Basic Op-Amp

The basic circuit connection using an op-amp is shown in Fig. 14.12. The circuit shown provides operation as a constant-gain multiplier. An input signal,V1, is applied through resistor R1to the minus input. The output is then connected back to the same minus input through resistor Rf. The plus input is connected to ground. Since the signal V1 is essentially applied to the minus input, the resulting output is opposite in phase to the input signal. Figure 14.13a shows the op-amp replaced by its ac equivalent circuit. If we use the ideal op-amp equivalent circuit, replacing Ri by an infinite resistance and Ro by zero resistance, the ac equivalent circuit is that shown in Fig. 14.13b. The circuit is then redrawn, as shown in Fig. 14.13c, from which circuit analysis is carried out.

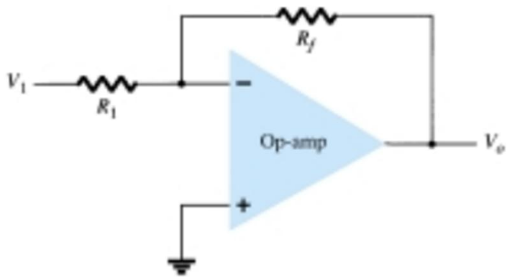
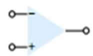


Figure 14.12 Basic op-amp connection.



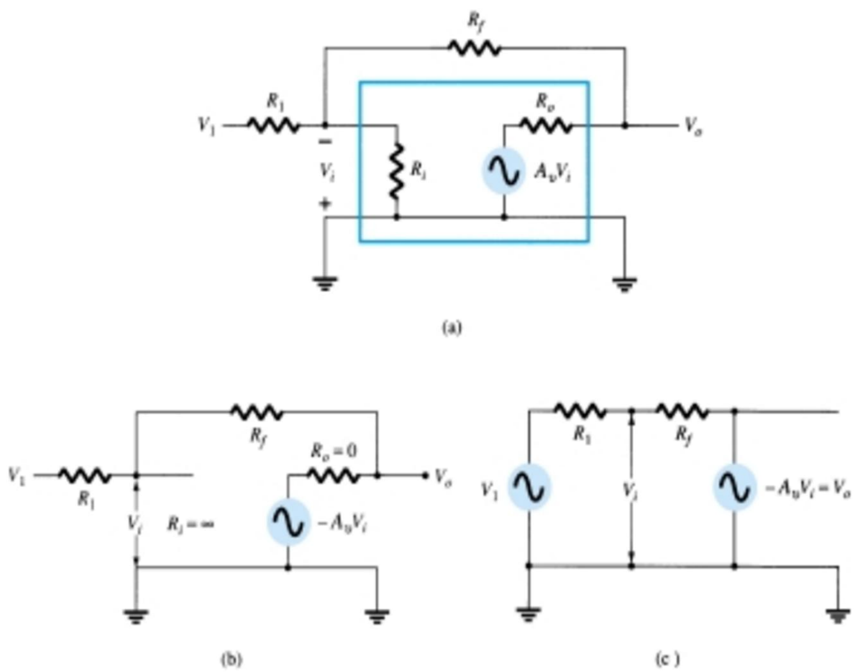


Figure 14.13 Operation of op-amp as constant-gain multiplier: (a) op-amp ac equivalent circuit; (b) ideal op-amp equivalent circuit; (c) redrawn equivalent circuit.

Using superposition, we can solve for the voltage V1in terms of the components due to each of the sources. For source V1only (-AvVi set to zero),

$$V_{i_1} = \frac{R_f}{R_1 + R_f} V_1$$

For source $-A_v V_i$ only (V_1 set to zero),

$$V_{i_2} = \frac{R_1}{R_1 + R_f}(-A_v V_i)$$

The total voltage V_i is then

$$V_i = V_{i_1} + V_{i_2} = \frac{R_f}{R_1 + R_f} V_1 + \frac{R_1}{R_1 + R_f}(-A_v V_i)$$

which can be solved for V_i as

$$V_i = \frac{R_f}{R_f + (1 + A_v)R_1} V_1 \qquad (14.7)$$

If $A_v \gg 1$ and $A_v R_1 \gg R_f$, as is usually true, then

$$V_i = \frac{R_f}{A_v R_1} V_1$$

Solving for V_o/V_i, we get

$$\frac{V_o}{V_i} = \frac{-A_v V_i}{V_i} = \frac{-A_v}{V_i}\frac{R_f V_1}{A_v R_1} = -\frac{R_f}{R_1}\frac{V_1}{V_i}$$

so that

$$\boxed{\frac{V_o}{V_1} = -\frac{R_f}{R_1}} \qquad (14.8)$$

The result, in Eq. (14.8), shows that the ratio of overall output to input voltage is dependent only on the values of resistors R1and Rf —provided that Av is very large.

Unity Gain

If $R_f = R_1$, the gain is

$$\text{voltage gain} = -\frac{R_f}{R_1} = -1$$

so that the circuit provides a unity voltage gain with 180° phase inversion. If R_f is exactly R_1, the voltage gain is exactly 1.

Constant Magnitude Gain

If R_f is some multiple of R_1, the overall amplifier gain is a constant. For example, if $R_f = 10R_1$, then

$$\text{voltage gain} = -\frac{R_f}{R_1} = -10$$

and the circuit provides a voltage gain of exactly 10 along with an 180° phase inversion from the input signal. If we select precise resistor values for R_f and R_1, we can obtain a wide range of gains, the gain being as accurate as the resistors used and is only slightly affected by temperature and other circuit factors.

Virtual Ground

The output voltage is limited by the supply voltage of, typically, a few volts. As stated before, voltage gains are very high. If, for example, $V_o = -10$ V and $A_v = 20{,}000$, the input voltage would then be

$$V_i = \frac{-V_o}{A_v} = \frac{10\text{ V}}{20{,}000} = 0.5\text{ mV}$$

If the circuit has an overall gain (V_o/V_1) of, say, 1, the value of V_1 would then be 10 V. Compared to all other input and output voltages, the value of V_i is then small and may be considered 0 V.

Note that although $V_i \approx 0$ V, it is not exactly 0 V. (The output voltage is a few volts due to the very small input V_i times a very large gain A_v.) The fact that $V_i \approx 0$ V leads to the concept that at the amplifier input there exists a virtual short circuit or virtual ground.

The concept of a virtual short implies that although the voltage is nearly 0 V, there is no current through the amplifier input to ground. Figure 14.14 depicts the virtual ground concept. The heavy line is used to indicate that we may consider that a short

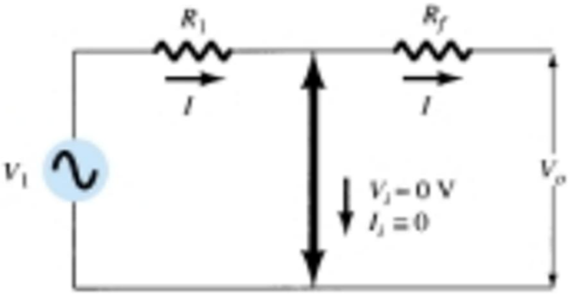


Figure 14.14 Virtual ground in an op-amp.

exists with $V_i \approx 0$ V but that this is a virtual short so that no current goes through the short to ground. Current goes only through resistors R1and Rf as shown. Using the virtual ground concept, we can write equations for the current I as follows:

$$I = \frac{V_1}{R_1} = -\frac{V_o}{R_f}$$

which can be solved for V_o/V_1:

$$\frac{V_o}{V_1} = -\frac{R_f}{R_1}$$

The virtual ground concept, which depends on Av being very large, allowed a simple solution to determine the overall voltage gain. It should be understood that although the circuit of Fig. 14.14 is not physically correct, it does allow an easy means for determining the overall voltage gain.

PRACTICAL OP-AMP CIRCUITS

The op-amp can be connected in a large number of circuits to provide various operating characteristics. In this section, we cover a few of the most common of these circuit connections.

Inverting Amplifier

The most widely used constant-gain amplifier circuit is the inverting amplifier, as shown in Fig. 14.15. The output is obtained by multiplying the input by a fixed or constant gain, set by the input resistor (R1) and feedback resistor (Rf)—this output also being inverted from the input. Using Eq. (14.8) we can write

$$V_o = -\frac{R_f}{R_1} V_1$$

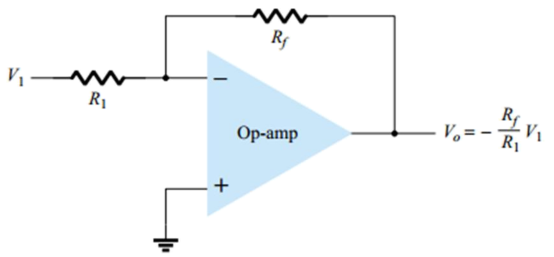


Figure 14.15 Inverting constant-gain multiplier.

If the circuit of Fig. 14.15 has $R_1 = 100\ \text{k}\Omega$ and $R_f = 500\ \text{k}\Omega$, what output voltage results for an input of $V_1 = 2$ V?

EXAMPLE 14.3

Solution

$$\text{Eq. (14.8): } V_o = -\frac{R_f}{R_1} V_1 = -\frac{500\ \text{k}\Omega}{100\ \text{k}\Omega}(2\ \text{V}) = \mathbf{-10\ V}$$

Noninverting Amplifier

The connection of Fig. 14.16a shows an op-amp circuit that works as a noninverting amplifier or constant-gain multiplier. It should be noted that the inverting amplifier connection is more widely used because it has better frequency stability (discussed later). To determine the voltage gain of the circuit, we can use the equivalent representation shown in Fig. 14.16b. Note that the voltage across R1 is V1 since $V_i \approx 0\ \text{V}$. This must be equal to the output voltage, through a voltage divider of R1 and Rf, so that

$$V_1 = \frac{R_1}{R_1 + R_f} V_o$$

which results in

$$\frac{V_o}{V_1} = \frac{R_1 + R_f}{R_1} = 1 + \frac{R_f}{R_1} \qquad (14.9)$$

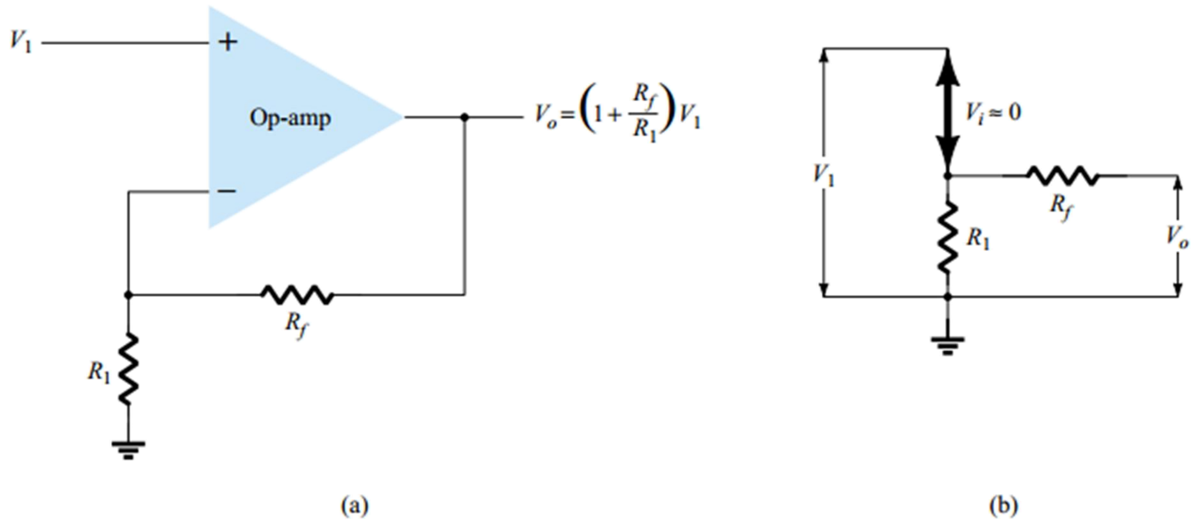


Figure 14.16 Noninverting constant-gain multiplier.

EXAMPLE 14.4 Calculate the output voltage of a noninverting amplifier (as in Fig. 14.16) for values of $V_1 = 2$ V, $R_f = 500$ kΩ, and $R_1 = 100$ kΩ.

Solution

Eq. (14.9): $V_o = \left(1 + \frac{R_f}{R_1}\right)V_1 = \left(1 + \frac{500\text{ k}\Omega}{100\text{ k}\Omega}\right)(2\text{ V}) = 6(2\text{ V}) = \mathbf{+12\ V}$

Unity Follower/Voltage follower

The unity-follower circuit, as shown in Fig. 14.17a, provides a gain of unity (1) with no polarity or phase reversal. From the equivalent circuit (see Fig. 14.17b) it is clear that

$$V_o = V_1 \qquad (14.10)$$

and that the output is the same polarity and magnitude as the input. The circuit operates like an emitter- or source-follower circuit except that the gain is exactly unity.

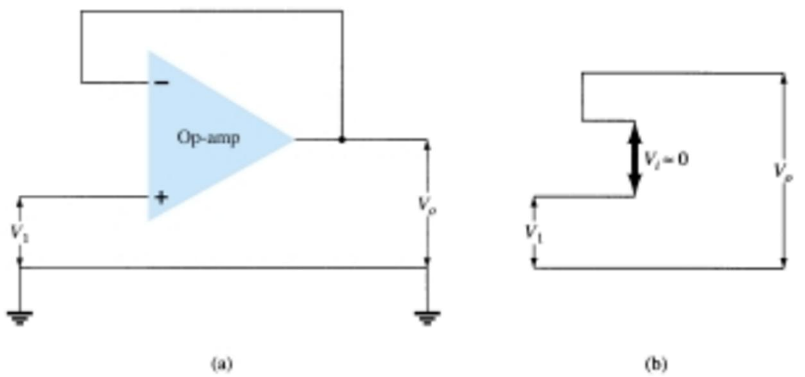


Figure 14.17 (a) Unity follower; (b) virtual-ground equivalent circuit.

Summing Amplifier

Probably the most used of the op-amp circuits is the summing amplifier circuit shown in Fig. 14.18a. The circuit shows a three-input summing amplifier circuit, which provides a means of algebraically summing (adding) three voltages, each multiplied by a constant-gain factor. Using the equivalent representation shown in Fig. 14.18b, the output voltage can be expressed in terms of the inputs as

$$V_o = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right) \tag{14.11}$$

In other words, each input adds a voltage to the output multiplied by its separate constant-gain multiplier. If more inputs are used, they each add an additional component to the output.

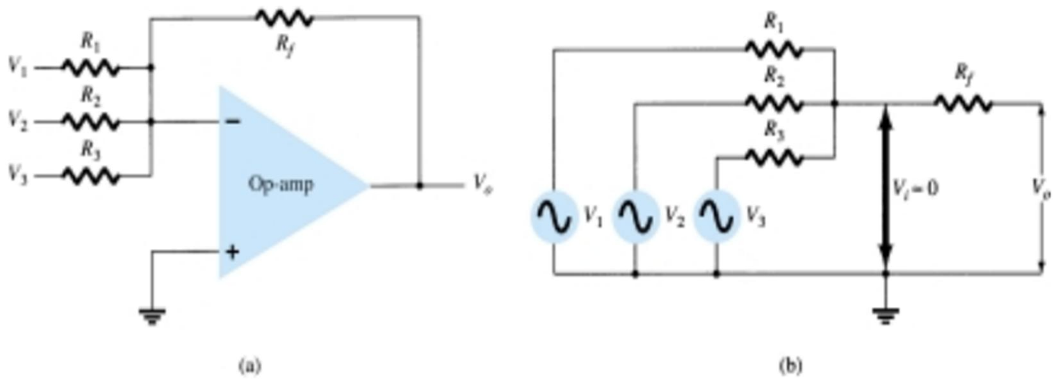


Figure 14.18 (a) Summing amplifier; (b) virtual-ground equivalent circuit.

EXAMPLE 14.5

Calculate the output voltage of an op-amp summing amplifier for the following sets of voltages and resistors. Use $R_f = 1\ \text{M}\Omega$ in all cases.

(a) $V_1 = +1$ V, $V_2 = +2$ V, $V_3 = +3$ V, $R_1 = 500\ \text{k}\Omega$, $R_2 = 1\ \text{M}\Omega$, $R_3 = 1\ \text{M}\Omega$.
(b) $V_1 = -2$ V, $V_2 = +3$ V, $V_3 = +1$ V, $R_1 = 200\ \text{k}\Omega$, $R_2 = 500\ \text{k}\Omega$, $R_3 = 1\ \text{M}\Omega$.

Solution

Using Eq. (14.11):

$$(a)\ V_o = -\left[\frac{1000\ k\Omega}{500\ k\Omega}(+1\ V) + \frac{1000\ k\Omega}{1000\ k\Omega}(+2\ V) + \frac{1000\ k\Omega}{1000\ k\Omega}(+3\ V)\right]$$

$$= -[2(1\ V) + 1(2\ V) + 1(3\ V)] = \mathbf{-7\ V}$$

$$(b)\ V_o = -\left[\frac{1000\ k\Omega}{200\ k\Omega}(-2\ V) + \frac{1000\ k\Omega}{500\ k\Omega}(+3\ V) + \frac{1000\ k\Omega}{1000\ k\Omega}(+1\ V)\right]$$

$$= -[5(-2\ V) + 2(3\ V) + 1(1\ V)] = \mathbf{+3\ V}$$

Integrator

So far, the input and feedback components have been resistors. If the feedback component used is a capacitor, as shown in Fig. 14.19a, the resulting connection is called an integrator. The virtual-ground equivalent circuit (Fig. 14.19b) shows that an expression for the voltage between input and output can be derived in terms of the current I, from input to output. Recall that virtual ground means that we can consider the voltage at the junction of R and X_c to be ground (since $V_i \approx 0\ V$) but that no current goes into ground at that point. The capacitive impedance can be expressed as

$$X_C = \frac{1}{j\omega C} = \frac{1}{sC}$$

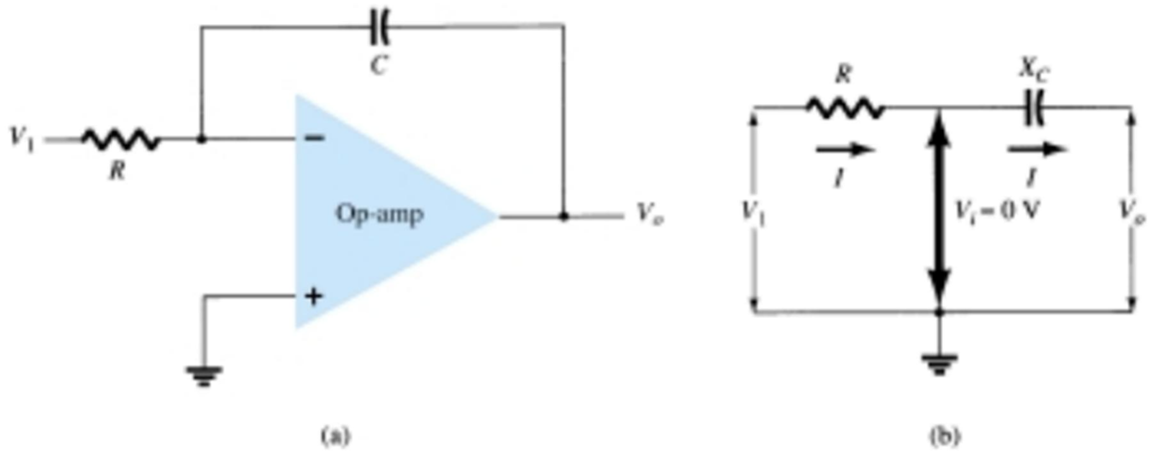


Figure 14.19 Integrator.

where $s = j\omega$ is in the Laplace notation.* Solving for V_o/V_1 yields

$$I = \frac{V_1}{R} = -\frac{V_o}{X_C} = \frac{-V_o}{1/sC} = -sCV_o$$

$$\frac{V_o}{V_1} = \frac{-1}{sCR} \tag{14.12}$$

The expression above can be rewritten in the time domain as

$$v_o(t) = -\frac{1}{RC}\int v_1(t)\,dt \qquad (14.13)$$

*Laplace notation allows expressing differential or integral operations which are part of calculus in algebraic form using the operator **s**. Readers unfamiliar with calculus should ignore the steps leading to Eq. (14.13) and follow the physical meaning used thereafter.

Equation (14.13) shows that the output is the integral of the input, with an inversion and scale multiplier of 1/RC. The ability to integrate a given signal provides the analog computer with the ability to solve differential equations and therefore provides the ability to electrically solve analogs of physical system operation. The integration operation is one of summation, summing the area under a waveform or curve over a period of time. If a fixed voltage is applied as input to an integrator circuit, Eq. (14.13) shows that the output voltage grows over a period of time, providing a ramp voltage. Equation (14.13) can thus be understood to show that the output voltage ramp (for a fixed input voltage) is opposite in polarity to the input voltage and is multiplied by the factor 1/RC. While the circuit of Fig. 14.19 can operate on many varied types of input signals, the following examples will use only a fixed input voltage, resulting in a ramp output voltage. As an example, consider an input voltage, V1 = 1 V, to the integrator circuit of Fig. 14.20a. The scale factor of 1/RC is

$$-\frac{1}{RC} = \frac{1}{(1\ \text{M}\Omega)(1\ \mu\text{F})} = -1$$

so that the output is a negative ramp voltage as shown in Fig. 14.20b. If the scale factor is changed by making $R = 100\ \text{k}\Omega$, for example, then

$$-\frac{1}{RC} = \frac{1}{(100\ \text{k}\Omega)(1\ \mu\text{F})} = -10$$

and the output is then a steeper ramp voltage, as shown in Fig. 14.20c.

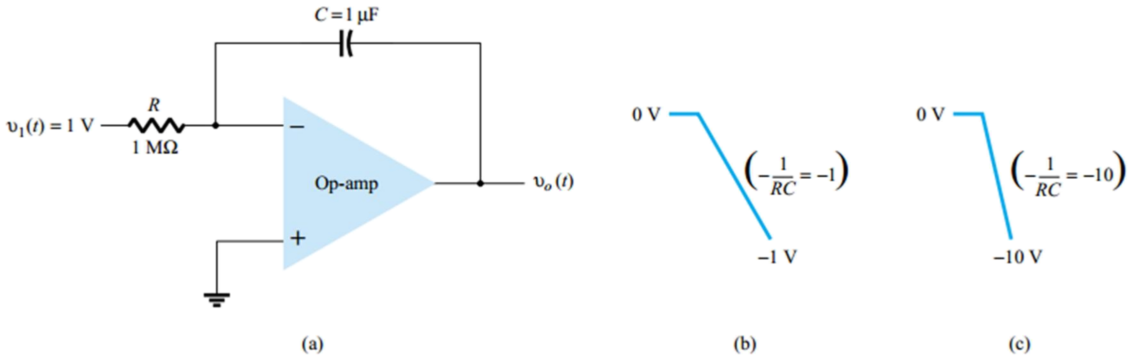


Figure 14.20 Operation of integrator with step input.

More than one input may be applied to an integrator, as shown in Fig. 14.21, with the resulting operation given by

$$v_o(t) = -\left[\frac{1}{R_1C}\int v_1(t)\,dt + \frac{1}{R_2C}\int v_2(t)\,dt + \frac{1}{R_3C}\int v_3(t)\,dt\right] \quad (14.14)$$

An example of a summing integrator as used in an analog computer is given in Fig. 14.21. The actual circuit is shown with input resistors and feedback capacitor, whereas the analog-computer representation indicates only the scale factor for each input.

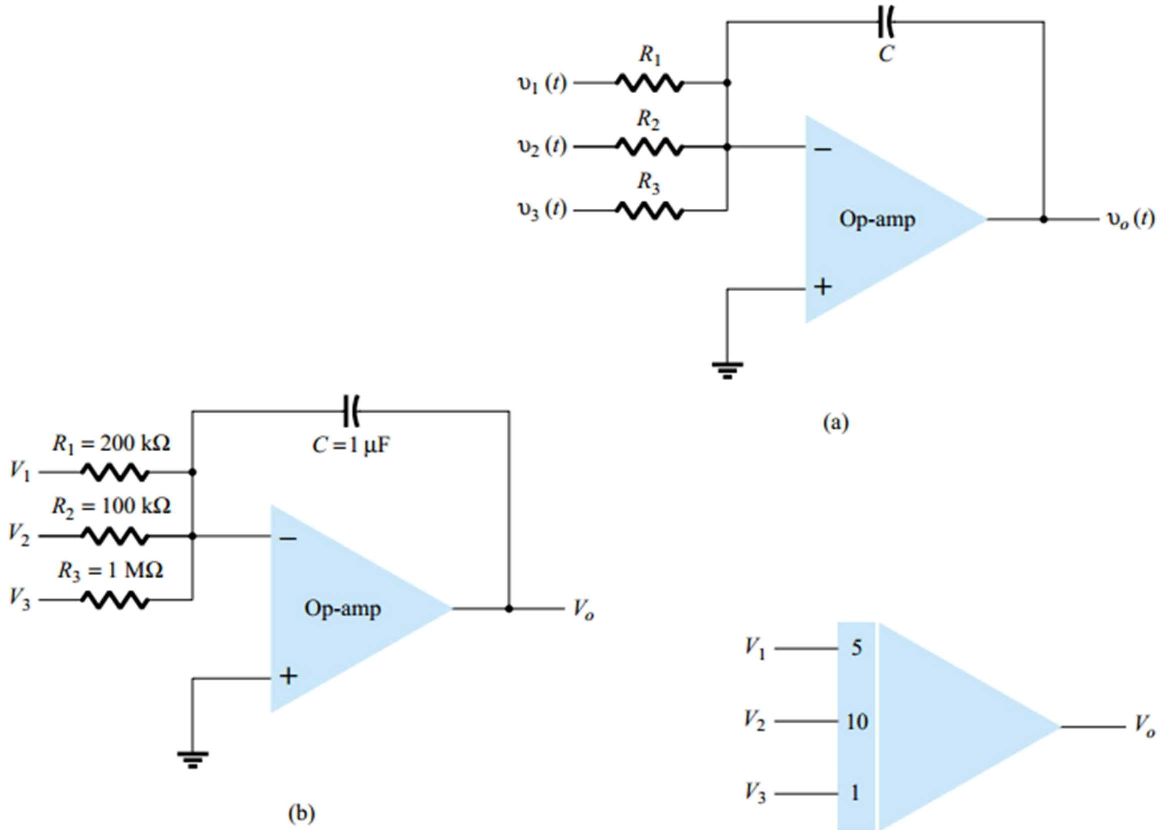


Figure 14.21 (a) Summing-integrator circuit; (b) component values; (c) analog-computer, integrator-circuit representation.

Differentiator

A differentiator circuit is shown in Fig. 14.22. While not as useful as the circuit forms covered above, the differentiator does provide a useful operation, the resulting relation for the circuit being

$$v_o(t) = -RC\frac{dv_1(t)}{dt} \quad (14.15)$$

where the scale factor is $-RC$.

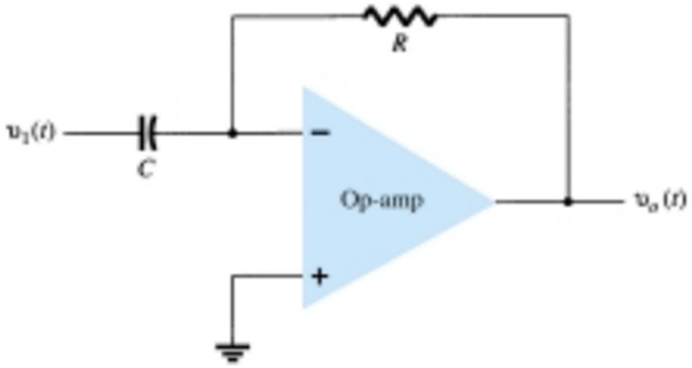


Figure 14.22 Differentiator circuit.

Closed-Loop Voltage Gain, Acl

The closed-loop voltage gain is the voltage gain of an op-amp with external feedback. The amplifier configuration consists of the op-amp and an external negative feedback circuit that connects the output to the inverting input. The closed-loop voltage gain is determined by the external component values and can be precisely controlled by them.

Noninverting Amplifier

An op-amp connected in a closed-loop configuration as a noninverting amplifier with a controlled amount of voltage gain is shown in Figure 12–16. The input signal is applied to the noninverting (+) input. The output is applied back to the inverting input through the feedback circuit (closed loop) formed by the input resistor Ri and the feedback resistor Rf. This creates negative feedback as follows. Resistors Ri and Rf form a voltage-divider circuit, which reduces Vout and connects the reduced voltage V_f to the inverting input. The feedback voltage is expressed as

$$V_f = \left(\frac{R_i}{R_i + R_f}\right)V_{out}$$

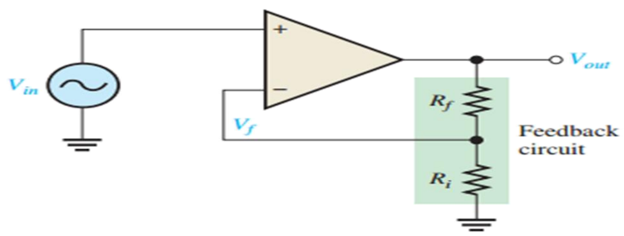


FIGURE 12–16
Noninverting amplifier.

The difference of the input voltage, Vin, and the feedback voltage, Vf, is the differential input to the op-amp, as shown in Figure 12–17. This differential voltage is amplified by the open-loop voltage gain of the op-amp (Aol) and produces an output voltage expressed as

$$V_{out} = A_{ol}(V_{in} - V_f)$$

The attenuation, B, of the feedback circuit is

$$B = \frac{R_i}{R_i + R_f}$$

Substituting BV_{out} for V_f in the V_{out} equation,

$$V_{out} = A_{ol}(V_{in} - BV_{out})$$

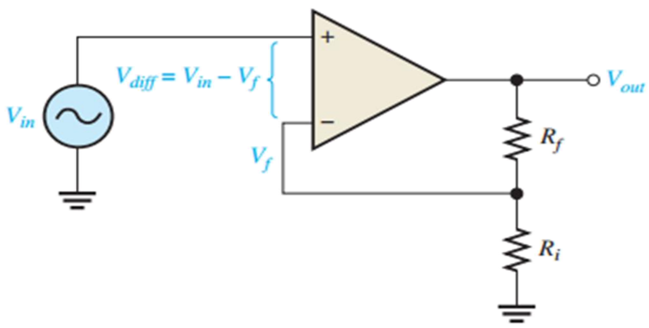


FIGURE 12–17

Differential input, $V_{in} - V_f$.

Then applying basic algebra,

$$V_{out} = A_{ol}V_{in} - A_{ol}BV_{out}$$
$$V_{out} + A_{ol}BV_{out} = A_{ol}V_{in}$$
$$V_{out}(1 + A_{ol}B) = A_{ol}V_{in}$$

Since the overall voltage gain of the amplifier in Figure 12–16 is V_{out}/V_{in}, it can be expressed as

$$\frac{V_{out}}{V_{in}} = \frac{A_{ol}}{1 + A_{ol}B}$$

The product $A_{ol}B$ is typically much greater than 1, so the equation simplifies to

$$\frac{V_{out}}{V_{in}} \cong \frac{A_{ol}}{A_{ol}B} = \frac{1}{B}$$

The closed-loop gain of the noninverting (NI) amplifier is the reciprocal of the attenuation (B) of the feedback circuit (voltage-divider).

$$A_{cl(NI)} = \frac{V_{out}}{V_{in}} \cong \frac{1}{B} = \frac{R_i + R_f}{R_i}$$

Therefore,

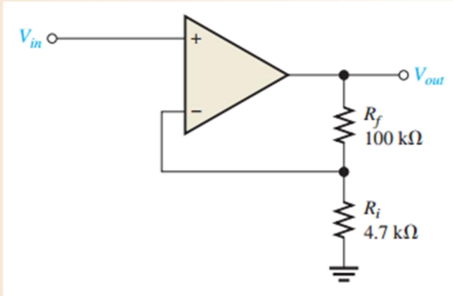
Equation 12–8

$$\mathbf{A_{cl(NI)} = 1 + \frac{R_f}{R_i}}$$

Notice that the closed-loop voltage gain is not at all dependent on the op-amp's open-loop voltage gain under the condition The closed-loop gain can be set by selecting values of Ri and Rf.

EXAMPLE 12–3 Determine the closed-loop voltage gain of the amplifier in Figure 12–18.

▶ FIGURE 12–18



Solution This is a noninverting op-amp configuration. Therefore, the closed-loop voltage gain is

$$A_{cl(NI)} = 1 + \frac{R_f}{R_i} = 1 + \frac{100\,\text{k}\Omega}{4.7\,\text{k}\Omega} = \mathbf{22.3}$$

Related Problem If R_f in Figure 12–18 is increased to 150 kΩ, determine the closed-loop gain.

OP-AMP SPECIFICATIONS—DC OFFSET PARAMETERS

Before going into various practical applications using op-amps, we should become familiar with some of the parameters used to define the operation of the unit. These specifications include both dc and transient or frequency operating features, as covered next.

Offset Currents and Voltages

While the op-amp output should be 0 V when the input is 0 V, in actual operation there is some offset voltage at the output. For example, if one connected 0 V to both op-amp inputs and then measured 26 mV(dc) at the output, this would represent 26 mV of unwanted voltage generated by the circuit and not by the input signal. Since the user may connect the amplifier circuit for various gain and polarity operations, however, the manufacturer specifies an input offset voltage for the op-amp. The output offset voltage is then determined by the input offset voltage and the gain of the amplifier, as connected by the user. The output offset voltage can be shown to be affected by two separate circuit conditions. These are: (1) an input offset voltage, V_{IO}, and (2) an offset current due to the difference in currents resulting at the plus (+) and minus (-) inputs.

INPUT OFFSET VOLTAGE, V_{IO}

The manufacturer's specification sheet provides a value of V_{IO} for the op-amp. To determine the effect of this input voltage on the output, consider the connection shown in Fig. 14.23. Using Vo = AVi, we can write

$$V_o = AV_i = A\left(V_{IO} - V_o \frac{R_1}{R_1 + R_f}\right)$$

Solving for V_o, we get

$$V_o = V_{IO}\frac{A}{1 + A[R_1/(R_1 + R_f)]} \approx V_{IO}\frac{A}{A[R_1/(R_1 + R_f)]}$$

from which we can write

$$V_o(\text{offset}) = V_{IO}\frac{R_1 + R_f}{R_1} \qquad (14.16)$$

Equation (14.16) shows how the output offset voltage results from a specified input offset voltage for a typical amplifier connection of the op-amp.

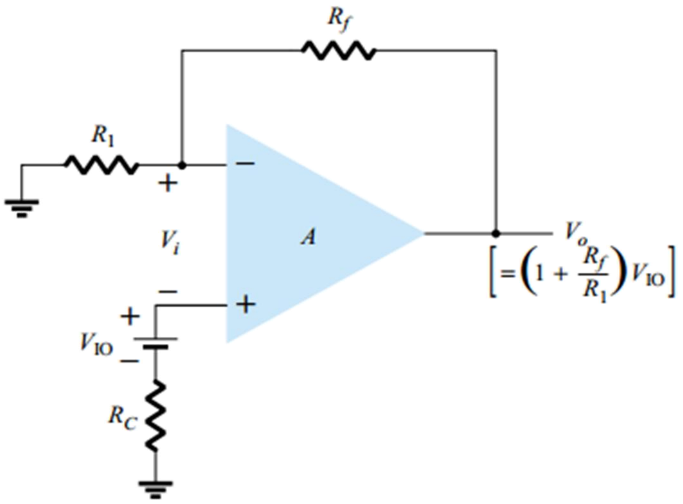


Figure 14.23 Operation showing effect of input offset voltage, V_{IO}.

EXAMPLE 14.6 Calculate the output offset voltage of the circuit in Fig. 14.24. The op-amp spec lists $V_{IO} = 1.2$ mV.

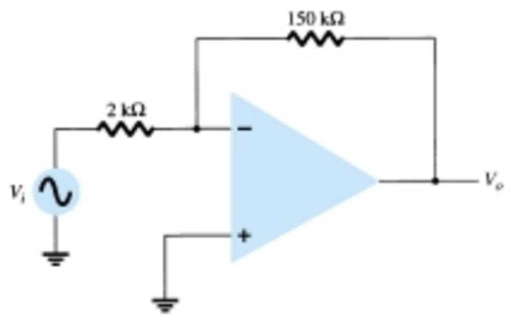


Figure 14.24 Op-amp connection for Examples 14.6 and 14.7.

Solution

Eq. (14.16): $V_o(\text{offset}) = V_{IO}\frac{R_1 + R_f}{R_1} = (1.2\text{ mV})\left(\frac{2\text{ k}\Omega + 150\text{ k}\Omega}{2\text{ k}\Omega}\right) = \mathbf{91.2\text{ mV}}$

OUTPUT OFFSET VOLTAGE DUE TO INPUT OFFSET CURRENT, I_{IO}

An output offset voltage will also result due to any difference in dc bias currents at both inputs. Since the two input transistors are never exactly matched, each will operate at a slightly different current. For a typical op-amp connection, such as that shown in Fig. 14.25, an output offset voltage can be determined as follows. Replacing the bias currents through the input resistors by the voltage drop that each develops, as shown in Fig. 14.26, we can determine the expression for the resulting output voltage. Using superposition, the output voltage due to input bias current I^+_{IB}, denoted by V^+_o, is

$$V_o^+ = I_{IB}^+ R_C\left(1 + \frac{R_f}{R_1}\right)$$

while the output voltage due to only I_{IB}^-, denoted by V_o^-, is

$$V_o^- = I_{IB}^- R_1\left(-\frac{R_f}{R_1}\right)$$

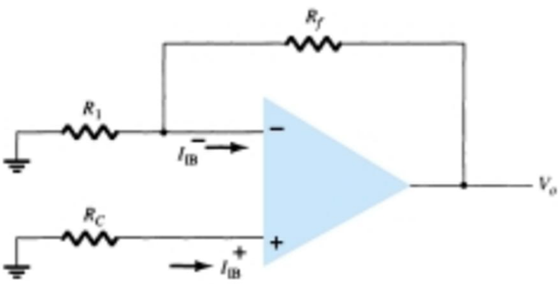


Figure 14.25 Op-amp connection showing input bias currents.

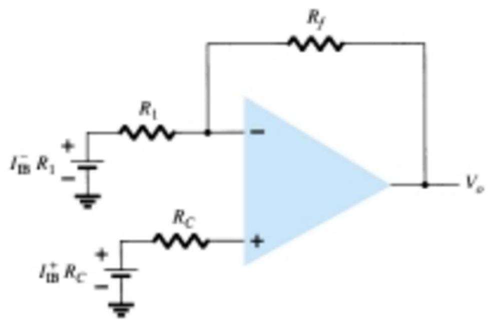


Figure 14.26 Redrawn circuit of Fig. 14.25.

for a total output offset voltage of

$$V_o(\text{offset due to } I_{IB}^+ \text{ and } I_{IB}^-) = I_{IB}^+ R_C\left(1 + \frac{R_f}{R_1}\right) - I_{IB}^- R_1\frac{R_f}{R_1} \qquad (14.17)$$

Since the main consideration is the difference between the input bias currents rather than each value, we define the offset current I_{IO} by

$$I_{IO} = I_{IB}^+ - I_{IB}^-$$

Since the compensating resistance R_C is usually approximately equal to the value of R_1, using $R_C = R_1$ in Eq. (14.17) we can write

$$V_o(\text{offset}) = I_{IB}^+(R_1 + R_f) - I_{IB}^- R_f$$

$$= I_{IB}^+ R_f - I_{IB}^- R_f = R_f(I_{IB}^+ - I_{IB}^-)$$

resulting in

$$\boxed{V_o(\text{offset due to } I_{IO}) = I_{IO} R_f} \qquad (14.18)$$

EXAMPLE 14.7

Calculate the offset voltage for the circuit of Fig. 14.24 for op-amp specification listing $I_{IO} = 100$ nA.

Solution

Eq. (14.18): $V_o = I_{IO} R_f = (100 \text{ nA})(150 \text{ k}\Omega) = \mathbf{15\ mV}$

TOTAL OFFSET DUE TO V_{IO} AND I_{IO}

Since the op-amp output may have an output offset voltage due to both factors covered above, the total output offset voltage can be expressed as

$$|V_o(\text{offset})| = |V_o(\text{offset due to } V_{IO})| + |V_o(\text{offset due to } I_{IO})| \qquad (14.19)$$

The absolute magnitude is used to accommodate the fact that the offset polarity may be either positive or negative.

EXAMPLE 14.8

Calculate the total offset voltage for the circuit of Fig. 14.27 for an op-amp with specified values of input offset voltage, $V_{IO} = 4$ mV and input offset current $I_{IO} =$ 150 nA.

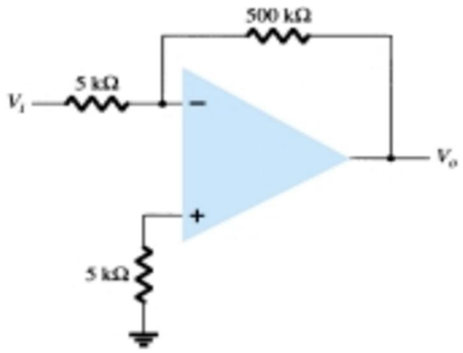


Figure 14.27 Op-amp circuit for Example 14.8.

Solution

The offset due to V_{IO} is

$$\text{Eq. (14.16):}\quad V_o(\text{offset due to } V_{IO}) = V_{IO}\frac{R_1 + R_f}{R_1} = (4\text{ mV})\left(\frac{5\text{ k}\Omega + 500\text{ k}\Omega}{5\text{ k}\Omega}\right)$$

$$= 404\text{ mV}$$

$$\text{Eq. (14.18):}\quad V_o(\text{offset due to } I_{IO}) = I_{IO}R_f = (150\text{ nA})(500\text{ k}\Omega) = 75\text{ mV}$$

resulting in a total offset

$$\text{Eq. (14.19):}\quad V_o(\text{total offset}) = V_o(\text{offset due to } V_{IO}) + V_o(\text{offset due to } I_{IO})$$

$$= 404\text{ mV} + 75\text{ mV} = \mathbf{479\text{ mV}}$$

INPUT BIAS CURRENT, I_{IB}

A parameter related to I_{IO} and the separate input bias currents I^+_{IB} and I^-_{IB} is the average bias current defined as

$$I_{IB} = \frac{I^+_{IB} + I^-_{IB}}{2} \qquad (14.20)$$

One could determine the separate input bias currents using the specified values I_{IO} and I_{IB}. It can be shown that for $I^{+}_{IB} > I^{-}_{IB}$

$$I^{+}_{IB} = I_{IB} + \frac{I_{IO}}{2} \quad (14.21)$$

$$I^{-}_{IB} = I_{IB} - \frac{I_{IO}}{2} \quad (14.21)$$

EXAMPLE 14.9 Calculate the input bias currents at each input of an op-amp having specified values of $I_{IO} = 5$ nA and $I_{IB} = 30$ nA.

Solution

Using Eq. (14.21):

$$I^{+}_{IB} = I_{IB} + \frac{I_{IO}}{2} = 30 \text{ nA} + \frac{5 \text{ nA}}{2} = \mathbf{32.5 \text{ nA}}$$

$$I^{-}_{IB} = I_{IB} - \frac{I_{IO}}{2} = 30 \text{ nA} - \frac{5 \text{ nA}}{2} = \mathbf{27.5 \text{ nA}}$$

OP-AMP SPECIFICATIONS - FREQUENCY PARAMETERS

An op-amp is designed to be a high-gain, wide-bandwidth amplifier. This operation tends to be unstable (oscillate) due to positive feedback (see Chapter 4). To ensure stable operation, op-amps are built with internal compensation circuitry, which also causes the very high open-loop gain to diminish with increasing frequency. This gain reduction is referred to as roll-off. In most op-amps, roll-off occurs at a rate of 20 dB per decade (-20 dB/decade) or 6 dB per octave (-6 dB/octave). (Refer to introductory coverage of dB and frequency response.)

Note that while op-amp specifications list an open-loop voltage gain (A_{VD}), the user typically connects the op-amp using feedback resistors to reduce the circuit voltage gain to a much smaller value (closed-loop voltage gain, A_{CL}). A number of circuit improvements result from this gain reduction. First, the amplifier voltage gain is a more stable, precise value set by the external resistors; second, the input impedance of the circuit is increased over that of the op-amp alone; third, the circuit output impedance is reduced from that of the op-amp alone; and finally, the frequency response of the circuit is increased over that of the op-amp alone.

Gain–Bandwidth

Because of the internal compensation circuitry included in an op-amp, the voltage gain drops off as frequency increases. Op-amp specifications provide a description of the gain versus bandwidth. Figure 14.28 provides a plot of gain versus frequency for a typical op-amp. At low frequency down to dc operation the gain is that value listed by the manufacturer's specification A_{VD}(voltage differential gain) and is typically a very large value. As the frequency of the input signal increases the open-loop gain drops off until it finally reaches the value of 1 (unity). The frequency at this gain value is specified by the manufacturer as the unity-gain bandwidth, B1. While this value is a frequency (see Fig. 14.28) at which the gain becomes 1, it can be considered a bandwidth, since the frequency band from 0 Hz to the unity-gain frequency is also a bandwidth. One could therefore refer to the point at which the gain reduces to 1 as the unity-gain frequency (f1) or unity-gain bandwidth (B1).

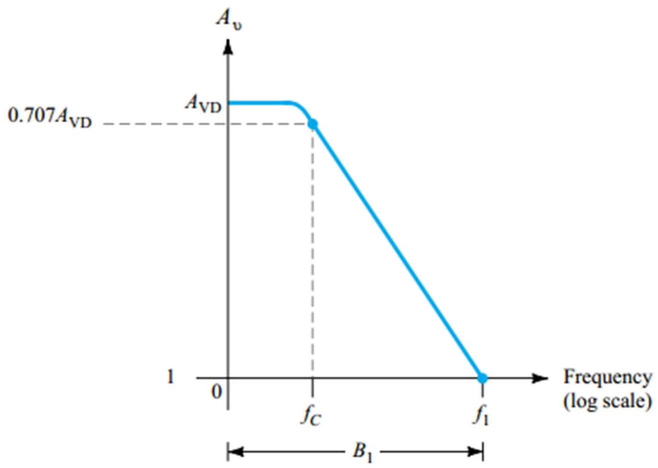


Figure 14.28 Gain versus frequency plot.

Another frequency of interest is that shown in Fig. 14.28, at which the gain drops by 3 dB (or to 0.707 the dc gain, A_{VD}), this being the cutoff frequency of the op-amp, f_C. In fact, the unity-gain frequency and cutoff frequency are related by

$$f_1 = A_{VD} f_C \quad (14.22)$$

Equation (14.22) shows that the unity-gain frequency may also be called the gain-bandwidth product of the op-amp.

EXAMPLE 14.10 Determine the cutoff frequency of an op-amp having specified values $B_1 = 1$ MHz and $A_{VD} = 200$ V/mV.

Solution

Since $f_1 = B_1 = 1$ MHz, we can use Eq. (14.22) to calculate

$$f_C = \frac{f_1}{A_{VD}} = \frac{1\text{ MHz}}{200\text{ V/mV}} = \frac{1 \times 10^6}{200 \times 10^3} = \mathbf{5\ Hz}$$

Slew Rate, SR

Another parameter reflecting the op-amp's ability to handling varying signals is slew rate, defined as

slew rate = maximum rate at which amplifier output can change in volts per microsecond (V/µs)

$$\boxed{SR = \frac{\Delta V_o}{\Delta t} \quad V/\mu s} \quad \text{with } t \text{ in } \mu s \qquad (14.23)$$

The slew rate provides a parameter specifying the maximum rate of change of the output voltage when driven by a large step-input signal. If one tried to drive the output at a rate of voltage change greater than the slew rate, the output would not be able to change fast enough and would not vary over the full range expected, resulting in signal clipping or distortion. In any case, the output would not be an amplified duplicate of the input signal if the op-amp slew rate is exceeded.

EXAMPLE 14.11 For an op-amp having a slew rate of SR = 2 V/μs, what is the maximum closed-loop voltage gain that can be used when the input signal varies by 0.5 V in 10 μs?

Solution

Since $V_o = A_{CL}V_i$, we can use

$$\frac{\Delta V_o}{\Delta t} = A_{CL}\frac{\Delta V_i}{\Delta t}$$

from which we get

$$A_{CL} = \frac{\Delta V_o/\Delta t}{\Delta V_i/\Delta t} = \frac{SR}{\Delta V_i/\Delta t} = \frac{2\ V/\mu s}{0.5\ V/10\ \mu s} = \mathbf{40}$$

Any closed-loop voltage gain of magnitude greater than 40 would drive the output at a rate greater than the slew rate allows, so the maximum closed-loop gain is 40.