Comparison of Op-Amp Parameters

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

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

▼ TABLE 12–1

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

[1] Depends on gain; gain = 10 is shown

[2] Depends on gain; gain = 2 is shown

[3] Small signal

SECTION 12–2 CHECKUP

1. Distinguish between single-ended and double-ended differential mode.
2. Define *common-mode rejection.*
3. For a given value of open-loop differential gain, does a higher common-mode gain result in a higher or lower CMRR?
4. List at least ten op-amp parameters.
5. How is slew rate measured?

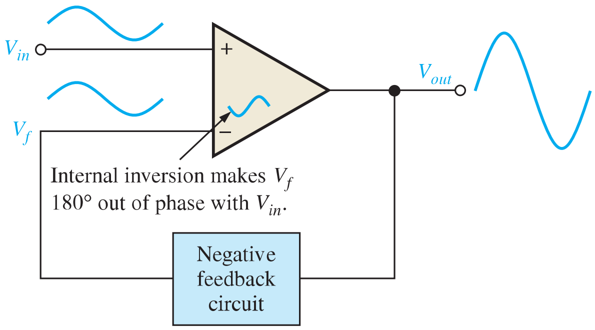
12–3 NEGATIVE FEEDBACK

Negative feedback is one of the most useful concepts in electronics, particularly in op-amp applications. **Negative feedback** is the process whereby a portion of the output voltage of an amplifier is returned to the input with a phase angle that opposes (or subtracts from) the input signal.

After completing this section, you should be able to

- ❑ **Explain negative feedback in op-amps**
- ❑ Discuss why negative feedback is used
  - ◆ Describe the effects of negative feedback on certain op-amp parameters

Negative feedback is illustrated in Figure 12–14. The inverting (−) input effectively makes the feedback signal 180° out of phase with the input signal.



◀ FIGURE 12–14

Illustration of negative feedback.

Why Use Negative Feedback?

As you can see in Table 12–1, the inherent open-loop voltage gain of a typical op-amp is very high (usually greater than 100,000). Therefore, an extremely small input voltage drives the op-amp into its saturated output states. In fact, even the input offset voltage of the op-amp can drive it into saturation. For example, assume $V_{IN} = 1$ mV and $A_{ol} =$ 100,000. Then,

$$V_{IN}A_{ol} = (1 \text{ mV})(100{,}000) = 100 \text{ V}$$

Since the output level of an op-amp can never reach 100 V, it is driven deep into saturation and the output is limited to its maximum output levels, as illustrated in Figure 12–15 for both a positive and a negative input voltage of 1 mV.

The usefulness of an op-amp operated without negative feedback is generally limited to comparator applications (to be studied in Chapter 13). With negative feedback, the closed-loop voltage gain (A_{cl}) can be reduced and controlled so that the op-amp can function as a

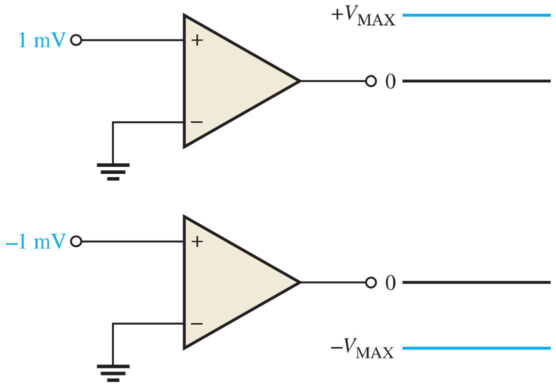


FIGURE 12–15

Without negative feedback, a small input voltage drives the op-amp to its output limits and it becomes nonlinear.

linear amplifier. In addition to providing a controlled, stable voltage gain, negative feedback also provides for control of the input and output impedances and amplifier bandwidth. Table 12–2 summarizes the general effects of negative feedback on op-amp performance.

TABLE 2–2

	VOLTAGE GAIN	INPUT *Z*	OUTPUT *Z*	BANDWIDTH
Without negative feedback	A_{ol} is too high for linear amplifier applications	Relatively high (see Table 12–1)	Relatively low	Relatively narrow (because the gain is so high)
With negative feedback	A_{cl} is set to desired value by the feedback circuit	Can be increased or reduced to a desired value depending on type of circuit	Can be reduced to a desired value	Significantly wider

SECTION 12–3 CHECKUP

1. What are the benefits of negative feedback in an op-amp circuit?
2. Why is it generally necessary to reduce the gain of an op-amp from its open-loop value?

12–4 OP-AMPS WITH NEGATIVE FEEDBACK

An op-amp can be connected using negative feedback to stabilize the gain and increase frequency response. Negative feedback takes a portion of the output and applies it back out of phase with the input, creating an effective reduction in gain. This closed-loop gain is usually much less than the open-loop gain and independent of it.

After completing this section, you should be able to

- **Analyze op-amps with negative feedback**
- Discuss closed-loop voltage gain
- Identify and analyze the noninverting op-amp configuration
- Identify and analyze the voltage-follower configuration
- Identify and analyze the inverting amplifier configuration

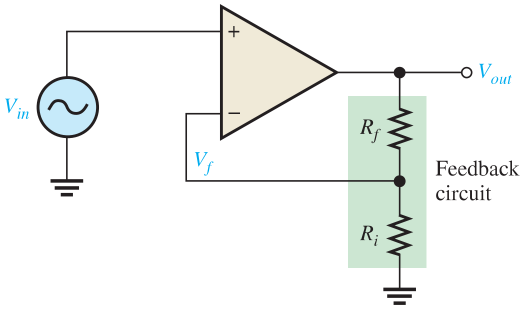
Closed-Loop Voltage Gain, A_{cl}

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 R_i and the feedback resistor R_f. This creates negative feedback as follows. Resistors R_i and R_f form a voltage-divider circuit, which reduces V_{out} 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, V_{in}, and the feedback voltage, V_f, 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 (A_{ol}) and produces an output voltage expressed as

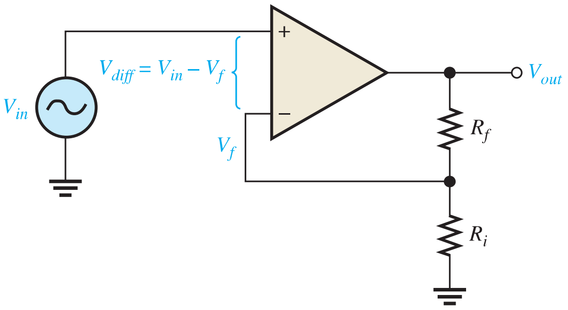
$$V_{out} = A_{ol}(V_{in} - V_f)$$

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,

$$\begin{aligned} V_{out} &= A_{ol}V_{in} - A_{ol}BV_{out} \\ V_{out} + A_{ol}BV_{out} &= A_{ol}V_{in} \\ V_{out}(1 + A_{ol}B) &= A_{ol}V_{in} \end{aligned}$$

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).

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

Therefore,

Equation 12–8

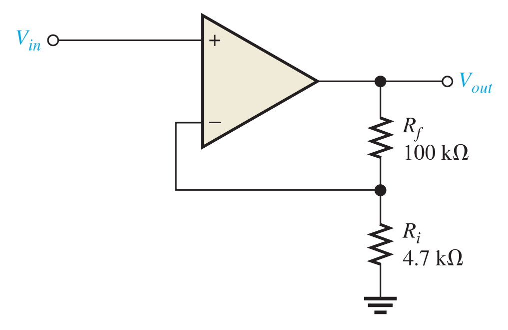
$$\boldsymbol{A_{cl(\mathrm{NI})} = 1 + \frac{R_f}{R_i}}$$

Notice that the closed-loop voltage gain is not at all dependent on the op-amp's open-loop voltage gain under the condition $A_{ol}B \gg 1$. The closed-loop gain can be set by selecting values of R_i and R_f.

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

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

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

Open the Multisim file E12-03 in the Examples folder on the companion website. Measure the closed-loop voltage gain of the amplifier and compare with the calculated value.

Voltage-Follower

The **voltage-follower** configuration is a special case of the noninverting amplifier where all of the output voltage is fed back to the inverting (−) input by a straight connection, as shown in Figure 12–19. As you can see, the straight feedback connection has a voltage gain of 1 (which means there is no gain). The closed-loop voltage gain of a noninverting amplifier is $1/B$ as previously derived. Since $B = 1$ for a voltage-follower, the closed-loop voltage gain of the voltage-follower is

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

Equation 12–9

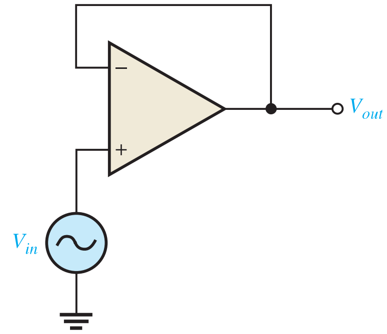


FIGURE 12–19

Op-amp voltage-follower.

The most important features of the voltage-follower configuration are its very high input impedance and its very low output impedance. These features make it a nearly ideal buffer amplifier for interfacing high-impedance sources and low-impedance loads. This is discussed further in Section 12–5.

Inverting Amplifier

An op-amp connected as an **inverting amplifier** with a controlled amount of voltage gain is shown in Figure 12–20. The input signal is applied through a series input resistor R_i to the inverting (−) input. Also, the output is fed back through R_f to the same input. The noninverting (+) input is grounded.

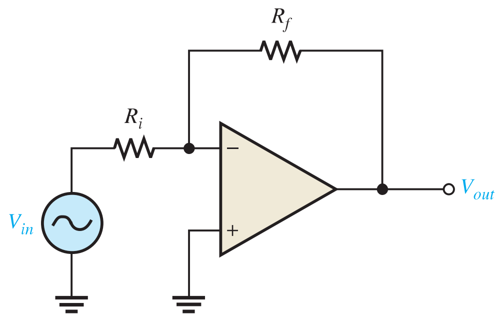


FIGURE 12–20

Inverting amplifier.

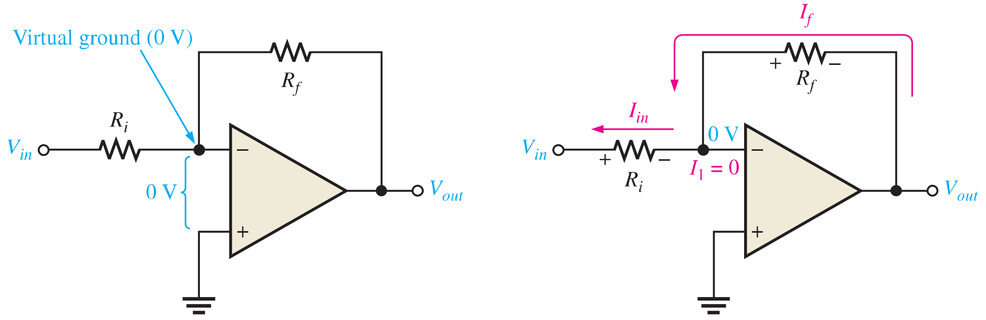
At this point, the ideal op-amp parameters mentioned earlier are useful in simplifying the analysis of this circuit. In particular, the concept of infinite input impedance is of great value. An infinite input impedance implies zero current at the inverting input. If there is zero current through the input impedance, then there must be *no* voltage drop between the inverting and noninverting inputs. This means that the voltage at the inverting (−) input is zero because the noninverting (+) input is grounded. This zero voltage at the inverting input terminal is referred to as *virtual ground.* This condition is illustrated in Figure 12–21(a).

Since there is no current at the inverting input, the current through R_i and the current through R_f are equal, as shown in Figure 12–21(b).

$$I_{in} = I_f$$

FIGURE 12–21

Virtual ground concept and closed-loop voltage gain development for the inverting amplifier.



(a) Virtual ground

(b) $I_{in} = I_f$ and current at the inverting input (I_1) is 0.

The voltage across R_i equals V_{in} because the resistor is connected to virtual ground at the inverting input of the op-amp. Therefore,

$$I_{in} = \frac{V_{in}}{R_i}$$

Also, the voltage across R_f equals $-V_{out}$ because of virtual ground, and therefore,

$$I_f = \frac{-V_{out}}{R_f}$$

Since $I_f = I_{in}$,

$$\frac{-V_{out}}{R_f} = \frac{V_{in}}{R_i}$$

Rearranging the terms,

$$\frac{V_{out}}{V_{in}} = -\frac{R_f}{R_i}$$

Of course, V_{out}/V_{in} is the overall gain of the inverting (I) amplifier.

Equation 12–10

$$\boldsymbol{A_{cl(\mathrm{I})} = -\frac{R_f}{R_i}}$$

Equation 12–10 shows that the closed-loop voltage gain of the inverting amplifier ($A_{cl(\mathrm{I})}$) is the ratio of the feedback resistance (R_f) to the input resistance (R_i). *The closed-loop gain is independent of the op-amp's internal open-loop gain.* Thus, the negative feedback stabilizes the voltage gain. The negative sign indicates inversion.

EXAMPLE 12–4

Given the op-amp configuration in Figure 12–22, determine the value of R_f required to produce a closed-loop voltage gain of -100.

FIGURE 12–22