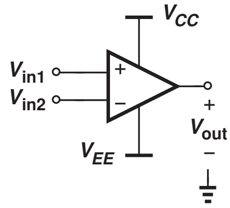


**Figure 8.4** Op amp with supply rails.

## 8.2 OP-AMP-BASED CIRCUITS

In this section, we study a number of circuits that utilize op amps to process analog signals. In each case, we first assume an ideal op amp to understand the underlying principles and subsequently examine the effect of the finite gain on the performance.

### 8.2.1 Noninverting Amplifier

Recall from Chapters 5 and 7 that the voltage gain of amplifiers typically depends on the load resistor and other parameters that may vary considerably with temperature or process.[3] As a result, the voltage gain itself may suffer from a variation of, say, ±20%. However, in some applications (e.g., A/D converters), a much more precise gain (e.g., 2.000) is required. Op-amp-based circuits can provide such precision.

**Did you know?**

Early op amps were implemented using discrete bipolar transistors and other components and packaged as a "module" with dimensions of 5 to 10 cm. More importantly, each of these op amps cost $100 to $200 (in the 1960s). By contrast, today's off-the-shelf op amp ICs, e.g., the 741, cost less than a dollar. Op amps realized within larger integrated circuits cost a small fraction of a cent.

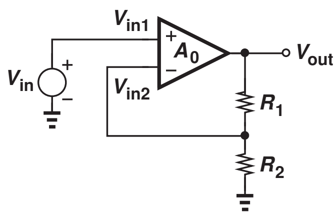


**Figure 8.5** Noninverting amplifier.

Illustrated in Fig. 8.5, the noninverting amplifier consists of an op amp and a voltage divider that returns a fraction of the output voltage to the inverting input:

$$V_{in2} = \frac{R_2}{R_1 + R_2} V_{out}. \tag{8.6}$$

Since a high op amp gain translates to a small difference between $V_{in1}$ and $V_{in2}$, we have

$$V_{in1} \approx V_{in2} \tag{8.7}$$

$$\approx \frac{R_2}{R_1 + R_2} V_{out}; \tag{8.8}$$

[3]Variation with process means that circuits fabricated in different "batches" exhibit somewhat different characteristics.

and hence

$$\frac{V_{out}}{V_{in}} \approx 1 + \frac{R_1}{R_2}. \tag{8.9}$$

Due to the positive gain, the circuit is called a "noninverting amplifier." We call this result the "closed-loop" gain of the circuit.

Interestingly, the voltage gain depends on only the *ratio* of the resistors; if $R_1$ and $R_2$ increase by 20%, $R_1/R_2$ remains constant. The idea of creating dependence on only the ratio of quantities that have the same dimension plays a central role in circuit design.

**Example 8.2** Study the noninverting amplifier for two extreme cases: $R_1/R_2 = \infty$ and $R_1/R_2 = 0$.

**Solution** If $R_1/R_2 \to \infty$, e.g., if $R_2$ approaches zero, we note that $V_{out}/V_{in} \to \infty$. Of course, as depicted in Fig. 8.6(a), this occurs because the circuit reduces to the op amp itself, with no fraction of the output fed back to the input. Resistor $R_1$ simply loads the output node, with no effect on the gain if the op amp is ideal.

If $R_1/R_2 \to 0$, e.g., if $R_2$ approaches infinity, we have $V_{out}/V_{in} \to 1$. Shown in Fig. 8.6(b), this case in fact reduces to the unity-gain buffer of Fig. 8.3 because the ideal op amp draws no current at its inputs, yielding a zero drop across $R_1$ and hence $V_{in2} = V_{out}$.

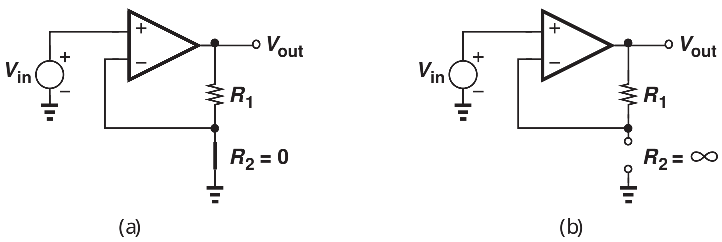


Figure 8.6 Noninverting amplifier with (a) zero and (b) infinite value for $R_2$.

**Exercise** Suppose the circuit is designed for a nominal gain of 2.00 but the $R_1$ and $R_2$ suffer from a mismatch of 5% (i.e., $R_1 = (1 \pm 0.05)R_2$). What is the actual voltage gain?

Let us now take into account the finite gain of the op amp. Based on the model shown in Fig. 8.1(b), we write

$$(V_{in1} - V_{in2})A_0 = V_{out}, \tag{8.10}$$

and substitute for $V_{in2}$ from Eq. (8.6):

$$\frac{V_{out}}{V_{in}} = \frac{A_0}{1 + \dfrac{R_2}{R_1 + R_2}A_0}. \tag{8.11}$$

As expected, this result reduces to Eq. (8.9) if $A_0R_2/(R_1 + R_2) \gg 1$. To avoid confusion between the gain of the op amp, $A_0$, and the gain of the overall amplifier, $V_{out}/V_{in}$, we call the former the "open-loop" gain and the latter the "closed-loop" gain.

Equation (8.11) indicates that the finite gain of the op amp creates a small error in the value of $V_{out}/V_{in}$. If much greater than unity, the term $A_0R_2/(R_1+R_2)$ can be factored from the denominator to permit the approximation $(1+\epsilon)^{-1} \approx 1-\epsilon$ for $\epsilon \ll 1$:

$$\frac{V_{out}}{V_{in}} \approx \left(1+\frac{R_1}{R_2}\right)\left[1-\left(1+\frac{R_1}{R_2}\right)\frac{1}{A_0}\right]. \tag{8.12}$$

Called the "gain error," the term $(1+R_1/R_2)/A_0$ must be minimized according to each application's requirements.

**Example 8.3** A noninverting amplifier incorporates an op amp having a gain of 1000. Determine the gain error if the circuit is to provide a nominal gain of (a) 5, or (b) 50.

**Solution** For a nominal gain of 5, we have $1+R_1/R_2=5$, obtaining a gain error of:

$$\left(1+\frac{R_1}{R_2}\right)\frac{1}{A_0}=0.5\%. \tag{8.13}$$

On the other hand, if $1+R_1/R_2=50$, then

$$\left(1+\frac{R_1}{R_2}\right)\frac{1}{A_0}=5\%. \tag{8.14}$$

In other words, a higher closed-loop gain inevitably suffers from less accuracy.

**Exercise** Repeat the above example if the op amp has a gain of 500.

With an ideal op amp, the noninverting amplifier exhibits an infinite input impedance and a zero output impedance. For a nonideal op amp, the I/O impedances are derived in Problem 8.6.

### 8.2.2 Inverting Amplifier

Depicted in Fig. 8.7(a), the "inverting amplifier" incorporates an op amp along with resistors $R_1$ and $R_2$ while the noninverting input is grounded. Recall from Section 8.1 that if the op amp gain is infinite, then a finite output swing translates to $V_{in1}-V_{in2}\to 0$; i.e., node $X$ bears a zero potential even though it is *not* shorted to ground. For this reason, node $X$ is called a "virtual ground." Under this condition, the entire input voltage appears across $R_2$, producing a current of $V_{in}/R_2$, which must then flow through $R_1$ if the op amp input draws no current [Fig. 8.7(b)]. Since the left terminal of $R_1$ remains at zero and the right terminal at $V_{out}$,

$$\frac{0-V_{out}}{R_1}=\frac{V_{in}}{R_2} \tag{8.15}$$

yielding

$$\frac{V_{out}}{V_{in}}=\frac{-R_1}{R_2}. \tag{8.16}$$