Using Op Amps

Practical applications of the ubiquitous op amp as an amplifier, a filter and a limiter

By Robert A. Witte

New integrated-circuit devices are as universally used as the ubiquitous operational amplifier —or "op amp," as it's affectionately known. It has become firmly established as the workhorse of low-frequency analog circuit design and is frequently found in digital circuits. What makes the op amp so appealing are its standard features: ideally infinite gain, infinite input impedance and zero output impedance.

Op amps usually require a dual power supply, such as +15 and −15 volts, although there are methods for powering them from a single supply (see box). These miniature electronic wonders are available in single, dual and quad chip configurations, with one, two or four op amps in a single IC package, as shown in Fig. 1. In these drawings, note that V+ indicates the positive power supply, V− the negative supply, and NC indicates no connection.

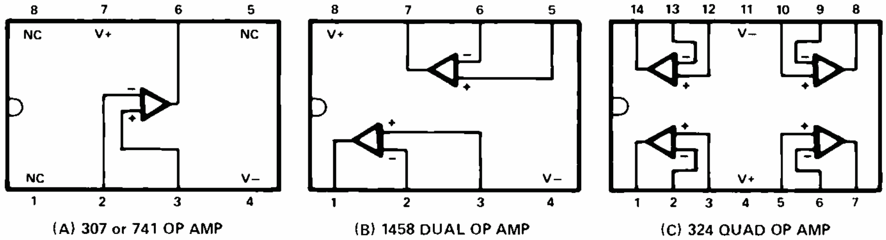

Fig. 1. Connection diagrams for several popular op-amp integrated circuits.

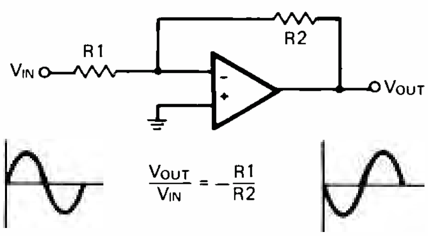

Fig. 2. Voltage gain of inverting amplifier is determined by ratio of the feedback resistor over input resistor.

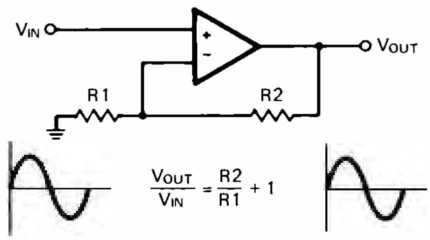

Fig. 3. The noninverting op-amp circuit provides voltage gain without inverting polarity of the input signal.

Inverting & Noninverting Amplifiers

The inverting amplifier configuration shown in Fig. 2 has a voltage gain (ratio of output voltage V_{out} to input voltage V_{in}) that is determined by the ratio of *R1/R2*. The negative sign in the formula indicates that the output is inverted relative to input voltage. If V_{in} is +5 volts dc, V_{out} will be −5 volts dc. If V_{in} is a 5-volt 0-to-peak sine wave, V_{out} will be a 5-volt 0-to-peak sine wave with a 180° phase shift with respect to the input. In many applications, it doesn't matter if the signal is inverted. For instance, a single audio tone will sound the same whether or not it's inverted.

Input impedance of the inverting amplifier is simply the value of *R1*, while output impedance is near zero.

If the polarity of the input signal must be preserved in the output, the noninverting amplifier configuration shown in Fig. 3 can be used. Voltage gain here is $R2/R1 + 1$. Operation of this circuit is very similar to that of the Fig. 2 inverting amplifier circuit, except that V_{out} is *not* inverted relative to V_{in}.

Since the input of the Fig. 3 circuit goes directly to the op amp, input impedance is very high. (Ideally, it is infinite. In practice, however, it is limited by the input specifications of the op amp.) Output impedance is very near zero.

Special Amplifiers

One special op-amp configuration is the difference amplifier shown in Fig. 4. Note that this arrangement uses both the inverting and noninverting configurations in a combination that yields a difference signal at the output.

As the difference amplifier's name implies, the output of the circuit is the difference of input voltages V_1 and V_2 multiplied by gain factor *R2/R1*. For example if $R2 = 3R1$, $V_1 = +2$ volts and $V_2 = +5$ volts, $V_{out} = 3(5 - 2) = 9$ volts.

The difference amplifier can be used wherever one signal or voltage must be subtracted from another.

Another special op amp circuit is the summing amplifier shown in Fig. 5. An extension of the inverting amplifier, the summing amplifier permits several different inputs to be added to produce the output. Notice that additional input resistors (*R1*, *R2* and *R3*) have been tacked onto the basic amplifier circuit to obtain this function. Any number of inputs can be accommodated by using the appropriate number of input resistors.

Since the summing amplifier is based on the inverting amplifier, the output is inverted with respect to the inputs. The voltage gain associated with each input is set independently by the ratio of feedback resistor R_f and the input resistor. If the same gain is desired for each input, just let $R1 = R2 = R3$.

The summing amplifier is often used for summing or "mixing" different audio sources into one audio signal, such as in public-address and recording systems.

Op-Amp Filters

The inverting amplifier can also be modified to serve as a low-pass filter simply by adding a capacitor across feedback resistor *R2* in the Fig. 6 circuit. Gain of the inverting amplifier is determined by *R2/R1*. At low frequencies, impedance of the capacitor is very large and, therefore, does not affect voltage gain. At high frequencies, however, capacitor impedance greatly diminishes and virtually shorts out *R2*, causing voltage gain to increase as frequency increases. What results is a low-pass filter in which the exact frequency at which voltage gain begins to noticeably decrease (cutoff frequency f_c) depends on the values of *R2* and *C*.

Usually, f_c is considered to be the frequency at which the output is 3 dB lower than its normal value at low frequencies. For this circuit, $f_c = 1/(2\pi R2C)$. This circuit doesn't have a particularly sharp rolloff beyond f_c, since voltage gain decreases by a relatively gentle 20 dB for every decade (factor of 10) in frequency.

Figure 6 also shows a plot of voltage in decibels versus logarithmic frequency. It's good design practice to provide some controlled rolloff beyond the particular frequency of interest to reduce high-frequency noise and other undesired signals, with cutoff frequency set high enough so that desired signals aren't affected.

If you add a capacitor in series with the input resistor, as shown in Fig. 7, you obtain a high-pass filter. For very low frequencies, capacitor impedance into the inverting amplifier circuit is very large and blocks virtually all of V_{in}, resulting in minuscule output from the op amp. For high frequencies, capacitor impedance becomes very small and passes virtually all of the input signal.

The slope of the high-pass filter below f_c is 20 dB per decade. Here, $f_c = 1/(2\pi R1C)$.

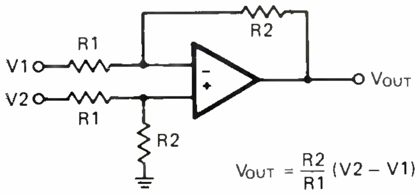

Fig. 4. The difference amplifier subtracts V_1 from V_2, amplifies result.

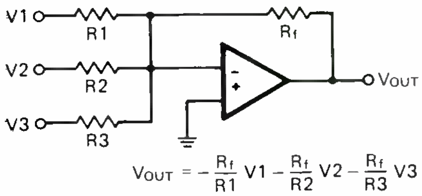

Fig. 5. Summing amplifier configuration adds several voltages. Each input can have different voltage gain.

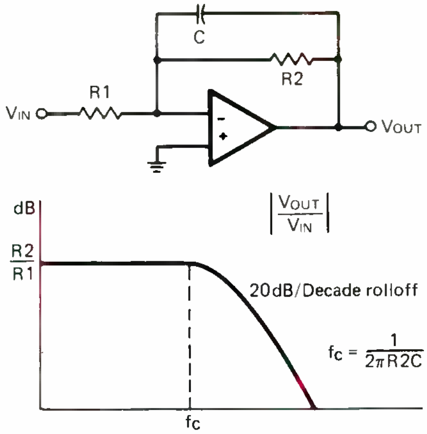

Fig. 6. In this low-pass filter circuit, feedback capacitor C effectively shorts out R2 at high frequencies. Also shown is the frequency-response curve of this filter circuit.

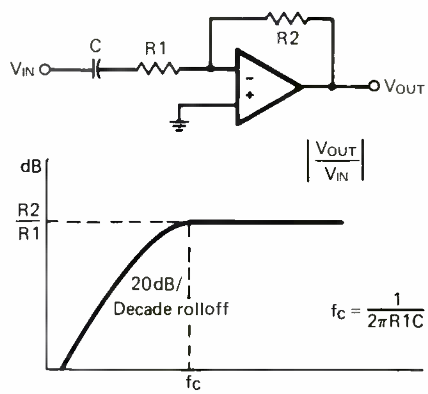

Fig. 7. By adding coupling capacitor C C to the input of the basic inverting amplifier, a high-pass filter is obtained, whose frequency-response characteristic is as shown by the curve.

Single-Supply Operation

Most op amps are designed to be powered by a dual, or "split," power supply. Although you can easily design a split supply, doing so increases the complexity and cost of small electronic projects. However, there are techniques for operating op amps from single supplies that, though they slightly increase circuit complexity, often are well worth eliminating the second supply required.

A very common way of solving the split-supply problem is to use a voltage divider, as shown in Fig. A. The two equal-value resistors divide the supply voltage in half and create a new "ground" at $V_{supply}/2$. The capacitor removes ripple and noise present on the original power supply's output.

When $V_{supply}/2$ is used as ground, V_{supply} becomes V+ and true ground becomes V− for the op-amp circuit. This technique works quite well as long as the current drawn from the $V_{supply}/2$ junction is less than one-tenth of the current through the divider resistors.

For inverting op-amp configurations, the ground connection is the + input of the op amp. This arrangement draws very little current. For circuits that require more current, the values of the 47,000-ohm resistors can be reduced to allow more current to flow through them, though the penalty for doing this is greater power consumption. This technique is shown in Fig. B, using an inverting amplifier.

The capacitor at the input of the Fig. B circuit serves as an ac coupler. This capacitor is usually necessary because the op amp is operating totally above ground potential. If the capacitor weren't included, a negative input signal applied directly to *R1* would be beyond the op amp's ability to handle, since it is outside the range of its V_{supply} and ground power supplies.

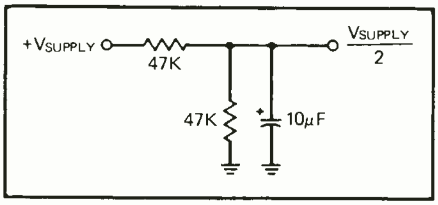

Fig. A. Two series resistors connected across power source creates a new ground for single-supply applications.

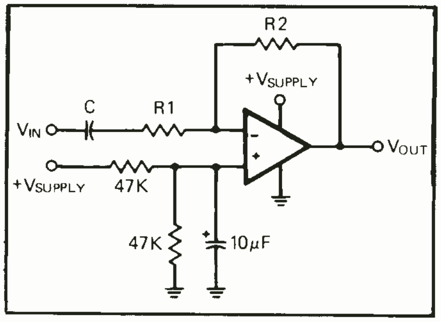

Fig. B. Ac-coupled inverting amplifier biased for single-supply operation.

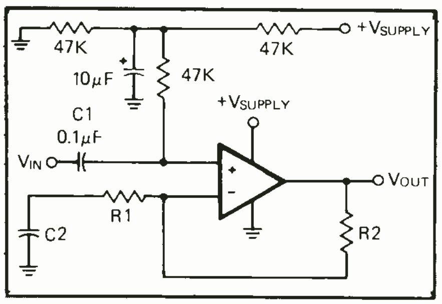

Fig. C. Ac-coupled noninverting amplifier biased for single-supply powering.

If the source of the input signal was another op amp biased for single-supply operation, the input would always be between V+ and ground and ac coupling wouldn't be necessary. However, if the source of the input signal is referenced to ground and has negative voltage swings—such as from a microphone, line output from a tape recorder, etc.—ac coupling is needed. Remember that the values of *R1* and *C1* must be chosen so that the high-pass cutoff frequency will be lower than the frequencies of interest.

Though the same biasing technique can also be used with the noninverting amplifier, the ground connection will no longer be the input of the op amp. Because of this, significant current may be drawn from $V_{supply}/2$, which may require that smaller-value resistors be used in the voltage divider.

An alternative method for the noninverting amplifier is shown in Fig. C. Here, $V_{supply}/2$ is connected to the + input of the op amp, along with small coupling capacitor *C1*. Capacitor *C2* is connected in series with *R1* to allow the op amp to "float" at the proper dc bias level required by $V_{supply}/2$. Also *R1* and *C2* create a high-pass characteristic with a cutoff frequency determined by $f_c = 1/(2\pi R1C2)$.

Choose the values of *R1* and *C2* to obtain the f_c that's below the frequencies of interest. If ac coupling isn't required (V_{in} is always between V_{supply} and ground), *C1* and the 47,000-ohm resistor can be eliminated and V_{in} can be connected directly to the + input.

Some op amps are designed with single-supply operation in mind, while others are designed for split-supply operation. In general, both types can be used for both single- and split-supply operation. The main advantage that single-supply op amps have is that V_{out} can swing all the way to ground. Most split-supply op amp outputs cannot swing all the way to the V+ and V− rails; so when operated with a single supply, their outputs cannot go completely to ground.

This circuit can be used to create a high-pass filter characteristic, or the series capacitor can be used for some other purposes, such as ac coupling. (Since a capacitor blocks dc but passes ac, it's often used to couple together circuits that may have different bias levels.) Regardless of the reason for using the series capacitor, the result will be a high-pass filter characteristic similar to that shown in the graphed plot in Fig. 7. If ac coupling is your goal, select *R1* and *C* so that f_c is sufficiently small for the frequencies of interest.

By combining the high-pass and low-pass circuits, you can produce a bandpass characteristic, the circuit

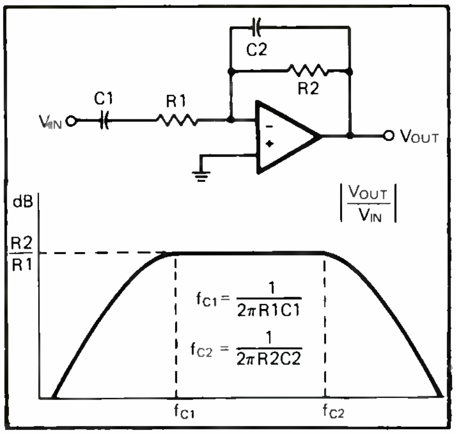

Fig. 8. Combining a feedback capacitor (C2) and input coupling capacitor (C1) with a basic inverting amplifier produces a bandpass filter whose passband is shown by the curve.

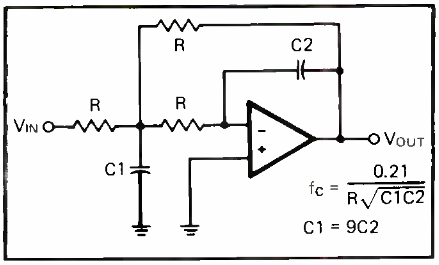

Fig. 9. Shown here is an example of a general-purpose low-pass filter with a 40-dB/decade rolloff characteristic.

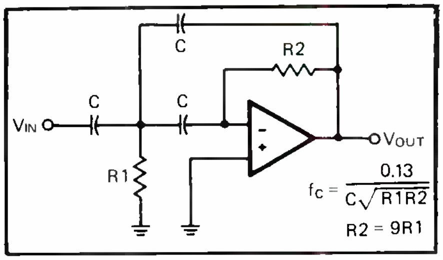

Fig. 10. A general-purpose high-pass filter with a 40-dB/decade rolloff.

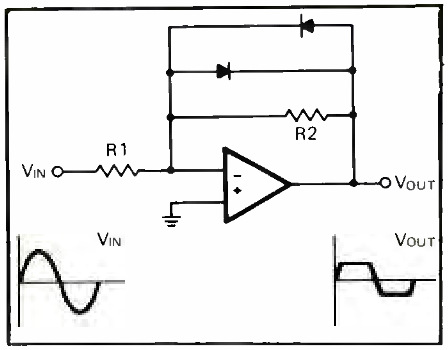

Fig. 11. A pair of diodes across the feedback resistor of the inverting amplifier produces the limiter circuit.

and plot for which are shown in Fig. 8. With this configuration, there are two cutoff frequencies—f_{c1} at the low-frequency and f_{c2} at the high-frequency ends of the passband. Frequencies lower than f_{c1} and greater than f_{c2} are attenuated, while those between these two points pass through at full amplitude.

As long as f_{c1} and f_{c2} aren't too close together, they are independent of each other and can be calculated using the same formulas for the high- and low-pass cutoff frequencies. However, if f_{c1} and f_{c2} are separated by less than a factor of 4, they will begin to interact and cause the results obtained from these formulas to be less accurate.

The bandpass circuit is best suited for moderate low- and high-frequency attenuation. It isn't suitable for very steep and narrow bandpass filtering applications.

Advanced Filters

More advanced filters with steeper rolloff characteristics can be designed using op amps. However, choosing component values becomes very complicated. Such parameters as flatness of the filter's frequency response and steepness of rolloff can be traded off to produce the optimum filter for any given application. Either an advanced analysis or a reference manual with a wide range of component values already computed can be used. For less critical applications, you can use the general-purpose filters to be described.

Figure 9 shows a low-pass filter with the appropriate design equation for the cutoff frequency. The three resistors all have the same value and *C1* = 9*C2*. This circuit has a fairly flat response below f_c (Q_{filter} = 1) and rolls off at a 40-dB-per-frequency-decade rate beyond f_c—twice as steep as the Fig. 6 low-pass filter.

A similar high-pass filter can be constructed, as shown in Fig. 10. All capacitors in this circuit have the same value and *R2* = 9*R1*. Note that the capacitor at the input causes this filter to be inherently ac-coupled. The filter is fairly flat beyond f_c (Q_{filter} = 1) and rolls off at a 40-dB-per-decade rate below f_c.

Op-Amp Limiter

There's one more general-purpose op-amp circuit that should prove of interest. That's the op-amp limiter shown in Fig. 11. Operation of this circuit is fairly straightforward.

Normally, the inverting amplifier will create an output voltage that is an amplified version of the input. At some V_{out} level, however, the op amp will no longer be able to produce an exact replica of V_{in}. At this point, usually near the V+ of the power supply connected to the circuit, the op-amp's output will clip.

In most cases, the clipping level is too large and uncontrolled to be of use. However, the same type of operation can be deliberately induced by adding a pair of diodes across the feedback resistor, as shown in Fig. 11. With this arrangement, when V_{out} is below the forward voltage drop of the diode, the diode is reverse biased and the circuit acts just like an ordinary inverting amplifier. When V_{out} exceeds the diode's forward voltage drop, the diode becomes forward biased, limiting output at that point. Two diodes, connected in opposition, are used to limit both positive and negative voltages. The diodes effectively reduce the value of *R2*—and thus the voltage gain—to zero when the diode is forward biased.

The forward drop of the diode depends on the type of diode used. It's

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0.6 volt for a silicon diode and 0.3 volt for a germanium diode.

This same concept can be expanded by using zener diodes across the feedback resistor, as shown in Fig. 12. Note how the zener diodes are connected in this circuit. With this arrangement, V_{out} is limited at the zener voltage plus the forward drop of the diodes. Since a wide variety of zener voltages are available with different zener diodes, this circuit is much more versatile than that in Fig. 10.

You can use limiter circuits wherever a signal amplitude must be limited to some maximum value. For example, a limiter is often used in tape recorders to prevent the audio signal from overloading the recording function. Bear in mind, however, that limiting produces distortion. So use this circuit only when the amount of distortion is tolerable compared to the effect being guarded against.

In Conclusion

From the foregoing, you can readily see that op amps can be used in a variety of applications, some configurations for which we've described here. There are many applications and configurations we haven't covered, particularly in the digital area.

When using the circuits presented here, keep in mind the effects of the capacitors in the circuits. They will introduce high- or low-frequency rolloff, whether you want them to or not. By paying careful attention to component value selection to obtain an appropriate cutoff frequency, you should be able to sidestep potential problems. **ME**

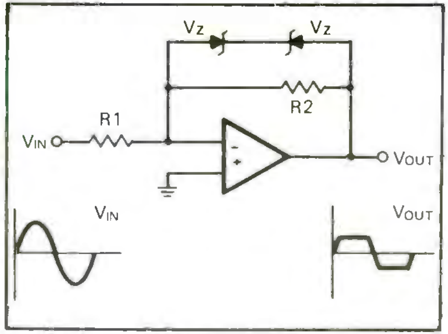

Fig. 12. Using zener diodes in place of ordinary diodes produces a circuit that can limit at almost any voltage.