), zero output impedance (an ideal source), and a gain, $A_v \rightarrow \infty$. (The symbols A_v and A_{VOL} are commonly used to represent the gain of an op amp.) Obviously an amplifier with a gain of infinity is of limited value, so an op amp is rarely used alone, but usually in conjunction with other elements that reduce its gain to a finite level.

Negative feedback can be used to limit the gain. Assume that the ideal amplifier is represented as A_V in the feedback system shown in Figure 15.5.

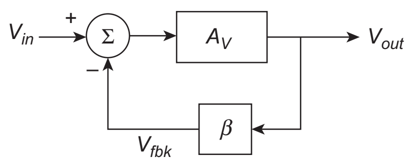


FIGURE 15.5 A basic feedback control system used to illustrate the use of feedback to set a finite gain in a system that has infinite feedforward gain, A_V.

The gain of the system can be found from the basic feedback equation introduced and derived in Example 6.1. When we insert A_V and β into the feedback equation, Equation 6.7, the overall system gain, G, becomes:

$$G = \frac{A_V}{1 + A_V\beta} \tag{15.4}$$

Now if we let the amplifier's gain, A_V, go to infinity:

$$G = \lim_{A_V \to \infty} \left| \frac{A_V}{1 + A_V\beta} = \lim_{A_V \to \infty} \right| \frac{A_V}{A_V\beta} = \frac{1}{\beta} \tag{15.5}$$

The overall gain expressed in decibel becomes:

$$G_{db} = 20 \log G = 20 \log\left(\frac{1}{\beta}\right) = -20 \log \beta \tag{15.6}$$

If $\beta < 1$, then the gain of the feedback system $G = V_{out}/V_{in}$ is >1 and the system increases the signal amplitude. If $\beta = 1$, then $G = 1$ and the amplitude of the output signal is the same as the input signal. This may seem useless, but there are times when such a system is used because we still get the benefits of the ideal input and output properties of the amplifier. We rarely make $\beta > 1$ because then $G < 1$, and the feedback system actually reduces the signal amplitude. If a reduction in gain is desired, it is easier to use a passive voltage divider, a series resistor pair with one resistor to ground. So in real op amp circuits, the feedback gain, β, is ≤ 1 and $G \geq 1$. This is fortunate, as all we need to produce a feedback gain <1 is a voltage divider network: one end of the two connected resistors goes to the output and the other end to ground, and the reduced feedback signal is taken from the intersection of the two resistors, Figure 15.6. A feedback gain of $\beta = 1$ is even easier: just feed the entire output back to the input.

The approach of beginning with an amplifier that has infinite gain then reducing that gain to a finite level with the addition of feedback seems needlessly convoluted. Why not design the amplifier to have a finite fixed gain to begin with? The answer is summarized in two

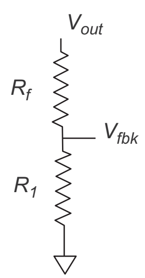


FIGURE 15.6 A voltage divider network that can be used to feed back a portion of the output signal as a negative feedback signal. To make the feedback signal, V_{fbk}, negative, it is fed to the inverting or negative input of an operational amplifier.

words: flexibility and stability. If feedback is used to set the gain of an op amp circuit, then only one basic amplifier needs to be produced: one with an infinite (or just very high) gain. Any desired gain can be achieved by modifying a simple two-resistor network. More importantly, the feedback network is almost always implemented using passive components: resistors and sometimes capacitors. Passive components are always more stable than transistor-based devices, that is, they are more immune to fluctuations owing to changes in temperature, humidity, age, and other environmental factors. Passive elements can also be more easily manufactured to tighter tolerances than active elements. For example, it is easy to buy resistors that have a 1% error in their values, whereas most common transistors vary in gain by a factor of two or more. Finally, back in the flexibility category, a wide variety of different feedback configurations can be used enabling one type of op amp to perform many different signal processing operations. Some of these different functions are explored in the section on op amp circuits at the end of this chapter.

15.4 THE NONINVERTING AMPLIFIER

In the noninverting amplifier, a two-resistor voltage divider feeds a reduced version of the output back to the inverting (i.e., negative) input of an op amp. Consider the voltage divider network in Figure 15.6. The feedback voltage, V_{fbk}, can be found by the simple application of Kirchhoff's voltage law (KVL). Assuming that V_{out} is an ideal source (which it is because it is the output of an ideal amplifier):

$$V_{out} - i(R_f + R_1) = 0; \quad i = \frac{V_{out}}{R_f + R_1}:$$

$$V_{fbk} = iR_1 = V_{out}\left(\frac{R_1}{R_1 + R_f}\right) \tag{15.7}$$

For the system diagram in Figure 15.5, we see that $\beta = V_{fbk}/V_{out}$. Using Equation 15.7 we can solve for β in terms of the voltage divider network:

$$\beta = \frac{V_{fbk}}{V_{out}} = \frac{R_1}{R_1 + R_f} \tag{15.8}$$

The transfer function of an op amp circuit that uses feedback to set the gain is just $1/\beta$ as given in Equation 15.5:

$$G \equiv \frac{V_{out}}{V_{in}} = \frac{1}{\beta} = \frac{1}{\dfrac{R_1}{R_1 + R_f}} = \frac{R_1 + R_f}{R_1} \tag{15.9}$$

An op amp circuit using this feedback network is shown in Figure 15.7. The gain of this amplifier is given by Equation 15.9. Since the input signal is fed to the positive side of the op amp, this circuit is termed a "noninverting amplifier."

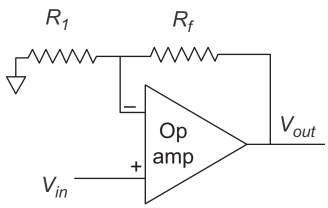


FIGURE 15.7 Noninverting operational amplifier (op amp) circuit. The gain of this op amp in terms of the feedback resistors is given by Equation 15.9.

The transfer function for the circuit in Figure 15.7 can also be found through circuit analysis, but a couple of helpful rules are needed.

1. Since the input resistance of the op amp approaches infinity, there is no current flowing into, or out of, either of the op amp's input terminals. Realistically, the input resistance of an op amp is so high that any current that does flow into the op amp's input is negligible.
2. Since the gain of the op amp approaches infinity, the only way the output can be finite is if the input is zero, that is, the difference between the plus input and the minus input must be zero. Stated yet another way, the voltage on the plus input terminal must be the same as the voltage on the minus input terminal of the op amp and vice versa. Realistically, the very high gain means that for reasonable output voltages, the voltage difference between the two input terminals is very small and can be ignored.

In practical op amps, the gain is large (up to 10^6) but not infinite, so the voltage difference in a practical op amp circuit might be a few millivolts. This small difference can generally be ignored. Similarly, the input resistance, although not infinite, is quite large: values of r_{in} (resistances internal to the op amp are denoted in lower case) are usually greater than $10^{12}\ \Omega$, so any input current will be very small and can be disregarded (especially since the input voltage must be zero or at least very small by Rule 2). We use these two rules to solve the transfer function of a noninverting amplifier in the following example.

EXAMPLE 15.1

Find the transfer function of the noninverting op amp circuit in Figure 15.7 using network analysis.

Solution: First, by Rule 2, the voltage between the two resistors, the voltage at the negative terminal, must equal V_{in} since V_{in} is applied to the lower terminal and the voltage difference between the upper and lower terminals is zero.

Define the three currents in and out of the node between the two resistors and apply Kirchhoff's current law (KCL) to that node as shown in Figure 15.8. Applying KCL:

By KCL: $-i_1 - i_{in} + i_f = 0$, but $i_{in} = 0$ according to Rule 1.

Hence if: $-i_1 - 0 + i_f = 0$, then $i_1 = i_f$

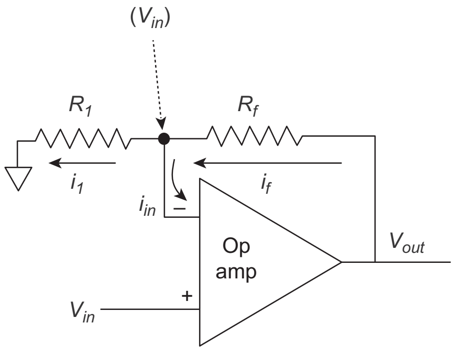


FIGURE 15.8 A noninverting operational amplifier circuit.

Applying Ohm's law to substitute the voltages for the currents and noting that the voltage at the node must equal V_{in} by Rule 2:

$$i_1 = \frac{V_{in}}{R_1} \text{ and } i_f = \frac{V_{out} - V_{in}}{R_f}$$

$$\text{Then since } i_1 = i_f\text{: } \frac{V_{in}}{R_1} = \frac{V_{out} - V_{in}}{R_f}$$

Solving for V_{out}:

$$V_{out} - V_{in} = V_{in}\left(\frac{R_f}{R_1}\right); \quad V_{out} = V_{in}\left(1 + \frac{R_f}{R_1}\right) = V_{in}\left(\frac{R_f + R_1}{R_1}\right)$$

and the transfer function becomes:

$$\frac{V_{out}}{V_{in}} = \frac{R_f + R_1}{R_1}$$

This is the same transfer function found using the feedback equation, Equation 15.9.

15.5 THE INVERTING AMPLIFIER

To construct an amplifier circuit that inverts the input signal, the ground and signal inputs of the noninverting amplifier are reversed as shown in Figure 15.9.

The transfer function of the inverting amplifier circuit is a little different from that of the noninverting amplifier, but can easily be found using the same approach (and tricks) used in Example 15.1.

EXAMPLE 15.2

Find the transfer function, or gain, of the inverting amplifier circuit shown in Figure 15.9.

Solution: Define the currents and apply KCL to the node between the two resistors, Figure 15.10. In this circuit the node between the two resistors must be at 0 volts by Rule 2, i.e., because the plus

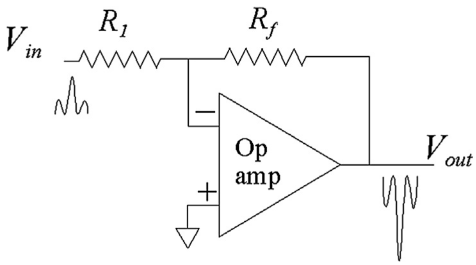


FIGURE 15.9 The operational amplifier circuit used to construct an inverting amplifier.

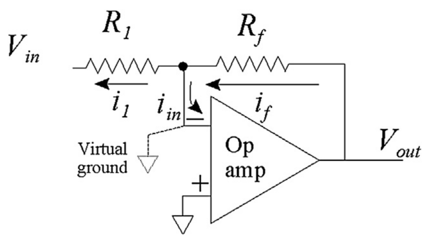


FIGURE 15.10 Inverting operational amplifier configuration showing currents assigned to the upper node. The upper node in this configuration must be at 0 volts by Rule 2 and is referred to as virtual ground.

side is grounded and the difference between the two terminals is 0, the minus side is effectively grounded. In fact, the inverting input terminal in this configuration is sometimes referred to as a "virtual ground," Figure 15.10.

As in Example 15.1, we apply KCL to the inverting terminal and find that $i_1 = i_f$ and by Ohm's law:

$$i_1 = \frac{0 - V_{in}}{R_1}; \quad i_f = \frac{V_{out} - 0}{R_f}; \quad \frac{-V_{in}}{R_1} = \frac{V_{out}}{R_f}$$

Again solving for V_{out}/V_{in}:

$$\frac{V_{out}}{V_{in}} = -\frac{R_f}{R_1} \tag{15.10}$$

The negative sign demonstrates that this is an inverting amplifier: the output is the negative, or inverse, of the input. The output is also larger than the input by a factor of R_f/R_1.

Equations 15.9 and 15.10 show that the gain of inverting and noninverting op amp circuits depend only on R_1 and R_f. The circuit designer can control the gain of these circuits simply by adjusting their values. If one of the resistors is variable (i.e., a potentiometer), then the amplifier would have a variable gain. The next example involves the design of a variable gain inverting amplifier.

EXAMPLE 15.3

Design an inverting amplifier circuit with a variable gain between 10 and 100. Assume you have a variable 1-MΩ potentiometer, that is, a resistor that can be varied between 0 and 1 MΩ. Also assume you have available a wide range of fixed resistors.

Solution: The amplifier circuit will have the general configuration of Figure 15.9. It is possible to put the variable resistance as part of either R_{in} or R_f, but let us assume that the potentiometer is part of R_f along with a fixed series resistance. This results in the circuit shown in Figure 15.11.

We vary feedback resistance, R_f, to get the desired gain variation. Assume that the variable resistor will be 0 Ω when the gain is 10 and 1 MΩ when the gain is 100. We can write two gain equations based on Equation 15.10 then solve for our two unknowns, R_1 and R_2.

For $G = 10$ the variable resistor is 0 Ω: $\frac{R_f}{R_1} = 10; \quad \frac{R_2+0}{R_1} = 10; \quad R_2 = 10R_1$

For $G = 100$ the variable resistor is 10^6 Ω:

$$\frac{R_2 + 10^6}{R_1} = 100; \quad \text{Substituting for } R_2; \quad 10R_1 + 10^6 = 100R_1$$

$$90R_1 = 10^6; \quad R_1 = 11.1 \text{ k}\Omega \quad R_2 = 111 \text{ k}\Omega \text{ and}$$

The final circuit is shown in Figure 15.12.

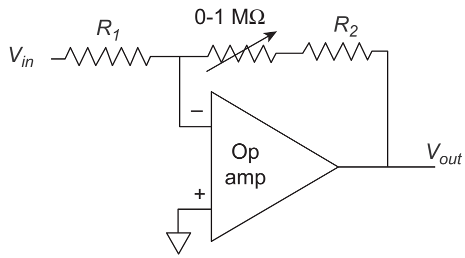


FIGURE 15.11 An inverting operational amplifier circuit with a variable resistor in the feedback path to allow for variable gain. In Example 15.3, the variable and fixed resistors are adjusted to provide an amplifier gain from 10 to 100.

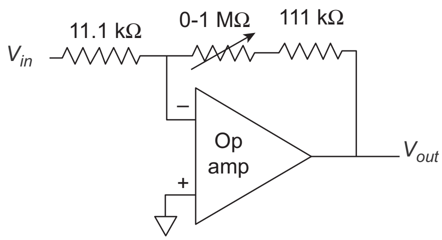


FIGURE 15.12 An inverting amplifier circuit with a gain between 10 and 100. In a real application the two fixed resistors would be rounded to 10 and 100 kΩ unless extreme precision was required.

The equation for the gain of noninverting and inverting op amp circuits can be extended to include feedback networks that contain capacitors and inductors. To modify these equations to include components other than resistors, simply substitute impedances for resistors. So the gain equation for a noninverting op amp circuit becomes:

$$\frac{V_{out}}{V_{in}} = \frac{Z_f + Z_1}{R_1} \tag{15.11}$$

and the equation for an inverting op amp circuit becomes:

$$\frac{V_{out}}{V_{in}} = -\frac{Z_f}{Z_1} \tag{15.12}$$

15.6 PRACTICAL OP AMPS

Practical op amps, the kind that you buy from electronics supply houses, differ in a number of ways from the idealizations used earlier. In many applications, perhaps most applications, the limitations inherent in real devices can be ignored. The problem is that any bioengineer who designs analog circuitry must know when the limitations are important and when they are not, and to do this he or she must understand the characteristics of real devices. Only the topics that involve the type of circuits the bioengineer is likely to encounter are covered here. Several excellent references can be found to extend these concepts to other circuits (Horowitz and Hill, 1989).

Deviations of real op amps from the ideal can be classified into three general areas: deviations in input characteristics, deviations in output characteristics, and deviations in transfer characteristics. Each of these areas is discussed in turn, beginning with the area likely to be of utmost concern to biomedical engineers: transfer characteristics.

15.6.1 Limitations in Transfer Characteristics of Real Operational Amplifiers

The most important limitations in the transfer characteristics of real op amps are bandwidth limitations and stability. In addition, real op amps have a large, but not infinite, gain. Bandwidth limitations occur because an op amp's magnitude gain is not only finite, but decreases with increasing frequency. The lack of stability results in unwanted oscillations and is due to the op amp's increased phase shifts with increasing frequency. Eventually these phase shifts can become so large that negative feedback turns into positive feedback and the circuit oscillates.

15.6.1.1 Bandwidth

The magnitude frequency characteristics of a popular op amp, the LF 356, are shown in Figure 15.13. Not surprisingly, even at low frequencies the gain of this op amp is less than infinity. This in itself would not be a cause for much concern as the gain is still quite high: approximately 106 dB or 199,530. The problem is that this gain is also a function of frequency

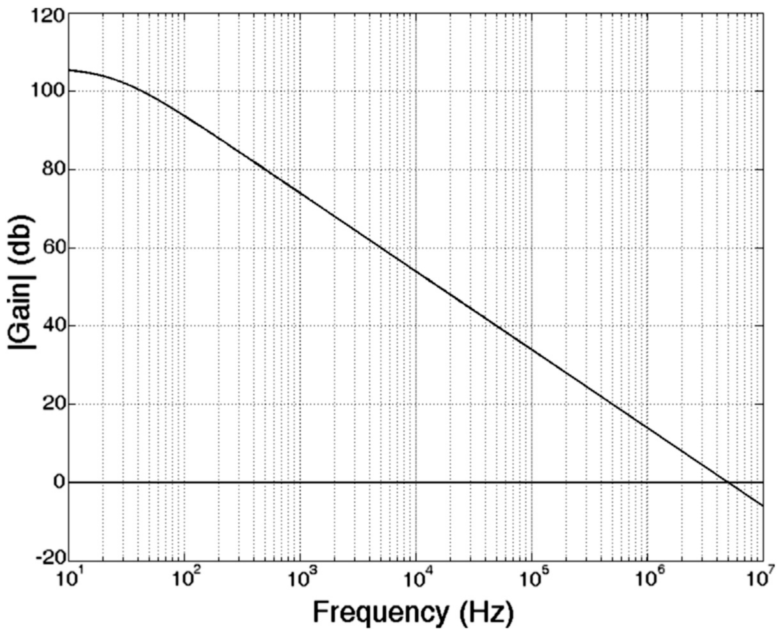


FIGURE 15.13 The open-loop magnitude gain characteristics of a popular operational amplifier, the LF 356.

so that at higher frequencies the gain becomes quite small. In fact, there is a frequency above which the gain is less than one. Thus at higher frequencies the transfer function equations no longer hold since they were based on the assumption that op amp gain is infinite. Since the bandwidth of a real op amp is limited, the bandwidth of an amplifier using such an op amp must also be limited. Essentially, the gain of an op amp circuit is limited by either the bandwidth limitations of the op amp or the feedback, whichever is lower.

An easy technique for determining the bandwidth of an op amp circuit is to plot the gain produced by the feedback circuit superimposed on the bandwidth curve of the real op amp. The former is referred to as the "closed-loop gain" since it includes the feedback, whereas the latter is termed the "open-loop gain" since it is the gain of the op amp without a feedback loop. The gain produced by the feedback network is, theoretically, $1/\beta$, Equation 15.5. The real transfer function gain is either this value or the op amp's open-loop gain, whichever is lower. (The gain in an op amp circuit can never be greater than what the op amp is capable of producing.) So to get the real gain, we plot $1/\beta$ superimposed on the open-loop curve. The real gain is simply the lower of the two curves. If the feedback network consists only of resistors, β will be constant for all frequencies, so $1/\beta$ will plot as a straight line on the frequency curve. (Although real resistors have some small inductance and capacitance, the effect of these "parasitic elements" can be ignored except at very high frequencies.)

For example, assume that 1/100 of the signal is fed back to the inverting terminal of a real op amp. Then the feedback gain is:

$$\beta = 0.01 = -40 \text{ dB} \text{ and } 1/\beta = 100 = 40 \text{ dB}$$

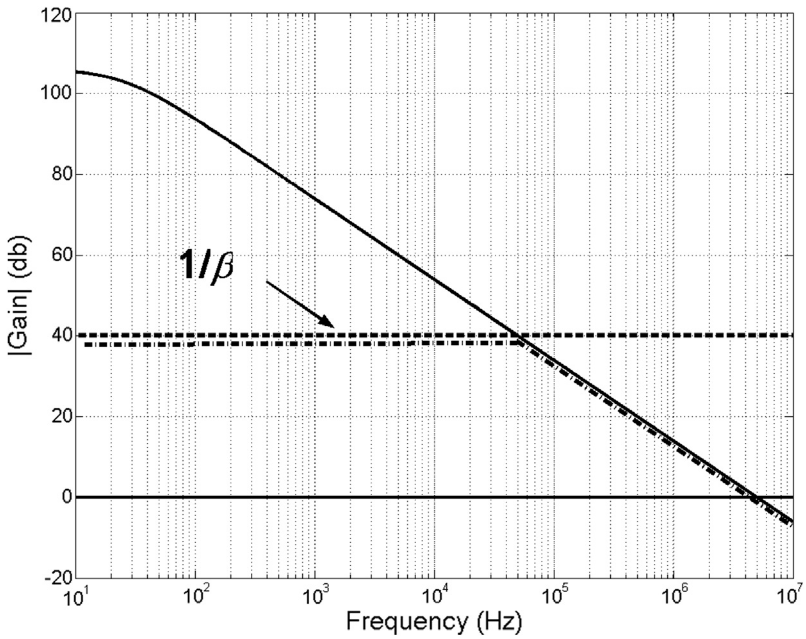


FIGURE 15.14 The open-loop magnitude spectrum of the LF 356 operational amplifier (*solid line*) with the frequency characteristics of $1/\beta$ (*dashed line* at 40 dB) superimposed. Since the feedback network contains only resistors, its spectrum is a constant at all frequencies. The gain of the amplifier circuit follows whichever curve is lower and is indicated by the heavy dashed line. The point occurs where the solid and dashed line intersect and indicates a bandwidth of approximately 50 kHz.

Figure 15.14 shows the open-loop gain characteristics of a typical op amp (LF 356) with the plot of $1/\beta$ superimposed (dashed line). The overall gain will follow the dashed line until it intersects the op amp's open-loop curve (solid line), where it will follow that curve (solid line) since this is less. The circuit's magnitude frequency characteristic will follow the heavy dash-dot lines seen in Figure 15.14. Given this particular op amp and this value of β, the bandwidth of the circuit, the intersection between the two curves, occurs at approximately 50 kHz. The intersection is taken as defining the bandwidth of the circuit, although the -3 dB point is at a slightly higher frequency. The feedback gain, β, is the same for both inverting and noninverting op amp circuits, so this approach for determining the amplifier bandwidth is the same in both configurations. The value $1/\beta$ is sometimes referred to as the "noise gain" because it is also the gain factor for input noise and errors, again irrespective of the specific configuration.

EXAMPLE 15.4

Find the bandwidth of the inverting amplifier circuit in Figure 15.15.

Solution: First determine the feedback gain, β, then plot the inverse ($1/\beta$) superimposed on the open-loop gain curve obtained from the op amp's specification sheets.

$$\frac{1}{\beta} = \frac{R_f + R_{in}}{R_{in}} = \frac{20+1}{1} \approx 20 = 26 \text{ dB}$$

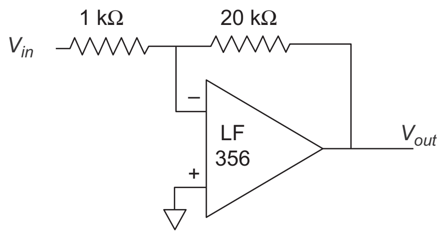


FIGURE 15.15 An inverting amplifier circuit. The bandwidth of this circuit is found in Example 15.4.

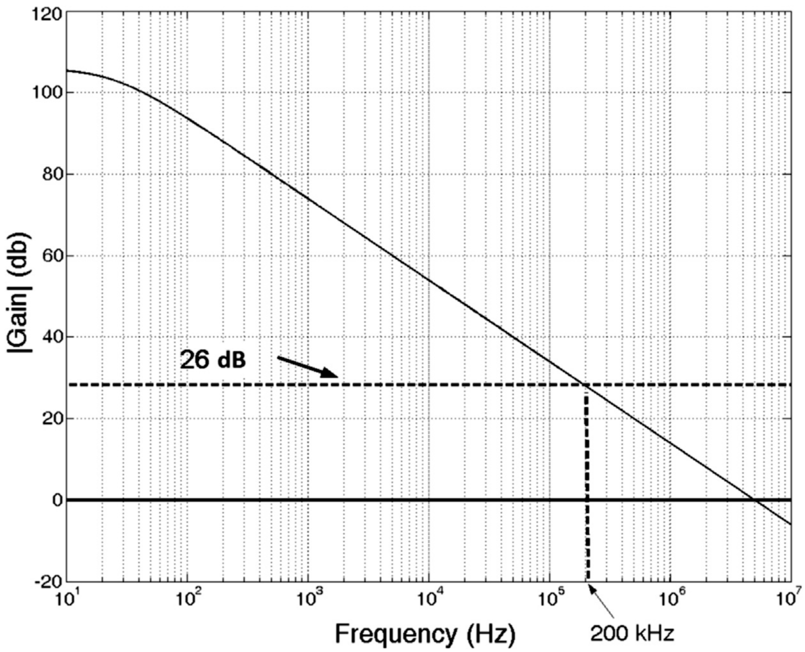


FIGURE 15.16 The open-loop gain curve of the LF356 with the $1/\beta$ line superimposed. This line intersects the operational amplifier's open-loop gain curve at around 200 kHz. This intersection defines the bandwidth of the amplifier circuit.

From the plot in Figure 15.16, showing the $1/\beta$ spectrum superimposed in the LF 356 open-loop spectrum, we see that the two curves intersect at approximately 200 kHz. Above 200 kHz the circuit gain drops off at 20 dB per decade. The intersection is used to define the circuit bandwidth, although the actual -3 dB point will be at a slightly higher frequency.

As shown in the open-loop gain curve of Figures 15.13, 15.14, and 15.16, a typical op amp not only has very high values of gain at low frequencies, but also a low cutoff frequency. Above this cutoff frequency, the gain curve rolls off at 20 dB/decade, the same as a first-order low-pass filter. Specifically, LF 356 has a low-frequency gain of around 106 dB but the open-loop bandwidth is only around 25 Hz. The addition of feedback dramatically lowers the overall gain, but just as dramatically increases the bandwidth. Indeed, the idea of using negative feedback in amplifier circuits was first introduced to improve bandwidth by trading reduced gain for increased bandwidth.

If the feedback gain is a multiple of 10, as is often the case, the bandwidth can be determined without actually plotting the two curves. The bandwidth can be determined directly from the amplifier gain and the frequency at which the open-loop curve intersects 0 dB. This frequency, where the op amp open-loop gain falls to 1.0 (i.e., 0 dB), is termed the "gain bandwidth product" (GBP). The GBP is given in the op amp specifications; for example, the GBP of the LF 356 is 5.0 MHz. To use the GBP to find the bandwidth of a feedback amplifier, start with the GBP frequency and knock off one decade in the bandwidth for every 20 dB in amplifier gain. Essentially you are sliding up the 20 dB/decade slope starting at 0 dB, the GBP. For example, if the amplifier has a gain of 1 (0 dB), the bandwidth equals the GBP, 5 MHz in the case of the LF356. For every 20 dB (or a factor of 10) above 0, the bandwidth is reduced by one decade. So an amplifier circuit with a gain of 10 (20 dB) would have a bandwidth of 500 kHz and an amplifier circuit with a gain of 100 (40 dB) would have a bandwidth of 50 kHz, assuming these circuits used the LF356. If the gain is 1000 (60 dB), the bandwidth would be reduced to 5 kHz. If the $1/\beta$ gain is not a power of 10, logarithmic interpolation would be required and it is easiest to use the plotting technique.

EXAMPLE 15.5

Using an LF 356, what is the maximum amplifier gain (i.e., closed-loop gain) that can be obtained with a bandwidth of 100 kHz.

Solution: From the open-loop curve given in Figure 15.13, the open-loop gain at 100 kHz is approximately 30 dB. This is the maximum close-loop gain that will reach the desired cutoff frequency. Designing the appropriate feedback network to attain this gain (and bandwidth) is straightforward using Equation 15.9 (noninverting) or Equation 15.10 (inverting).

15.6.1.2 Stability

Most op amp circuits use negative feedback: the feedback voltage, V_{fbk}, is fed to the inverting input of the op amp. Except in special situations, positive feedback is to be avoided. Positive feedback creates a vicious circle: the feedback signal enhances the feedforward signal, which enhances the feedback signal, which enhances the feedforward signal, and so on. A number of things can happen to a positive feedback network, most of them bad. The two most likely outcomes are that the output oscillates, sometimes between the maximum and minimum values the op amp can produce, or the output is driven into saturation and locked at the maximum or minimum level. When the word "stability" is used in context with an op amp circuit it means the absence of oscillation or other deleterious effects associated with positive feedback. The oscillation produced by positive feedback is a sustained repetitive waveform, which could be a sinusoid, but it may also be more complicated.

Positive feedback oscillation occurs in a feedback circuit where the overall gain or "loop-gain" (i.e., the gain of the feedback and feedforward circuits) is greater than or equal to 1.0 and has a phase shift of 360 degrees:

$$\text{Loop gain(for oscillation)} \equiv \text{Feedforward Gain} \times \text{Feedback Gain} \;\; \exists \;\; 1.0\pi 360 \;\; \text{degrees} \tag{15.13}$$

When this condition occurs, any small signal feeds back positively and grows to produce a sustained oscillation. Sometimes this amp oscillation will ride on top of the signal, sometimes it will overwhelm the signal, but in either case it is unacceptable.

Since the feedback signal is sent to the inverting input of the op amp, positive feedback should not occur.[1] But what if the op amp induces an additional phase shift of 180 degrees? Then the negative feedback becomes positive feedback since the total phase shift is 360 degrees. If the loop gain happens to be > 1 when this occurs, the conditions of Equation 15.13 are met and the circuit will oscillate. The base frequency of that oscillation will be equal to the frequency where the total phase shift becomes 360 degrees, that is, the frequency where the op amp contributes a phase shift of an additional 180 degrees. Hence, oscillation is a result of phase shifts induced by the op amp's phase characteristics at high frequencies.

A rigorous analysis of stability is beyond the scope of this text. However, since stability is so often a problem in op amp circuits, some discussion is warranted. Since the inverting input always contributes a180-degree phase shift (to make the feedback negative), to ensure stability we must make sure that everything else in the feedback loop contributes a phase shift that is less than 180 degrees, at least as long as the loop gain ≥ 1. If β is a constant, then any additional phase shift must come from the op amp, so all we need are op amps that never approach a phase shift of 180 degrees, at least for loop gains ≥ 1.0. Unfortunately, all op amps reach a phase shift of 180 degrees if we go high enough in frequency, so the only working strategy is to ensure that when the op amp reaches a phase shift of 180, the overall loop gain is <1.0.

The overall loop gain is just $A_V(\omega)\ \beta\ (\omega)$. Putting the condition for stability in terms of the gain symbols we have used thus far, the condition for stability is:

$$\text{Loop gain}_{\text{stability}} = A_V(\omega)\beta(\omega) < 1.0\angle 360 \text{ degrees.} \tag{15.14}$$

where A_V is the gain of the op amp at a specific frequency and β is the feedback gain. Alternatively, if we want to build an oscillator, the condition for oscillation would be as follows:

$$\text{Loop gain}_{\text{oscillation}} = A_V(\omega)\beta(\omega) \geq 1.0\angle 360 \text{ degrees.} \tag{15.15}$$

With respect to β, Equation 15.14 shows that the worst case for stability occurs when β is large. In most op amp circuits β is <1, but can sometimes be as large as 1. As mentioned, a feedback gain of $\beta = 1$ corresponds to the lowest op amp gain: a gain of 1 ($V_{out} = V_{in}$). Although it is somewhat counterintuitive, this means that stability is more likely to be a problem in low-gain amplifier circuits where β is large and most likely to be a problem when the gain is 1.0 since $\beta = 1$ in this case.

If the op amp gain, A_V, is less than 1.0 when its phase shift hits 180 degrees, and β is at most 1.0, then $Av\beta$ will be <1, and the conditions for stability are met (Equation 15.14). Stated in terms of phase, the op amp's phase shift should be less than 180 degrees for all frequencies where its gain is > 1. In fact, most op amps have a maximum phase shift that is less than

[1]At any given frequency, a sinusoid shifted by 180 degrees is the inverse of an upshifted sinusoid: $\sin x = -\sin(x \pm 180)$. So the inverting input induces a phase shift of 180 degrees at all frequencies and the feedback signal is inverted, i.e., negative.

120 degrees to be on the safe side for gains ≥ 1.0. Such op amps are said to be "unity gain stable" because they will not oscillate even when $\beta = 1$ where the amplifier has unity gain. However, achieving this criterion requires some compromise on the part of the op amp manufacture, usually some form of phase compensation that reduces the GBP. In many op amp applications where the gain will be high and β correspondingly low, unity gain stability is overkill and the unity gain compensation results in a needless reduction of high frequency performance.

Op amp manufacturers have come up with two strategies to overcome the performance loss due to unity gain stability: (1) produce different versions of the same basic op amp, one that has a higher bandwidth but requires a minimum gain and another that is unity gain stable but with a lower bandwidth or (2) produce a single version but have the user supply the compensation (usually as an external capacitor) to suit the application requirements. The former has become more popular since it does not require additional circuit components. The LF 356 is an example of the former strategy. The LF 356 has a GBP of 5 MHz and is unity gain stable, whereas its "sister" chip, the LF 357, requires a $1/\beta$ gain of 5 or more, but has a GBP of 20 MHz.

Unfortunately, using an op amp with unity gain stability still does not guarantee a stable circuit. Stability problems can occur if the feedback network introduces a phase shift. A feedback network containing only resistors might be considered safe, but parasitic elements, small inductances, and capacitances can create an undesirable phase shift. Consider the feedback circuit in Figure 15.17 in which a capacitor is placed in parallel with one of the resistors. With a capacitor in the feedback network, β becomes a function of frequency and will introduce an additional phase shift in the loop. Will this additional capacitance present a problem with regard to stability?

To answer this question, we need to find the phase shift of the network at the frequency when the loop gain is 1.0. The loop gain will be 1.0 when:

$$A_V\beta = 1; \quad A_V = \frac{1}{\beta} \tag{15.16}$$

Hence the loop gain is 1 when $1/\beta$ equals the op amp gain A_V. On the plot of A_V and $1/\beta$ such as in Figure 15.16, this is when the two curves intersect. In the circuit presented in

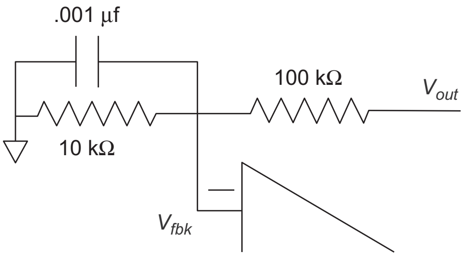


FIGURE 15.17 A feedback network that includes some capacitance either because of the intentional addition of a capacitor or because of parasitic elements. This feedback network will introduce an additional phase shift into the loop. This shift could be beneficial if it moves the overall loop phase shift away from 360 degrees or harmful if it moves it closer to 360 degrees.

Figure 15.17, the $1/\beta$ curve will not be a straight line, but can easily be found using the phasor circuit techniques.

For the voltage divider:

$$V_{fbk} = \frac{Z_1}{Z_1 + Z_f} V_{out}; \quad \text{Solving for } \beta: \ \frac{V_{fbk}}{V_{out}} = \beta = \frac{Z_1}{Z_1 + Z_f}$$

$$\text{where: } Z_1 = \frac{R_1\left(\frac{1}{j\omega C}\right)}{R_1 + \left(\frac{1}{j\omega C}\right)} = \frac{10^4\left(\frac{10^9}{j\omega}\right)}{10^4 + \left(\frac{10^9}{j\omega}\right)} = \frac{10^4}{1 + \frac{j\omega}{10^5}}$$

$$Z_f = 10^5 \Omega$$

Substituting in Z_1 and Z_f and solving for β:

$$\beta = \frac{\frac{10^4}{1 + \frac{j\omega}{10^5}}}{10^5 + \frac{10^4}{1 + \frac{j\omega}{10^5}}} = \frac{10^4}{10^5 + j\omega + 10^4} = \frac{.09}{1 + \frac{j\omega}{1.1 \times 10^5}} \tag{15.17}$$

This is just a low-pass filter with a cutoff frequency of 1.1×10^5 rad/s or 17.5 kHz. Figure 15.18 shows the magnitude frequency plot of β plotted from Equation 15.17 using standard Bode plot techniques.

Figure 15.19 shows the $1/\beta$ curve, the inverse of the curve in Figure 15.18, plotted superimposed on the open-loop gain curve of the LF 356. From Figure 15.19, the two curves intersect at around 85 kHz.

The phase shift contributed by the feedback network at 85 kHz can readily be determined from Equation 15.17. At 85 kHz, $\omega_1 = 2\pi\ (85 \times 10^3) = 5.34 \times 10^5$.

$$\beta = \frac{.09}{1 + \frac{j\omega}{1.1 \times 10^5}} = \frac{.09}{1 + \frac{j2\pi 85 \times 10^3}{1.1 \times 10^5}} = \frac{.09}{4.96\angle 78} = 0.018\angle -78$$

Thus the feedback network contributes a 78-degree phase shift to the overall loop gain. Although the phase shift of the op amp at 85 kHz is not known (detailed phase information is not often provided in op amp specifications), we can only be confident that the phase shift is no more than 120 degrees. Adding the worst case op amp phase shift to the feedback network phase shift (120 + 78) results in a total phase shift that is >180 degrees, so coupled with the 180 degrees from the negative feedback this circuit is likely to oscillate. A good rule of thumb is that the circuit will be unstable if the $1/\beta$ curve breaks upward before intersecting the A_V line of the op amp. The reverse is also true: the circuit will be stable if the $1/\beta$ line intersects the A_V line at a point where it is flat or going downward.

If a feedback network can make the op amp circuit unstable, it stands to reason that it can also make it less unstable. This occurs when capacitance is added in parallel to the feedback

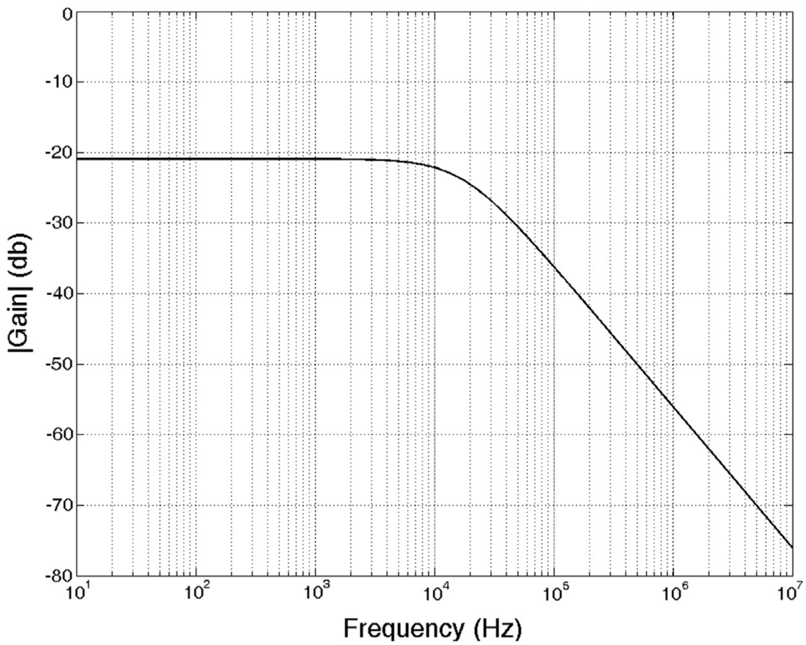


FIGURE 15.18 The magnitude frequency plot of the feedback gain, β, of the network shown in Figure 15.17. The equation for this curve (Equation 15.17) is found using standard phasor circuit analysis and plotted using Bode plot techniques.

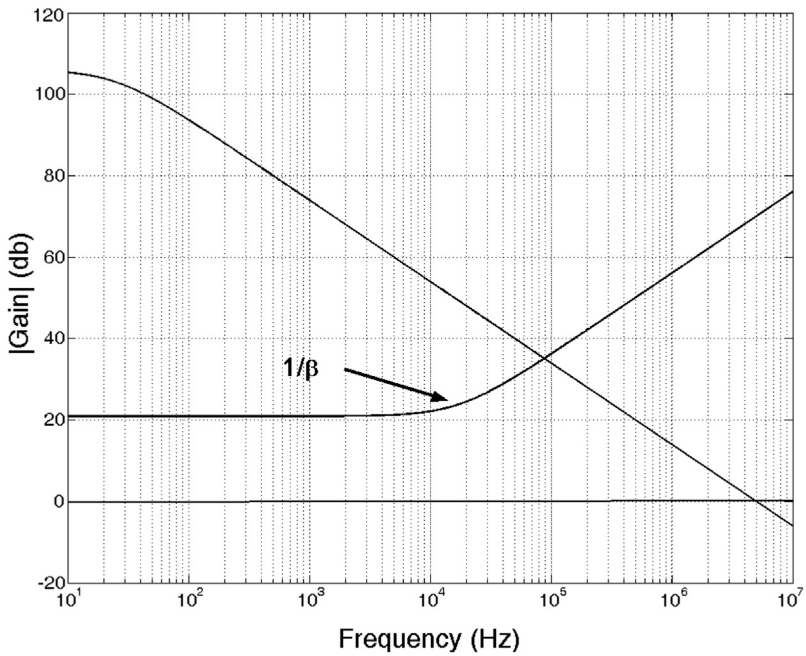


FIGURE 15.19 The inverse of the feedback gain given by Equation 15.17 (i.e., $1/\beta$) plotted superimposed against the A_V (i.e., open-loop) curve of the LF 356 operational amplifier.

resistor, the 100-kΩ resistor in Figure 15.17. In fact, the quick fix approach to oscillations in many op amp circuits is to add a capacitor to the feedback network in parallel with the feedback resistor. This usually works, although the capacitor might have to be fairly large. As shown in the section on filters, adding feedback capacitance reduces bandwidth: the larger the capacitance the greater the reduction in bandwidth. Sometimes a reduction in bandwidth is desired to reduce noise, but often it is disadvantageous. The influence of feedback capacitance on bandwidth is explored in the section on filters, whereas its influence on stability is demonstrated in a problem.

Stability problems are all too frequent and when they occur can be difficult and frustrating to correct. Possible problems include the feedback network, excessive capacitive load (which modifies the op amp's phase shift characteristics), use of an inappropriate op amp, and, most commonly, inadequate decoupling capacitors. The use of decoupling capacitors is discussed in Section 15.7.

15.6.2 Input Characteristics

The input characteristics of a real op amp can best be described as involved but not complicated. In addition to a large, but finite, input resistance, r_{in}, several voltage and current sources are found, Figure 15.20. The values of these elements are given for the LF 356 in parentheses.[2] The values assume the op amp is open loop; feedback may improve some values, so the values presented here can be taken as worst case. These sources have very small values and can often be ignored, but again it is important for the bioengineer to understand the importance of these elements to make intelligent decisions.

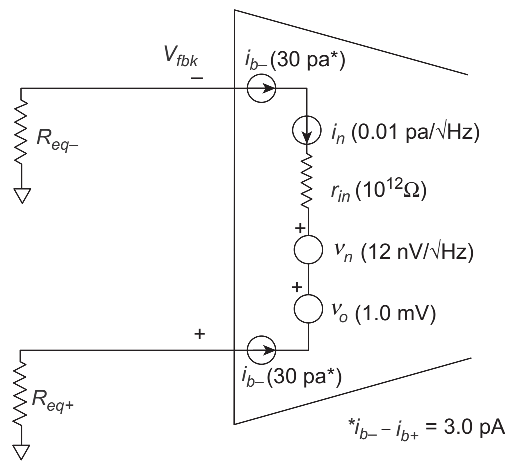


FIGURE 15.20 A schematic representation of the input elements of a practical operational amplifier. The input can be thought of as containing several voltage and current sources as well as a large input impedance. Each of these sources is discussed in the following sections.

[2]The curious units for the voltage and current noise sources, V/√Hz and pA/√Hz were introduced in the discussion of Johnson noise in Section 1.3.2.1.1 and are covered again later.

15.5.2.1 *Input Voltage Sources*

The voltage source, v_o, is a constant voltage source termed the "input offset voltage." It indicates that the op amp will have a nonzero output even if the input is zero, that is, even if $V_{in+} - V_{in-} = 0$. The output voltage produced by this small voltage source depends on the gain of the circuit. To find the output voltage under zero input conditions (the output offset voltage) simply multiply the input offset voltage by the $1/\beta$ gain. Again, this gain is the "noise gain" as explained later. Determination of the output offset voltage is demonstrated in the following example.

EXAMPLE 15.6

Find the offset voltage at the output of the amplifier circuit shown in Figure 15.21. In other words, determine the output, V_{out}, when $V_{in} = 0$.

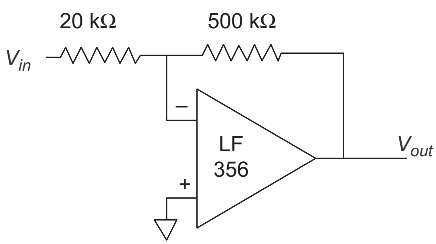


FIGURE 15.21 A typical inverting amplifier circuit. This amplifier will have a small output voltage even if $V_{in} = 0$. This offset voltage is determined in Example 15.6.

Solution: First find the noise gain, $1/\beta$, then multiply this by the input offset voltage, v_o, found in the LF 356 specifications sheet as 1.0 mV (see Appendix F). The value of $1/\beta$ is:

$$\frac{1}{\beta} = \frac{R_f + R_1}{R_1} = \frac{500 + 20}{20} = 26$$

Result: Given the typical value of v_o as 1.0 mV, V_{out} for zero input becomes:

$$V_{out} = v_o(26) = 1.0(26) = 26 \text{ mV}$$

The input offset voltage given in the specifications is a typical value, not necessarily the value of any individual op amp chip. This means that the input offset voltage will be around the value shown, but for any given chip it could be larger or smaller. It could also be either positive or negative, leading to a positive or negative output offset voltage. Sometimes, the specifications sheet also gives a maximum or "worst case" value.

The noise voltage source, v_n, specifies the noise normalized for bandwidth—more precisely, normalized to the square root of the bandwidth. This accounts for the strange units: $\text{nV}/\sqrt{\text{Hz}}$. Like Johnson noise and shot noise described in Chapter 1 (Section 1.3.2.1), noise in an op amp is distributed over the entire bandwidth of the op amp. To determine the actual noise in an amplifier it is necessary to multiply v_n by the square root of the circuit bandwidth as determined using the methods described previously. This value is then multiplied by the noise gain (i.e., $1/\beta$) to find the noise at the output. Finally we see why $1/\beta$ is also referred to as the noise gain: it multiples the noise at the input to produce the noise at the output, although it also multiplies offset voltage and other input errors. The next example shows how noise can be determined at the output of an amplifier circuit.

EXAMPLE 15.7

Find the noise at the output of the amplifier used in Example 15.6 that is due only to the op amp's noise voltage. (The resistors in the feedback network also contribute Johnson noise as does the input current noise source, i_n.)

Solution: There are multiple steps involved, but each is straightforward. Find the noise gain $1/\beta$; then determine the bandwidth from $1/\beta$ using the open-loop gain curve in Figure 15.13. Multiply the input noise voltage, v_n, by the square root of the bandwidth to find the noise at the input. Then multiply the result by the noise gain to find the value of the noise at the output.

From Example 15.6, the noise gain, $1/\beta$, was found to be 26, which corresponds to 28 dB. Referring to Figure 15.13, a $1/\beta$ line at 28 dB will intersect A_V at approximately 200 kHz. Taking the bandwidth as 200 kHz, the input noise voltage becomes:

$$v_{n\ \text{input}} = v_n\sqrt{BW} = 12 \times 10^{-9}\sqrt{200 \times 10^3} = 5.3\ \mu\text{V}$$

The noise at the output is this value multiplied by $1/\beta$:

$$V_{n\ \text{output}} = v_{n\ \text{input}}\left(\frac{1}{\beta}\right) = 5.3(26) = 137.8\ \mu\text{V}$$

The value of input voltage noise used in Example 15.7 is fairly typical for frequencies above 100 Hz. Op amp noise generally increases at lower frequencies and many op amp specifications include this information, including those of the LF 356. For the LF 356 the input voltage noise increases from 12 nV/$\sqrt{\text{Hz}}$ at 200 Hz and up to 60 nV/$\sqrt{\text{Hz}}$ at 10 Hz (see Appendix F). Presumably the voltage noise becomes even higher at lower frequencies, but values below 10 Hz are not given for this chip.

15.6.2.2 Input Current Sources

To evaluate the influence of input current sources, it is easiest to convert them to input voltages by multiplying by the equivalent resistance at the input terminals. Figure 15.20 notates the equivalent input resistances at the plus and minus terminals as R_{eq+} and R_{eq-}. These would have been determined by using the network reduction methods described in Chapter 14. The two current sources at the inputs, i_{b+} and i_{b-}, are known as the "bias currents." It may seem curious to show two current sources rather than one for both inputs, but this has to do with the fact that the offset currents at the two terminals are not exactly equal, although they do tend to be similar. Furthermore as with the bias voltage, the bias currents could be in either direction, in or out of their respective terminals.

To determine how these bias currents contribute to the output, we convert them to voltages by multiplying by the appropriate R_{eq}, and then multiplying that voltage by the noise gain. In most op amps, the two bias currents are approximately the same, so their influence on output offset voltage tends to cancel if the equivalent resistances at the two terminals are the same. Sometimes the op amp circuit designer tries to make the equivalent resistances at the two terminals the same just to achieve this cancellation. The amount by which the two bias currents are different, that is, the imbalance between the two currents, is called the "offset current" and is usually much less than the bias current. For example, in the LF 356, typical bias currents are 30 pA, whereas the offset current is only 3.0 pA, an order of magnitude less.

Figure 15.22 shows an inverting op amp circuit where a resistor has been added between the positive terminal and ground. The current flowing through this resistor is essentially zero (if you ignore the small bias currents) since the op amp's input impedance is quite large (recall Rule 1). So there is a negligible voltage drop across the resistor and the positive terminal is still at ground potential. This resistor performs no function in the circuit except to balance the voltage offset due to the bias currents. To achieve this balance, the resistor should be equal to the equivalent resistance at the op amp's negative terminal.

To determine the equivalent resistance at the negative terminal, we use the approaches described in Chapter 14 and make the usual assumption that the input to the op amp is an ideal source, Figure 15.23. We also assume that the output of the op amp is essentially an

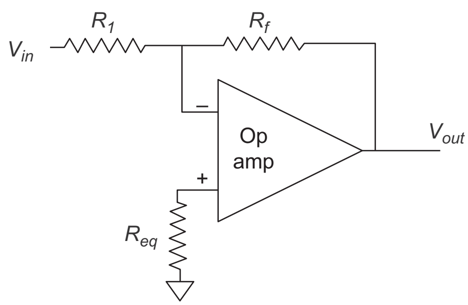


FIGURE 15.22 An inverting operational amplifier with a resistor added to the noninverting terminal to balance the bias currents. R_{eq} should be set to equal the equivalent resistance on the inverting terminal.

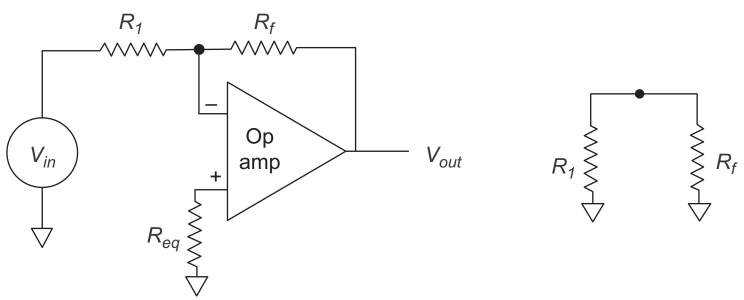


FIGURE 15.23 The left circuit is a typical inverting operational amplifier (op amp). If the op amp output, V_{out}, and the input, V_{in}, can be considered ideal sources, then they have effective impedances of 0 Ω. Since these two ideal sources are connected to ground, the ends of the two resistors are connected to ground, one through the ideal input and the other through the op amp's ideal. This makes them in parallel and the net resistance at the inverting input terminal is the parallel combination of R_1 and R_f.

ideal source. (Real op amp output characteristics are covered in the next section.) This means that both R_1 and R_f in Figure 15.23 are connected to ground at one end and the inverting input at the other. Since they are connected to the same points at both ends (ground and the inverting input) they are in parallel and the equivalent resistance hanging on the inverting terminal is the parallel combination of R_f and R_1, as shown on the right side:

$$R_{eq-} = \frac{R_f R_1}{R_f + R_1}; \quad \text{or more generally: } Z_{eq-} = \frac{Z_f Z_1}{Z_f + Z_1} \tag{15.18}$$

So to balance the resistances (or impedances) at the input terminals, the resistance at the positive terminal should be set to the parallel combination of the two feedback resistors (Equation 15.18). Sometimes, as an approximation, the resistance at the positive terminal is set to equal the resistor that has the smaller value of the two feedback network resistors (usually R_1). Another strategy is to make this resistor variable, and then adjust the resistance to cancel the output offset voltage from a given op amp. This has the advantage of removing any output offset voltage due to the input offset voltage, v_o, as well. The primary downside to this approach is that the resistor must be carefully adjusted after the circuit is built. If the feedback circuit contains capacitors, then Z_{eq} should be an impedance equivalent to the parallel combination of the feedback resistor and capacitor.

The current noise source is treated the same way as the bias currents: it is multiplied by the two equivalent resistances to find the input current noise, and then multiplied by the noise gain to find the output noise.

To find the total noise at the output, it is necessary to add in the voltage noise. Since the noise sources are independent, they add as the square root of the sum of the squares (Equation 1.9). In addition to the voltage and current noise of the op amp, the resistors will produce voltage noise as well. Repeating the equation for Johnson noise for a resistor from Chapter 1 (Equation 1.6):

$$V_J = \sqrt{4kT\,R\,BW}\ \text{V} \tag{15.19}$$

The three different noise sources associated with an op amp circuit are all dependent on bandwidth. The easiest way to deal with these three different sources is to combine them in one equation that includes the bandwidth:

$$V_{n\,in} = \left[\Big(\underbrace{v_n^2}_{\substack{\text{Op amp}\\\text{voltage}\\\text{noise}}} + \underbrace{\big(i_n(R_{eq+} + R_{eq-})\big)^2}_{\substack{\text{Op amp}\\\text{current}\\\text{noise}}} + \underbrace{4kT(R_{eq+} + R_{eq-})}_{\substack{\text{Johnson}\\\text{noise}}}\Big)BW\right]^{1/2} \tag{15.20}$$

This equation gives the summed input noise. To find the output noise, multiply $V_{n\,in}$ by the noise gain.

$$V_{n\ out} = V_{n\ in}(\text{Noise Gain}) = V_{n\ in}\left(\frac{1}{\beta}\right) \tag{15.21}$$

The use of this approach to calculate the noise out of a typical op amp amplifier circuit is shown in Example 15.8.

EXAMPLE 15.8

Find the noise at the output of the op amp circuit shown in Figure 15.22 where $R_f = 500$, $R_1 = 10$, and $R_{eq} = 9.8$ kΩ.

Solution: First find the noise gain, $1/\beta$. From $1/\beta$ determine the bandwidth of the amplifier using the open-loop gain curves in Figure 15.13. Apply Equation 15.20 to find the total input voltage noise, including both current and voltage noise. Then multiply this voltage by the noise gain to find output voltage noise (Equation 15.21).

The noise gain is:

$$\frac{1}{\beta} = \frac{R_f + R_1}{R_1} = \frac{500 + 10}{10} = 51$$

From the specifications of the LF 356, $v_n = 12$ nV/√Hz and $i_n = .01$ pA/√Hz. The equivalent resistance at the negative terminal is found from Equation 15.18 to be 9.8 kΩ (the parallel combination of 500 and 10 kΩ). For a $1/\beta$ of 51, the bandwidth is approximately 100 kHz (Figure 15.13) Using $T = 310$K, $4kT$ is 1.7×10^{-20} J, and Equation 15.20 becomes:

$$V_{n\ in} = \left[\left((12 \times 10^{-9})^2 + \left(0.01 \times 10^{-12}(19.6 \times 10^3)\right)^2 + 1.7 \times 10^{-20}(19.6 \times 10^3)\right)10^5\right]^{\frac{1}{2}}$$

$$V_{n\ in} = \left[(1.44 \times 10^{-16} + 3.8 \times 10^{-20} + 3.33 \times 10^{-16})10^5\right]^{\frac{1}{2}}$$

$$V_{n\ in} = \left[(4.77 \times 10^{-16})10^5\right]^{\frac{1}{2}} = 6.9\ \mu\text{V}$$

Result: The noise at the output is found by multiplying by the noise gain:

$$V_{n\ out} = V_{n\ in}(\text{Noise Gain}) = 6.9 \times 10^{-6}(51) = 0.35\ \text{mV}$$

Analysis: One advantage to including all the sources in a single equation is that the relative contributions of each source can be compared. After converting to a voltage, the current noise source is approximately four orders of magnitude less than the other two voltage noise sources, so its contribution is negligible. The op amp's voltage noise does contribute to the overall noise, but most of the noise is coming from the resistors. Finding an op amp with a lower noise voltage would lower the noise, but of the 0.35 mV noise at the output, 0.29 mV is from the resistors. Of course, this is using the value of noise voltage for frequencies above 200 Hz. The noise voltage of the op amp at 10 Hz is 60 nV/√Hz, four times the value used in this example. If noise at the lower frequencies is a concern, another op amp should be considered. (For example, the Op-27 op amp features a noise voltage of only 5.5 nV/√Hz at 10 Hz.)

15.6.2.3 Input Impedance

Although the input impedance of most op amps is quite large, the actual input impedance of the circuit depends on the configuration. The noninverting op amp has the highest input impedance, that of the op amp itself. In practice it may be difficult to attain the high impedance of many op amps because of leakage currents in the circuit board or wiring. Furthermore, the bias currents of an op amp will decrease its effective input impedance.

For an inverting amplifier, the input impedance is approximately equal to the input resistance, R_1 (Figure 15.9). This is because the input resistor is connected to "virtual ground" in the inverting configuration. Although this is much lower than the input impedance of the noninverting configuration, it is usually large enough for many applications. Where a very high input impedance is required, the noninverting configuration should be used. If even higher input impedances are required, op amps with particularly high input impedances are available, but the limitations on impedance are usually set by other components of the circuit such as the lead-in wires and circuit board.

15.6.3 Output Characteristics

Compared with the input characteristics, the output characteristics of an op amp are quite simple: a Thévenin source where the ideal source is $A_V\,(V_{in+} - V_{in-})$ and the resistance is r_{out}, Figure 15.24. For the LF 356, A_V is given as a function of frequency in Figure 15.13 and r_{out} varies between 0.05 and 50 Ω depending on the frequency and closed-loop gain.[3] The value of the output resistance is the lowest at lower frequencies and when the closed-loop gain is 1 (i.e., $\beta = 1$).

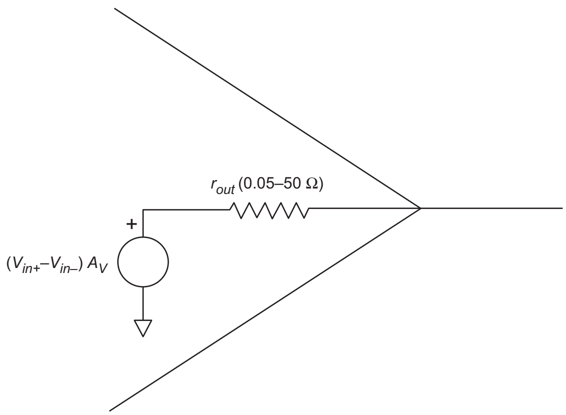


FIGURE 15.24 The output characteristics of an operational amplifier are those of a Thévenin source, including an ideal voltage source, $A_V\,(V_{in+} - V_{in-})$, and an output resistor, r_{out}.

[3]As with the input characteristics (specifically r_{in}), the value given in the specification sheet for r_{out} assumes the op amp is open loop. The presence of feedback reduces the effective output resistance.

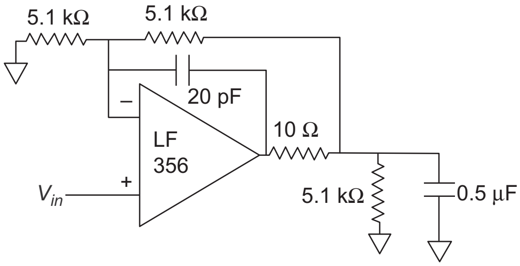


FIGURE 15.25 An operational amplifier (op amp) circuit that can be used to drive a large capacitive load. Note that this is a noninverting amplifier with a gain of only 2.0. This suggests that the main purpose of this circuit is to provide a drive to the capacitive load, not to amplify the signal. A number of additions to the classic noninverting amplifier (see Figure 15.6) are shown: a small (20-pf) feedback capacitor, a resistor in parallel with the capacitive load, and a small resistor in series between the op amp output and the load.

In some circumstances, other features of the output must be considered. Maximum voltage swing at the output is always a few volts less than the voltage that powers the op amp (see next section). The range of the output signal can become further limited at higher frequencies. In addition, many op amps have stability problems when driving a capacitive load. Figure 15.25 shows a circuit taken from the specifications sheet that can be used to drive a large capacitive load. In this circuit, the desired load is a 0.5-μf capacitor, which is considered fairly large in electronic circuits. Several strategies are used to reduce oscillation. A small feedback capacitor ($20\ \mathrm{pf} = 20 \times 10^{-12}$) is added to improve phase characteristics as mentioned previously. Another circuit addition is to place a resistor in parallel with the capacitor load so that the load is no longer purely capacitive. Yet another strategy is to place a small resistor at the output of the op amp before the feedback resistor providing a little isolation between the load and the op amp output. These strategies are often implemented on an ad hoc basis, but the design engineer should anticipate possible problems when capacitive (or inductive) loads are involved.

15.7 POWER SUPPLY

Op amps are active devices and require external power to operate. This external power is delivered as a constant voltage or voltages from a device known, logically, as a "power supply." Power supplies are commercially available in a wide range of voltages and current capabilities. Many op amps are "bipolar," that is, they handle both positive and negative voltages. (Unlike its use in psychology, in electronics the term bipolar has nothing to do with stability.) Bipolar applications require both positive and negative power supply voltages, and values of ±12 or ±15 V are common. The higher the power supply voltage, the larger the output voltages the op amp can produce, but all op amps have a maximum voltage limit. The maximum voltage for the LF 356 is ±18 V, but a special version, the LF 356B, can handle ± 22 V. High-voltage op amps are available as are low-voltage op amps for battery use. The latter also feature lower current consumption. (The LF 356 uses a nominal 5–10 mA and a few of them in a circuit will go through a 9-V battery fairly quickly.)

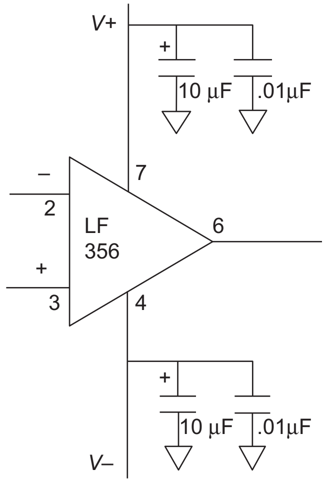


FIGURE 15.26 An LF356 operational amplifier connected to positive and negative power supply lines. The number next to each line indicates the pin number of a common version of the chip (the eight-pin DIP package). The capacitors are used to remove noise or fluctuations on the power supply lines that may be produced by other components in the system. These capacitors are called "decoupling capacitors."

The power supply connections are indicated on the op amp schematic by vertical lines coming from the side of the amplifier icon as shown in Figure 15.26. Sometimes the actual chip pins are indicated on the schematic as in this figure. Figure 15.26 also shows a curious collection of capacitors attached to the two supply voltages. Power supply lines often go to a number of different op amps or other analog circuitry.[4] These common power supply lines make great pathways for spreading signal artifacts, noise, positive feedback signals, and other undesirable fluctuations. One op amp circuit might induce fluctuations on the power supply line(s), and these fluctuations then pass to all the other circuits. Practical op amps do have some immunity to power supply fluctuations, but this immunity falls significantly with the frequency of the fluctuations. For example, the LF 356 will attenuate power supply variations at 100 Hz by 90 dB (a factor of 31,623), but this attenuation falls to 10 dB (a factor of 3) at 1 MHz.

A capacitor placed right at the power supply pin will tend to smooth out voltage fluctuations and reduce artifacts induced by the power supply. Since such a capacitor tends to isolate the op amp from power line noise, it is called a "decoupling capacitor." Figure 15.26 shows two capacitors on each supply line: a large 10-μf capacitor and a small 0.01-μf capacitor. Since the two capacitors are in parallel they are in theory equivalent to a single 10.01-μf capacitor. The small capacitor would appear to be contributing very little. In fact, the small capacitor is there because large capacitors have poor high-frequency performance: they look more like inductors than capacitors at higher frequencies. The small capacitor serves to reduce high-frequency fluctuations, whereas the large capacitor does the same at low frequencies. Although a given op amp circuit may not need both these decoupling capacitors,

[4]Digital circuits that may also be present in the system usually have their own power supply.

the 0.01 μF capacitor is routinely included by most design engineers on every power supply pin of every op amp. The larger capacitor may be added if strong low-frequency signals are present in the network.

15.8 OPERATIONAL AMPLIFIER CIRCUITS OR 101 THINGS TO DO WITH AN OPERATIONAL AMPLIFIER

Although there are more than 101 different signal processing operations that can be performed by op amp circuits, this is an introductory course so only a handful will be presented. However, they are the handful that you are most likely to need. For a look at the other 90+, see "*Art of Electronics*" by Horowitz and Hill (1989).

15.8.1 The Differential Amplifier

We have already shown how to construct inverting and noninverting amplifiers. Why not throw the two together to produce an amplifier that does both: a differential amplifier? As shown in Figure 15.27, a differential amplifier is a combination of inverting and noninverting amplifiers.

To derive the transfer function of the circuit in Figure 15.27, we once again employ the principle of superposition. Setting V_{in2} to zero effectively grounds the lower R_1 resistor, and the circuit becomes a standard inverting op amp with a resistance between the positive terminal and ground, Figure 15.28 left side. As stated previously, the only effect of this resistance is to balance the bias currents. For this partial circuit, the transfer function is:

$$V_{out} = -\frac{R_f}{R_1} V_{in1}$$

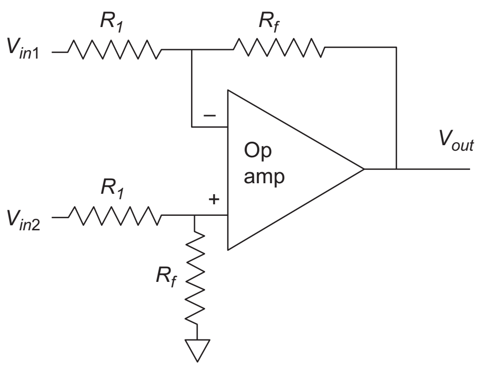


FIGURE 15.27 A differential amplifier circuit. This amplifier combines both inverting and noninverting amplifiers into a single circuit. As shown in the text, this circuit amplifies the difference between the two input voltages: $V_{out} = \frac{R_f}{R_{in}}(V_{in2} - V_{in1})$.

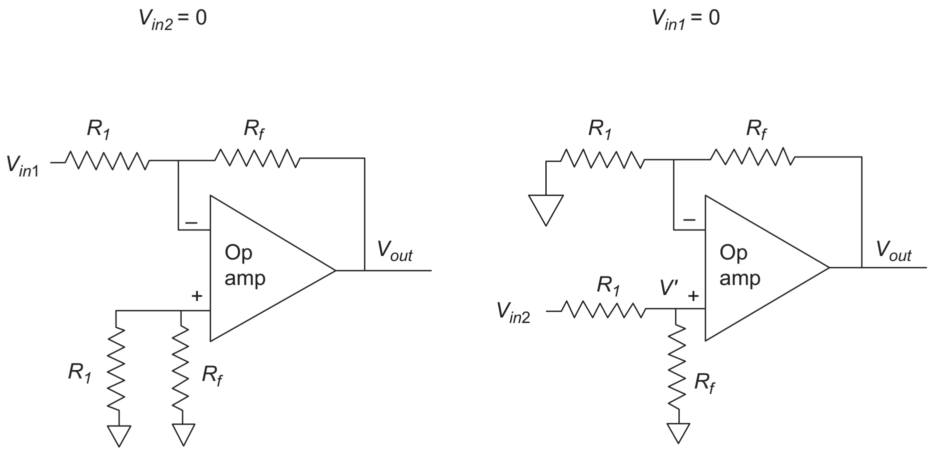


FIGURE 15.28 Superposition applied to the differential amplifier. Left circuit: The V_{in2} input is set to zero (i.e., grounded), leaving a standard inverting amplifier circuit. Right circuit: The V_{in1} input is grounded, leaving a noninverting operational amplifier with a voltage divider circuit on the input. Each one of these circuits will be solved separately and the overall transfer function determined by superposition.

Setting V_{in1} to zero grounds the upper R_1 resistor, and the circuit becomes a noninverting amplifier with a voltage divider on the input. With respect to the voltage V' (Figure 15.28 right side), the circuit is a standard noninverting op amp:

$$V_{out} = \frac{R_f + R_1}{R_1} V'$$

The relationship between V_{in2} and V' is given by the voltage divider equation:

$$V' = \frac{R_f}{R_f + R_1} V_{in2}$$

Substituting and solving for V_{in2}:

$$V_{out} = \frac{R_f + R_1}{R_1} V' = \frac{R_f + R_1}{R_1} \frac{R_f}{R_f + R_1} V_{in2} = \frac{R_f}{R_1} V_{in2}$$

By superposition, the two partial solutions can be combined to find the transfer function when both voltages are present.

$$V_{out} = -\frac{R_f}{R_1} V_{in1} + \frac{R_f}{R_1} V_{in2} = \frac{R_f}{R_1} (V_{in2} - V_{in1}) \tag{15.22}$$

Thus the circuit shown in Figure 15.27 amplifies the difference between the two input voltages.

15.8.2 The Adder

If the sum of two or more voltages is desired, the circuit shown in Figure 15.29 can be used. It is easy to show using an extension of the approach used in Example 15.2 that the transfer function of this circuit is:

$$V_{out} = \left(\frac{R_f}{R_1}\right)V_{in1} + \left(\frac{R_f}{R_2}\right)V_{in2} + \left(\frac{R_f}{R_3}\right)V_{in3} \tag{15.23}$$

The derivation of this equation can be found as an exercise at the end of the chapter. This circuit can be extended to any number of inputs by adding more input resistors. If $R_1 = R_2 = R_3$, then the output is the straight sum of the three input signals amplified by R_f/R_1.

15.8.3 The Buffer Amplifier

At first glance the circuit in Figure 15.30 appears to be of little value. In this circuit all of the output is feedback to the inverting input terminal, so the feedback gain, β, equals 1. Since the gain of a noninverting amplifier is $1/\beta$, the gain of this amplifier is 1 and $V_{out} = V_{in}$. (This can also be shown using circuit analysis; this is an exercise in the problem section.) Although this

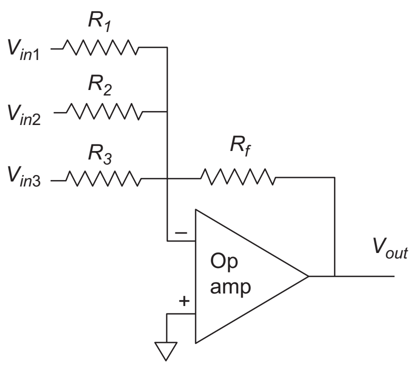


FIGURE 15.29 An operational amplifier circuit that takes a weighted sum of three input voltages, V_{in1}, V_{in2}, and V_{in3}.

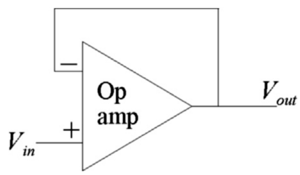


FIGURE 15.30 A "buffer amplifier" circuit. This amplifier provides no gain ($G = 1/\beta = 1$), but presents a very high impedance to the signal source, nearly an ideal load, and generates a low-impedance signal that looks like a nearly ideal source.

amplifier does nothing to enhance the amplitude of the signal, it does a great deal when it comes to impedance. Specifically, the incoming signal sees a very large impedance, the input impedance of the op amp ($>10^{12}\ \Omega$ for the LF 356), whereas the output impedance is very low (0.02 Ω at 10 kHz for the LF 356), approaching that of an ideal source. This circuit can take a signal from a high-impedance Thévenin source and provide a low-impedance, nearly ideal, source that can be used to drive several other devices. Although all noninverting op amp circuits have this impedance transformation function, the unity gain circuits are particularly effective and have the highest bandwidth since $1/\beta = 1$. Since this circuit provides a buffer between the high-impedance source and the other devices, it is sometimes referred to as a "buffer amplifier." The low output impedance also reduces noise pick up, and this circuit can be invaluable whenever a signal is sent over long wires or even off the circuit board. Many design engineers routinely use a buffer amplifier as the output to any signal that will be sent any distance, particularly if it is sent out of the instrument.

15.8.4 The Transconductance Amplifier[5]

Figure 15.31 shows another simple circuit that looks like an inverting op amp circuit except the input resistor is missing.

The input to this circuit is a current, not a voltage, and the circuit is used to convert this current into a voltage. Applying KCL to the negative input terminal, the transfer function for this circuit is easily determined.

$$i_n = i_f = \frac{V_{out}}{R_f};$$

Solving for V_{out}:

$$V_{out} = R_f i_n \tag{15.24}$$

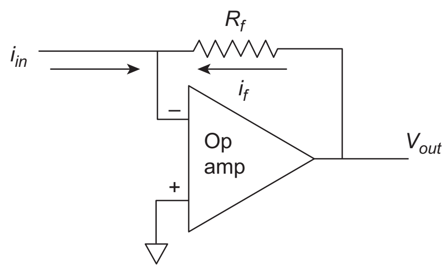


FIGURE 15.31 An operational amplifier circuit used to convert a current to a voltage. Because of this current-to-voltage transformation, this circuit is also referred to as a "transconductance amplifier."

[5]The transconductance amplifier described here takes in a current and puts out a voltage. There are also transconductance amplifiers that do the opposite: output a current proportional to an input voltage.

Some transducers produce current as their output and this circuit is used as the first stage to convert that current signal to a voltage. A common example in medical instruments is the photodetector transducer. These light-detecting transducers usually produce a current proportional to the light falling on them. These currents can be very small, in the nanoamps or picoamps. If R_f is chosen to be very large (10−100 MΩ), a reasonable output voltage is produced. Generally this output voltage requires additional amplification by a "second-stage" op amp amplifier.

Since the input to the op amp is current, noise depends only on current noise. This would include the noise current generated by both the op amp and the resistor. The net input current noise is then multiplied by R_f to find the output voltage noise. This approach is illustrated in the practical problem posed in Example 15.9.

EXAMPLE 15.9

A transconductance amplifier shown in Figure 15.32 is used to convert the output of a photodetector into a voltage. The traditional symbol for a photodetector is a diode with squiggly arrows as shown on the left side of Figure 15.32.

The photodetector has a sensitivity of R = 0.01 μA/μW. The R stands for "responsivity," which is the same as sensitivity. Sensitivity functions as the transfer function of a transducer describing the output for a given input. The photodiode has a noise current, which is called "dark current." The dark current of this photodiode is $i_d = .05$ pA/$\sqrt{\text{Hz}}$. What is the minimum light flux, φ, in microwatts that can be detected with an SNR of 20 dB and a bandwidth of 1 kHz?

Solution: This problem requires a number of steps, but the heart of the problem is how much current noise is generated at the input of the op amp. Once this is determined, the minimum signal current can be determined as 20 dB, or a factor of 10, times this current noise. The responsivity defines the output for a given input (R = φ/i), so once the minimum signal current is found, the minimum light flux, φ_{min}, can be calculated as i_{min}/R. To find the total noise current, modify Equation 15.20 for current noise rather than voltage noise. For resistor current noise, use Equation 1.7. Adding in the diode noise to the resistor and op amp current noise:

$$i_{n\ \ Total} = \left[\left(i_d^2 + i_n^2 + \frac{4kT}{R_f}\right)BW\right]^{\frac{1}{2}} = \left[\left(2q\ i_d + i_n^2 + \frac{4kT}{R_f}\right)BW\right]^{\frac{1}{2}} \qquad (15.25)$$

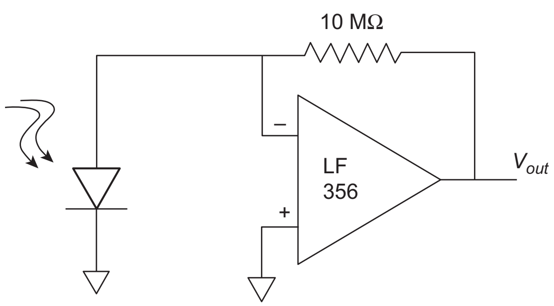


FIGURE 15.32 The output of a photodetector is fed to a transconductance amplifier. This circuit is used in Example 15.9 to determine the minimum light flux that can be detected with a signal to noise ratio (SNR) of 20 dB.

Note that the value of current noise decreases for increased values of R_f, so a good design would use as large a value of R_f as is practical and needed.

Solving into Equation 15.25 using the value of i_n from the LF 356 specifications sheet, the value of i_d from the photodetector, an R_f of 10 MΩ, then multiplying by the 1 kHz bandwidth:

$$i_{n\ Total} = \left[\left(\left(2 * 1.6 \times 10^{-19}\right)\left(1 \times 10^{-12}\right) + \left(.01 \times 10^{-12}\right)^2 + \frac{1.7 \times 10^{-20}}{10^7}\right)10^3\right]^{\frac{1}{1}}$$

$$= \left[\left(1.6 \times 10^{-32} + 1 \times 10^{-28} + 1.7 \times 10^{-27}\right)10^3\right]^{\frac{1}{2}} = 1.34 \times 10^{-12}\ \text{A} = 1.34\ \text{pA}$$

Thus the minimum signal required for an SNR of 20 dB is $10 \times 1.34 = 13.4$ pA. From the sensitivity of the photodetector, the minimum light flux that can be detected is:

$$\varphi_{min} = \frac{i_{min}}{\text{R}} = \frac{13.4 \times 10^{-12}}{0.01} = 1.34 \times 10^{-9}\ \text{W} = 1.34 \times 10^{-3}\ \mu\text{W}$$

Note that since R is in μA/μW and all the units used here are scaled versions of A/W, it is not necessary to scale this number. To determine the output voltage produced by this minimum signal, or any other signal for that matter, simply multiply this input current by R_f:

$$V_{out} = i_{in}R_f = 1.34 \times 10^{-9}\left(10^7\right) = 13.4\ \text{mV}$$

This is small signal, so it would be a good idea to increase the value of R_f. Since R_f is the largest contributor of noise, increasing its value by a factor of 10 would both increase the output signal by that amount and decrease the noise (since noise *current* is inversely related to the resistance). Modest additional improvement might then be obtained by using an op amp with a lower current noise since, as seen in the calculations, this is the second largest noise source.

15.8.5 Analog Filters

A simple single-pole low-pass filter can be constructed using an R-C circuit. An op amp can also be used to construct a low-pass filter with improved input and output characteristics and also provide increased signal amplitude. The easiest way to construct an op amp low-pass filter is to add a capacitor in parallel to the feedback resistor as shown in Figure 15.33.

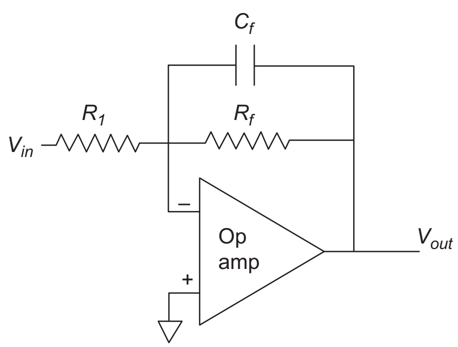


FIGURE 15.33 An inverting amplifier that also functions as a low-pass filter. As shown in the text, the low-frequency gain of this amplifier is R_f/R_1 and the cutoff frequency is $\omega = 1/R_f C_f$.

The equation for the transfer function of an inverting op amp with impedances in the feedback circuit is given in Equation 15.12 and repeated here:

$$\frac{V_{out}}{V_{in}} = -\frac{Z_f}{Z_1} \tag{15.26}$$

Applying Equation 15.26 to the circuit in Figure 15.33:

$$\frac{V_{out}}{V_{in}} = -\frac{Z_f}{Z_1} = -\frac{\dfrac{R_f\frac{1}{j\omega C_f}}{Rf + \frac{1}{j\omega C_f}}}{R_1} = \left(\frac{R_f}{R_1}\right)\frac{1}{(1 + j\omega R_f C_f)} \tag{15.27}$$

At frequencies well below the cutoff frequency, the second term goes to 1 and the gain is R_f / R_1. The second term is a low-pass filter with a cutoff frequency of $\omega = 1/R_f C_f$ rad/s or $f = 1/2\pi R_f C_f$ Hz. Design of an active low-pass filter is found in the problems.

It is also possible to construct a second-order filter using a single op amp. A popular second-order op amp circuit is shown in Figure 15.34.

Derivation of the transfer function requires applying KCL to two nodes and is provided in Appendix A. The transfer function is:

$$\frac{V_{out}}{V_{in}} = \frac{\dfrac{G}{(RC)^2}}{s^2 + \dfrac{3-G}{RC}s + \dfrac{1}{(RC)^2}} \quad \text{where}: \quad G = \frac{R_f + R_1}{R_1} \tag{15.28}$$

where G is the gain of the noninverting amplifier and equals $1/\beta$. Equating coefficients of Equation 15.28 with the standard Laplace transfer function of a second-order system (Equation 6.31):

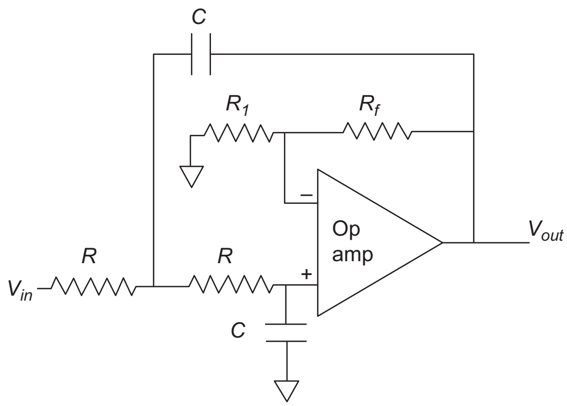


FIGURE 15.34 A two-pole active low-pass filter constructed using a single operational amplifier.

$$\omega_o = \frac{1}{RC}; \quad \delta = \frac{3 - G}{2} \tag{15.29}$$

EXAMPLE 15.10

Design a second-order filter with a cutoff frequency of 5 kHz and a damping of 1.0.

Solution: Since there are more unknowns than equations, several component values may be set arbitrarily with the rest determined by Equation 15.29. To find R and C, pick a value for C that is easy to obtain, then calculate the value for R (capacitor values are more limited than resistor values). Assume $C = 0.001$ μf, a common value. Then the value of R is:

$$\omega_o = 2\pi f = \frac{1}{RC} = 2\pi(5000) = 31,416 \text{ rad/s}$$

$$R = \frac{1}{31,416(0.001 \times 10^{-6})} = 31.8 \text{ k}\Omega$$

The value for G, the gain of the noninverting amplifier would be:

$$\delta = \frac{3 - G}{2} = 1.0; \quad G = 3 - 2\delta = 3 - 2 = 1$$

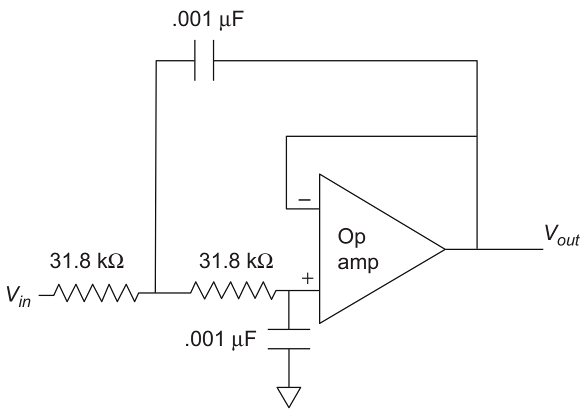


FIGURE 15.35 A two-pole low-pass filter with a cutoff frequency of 5 kHz and a damping factor of 1.0.

Hence for this particular damping, $G = 1/\beta = 1$ and $\beta = 1.0$. So all of the output is feedback to the noninverting input and a resistor divider network is not required. Other values of damping require the standard resistor divider network to achieve the desired gain. A second-order active filter having the desired cutoff frequency and damping is shown in Figure 15.35.

15.8.6 Instrumentation Amplifier

The differential amplifier shown in Figure 15.27 is useful in a number of biomedical engineering applications, specifically to amplify signals from biotransducers that produce a

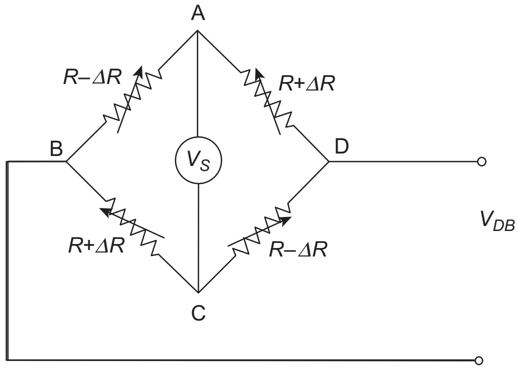


FIGURE 15.36 A bridge circuit that produces a differential output. The voltage at D moves in opposition to the voltage at B. The output voltage is best amplified by a differential amplifier.

differential output. Such transducers actually produce two voltages that move in opposite directions to a given input. An example of such a transducer is the strain gage bridge shown in Figure 15.36.

Here the strain gages are arranged in such a way that when a force is applied to the gages, two of them (A—B and C—D) undergo tension, whereas the other two (B—C and D—A) undergo compression. The two gages under tension decrease their resistance, whereas the two under compression increase their resistance. The net effect is that the voltage at B increases, whereas the voltage at D decreases an equal amount in response to the applied force. If the difference between these voltages is amplified using a differential amplifier such as that shown in Figure 15.27, the output voltage will be the difference between the two voltages and reflect the force applied. If the force reverses, the output voltage will change sign.

One of the significant advantages of this differential operation is that much of the noise, particularly noise picked up by the wires leading to the differential amplifier, will be common to both of the inputs and will tend to cancel. To optimize this kind of noise cancellation, the gain of each of the two inputs must be exactly equal in magnitude (but opposite in sign, of course). Not only must the two inputs be balanced, but the input impedance should also be balanced and often it is desirable that the input impedance be quite high. An "instrumentation amplifier" is a differential amplifier circuit that meets these criteria: balanced gain along with balanced and high input impedance. In addition, low noise is a common and desirable feature of instrumentation amplifiers.

A circuit that fulfills this role is shown in Figure 15.37. The output op amp performs the differential operation, and the two leading op amps configured as unity gain buffer amplifier provide similar high-impedance inputs. If the requirements for balanced gain are high, one of the resistors is adjusted until the two channels have equal but opposite gains. It is common to adjust the lower R_2 resistor. Since the two input op amps provide no gain, the transfer function of this circuit is just the transfer function of the second stage, which is shown in Equation 15.22 to be:

$$V_{out} = \frac{R_1 + R_2}{R_1}(V_{in2} - V_{in1}) \tag{15.30}$$

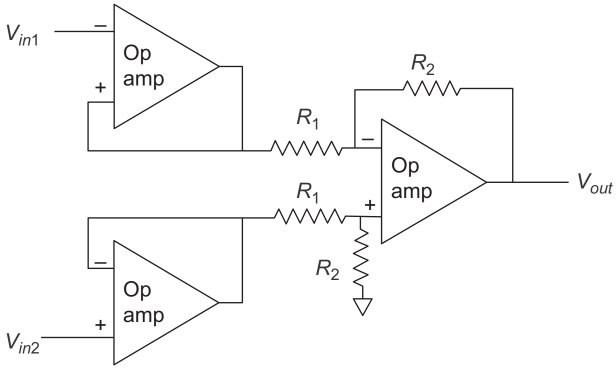


FIGURE 15.37 A differential amplifier circuit with high input impedance. Resistor R_1 can be adjusted to balance the differential gain so that the two channels have equal but opposite gains. In the interest of symmetry, it is common to reverse the position of the positive and negative operational amplifier (op amp) inputs in the upper input op amp.

There is one serious drawback to the circuit in Figure 15.37. To increase or decrease the gain it is necessary to change two resistors simultaneously: either both R_1's or both R_2's. Moreover, to maintain balance, they both have to be changed by exactly the same amount. This can present practical difficulties. A differential amplifier circuit that requires only one resistor change for gain adjustment is shown in Figure 15.38. The derivation for the input–output relationship of this circuit is more complicated than for the previous circuit, and is given in Appendix A:

$$V_{out} = \frac{R_4}{R_3}\left(\frac{R_1 + 2R_2}{R_1}\right)(V_{in2} - V_{in1}) \tag{15.31}$$

Since R_1 is now a single resistor, the gain can be adjusted by modifying this resistor. As this resistor is common to both channels, changing its value affects the gain of each channel

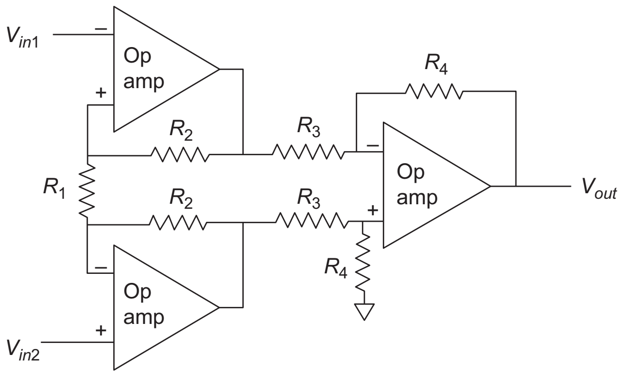


FIGURE 15.38 An instrumentation amplifier circuit. This circuit has all the advantages of the one in Figure 15.37 (i.e., balanced channel gains and high input impedance), but with the added advantage that the gain can be adjusted by modifying a single resistor, R_1.

equally and does not alter the balance between the gains of the two channels. It would be unusual to actually construct the circuit in Figure 15.38 since there are a number of integrated circuit instrumentation amplifiers that combine these components on a single chip. Such packages generally have very good balance between the two channels, very high input impedance, and low noise. For example, an instrumentation amplifier made by Analog Devices, Inc, the ADC624, has an input impedance of 10^9 Ω, a noise voltage of 4.0 nV/$\sqrt{\text{Hz}}$ at 1.0 kHz. Such chips also include a collection of highly accurate internal resistors that can be used to set specific amplifier gains by jumpers between selected pins with no need of external components.

The balance between the channels is measured in terms of V_{out} when the two inputs are at the same voltage. The voltage that is common (i.e., the same) to both input terminals is termed the "common mode voltage." In theory, the output should be zero no matter what the input voltage is so long as it is the same at both inputs. However, any imbalance between the gains of the two channels will produce some output voltage, and this voltage will be proportional to the common mode voltage. Since the idea is to have the most cancellation and the smallest output voltage to a common mode signal, the common mode voltage out of the amplifier is specified in terms of inverse gain. This inverse gain is called the "common mode rejection ratio" (CMRR), and is usually given in decibels.

$$V_{out} = \frac{V_{CM}}{\text{CMRR}} \tag{15.32}$$

The higher the CMRR the smaller the output voltage that results from the common mode voltage and the better the noise cancellation. The ADC624 has a CMRR of 120 dB. This means that the common mode gain is −120 dB. For example, if +10 V were applied to both input terminals (i.e., $V_{in1} = V_{in2} = 10$ V), V_{out} would be:

$$V_{out} = \frac{V_{CM}}{\text{CMRR}} = \frac{10}{120\ \text{dB}} = \frac{10}{10^{120/20}} = \frac{10}{10^6} = 10\ \mu\text{V}$$

Although this value is not zero, it will be close to the noise level for most applications.

15.9 SUMMARY

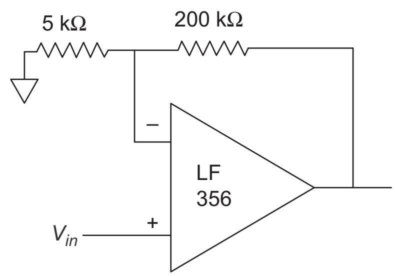
There is more to analog electronics than just op amp circuits, but they do encompass the majority of analog applications. The ideal op amp is an extension of the concept of an ideal amplifier. An ideal amplifier has infinite input impedance, zero output impedance, and a fixed gain at all frequencies. An ideal op amp has infinite input impedance and zero output impedance, but has infinite gain. The actual gain of an op amp circuit is determined by the feedback network, which is generally constructed from passive devices. This provides great flexibility with a wide variety of design options and the inherent robustness and long-term stability of passive elements.

Real op amps come reasonably close to the idealization. They have very high input impedances and quite low output impedances. Deviations from the ideal fall into three categories: deviations in transfer characteristics, deviations in input characteristics, and deviations in output characteristics. The two most important transfer characteristics are bandwidth and stability, where stability means the avoidance of oscillation. The bandwidth of an op amp circuit can be determined by combining the frequency characteristics of the feedback network with the frequency characteristics of the op amp itself. The immunity of an op amp circuit from oscillation can also be estimated from the frequency characteristics of the particular op amp and those of the feedback network. Input errors include bias voltages and currents, and noise voltages and currents. The bias and noise currents are usually converted to voltages by multiplying them by the equivalent resistance at each of the input terminals. The effect of these input errors on the output can be determined by multiplying all the input voltage errors by the noise gain, $1/\beta$. Output deviations consist of small nonzero impedances and limitations on the voltage swing.

There is a wide variety of useful analog circuits based on the op amp. These include both inverting and noninverting amplifiers, filters, buffers, adders, subtractors including differential amplifiers, transconductance amplifiers, and many more circuits not discussed here. The design and construction of real circuits that use op amps is fairly straightforward, although some care may be necessary to prevent noise and artifact from spreading through the power supply lines. Decoupling capacitors, capacitors running from the power supply lines to ground, are placed at the op amp's power supply feed to reduce the spread of noise through the power lines.

PROBLEMS

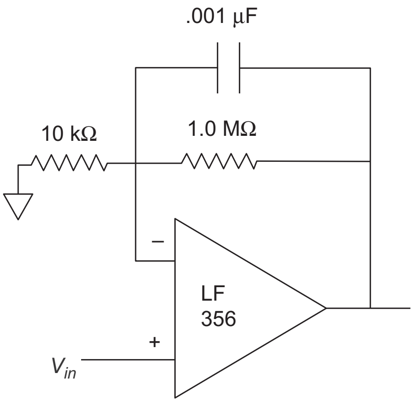
1. Design a noninverting amplifier circuit with a gain of 500.
2. Design an inverting amplifier with a variable gain from 50 to 250.
3. What is the bandwidth of the following noninverting amplifier? If the same feedback network were used to design an inverting amplifier, what would be the bandwidth of this circuit?



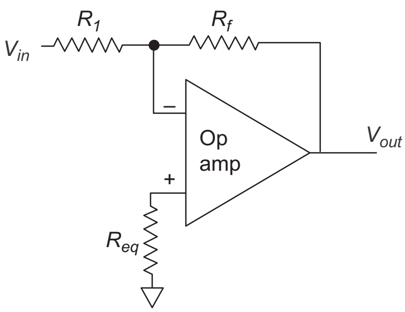
4. An amplifier has a GBP of 10 MHz. It is used in a noninverting amplifier where $\beta = 0.01$. What is the gain of the amplifier? What is the bandwidth?

5. An LF 356 is used to implement the variable gain amplifier in Example 15.3. What are the bandwidths of this circuit at the two extremes of the gain?

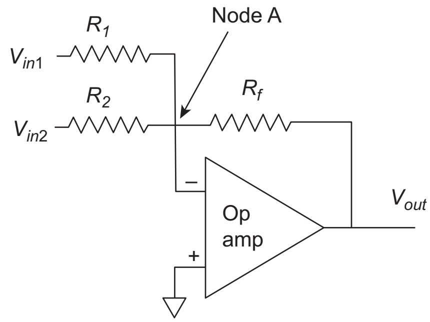
6. A .001μf capacitor is added to the feedback circuit of the following inverting op amp circuit. You can assume that before the capacitor was added the phase shift due to the amplifier when $Av\beta = 1$ was 120 degrees. (Recall the criterion for stability is that the phase shift induced by the op amp and the feedback network must be less than 180 degrees when $Av\beta = 1$.) After the capacitor is added, what is the phase shift of the op amp plus feedback network at the frequency where $Av\beta = 1$? Follow the example given in the section on stability.



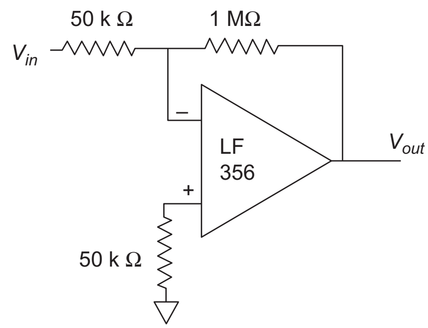
7. For the following circuit, assume $R_1 = 500$ kΩ, $R_f = 1.0$ MΩ, and R_{eq} = the parallel combination of R_1 and R_f. What is the total offset voltage at the output? How much is this offset voltage increased if R_{eq} is replaced with a short circuit?



8. Derive the transfer function of the following adder circuit. Use KVL applied to node A.



9. Find the total noise at the output of the following circuit. Identify the major source(s) of noise. What will the output noise be if the 50-kΩ ground resistor at the positive terminal is replaced with a short circuit? (Note this resistor adds to both the Johnson noise from the resistors and to the voltage noise generated by the op amp's noise current.)



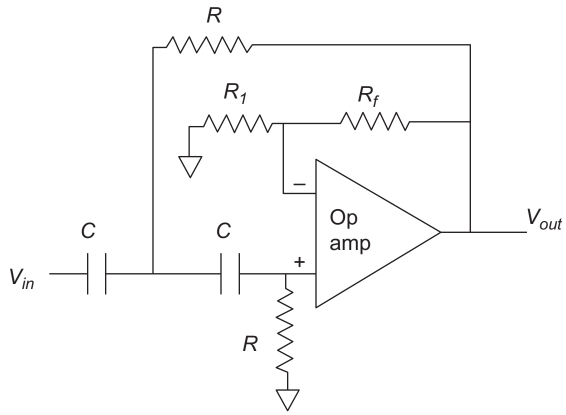
10. For the circuit in Problem 9, what is the minimum signal that can be detected with an SNR of 10 dB? What will be the voltage of such a signal at V_{out}?

11. An op amp has a noise current of 0.1 pA$\sqrt{\text{Hz}}$. This op amp is used as a transconductance amplifier (Figure 15.31). What should the minimum value of feedback resistance be so that the noise contribution from the resistor is less than the noise contribution from the op amp?

12. Design a one-pole low-pass filter with a bandwidth of 1 kHz. Assume you have capacitor values of 0.001, 0.01, 0.05, and 0.1 μF, and a wide range of resistors.

13. Design a two-pole low-pass filter with a cutoff frequency of 500 Hz and a damping factor of 0.8. Assume the same component availability as in Problem 15.

14. Design a two-pole high-pass filter with a cutoff frequency of 10 kHz and a damping factor of 0.707. (The circuit for a high-pass filter is the same as that for a low-pass filter except that the capacitors and resistors are reversed as shown in the following figure.)



15. Design an instrumentation amplifier with a switchable gain of 10, 100, and 1000. (Hint: switch the necessary resistors in or out of the circuit as needed.)