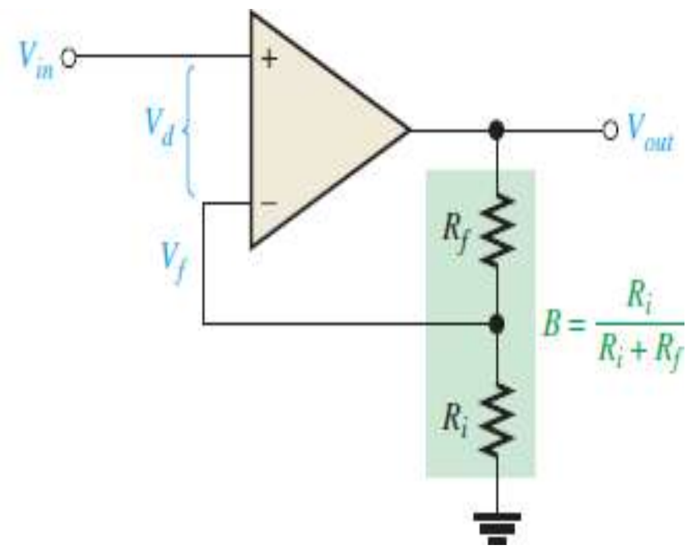
The Operational Amplifier

Effect of Negative FeedBack On OP-AMP Impedances

- **Impedances of a Non-inverting Amplifier**
  - ***Input Impedance***
    - The input impedance of a non-inverting amplifier can be developed with the aid of figure 12-23.
    - For this Analysis, assume a small differential voltage, V_d, exists between the two input terminals as indicated. This means that you cannot assume the op-amp's input impedance to be infinite or the input current to be 0.

FIGURE 12–23



Effect of Negative FeedBack On OP-AMP Impedances Continue…

- **Impedances of a Non-inverting Amplifier**
  - ***Input Impedance continue…***
    - The input voltage can be expressed as

$$V_{in} = V_d + V_f$$

Substituting BV_{out} for the feedback voltage, V_f, yields

$$V_{in} = V_d + BV_{out}$$

Remember, B is the attenuation of the negative feedback circuit and is equal to $R_i/(R_i + R_f)$.

Effect of Negative FeedBack On OP-AMP Impedances Continue…

- **Impedances of a Non-inverting Amplifier**
  - ***Input Impedance continue…***

Since $V_{out} \cong A_{ol}V_d$ (A_{ol} is the open-loop gain of the op-amp),

$$V_{in} = V_d + A_{ol}BV_d = (1 + A_{ol}B)V_d$$

Now substituting $I_{in}Z_{in}$ for V_d,

$$V_{in} = (1 + A_{ol}B)I_{in}Z_{in}$$

where Z_{in} is the open-loop input impedance of the op-amp (without feedback connections).

$$\frac{V_{in}}{I_{in}} = (1 + A_{ol}B)Z_{in}$$

V_{in}/I_{in} is the overall input impedance of a closed-loop noninverting amplifier configuration.

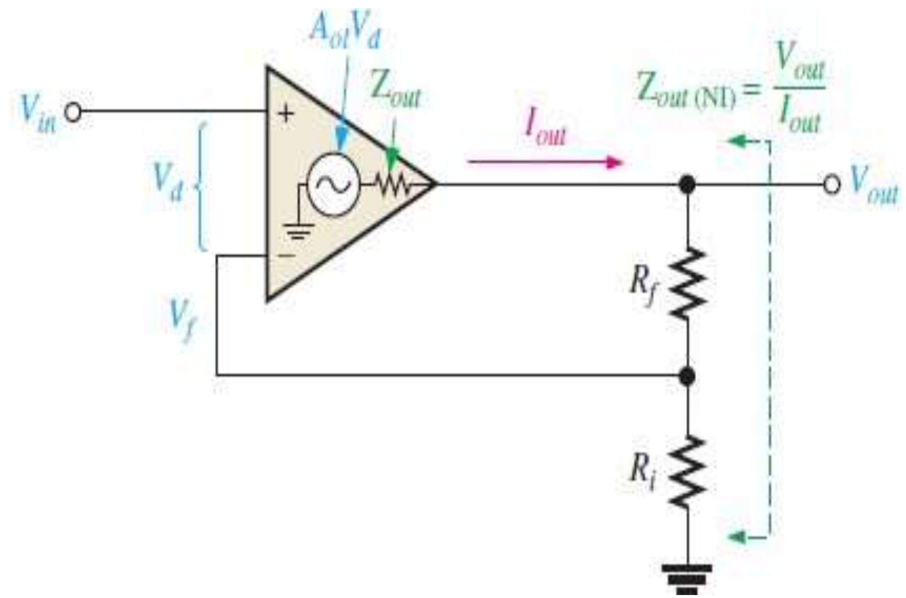
$$\mathbf{Z_{in(NI)} = (1 + A_{ol}B)Z_{in}}$$

This equation shows that the input impedance of the noninverting amplifier configuration with negative feedback is much greater than the internal input impedance of the op-amp itself (without feedback).

Effect of Negative FeedBack On OP-AMP Impedances Continue…

- **Impedances of a Non-inverting Amplifier**
  - ***Output Impedance***
    - An expression for output impedance of a non-inverting amplifier can be developed with the aid of figure 12-24.

FIGURE 12–24



Effect of Negative FeedBack On OP-AMP Impedances Continue…

- **Impedances of a Non-inverting Amplifier**
  - ***Output Impedance continue…***
    - By applying KVL to the output circuit of fig 12-24

$$V_{out} = A_{ol}V_d - Z_{out}I_{out}$$

The differential input voltage is $V_d = V_{in} - V_f$; therefore, by assuming that $A_{ol}V_d \gg Z_{out}I_{out}$, you can express the output voltage as

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

Substituting BV_{out} for V_f,

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

Expanding and factoring yields

$$V_{out} \cong A_{ol}V_{in} - A_{ol}BV_{out}$$

$$A_{ol}V_{in} \cong V_{out} + A_{ol}BV_{out} \cong (1 + A_{ol}B)V_{out}$$

Effect of Negative FeedBack On OP-AMP Impedances Continue…

- **Impedances of a Non-inverting Amplifier**
  - ***Output Impedance continue…***

Since the output impedance of the noninverting amplifier configuration is $Z_{out(\mathrm{NI})} = V_{out}/I_{out}$, you can substitute $I_{out}Z_{out(\mathrm{NI})}$ for V_{out}; therefore,

$$A_{ol}V_{in} = (1 + A_{ol}B)I_{out}Z_{out(\mathrm{NI})}$$

Dividing both sides of the previous expression by I_{out},

$$\frac{A_{ol}V_{in}}{I_{out}} = (1 + A_{ol}B)Z_{out(\mathrm{NI})}$$

The term on the left is the internal output impedance of the op-amp (Z_{out}) because, without feedback, $A_{ol}V_{in} = V_{out}$. Therefore,

$$Z_{out} = (1 + A_{ol}B)Z_{out(\mathrm{NI})}$$

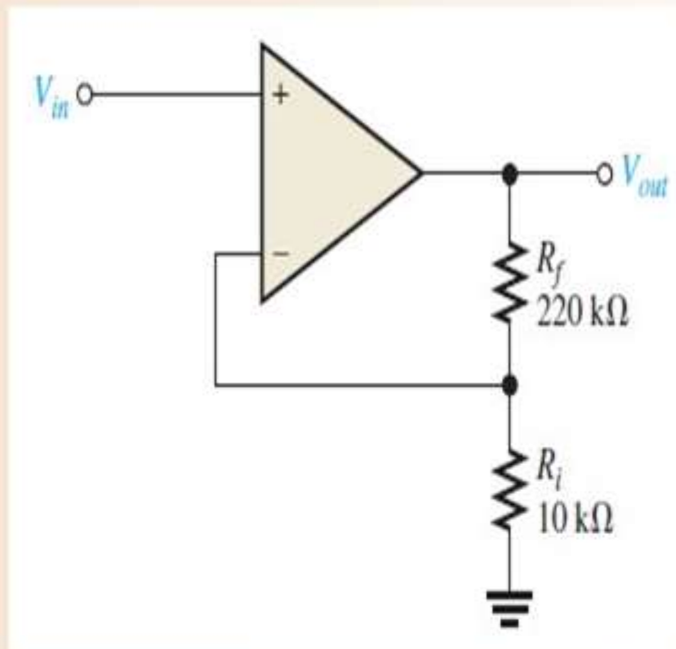
Thus,

$$Z_{out(\mathrm{NI})} = \frac{Z_{out}}{1 + A_{ol}B}$$

This equation shows that the output impedance of the noninverting amplifier configuration with negative feedback is much less than the internal output impedance, Z_{out}, of the op-amp itself (without feedback) because Z_{out} is divided by the factor $1 + A_{ol}B$.

(a) Determine the input and output impedances of the amplifier in Figure 12–25. The op-amp datasheet gives $Z_{in} = 2\,M\Omega$, $Z_{out} = 75\,\Omega$, and $A_{ol} = 200{,}000$.

(b) Find the closed-loop voltage gain.



Solution (a) The attenuation, B, of the feedback circuit is

$$B = \frac{R_i}{R_i + R_f} = \frac{10\,\text{k}\Omega}{230\,\text{k}\Omega} = 0.0435$$

$$Z_{in(\text{NI})} = (1 + A_{ol}B)Z_{in} = [1 + (200{,}000)(0.0435)](2\,\text{M}\Omega)$$
$$= (1 + 8700)(2\,\text{M}\Omega) = \mathbf{17.4\,G\Omega}$$

This is such a large number that, for all practical purposes, it can be assumed to be infinite as in the ideal case.

$$Z_{out(\text{NI})} = \frac{Z_{out}}{1 + A_{ol}B} = \frac{75\,\Omega}{1 + 8700} = \mathbf{8.6\,m\Omega}$$

This is such a small number that, for all practical purposes, it can be assumed to be zero as in the ideal case.

(b) $A_{cl(\text{NI})} = 1 + \dfrac{R_f}{R_i} = 1 + \dfrac{220\,\text{k}\Omega}{10\,\text{k}\Omega} = \mathbf{23.0}$

Effect of Negative FeedBack On OP-AMP Impedances Continue…

- **Voltage-Follower Impedances**
  - Since a voltage follower is a special case of the non-inverting amplifier configuration, the same impedance formulas are used but with $B = 1$.

$$Z_{in(VF)} = (1 + A_{ol})Z_{in}$$

$$Z_{out(VF)} = \frac{Z_{out}}{1 + A_{ol}}$$

  - Notice that the voltage-follower input impedance is greater for a given A_{ol} and Z_{in} than for the non-inverting amplifier configuration with voltage-divider feedback circuit. Also the output impedance is much smaller.

The op-amp in Example 12–5 is used in a voltage-follower configuration. Determine the input and output impedances.

Solution Since $B = 1$,

$$Z_{in(VF)} = (1 + A_{ol})Z_{in} = (1 + 200{,}000)(2\ \text{M}\Omega) \cong \mathbf{400\ G\Omega}$$

$$Z_{out(VF)} = \frac{Z_{out}}{1 + A_{ol}} = \frac{75\ \Omega}{1 + 200{,}000} = \mathbf{375\ \mu\Omega}$$

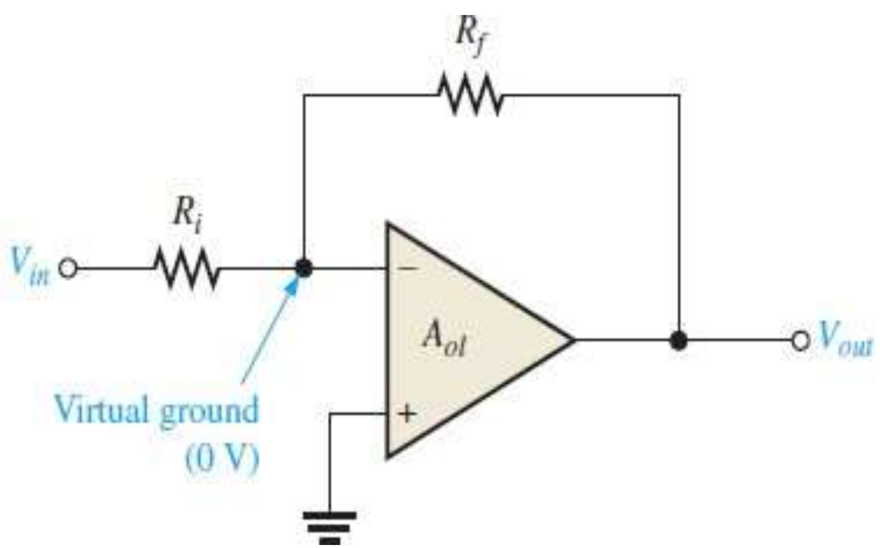
Notice that $Z_{in(VF)}$ is much greater than $Z_{in(NI)}$, and $Z_{out(VF)}$ is much less than $Z_{out(NI)}$ from Example 12–5. Again for all practical purposes, the ideal values can be assumed.

Effect of Negative FeedBack On OP-AMP Impedances Continue…

- **Impedances of an Inverting Amplifier**
  - ***Input Impedance***
    - The input impedance of an inverting amplifier can be developed with the aid of figure 12-26.
    - The input signal is applied through a series resistor , R_i , to inverting (-) terminal.
    - The input impedance of an inverting amplifier is $Z_{in\ (\mathrm{I})} \approx R_i$

FIGURE 12–26

Inverting amplifier.



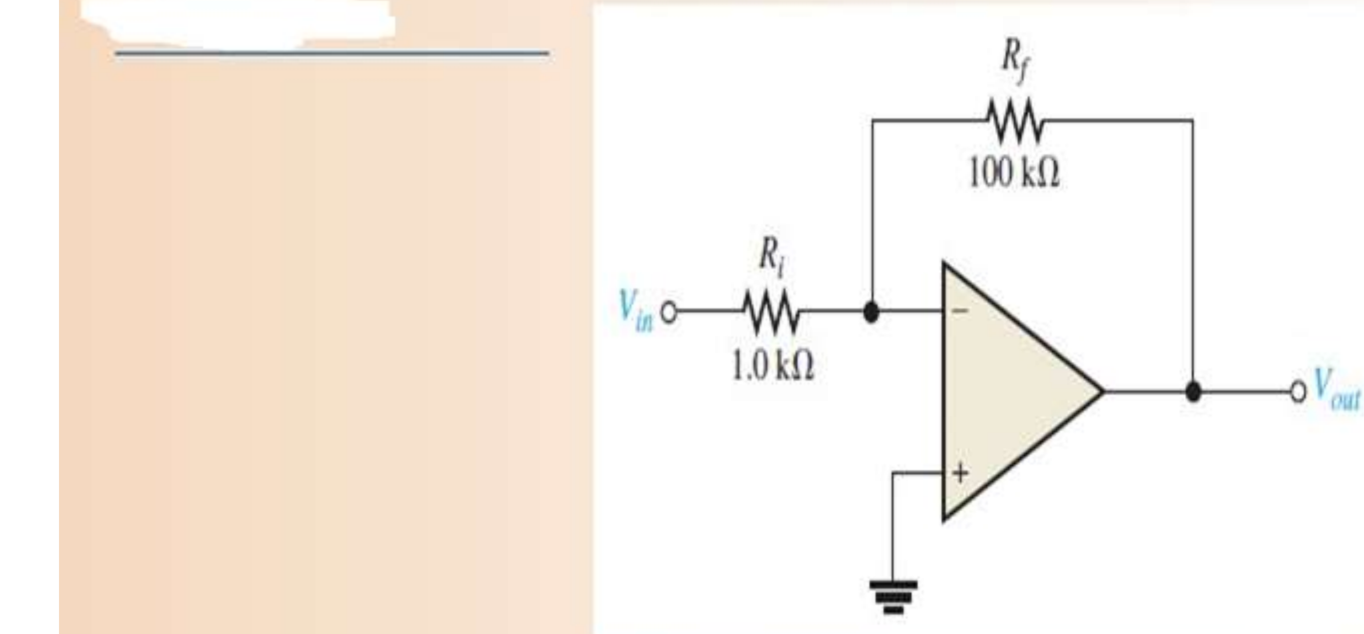
Effect of Negative FeedBack On OP-AMP Impedances Continue…

- **Impedances of an Inverting Amplifier**
  - ***Output Impedance***
    - As with a non-inverting amplifier, the output impedance of an inverting amplifier is also decreased by the negative feedback, the expression is the same as for the non-inverting case.

$$Z_{out(I)} = \frac{Z_{out}}{1 + A_{ol}B}$$

    - The output impedance of both the non-inverting and the inverting amplifier configurations is very low; in fact it is almost zero in practical cases.

Find the values of the input and output impedances in Figure 12–28. Also, determine the closed-loop voltage gain. The op-amp has the following parameters: $A_{ol} = 50{,}000$; $Z_{in} = 4\ \text{M}\Omega$; and $Z_{out} = 50\ \Omega$.



Solution

$$Z_{in(\mathrm{I})} \cong R_i = \mathbf{1.0\,k\Omega}$$

The feedback attenuation, B, is

$$B = \frac{R_i}{R_i + R_f} = \frac{1.0\,\mathrm{k\Omega}}{101\,\mathrm{k\Omega}} = 0.001$$

Then

$$Z_{out(\mathrm{I})} = \frac{Z_{out}}{1 + A_{ol}B} = \frac{50\,\Omega}{1 + (50{,}000)(0.001)}$$

$$= \mathbf{980\,m\Omega} \text{ (zero for all practical purposes)}$$

The closed-loop voltage gain is

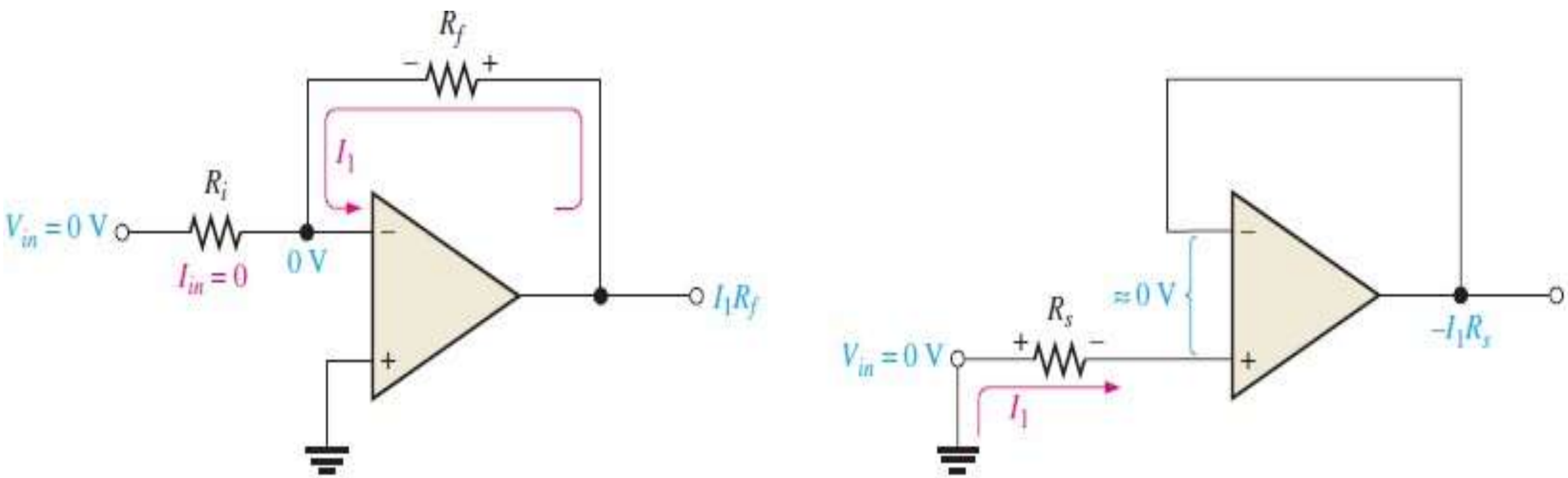
$$A_{cl(\mathrm{I})} = -\frac{R_f}{R_i} = -\frac{100\,\mathrm{k\Omega}}{1.0\,\mathrm{k\Omega}} = \mathbf{-100}$$

Bias Current and Offset Voltage

- The practical op-amp has small input bias currents typically in nA range. Also small internal imbalances in the transistors effectively produce a small offset voltage between the inputs.
- **Effect of an Input Bias Current**
  - Figure 12-29 (a) next slide is an inverting amplifier with zero input voltage.
  - Ideally the current through R_i is zero because the input voltage is zero and the voltage at the inverting (-) terminal is zero.
  - The small input bias current, I_1 is through R_f from the output terminal.
  - I_1 creates a voltage drop across R_f as indicated.
  - The positive side of R_f is the output terminal, thus the output error voltage is $+ I_1R_f$ when it should be zero

Bias Current and Offset Voltage Continue…

- **Effect of an Input Bias Current**



(a) Input bias current creates output error voltage (I_1R_f) in an inverting amplifier.

(b) Input bias current creates output error voltage in a voltage-follower.

FIGURE 12–29

Effects of bias currents.

Bias Current and Offset Voltage Continue…

- **Effect of an Input Bias Current**
  - Figure 12-29 (b) previous slide is a voltage follower with zero input voltage and a source resistance R_s .
  - Input bias current I_1, produces a drop across R_s and creates an output voltage error as shown.
  - The voltage at the inverting terminal decreases to $-I_1R_s$ because the negative feedback tends to maintain a differential voltage of zero as indicated.
  - Since the inverting terminal is connected directly to the output terminal, the output error voltage is $-I_1R_s$.

Bias Current and Offset Voltage Continue...

- **Effect of an Input Bias Current**
  - Figure 12-30 is a non-inverting amplifier with zero input voltage.
  - Ideally the voltage at the inverting terminal is also zero.
  - The input bias current I_1, produces a voltage drop across R_f and thus creates an output error voltage of I_1R_f

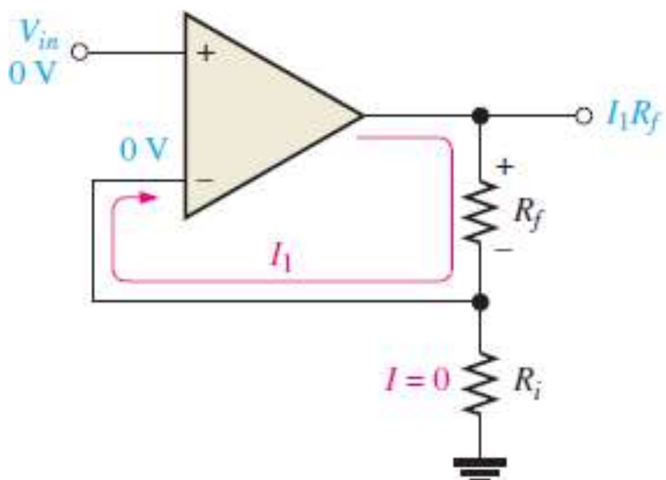


FIGURE 12–30

Input bias current creates output error voltage in a noninverting amplifier.

Bias Current and Offset Voltage Continue…

- **Bias Current Compensation in a Voltage-Follower**
  - The output error voltage due to bias current in a voltage-follower can be significantly reduced by adding a resistor R_f equal to the source resistor R_s in the feedback path as shown in figure 12-31 next slide.
  - The voltage drop created by I_1 across the added resistor subtracts from the $-I_2R_s$ output error voltage.
  - If $I_1 = I_2$, then the output volage is zero
  - Usually I_1 does not equal I_2 but even in this cases, the output error voltage is reduced as follows because I_{OS} is less than I_2

$$V_{OUT(error)} = |I_1 - I_2|R_s = I_{OS}R_s$$

Bias Current and Offset Voltage Continue…

- **Bias Current Compensation in a Voltage-Follower**

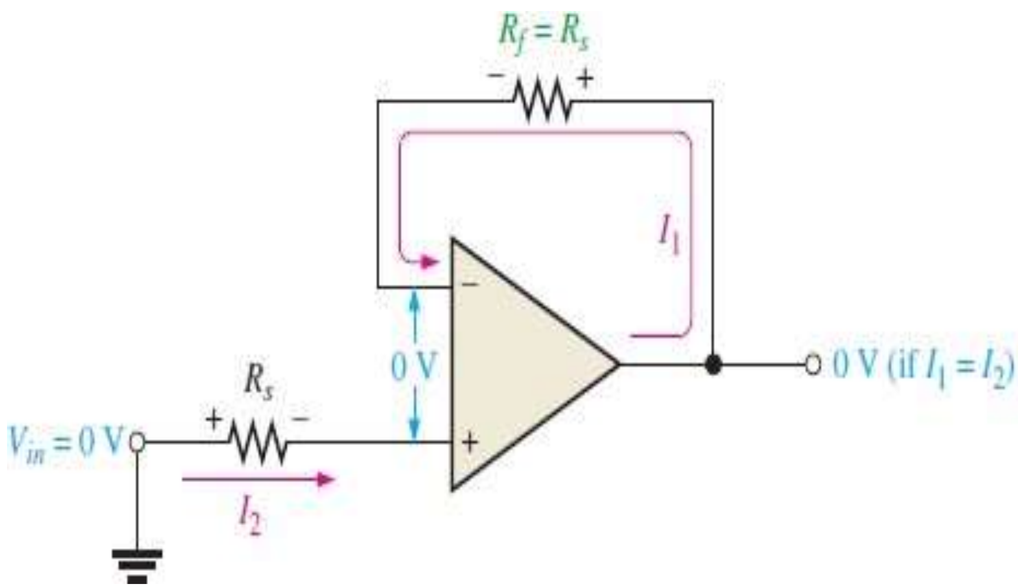


FIGURE 12–31

Bias current compensation in a voltage-follower.

Bias Current and Offset Voltage Continue…

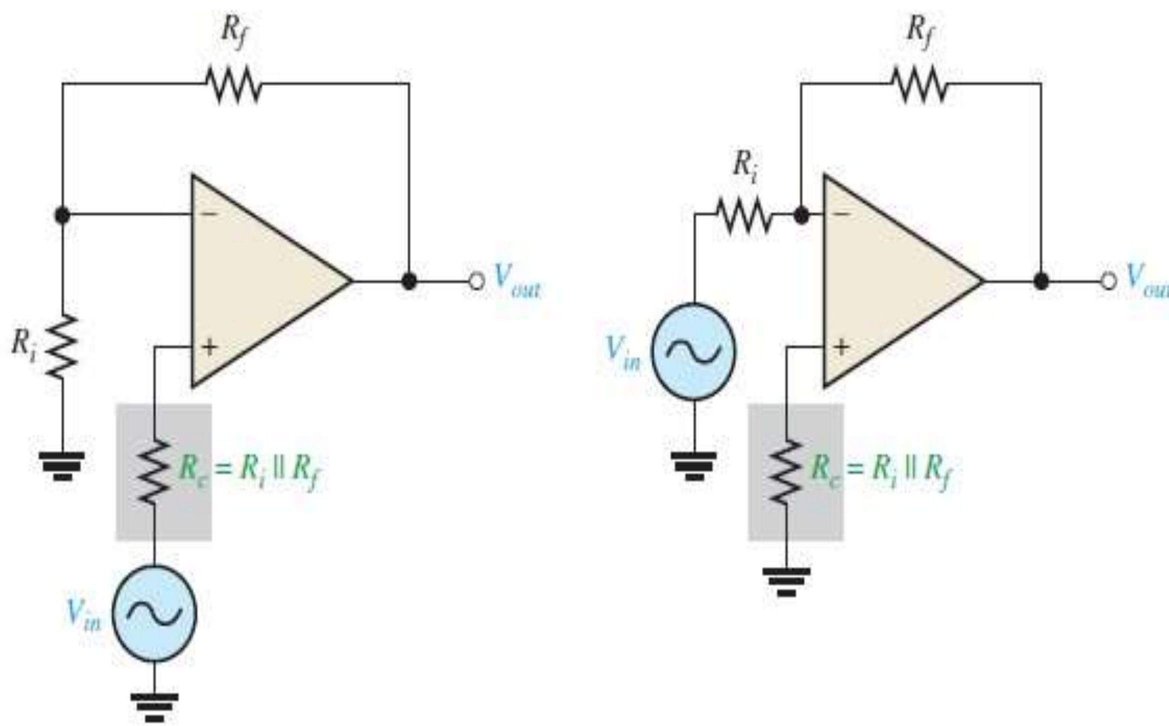
- **Bias Current Compensation in Other Op-Amp Configurations**
  - Practical op-amp has very small finite input bias currents on both of its inputs.
  - These two bias currents (I_1 and I_2) can produce a small dc output voltage ($V_{\mathrm{OUT}(error)}$) even when the input voltage is zero.
  - The easiest way to minimize this problem is by including a compensating resistor R_c in series with the non-inverting input of a non-inverting amplifier as shown in figure 12-32 (a) next slide.
  - The compensating resistor R_c value equals the parallel combination of R_i and R_f.
  - R_c Provides high input impedance which will significantly reduce the magnitudes of bias currents.
  - The inverting amplifier is similarly compensated shown in 12-32 (b)

Bias Current and Offset Voltage Continue…

- **Bias Current Compensation in Other Op-Amp Configurations**

FIGURE 12–32

Bias current compensation in the noninverting and inverting amplifier configurations.



(a) Noninverting amplifier

(b) Inverting amplifier

Bias Current and Offset Voltage Continue...

- **Effect of Input Offset Voltage**
- **Input Offset Voltage Compensation**

Open-Loop Response

- In this section, we will learn about the open-loop frequency response and the open-loop phase response of an op-amp.
- Open-loop responses relate to an op-amp with no external feedback.
- The frequency response indicates how the voltage gain changes with frequency.
- The phase response indicates how the phase shift between the input and output signal changes with frequency.
- The open-loop gain, like the β of a transistor, varies greatly from one device to the next of the same type and cannot be dependent upon to have a constant value.

Open-Loop Response Continue…

- **Voltage Gain is Frequency Dependent**
  - Previously, all of the voltage gain expressions were based on the midrange gain and were considered independent of the frequency.
  - The midrange open-loop gain of an op-amp extends from zero frequency up to a critical frequency at which the gain is 3 dB less than the midrange value.
  - Op-Amp are dc amplifiers (no coupling capacitors between stages), and therefore no lower critical frequency.
  - An open-loop response curve (Bode Plot) for a certain amplifier is shown in figure 12-36 next slide.
  - Notice that the curve rolls off (decrease) at -20 dB per decade (-6 dB per octave).
  - The midrange gain is 200,000, which is 106 dB and the critical (cutoff) frequency is approximately 10 Hz.

Open-Loop Response Continue…

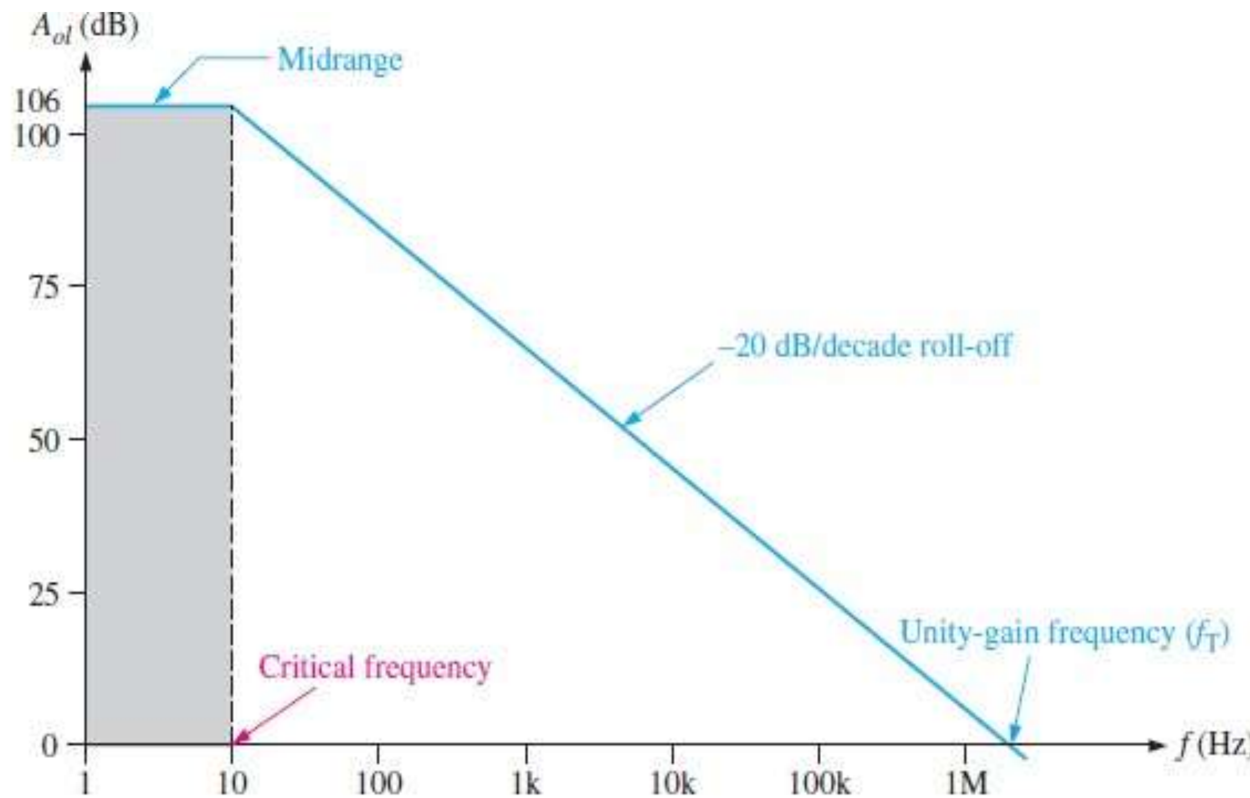


FIGURE 12–36

Ideal plot of open-loop voltage gain versus frequency for a typical op-amp. The frequency scale is logarithmic.

Open-Loop Response Continue…

- **3 dB Open-Loop Bandwidth**
  - Generally the B.W equals the upper critical frequency minus the lower critical frequency.
    - BW= f_{cu} - f_{cl}
  - Since f_{cl} for an op-amp is zero, the B.W is simply equal to the upper critical frequency.
    - BW= f_{cu}
  - From now on, we will refer to f_{cu} as simply f_c ; and we will use open-loop(*ol*) or closed-loop (*cl)* subscript designators, for example, $f_{c(ol)}$.

Open-Loop Response Continue…

- **Unity-Gain Bandwidth**
  - Notice in figure 12-36 that the gain steadily decreases to a point where it is equal to unity (1 or 0 dB). The value of the frequency at which this unity gain occurs is the *unity-gain bandwidth* designated f_T
    - $f_T = A_{ol} BW = A_{ol} f_{cu} = A_{ol} f_{c(ol)}$

- **Gain-Versus-Frequency Analysis**
  - The *RC* lag (low-pass) circuits within an op-amp are responsible for the roll-off in gain as the frequency increases. From basic ac circuit theory, the attenuation of an *RC* lag circuit such as in figure 12-37 next slide is expressed as

$$\frac{V_{out}}{V_{in}} = \frac{X_C}{\sqrt{R^2 + X_C^2}}$$

Open-Loop Response Continue…

- **Gain-Versus-Frequency Analysis**

Dividing both the numerator and denominator to the right of the equals sign by X_C,

$$\frac{V_{out}}{V_{in}} = \frac{1}{\sqrt{1 + R^2/X_C^2}}$$

The critical frequency of an *RC* circuit is

$$f_c = \frac{1}{2\pi RC}$$

Dividing both sides by f gives

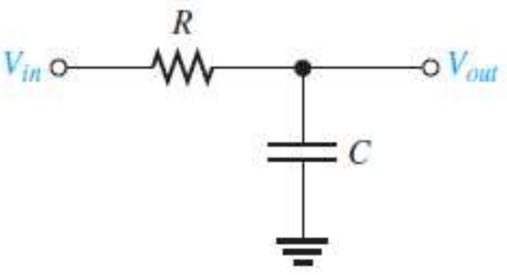
$$\frac{f_c}{f} = \frac{1}{2\pi RCf} = \frac{1}{(2\pi fC)R}$$

Since $X_C = 1/(2\pi fC)$, the previous expression can be written as

$$\frac{f_c}{f} = \frac{X_C}{R}$$

Substituting this result in the previous equation for V_{out}/V_{in} produces the following expression for the attenuation of an *RC* lag circuit in terms of frequency:

$$\frac{V_{out}}{V_{in}} = \frac{1}{\sqrt{1 + f^2/f_c^2}}$$



▲ FIGURE 12–37

RC lag circuit.

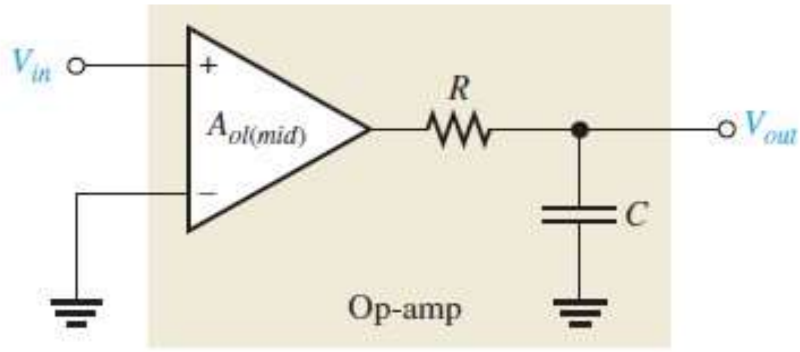
Open-Loop Response Continue…

- **Gain-Versus-Frequency Analysis**

If an op-amp is represented by a voltage gain element with a gain of $A_{ol(mid)}$ plus a single *RC* lag circuit, as shown in Figure 12–38, it is known as a compensated op-amp. The total open-loop gain of the op-amp is the product of the midrange open-loop gain, $A_{ol(mid)}$, and the attenuation of the *RC* circuit.

FIGURE 12–38

Op-amp represented by a gain element and an internal *RC* circuit.



$$A_{ol} = \frac{A_{ol(mid)}}{\sqrt{1 + f^2/f_c^2}}$$ Equation 12–19

As you can see from Equation 12–19, the open-loop gain equals the midrange gain when the signal frequency f is much less than the critical frequency f_c and drops off as the frequency increases. Since f_c is part of the open-loop response of an op-amp, we will refer to it as $f_{c(ol)}$.

Determine A_{ol} for the following values of f. Assume $f_{c(ol)} = 100$ Hz and $A_{ol(mid)} = 100{,}000$.

(a) $f = 0$ Hz (b) $f = 10$ Hz (c) $f = 100$ Hz (d) $f = 1000$ Hz

Solution

(a) $A_{ol} = \dfrac{A_{ol(mid)}}{\sqrt{1 + f^2/f^2_{c(ol)}}} = \dfrac{100{,}000}{\sqrt{1+0}} = \mathbf{100{,}000}$

(b) $A_{ol} = \dfrac{100{,}000}{\sqrt{1 + (0.1)^2}} = \mathbf{99{,}503}$

(c) $A_{ol} = \dfrac{100{,}000}{\sqrt{1 + (1)^2}} = \dfrac{100{,}000}{\sqrt{2}} = \mathbf{70{,}710}$

(d) $A_{ol} = \dfrac{100{,}000}{\sqrt{1 + (10)^2}} = \mathbf{9950}$

Open-Loop Response Continue…

- **Phase Shift**
  - An *RC* circuit causes a propagation delay from input to output thus creating a phase shift between the input signal and output signal.
  - An *RC* lag circuit such as found in an op-amp stage causes the output signal voltage to lag the input as shown in figure 12-39. From basic ac circuit theory, the phase shift θ is

$$\theta = -\tan^{-1}\left(\frac{R}{X_C}\right)$$

Since $R/X_C = f/f_c$,

$$\theta = -\tan^{-1}\left(\frac{f}{f_c}\right)$$

Open-Loop Response Continue…

- **Phase Shift**

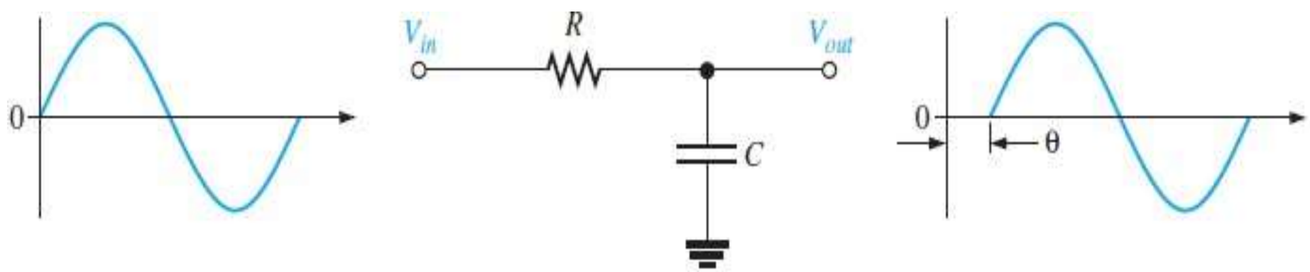


FIGURE 12–39

Output voltage lags input voltage.

The negative sign indicates that the output lags the input. This equation shows that the phase shift increases with frequency and approaches −90° as f becomes much greater than f_c.

Calculate the phase shift for an *RC* lag circuit for each of the following frequencies, and then plot the curve of phase shift versus frequency. Assume $f_c = 100\text{ Hz}$.

(a) $f = 1\text{ Hz}$ **(b)** $f = 10\text{ Hz}$ **(c)** $f = 100\text{ Hz}$
(d) $f = 1000\text{ Hz}$ **(e)** $f = 10{,}000\text{ Hz}$

Solution **(a)** $\theta = -\tan^{-1}\left(\frac{f}{f_c}\right) = -\tan^{-1}\left(\frac{1\text{ Hz}}{100\text{ Hz}}\right) = \mathbf{-0.573^\circ}$

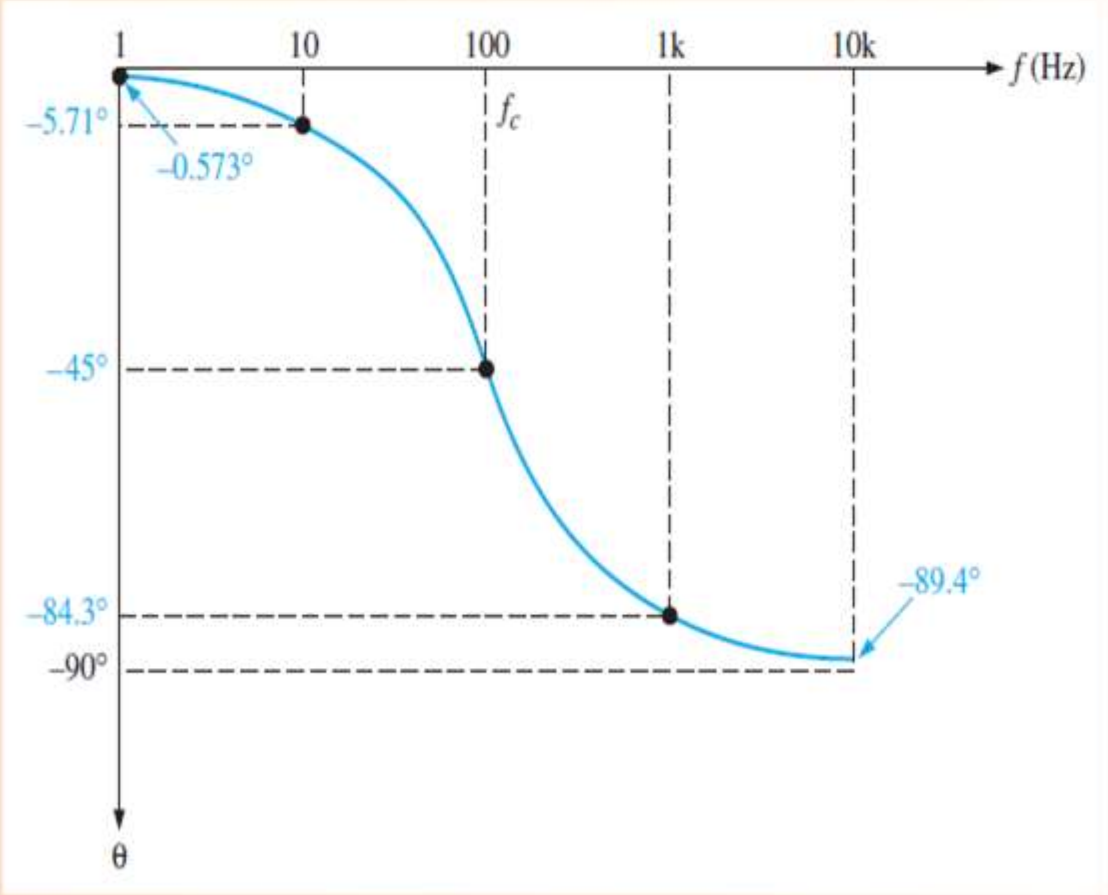
(b) $\theta = -\tan^{-1}\left(\frac{10\text{ Hz}}{100\text{ Hz}}\right) = \mathbf{-5.71^\circ}$

(c) $\theta = -\tan^{-1}\left(\frac{100\text{ Hz}}{100\text{ Hz}}\right) = \mathbf{-45^\circ}$

(d) $\theta = -\tan^{-1}\left(\frac{1000\text{ Hz}}{100\text{ Hz}}\right) = \mathbf{-84.3^\circ}$

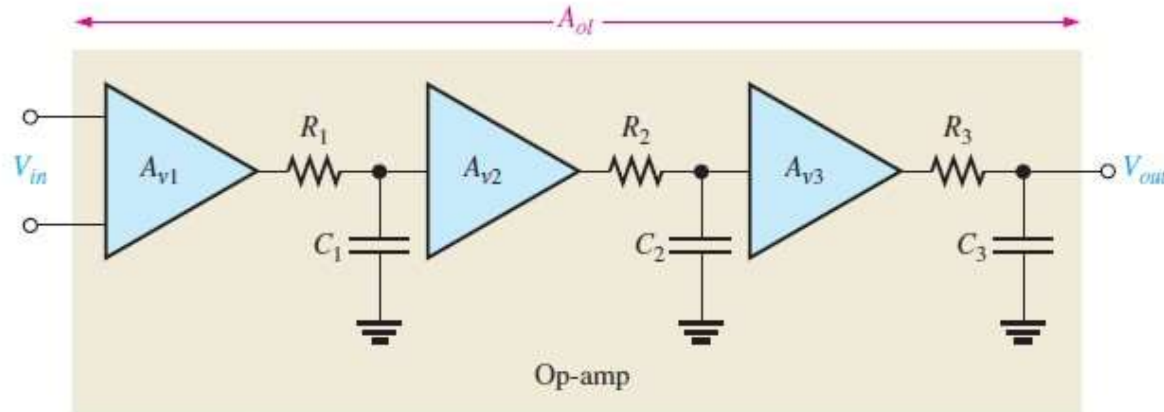
(e) $\theta = -\tan^{-1}\left(\frac{10{,}000\text{ Hz}}{100\text{ Hz}}\right) = \mathbf{-89.4^\circ}$

The phase shift-versus-frequency curve is plotted in Figure 12–40. Note that the frequency axis is logarithmic.

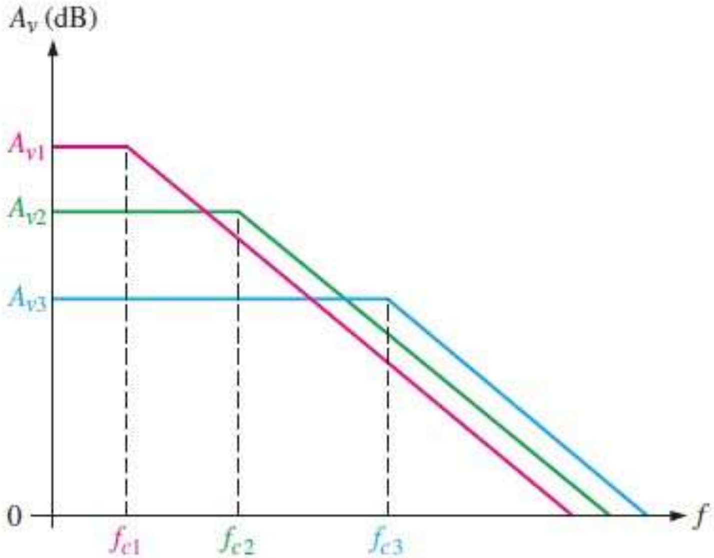


Open-Loop Response Continue…

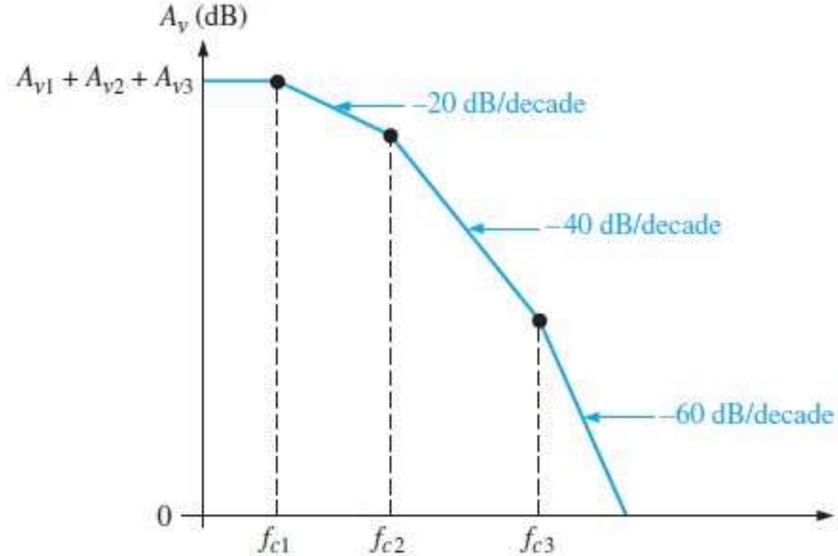
- **Complete Frequency Response**
  - Previously an op-amp was assumed to have a constant roll-off of -20 dB/decade above its critical frequency. For most op-amps it is the case.
  - However , the situation is more complex when IC op-amp may consist of two or more cascaded amplifier stages.
  - The gain of each stage is frequency dependent and rolls off at -20 dB/decade above its critical frequency.
  - Therefore the total response of an op-amp is a composite of the individual responses of the internal stages.
  - As an example, a three-stage op-amp is represented in figure 12-41 (a)next slide, the frequency response of each stage is shown in figure 12-41(b), since gains are added so that the total op-amp frequency response is shown in figure 12-41(c)



(a) Representation of an op-amp with three internal stages



(b) Individual responses



(c) Composite response

▲ **FIGURE 12–41**

Op-amp open-loop frequency response.

Open-Loop Response Continue…

- **Complete Phase Response**
  - In multistage amplifier, each stage contributes to the total phase lag.
  - Since each RC circuit can produce up to a -90° phase shift. Therefore an op-amp with three internal stages can have a maximum phase lag of -270°.
  - The phase lag of each stage is less than-45° when the frequency is below the critical frequency, equal to -45° at the critical frequency and greater than -45° when the frequency is above critical frequency.
  - The phase lags of the stages(three stages) of an-amp are added to produce a total phase lag as follows

$$\theta_{tot} = -\tan^{-1}\left(\frac{f}{f_{c1}}\right) - \tan^{-1}\left(\frac{f}{f_{c2}}\right) - \tan^{-1}\left(\frac{f}{f_{c3}}\right)$$

A certain op-amp has three internal amplifier stages with the following gains and critical frequencies:

Stage 1: $A_{v1} = 40\text{ dB}, f_{c1} = 2\text{ kHz}$

Stage 2: $A_{v2} = 32\text{ dB}, f_{c2} = 40\text{ kHz}$

Stage 3: $A_{v3} = 20\text{ dB}, f_{c3} = 150\text{ kHz}$

Determine the open-loop midrange gain in decibels and the total phase lag when $f = f_{c1}$.

Solution $A_{ol(mid)} = A_{v1} + A_{v2} + A_{v3} = 40\text{ dB} + 32\text{ dB} + 20\text{ dB} = 92\text{ dB}$

$$\theta_{tot} = -\tan^{-1}\left(\frac{f}{f_{c1}}\right) - \tan^{-1}\left(\frac{f}{f_{c2}}\right) - \tan^{-1}\left(\frac{f}{f_{c3}}\right)$$

$$= -\tan^{-1}(1) - \tan^{-1}\left(\frac{2}{40}\right) - \tan^{-1}\left(\frac{2}{150}\right) = -45^\circ - 2.86^\circ - 0.76^\circ = \mathbf{-48.6^\circ}$$

Closed-Loop Response

- Op-Amps are normally used in a closed-loop configuration with negative feedback in order to achieve precise control of the gain and bandwidth.
- Re ... nge open-
  loc ... dback. For
  a r

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

For an inverting amplifier,

$$A_{cl(I)} \cong -\frac{R_f}{R_i}$$

For a voltage-follower,

$$A_{cl(VF)} = 1$$

Closed-Loop Response Continue…

- **Effect of Negative Feedback on Bandwidth**
  - The closed-loop critical frequency of an op-amp is
    - $f_{c(cl)} = f_{c(ol)}(1 + BA_{ol(mid)})$
  - This expression shows that the closed-loop critical frequency $f_{c(cl)}$ is higher than the open-loop critical frequency $f_{c(ol)}$ by the factor $1 + BA_{ol(mid)}$.
  - $BW_{c(cl)} = BW_{c(ol)}(1 + BA_{ol(mid)})$

Closed-Loop Response Continue…

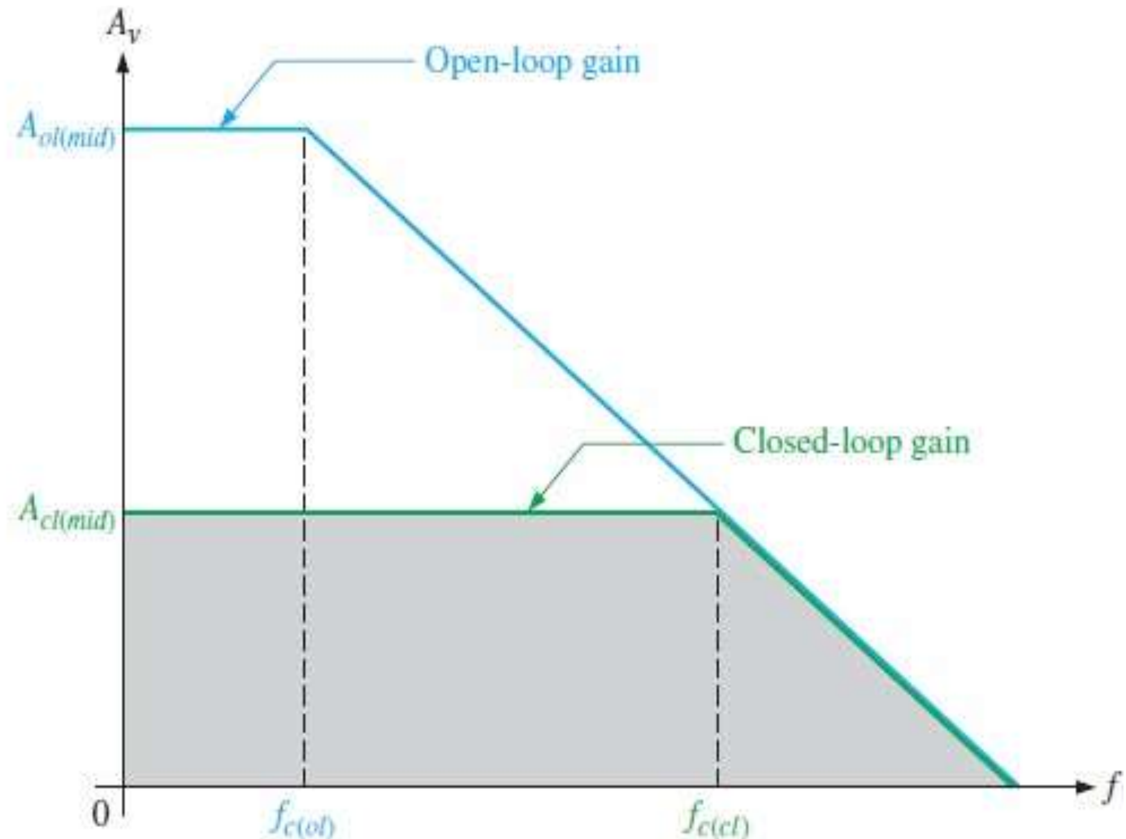
- **Effect of Negative Feedback on Bandwidth**
  - Figure 12-42 next slide graphically illustrates the concept of closed-loop response.
  - When the open-loop gain of an op-amp is reduced by negative feedback, the bandwidth is increased.
  - The closed-loop gain is independent of the open-loop gain up to the point of intersection of two gain curves.
  - This point of the intersection is the critical frequency $f_{c(cl)}$ for the closed-loop response.
  - Notice that the closed-loop gain has the same roll-off rate as the open-loop gain, beyond the closed-loop critical frequency.

12-8 Closed-Loop Response Continue...

- **Effect of Negative Feedback on Bandwidth**

FIGURE 12–42

Closed-loop gain compared to open-loop gain.



Closed-Loop Response Continue…

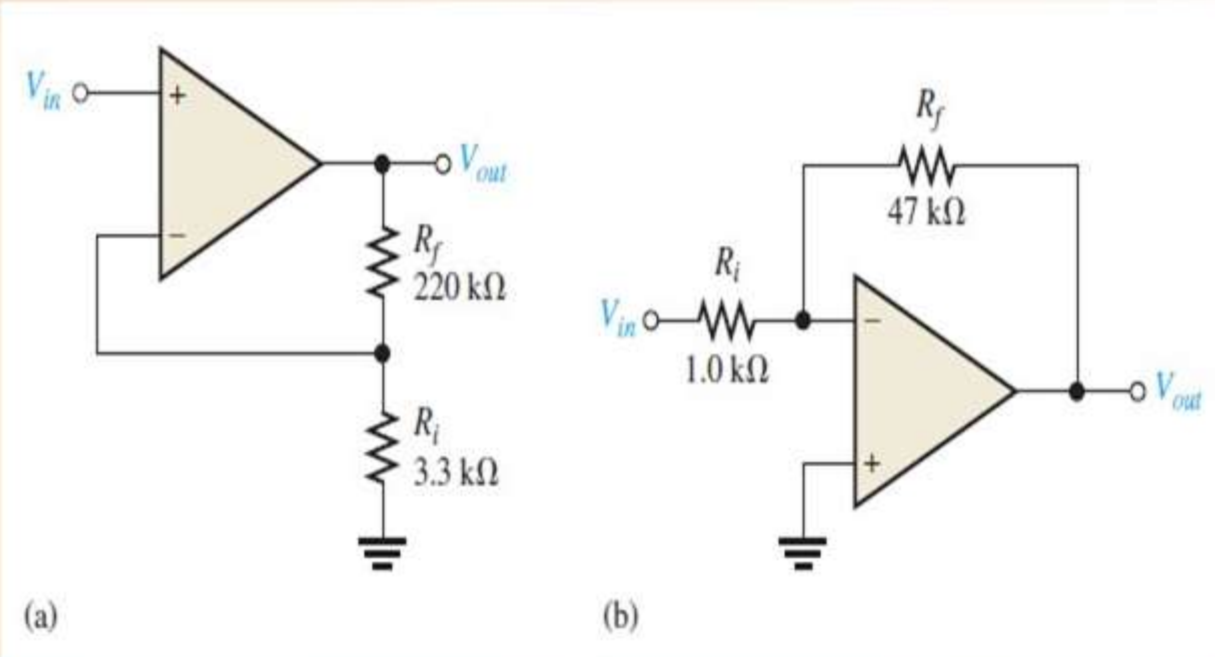
- **Gain-Bandwidth Product**
  - An increase in closed-loop gain causes a decrease in the bandwidth and vice versa.
  - This is true as long as the roll-off rate is fixed.

- **Unity-Gain Bandwidth**
  - $f_T = A_{cl} BW_{cl} = A_{cl} f_{cl} = A_{cl} f_{c(cl)}$

A certain amplifier has an open-loop midrange gain of 150,000 and an open-loop 3 dB bandwidth of 200 Hz. The attenuation (B) of the feedback loop is 0.002. What is the closed-loop bandwidth?

Solution $BW_{cl} = BW_{ol}(1 + BA_{ol(mid)}) = 200\text{ Hz}[1 + (0.002)(150{,}000)] = \mathbf{60.2\text{ kHz}}$

Determine the bandwidth of each of the amplifiers in Figure 12–43. Both op-amps have an open-loop gain of 100 dB and a unity-gain bandwidth (f_T) of 3 MHz.



Solution **(a)** For the noninverting amplifier in Figure 12–43(a), the closed-loop gain is

$$A_{cl} = 1 + \frac{R_f}{R_i} = 1 + \frac{220\text{ k}\Omega}{3.3\text{ k}\Omega} = 67.7$$

Use Equation 12–23 and solve for $f_{c(cl)}$ (where $f_{c(cl)} = BW_{cl}$).

$$f_{c(cl)} = BW_{cl} = \frac{f_T}{A_{cl}}$$

$$BW_{cl} = \frac{3\text{ MHz}}{67.7} = \mathbf{44.3\text{ kHz}}$$

(b) For the inverting amplifier in Figure 12–43(b), the closed-loop gain is

$$A_{cl} = -\frac{R_f}{R_i} = -\frac{47\text{ k}\Omega}{1.0\text{ k}\Omega} = -47$$

Using the absolute value of A_{cl}, the closed-loop bandwidth is

$$BW_{cl} = \frac{3\text{ MHz}}{47} = \mathbf{63.8\text{ kHz}}$$