PDHonline Course E272 (5 PDH)

Operational Amplifier Fundamentals and Design

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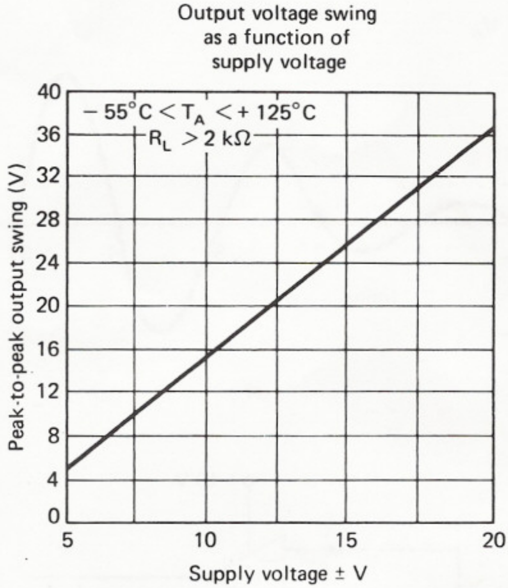
THE OP AMP WITH AND WITHOUT FEEDBACK

The available open-loop gain of an Op Amp is never used in linear applications. It is too large. If we tried to use the available A_{VOL}, even very small differential input signals V_{id} will drive an Op Amp's output into its rails causing severe clipping (distortion) of the resulting output V_o. In this chapter we will see how negative feedback is used with an Op Amp to reduce and stabilize its effective voltage gain. This effective voltage gain is called the *closed-loop* gain A_v. In fact, with feedback we are able to select any specific gain we need as long as it is less than the Op Amp's open-loop gain A_{VOL}.

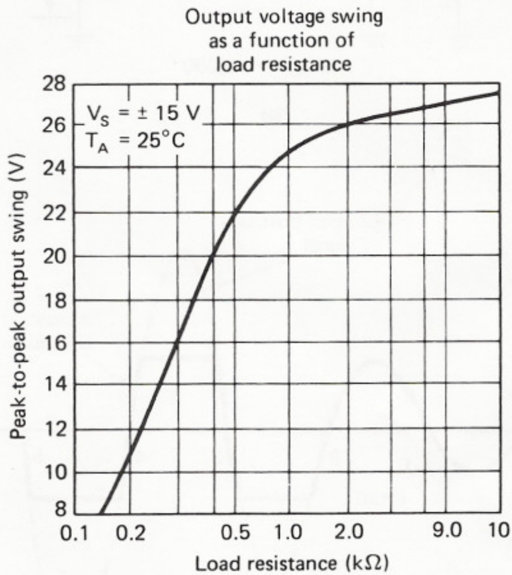
3.1 OPEN-LOOP CONSIDERATIONS

The Op Amp is generally classified as a linear device. This means that its output voltage V_o tends to proportionally follow changes in the applied differential input V_{id}. Within limits, the changes in output voltage V_o are larger than the changes in the input V_{id} by the open-loop gain A_{VOL} of the Op Amp. The amount that the output voltage V_o can change (swing), however, is limited by the dc supply voltages and the load resistance R_L. Generally, the output voltage swing is restricted to values between the rails. As shown in Fig. 3-1, manufacturers provide curves showing their Op Amps' maximum output voltage swing versus supply voltage and also versus load resistance R_L. Note that smaller supply voltages and load resistances reduce an Op amp's signal output capability. Any attempt to drive the Op Amp beyond its limits results in sharp clipping of its output signals.

For example, the Op Amp in Fig. 3-2 is shown with a small input signal V_{id} applied to its inverting input 1 and its resulting output V_o. Note that the



(a)



(b)

Figure 3-1 Typical Op Amp characteristics: (a) output voltage V_o swing vs. dc supply voltage, (b) output voltage V_o swing vs. load resistance R_L.

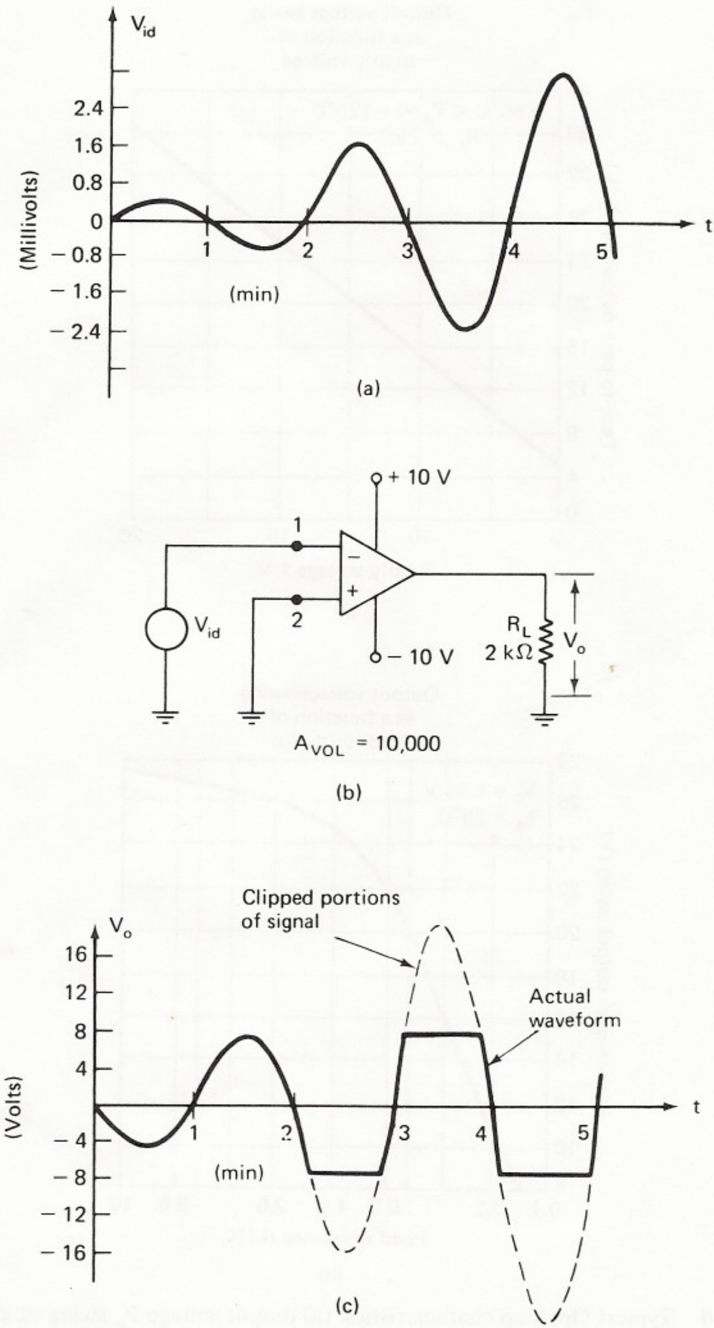


Figure 3-2 (a) Differential input signal, (b) Op Amp with no feedback (inverting mode), (c) output signal waveform if $A_{VOL} = 10^4$.

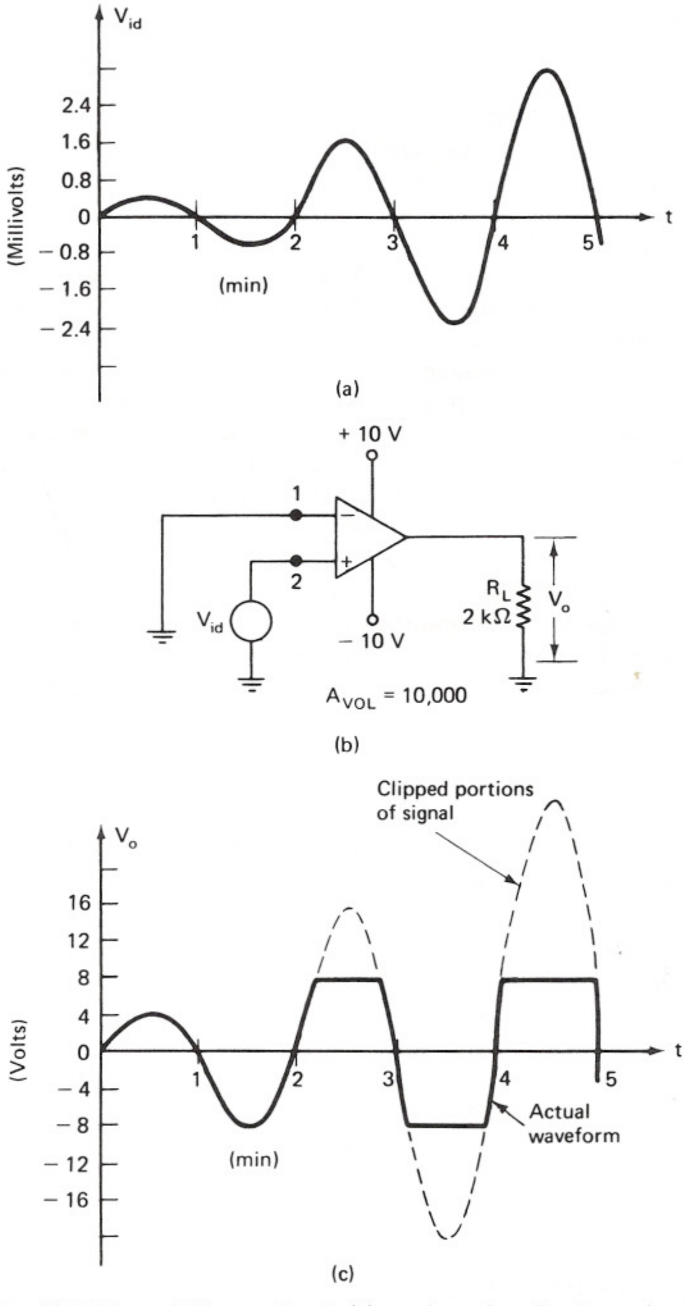


Figure 3-3 (a) Differential input signal, (b) noninverting Op Amp circuit with no feedback, (c) output signal waveform.

output voltage $V_o = 0$ V at the times when $V_{id} = 0$ V, that is, the circuit is nulled. (For reasons we will see later, it is difficult to null the output of an Op Amp if no feedback is used.) Note also that the gain $A_{VOL} = 10{,}000$, which means that the output signal V_o is -10^4 times larger than the input V_{id}, but within limits. In this case, the limits are the rails, plus and minus 8 V, as indicated by the fact that the output signal V_o is clipped at $+8$ V on some positive alternations and at -8 V on some negative alternations. Apparently, this Op Amp has output voltage swing vs. supply voltage characteristics as shown in Fig. 3-1a. Note that, although the input V_{id} varies somewhat sinusoidally and with relatively low amplitudes, the output V_o is -10^4 times larger and runs into the positive and negative rails. Consequently severe clipping occurs. Only the smaller input signals—1.6 mV peak to peak or less—are amplified without clipping. There are applications where the Op Amp is purposely used as a signal-squaring circuit in which deliberately driving its input with a relatively large signal results in a square-wave output. This output appears more square and less like a trapezoid when the input signals have larger amplitudes.

If the same input signal is applied to the noninverting input 2, as shown in Fig. 3-3, the output is $+10^4$ times larger, within limits of course. In this case, the output swings positively and then negatively on the positive and negative alternations of the input signal, respectively. Clipping occurs when the output attempts to exceed the Op Amp's rails, just as in the inverting mode.

Example 3-1

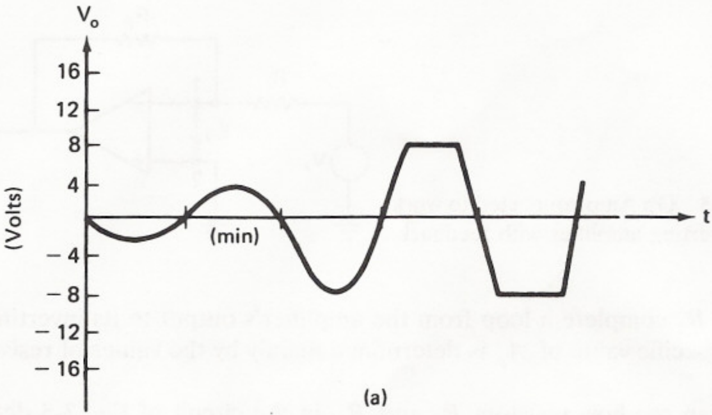
Sketch output voltage waveforms of an Op Amp, such as in Fig. 3-2, if the input signal is as shown but with:

(a) an Open-loop gain $A_{VOL} = 5000$.
(b) an Open-loop gain $A_{VOL} = 100{,}000$.

Answer. See Fig. 3-4. Note that with a larger gain, A_{VOL}, a given input signal tends to be more distorted. This does not mean that a high open-loop gain is undesirable; on the contrary, the larger A_{VOL} is, the better. As we will see, clipping can easily be controlled with feedback.

3.2 FEEDBACK AND THE INVERTING AMPLIFIER

Negative feedback is used with Op Amps in linear applications. Feedback enables the Op Amp circuit designer to easily select and control voltage gain. Generally, an amplifier has negative feedback if a portion of its output is fed



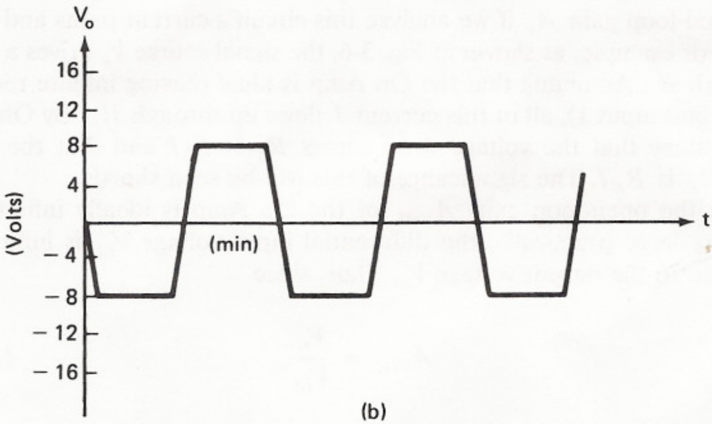


Figure 3-4 (a) Output voltage of the Op amp in Fig. 3-2 if $A_{VOL} = 5000$, (b) output voltage of the Op Amp in Fig. 3-2 if $A_{VOL} = 100{,}000$.

back to its inverting input. The Op amp circuit in Fig. 3-5 has negative feedback. Note that a resistor R_F is across the Op Amp's output and inverting input terminals. This, along with R_1, causes a portion of the output signal V_o to be fed back to the inverting input terminal. With this feedback, the circuit's effective (closed-loop) voltage gain A_v is typically much smaller than the Op Amp's open-loop gain A_{VOL}.

In the circuit shown in Fig. 3-5, the input signal is voltage V_s; therefore, its closed-loop voltage gain is

$$\boxed{A_v = \frac{V_o}{V_s}}. \qquad (3\text{-}1)$$

This ratio is called the *closed-loop gain* because it is the gain when resistors

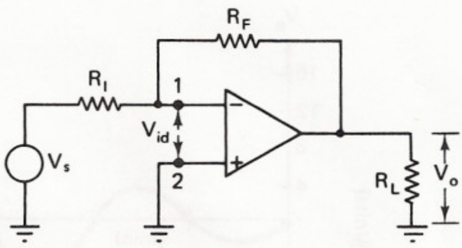


Figure 3-5 Op Amp connected to work as an inverting amplifier with feedback.

R_F and R_1 complete a loop from the amplifier's output to its inverting input 1. The specific value of A_v is determined mainly by the values of resistors R_F and R_1.

We can see how resistors R_1 and R_F in the circuit of Fig. 3-5 determine the closed-loop gain A_v if we analyze this circuit's current paths and voltage drops. For example, as shown in Fig. 3-6, the signal source V_s drives a current I through R_1. Assuming that the Op Amp is ideal (having infinite resistance looking into input 1), all of this current I flows up through R_F. By Ohm's law we can show that the voltage drop across R_1 is R_1I and that the voltage across R_F is R_FI. The significance of this will be seen shortly.

Since the open-loop gain A_{VOL} of the Op Amp is ideally infinite or at least very large practically, the differential input voltage V_{id} is infinitesimal compared to the output voltage V_o. Thus, since

$$A_{VOL} = \frac{V_o}{V_{id}}, \tag{2-3a}$$

then

$$V_{id} = \frac{V_o}{A_{VOL}}$$

This last equation shows that the larger A_{VOL} is with any given V_o, the

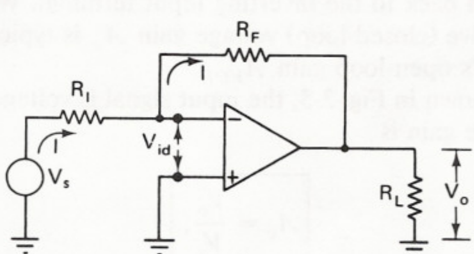


Figure 3-6 Currents in R_1 and R_F are equal if the Op Amp is ideal; they are approximately equal with practical Op Amp if R_F is not too large.

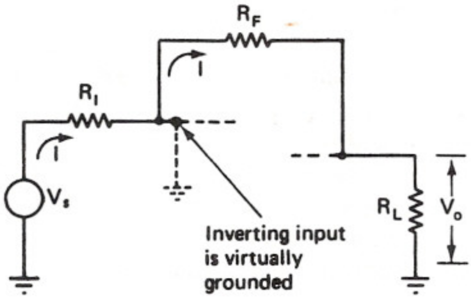


Figure 3-7 Equivalent circuit of Figs. 3-5 and 3-6; $V_s \cong R_1 I$ and $V_o \cong R_F I$.

smaller V_{id} must be compared to V_o. The point is, the voltage V_{id} across inputs 1 and 2 is practically zero because of the large open-loop gain A_{VOL} of the typical Op Amp. Therefore, with *virtually* no potential difference between inputs 1 and 2, and with the noninverting input 2 grounded, the inverting input is *virtually* grounded too. This circuit's equivalent can therefore be shown as in Fig. 3-7. With voltage V_o to ground at the right of R_F and virtual ground at its left, the voltage across R_F is V_o for practical purposes. By Ohm's law,

$$\boxed{V_o \cong R_F I.} \tag{3-2}$$

Similarly, we can see that the voltage V_s to ground is applied to the left of R_1, while its right end is virtually grounded. Therefore, for most practical purposes, the voltage across R_1 is V_s. Again with Ohm's law we can show that

$$\boxed{V_s \cong R_1 I.} \tag{3-3}$$

Since the closed-loop gain A_v is the ratio of the output signal voltage V_o to the input signal voltage V_s, we can substitute Eqs. (3-2) and (3-3) into this ratio and show that

$$\boxed{A_v = \frac{V_o}{V_s} \cong -\frac{R_F I}{R_1 I} \cong -\frac{R_F}{R_1}.} \tag{3-4}$$

The negative sign means that the input and output signals are out of phase. This last equation shows that by selecting a ratio of feedback resistance R_F

to the input resistance R_1, we select the inverting amplifier's closed-loop gain A_v.

There are limits on the usable values of R_F and R_1 which are caused by practical design problems. Though these design problems are discussed in later chapters, for the present we should know that the feedback resistance R_F is rarely larger than 10 MΩ. More frequently, R_F is 1 MΩ or less. Since one end of the signal source V_s is grounded and one end of R_1 is virtually grounded, V_s sees R_1 as the amplifier's input resistance. To avoid loading of (excessive current drain from) the signal source V_s, R_1 is typically 1 kΩ or more.

Example 3-2

Referring to the circuit in Fig. 3-8a, find its voltage gain V_o/V_s when the switch S is in:

(a) position 1,
(b) position 2, and
(c) position 3.
(d) If the switch is in position 2 and the input voltage V_s has the waveform shown in Fig. 3-8b, sketch the output voltage waveform V_o. Assume that when V_s was zero, the output V_o was zero (nulled).
(e) What is the resistance seen by the signal source V_s for each of the switch positions?

Answers

(a) When the switch S is in position 1, the feedback resistance $R_F =$ 10 kΩ. The input resistor $R_1 = 1$ kΩ regardless of the switch position. Therefore, the gain is

$$A_v \cong -\frac{R_F}{R_1} = -\frac{10\text{ k}\Omega}{1\text{ k}\Omega} = -10. \tag{3-4}$$

(b) With the switch S in position 2, $R_F = 100$ kΩ; therefore

$$A_v \cong -\frac{100\text{ k}\Omega}{1\text{ k}\Omega} = -100.$$

(c) With the switch S in position 3, $R_F = 1$ MΩ; therefore,

$$A_v \cong -\frac{1\text{ M}\Omega}{1\text{ k}\Omega} = -1000.$$

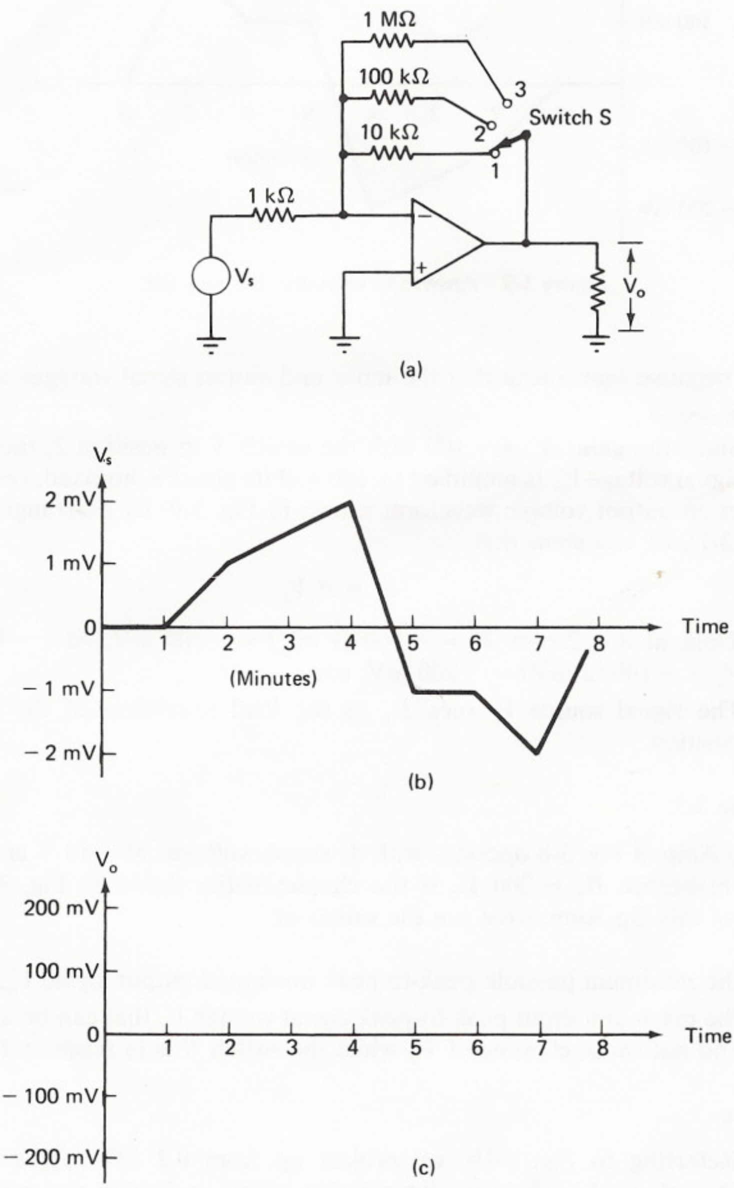


Figure 3-8 Circuit for Example 3-2.

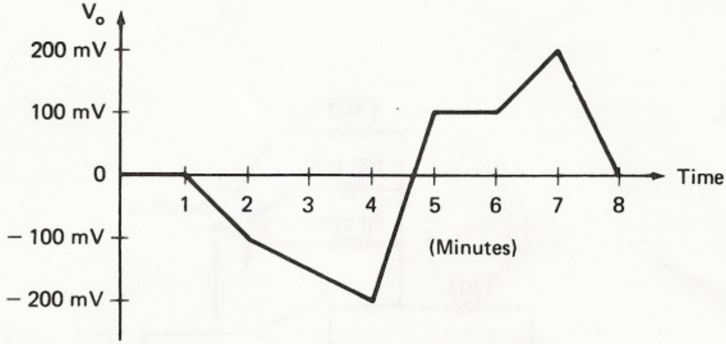


Figure 3-9 Answer to Example 3-2, part (d).

The negative signs mean that the input and output signal voltages are out of phase.

(d) Since the gain $A_v = -100$ with the switch S in position 2, the input signal voltage V_o is amplified by 100 and its phase is inverted, resulting in an output voltage waveform shown in Fig. 3-9. By rearranging Eq. (3-1), we can show that

$$V_o = A_v V_s.$$

Thus, at it = 2 min, $V_o = -100$ (1 mV) = -100 mV. At $t = 4$ min, $V_o = -100$ (2 mV) = -200 mV, etc.

(e) The signal source V_s sees R_1 as the load regardless of the switch position.

Example 3-3

The Op Amp in Fig. 3-8 operates with dc supply voltages of ± 15 V and with a load resistance $R_L = 200\ \Omega$. If the characteristics shown in Fig. 3-1 are typical of this Op Amp, what are the values of:

(a) the maximum possible peak-to-peak unclipped output signal V_o, and
(b) the maximum input peak-to-peak signal voltage V_s that can be applied and not cause clipping of V_o while the switch S is in position 2?

Answers

(a) Referring to Fig. 3-1b, we project up from 0.2 kΩ to the curve. Directly to the left of the intersection of our projection and curve, we see that this amplifier's peak-to-peak output swing capability is about 11 V. This means that clipping will occur if we attempt to drive the output V_o beyond +5.5 V or -5.5 V.

(b) With the switch S in position 2, the gain is -100 as we found in the previous problem. Since the maximum peak-to-peak output swing is about 11 V, the maximum peak-to-peak input swing is determined as follows. Since

$$A_v = \frac{V_o}{V_s}, \tag{3-1}$$

then

$$V_s = \frac{V_o}{V_v} \cong \frac{11\text{ V (p-p)}}{-100} = |110\text{ mV (p-p)}|.$$

3.3 FEEDBACK AND THE NONINVERTING AMPLIFIER

We can use the Op Amp, with feedback, in a noninverting mode much as we used it in the inverting mode discussed in the previous section. We can drive the noninverting input 2 with a signal source V_s instead of indirectly driving the inverting input 1 as shown in Figs. 3-3 and 3-10. As with the inverting amplifier, the values of externally connected resistors R_1 and R_F determine the circuit's closed-loop voltage gain A_v. A gain equation in terms of R_1 and R_F can be worked out if we analyze the noninverting amplifier's currents and voltages.

As shown in Fig. 3-11a, the signal current I is the same through resistors R_1 and R_F as long as the resistance R_i looking into the inverting input 1 is infinite or at least very large. In other words, R_1 and R_F are effectively in series. As before, the voltge drops across these resistors can be shown as $R_1 I$ and $R_F I$. At the right side of R_F we have the output voltage V_o to ground. This voltage is also across R_1 and R_F because these resistors are effectively in series and the left side of R_1 is grounded. Thus, we can show that the output voltage V_o is the sum of the drops across R_1 and R_F; that is

$$V_o \cong R_1 I + R_F I.$$

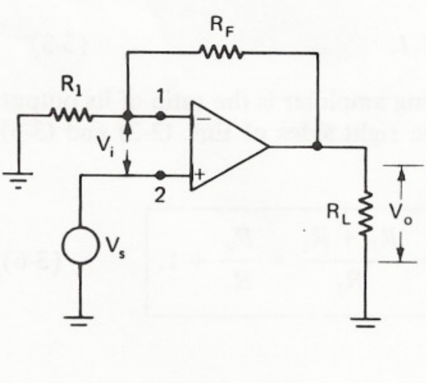
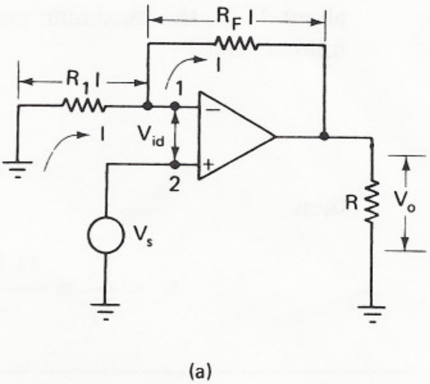


Figure 3-10 Op Amp wired to work as a noninverting amplifier (noninverting mode).



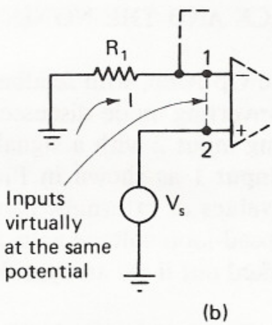


Figure 3-11 (a) Noninverting amplifier with currents and voltage drops shown; (b) the difference voltage V_{id} across inputs 1 and 2 is so small compared to V_s that these inputs are virtually shorted.

Factoring I out, we get

$$\boxed{V_o \cong (R_1 + R_F)I.} \tag{3-5}$$

As with the inverting amplifier, the differential input voltage V_{id} is zero for most practical purposes. Due to the very large open-loop gain A_{VOL} of the typical Op Amp, we can assume that there is practically no potential difference between points 1 and 2 as shown in Fig. 3-11b. Therefore, nearly all of the input signal voltage V_s appears across R_1, and by Ohm's law, we can again show that

$$V_s \cong R_1 I. \tag{3-3}$$

The voltage gain A_v of the noninverting amplifier is the ratio of its output V_o to its input V_s. Thus, substituting the right sides of Eqs. (3-3) and (3-5) into this ratio yields

$$\boxed{A_v = \frac{V_o}{V_s} \cong \frac{(R_F + R_1)I}{R_1 I} = \frac{R_F + R_1}{R_1} = \frac{R_F}{R_1} + 1.} \tag{3-6}$$

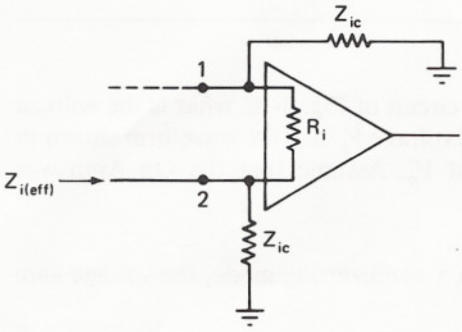


Figure 3-12 Equivalent circuit of an Op Amp; R_i is the resistance between inputs 1 and 2 specified by the manufacturer; Z_{ic} is the impedance to ground or common from either input which is actually internal to the Op Amp.

Since the resistance seen looking into the noninverting input is infinite if the Op Amp is ideal (or at least very large with a practical Op Amp), the signal source V_s sees a very large resistance looking into the Op Amp of Fig. 3-10. Generally, the effective input resistance of the noninverting amplifier is larger with circuits wired to have lower closed-loop gains. More specifically, the effective opposition to signal current flow into the noninverting input is an impedance $Z_{i(\text{eff})}$ when input capacitances are considered. Looking into the noninverting input 2, the signal current sees parallel paths: through an impedance Z_{ic} and through the Op Amp's resistance R_i (see Fig. 3-12). Thus the total effective input resistance is

$$\boxed{R_{i(\text{eff})} \cong \frac{1}{A_v/A_{VOL}R_i + 1/Z_{ic}}} \qquad (3\text{-}7a)$$

where R_i is the input resistance measured between input 1 and 2, open-loop, and its value is provided on the manufacturer's spec sheets,

Z_{ic} is the impedance to ground or common measured from either input,

A_{VOL} is the open-loop gain, and

A_v is the closed-loop gain.

Typically, Z_{ic} is much larger than R_i, especially at lower frequencies. If we assume that Z_{ic} is relatively very large, Eq. (3-7a) can be simplified to

$$\boxed{R_{i(\text{eff})} \cong \frac{1}{A_v/A_{VOL}R_i} = \left(\frac{A_{VOL}}{A_v}\right)R_i.} \qquad (3\text{-}7b)$$

Note that if the Op Amp is wired to have a low closed-loop gain A_v, say approaching 1, the effective input resistance $R_{i(\text{eff})}$ theoretically approaches a value that is A_{VOL} times larger than the manufacturer's specified R_i.

Example 3-4

If $R_1 = 1\ \text{k}\Omega$ and $R_F = 10\ \text{k}\Omega$ in the circuit of Fig. 3-10, what is the voltage gain V_o/V_s? If this circuit's input signal voltage V_s has the waveform shown in Fig. 3-13a, sketch the resulting output V_o. Assume that the Op Amp was initially nulled.

Answer. Since this Op Amp is wired in a noninverting mode, the voltage gain can be determined with Eq. (3-6):

$$A_v \cong \frac{R_F}{R_1} + 1 = 11.$$

Therefore, the output voltage is 11 times larger than, and in phase with, the input signal V_s. Thus at $t = 2$ min, $V_o = 11(-20\ \text{mV}) = -220$ mV. Similarly, at $t = 5$ min, $V_o = 11(10\ \text{mV}) = 110$ mV, etc. (See Fig. 3-14 for the complete output waveform.)

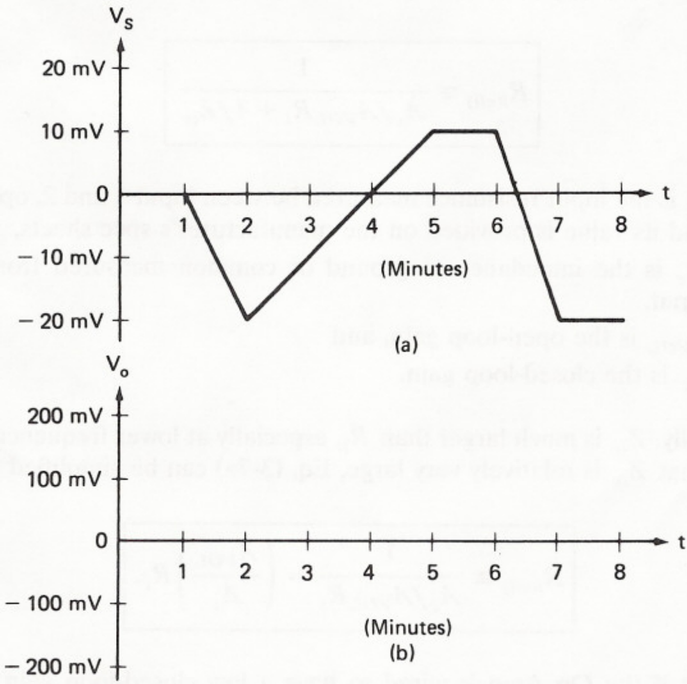


Figure 3-13

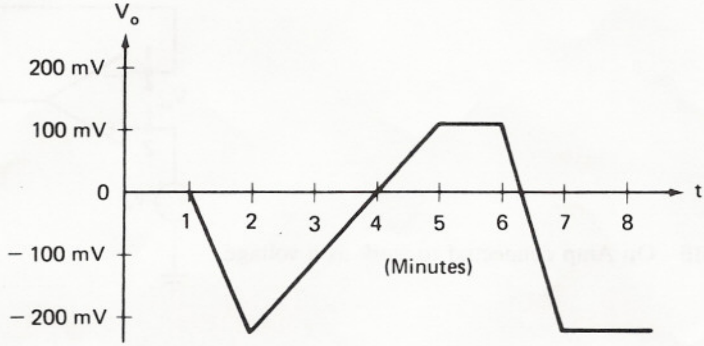


Figure 3-14 Answer to Example 3-4.

Example 3-5

Refer to the circuit described in Example 3-4. If the Op Amp is a 741 C type as listed in Appendix E, what approximate minimum resistance does the signal source V_s see if the impedance to ground from either input is assumed to be infinite?

Answer. As shown in Appendix E, the 741C's minimum A_{VOL} and R_i values are 20,000 and 150 kΩ, respectively. Since the circuit is wired externally for a closed-loop gain of 11, we can find the minimum effective impedance seen by V_s with Eq. (3-7b). Thus in this case

$$R_{i(\text{eff})} \cong \left(\frac{20{,}000}{11}\right) 150\ \text{k}\Omega \cong 273\ \text{M}\Omega. \tag{3-7b}$$

3.4 THE VOLTAGE FOLLOWER

In some applications, an amplifier's voltage gain is not as important as its ability to match a high-internal-resistance signal source to a low, possibly varying, resistance load. The Op Amp in Fig. 3-15 is connected to work as a *voltage follower* which has an extremely large input resistance and is capable of driving a relatively low-resistance load. The voltage follower's output resistance is very small; therefore, variations in its load resistance negligibly affect the amplitude of the output signal. When used between a high-internal-resistance signal source and a smaller, varying-resistance load, the voltage follower is called a *buffer amplifier*.

The voltage follower is simply a noninverting amplifier, similar to the one in Fig. 3-11a, where R_1 is replaced with infinite ohms (an open) and R_F is replaced with zero ohms (a short). (See Fig. 3-16.) Due to the Op Amp's

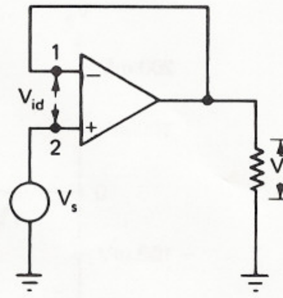


Figure 3-15 Op Amp connected to work as a voltage follower.

large open-loop gain A_{VOL}, the differential input voltage V_{id} is very small; therefore, the inputs 1 and 2 are virtually at the same potential. Since the output signal V_o is the voltage ato input 1, and since the input signal V_s is directly applied to input 2, then

$$V_o \cong V_s.$$

With the input and output signal voltages equal, the voltage gain of the voltage follower is 1 (unity). We can see this another way—by substituting $R_1 = \infty\ \Omega$ into the gain Eq. (3-6). The term R_F/R_1 becomes zero and $A_v = 1$. The term *voltage follower* therefore describes the circuit's function: The output voltage V_o follows the input voltage V_s waveform.

As with the noninverting amplifier, the effective input $R_{in(\text{eff})}$ of the voltage follower is about A_{VOL}/A_v times larger than R_i, where R_i is the differential input resistance measured under open-loop conditions. Since the voltage follower's closed-loop gain $A_v \cong 1$, the ratio A_{VOL}/A_v is very large—equal to A_{VOL}. This accounts for the extremely high input impedance of the voltage follower.

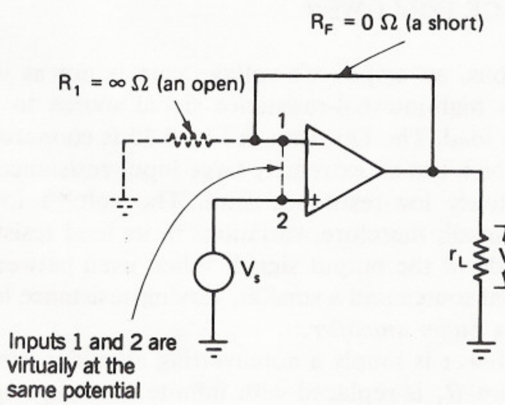


Figure 3-16 The voltage follower of Fig. 3-10 can be shown to be a noninverting amplifier.

As the input impedance $Z_{in(\text{eff})}$ is made more ideal (increased) by the use of negative feedback, the output resistance is also improved (reduced). More specifically, the effective output resistance $R_{o(\text{eff})}$ of an Op Amp is smaller than the output resistance R_o measured with open-loop conditions by the factor A_v/A_{VOL}. That is,

$$R_{o(\text{eff})} \cong \left(\frac{A_v}{A_{VOL}}\right) R_o. \tag{3-8}$$

This shows that the smaller the closed-loop gain A_v, the smaller the effective output resistance $R_{o(\text{eff})}$.

Example 3-6

(a) If the circuit in Fig. 3-15 has the input voltage waveform V_s shown in Fig. 3-8a, sketch the output voltage waveform. Assume that initially the Op amp was nulled.

(b) If a signal source has 100 kΩ of internal resistance and an output of 4 mV *before* being connected to input 2 (open circuited), what is the output of the signal source *after* it is connected to the input 2 of this circuit?

Answers

(a) Since the gain A_v of the voltage follower is unity, and since there is no phase inversion, the output V_o has the same waveform as the input V_s.

(b) The input impedance of the voltage follower is in the range of hundreds of megohms and therefore appears as an open compared to the 100 kΩ internal resistance of the signal source. Thus, there is essentially no signal voltage drop across the internal resistance, and the output of the signal generator remains very close to its 4-mV open-circuit value after being connected to input 2. Therefore the output of this voltage follower is also about 4 mV.