Nonlinear low-pass filter rejects impulse signals

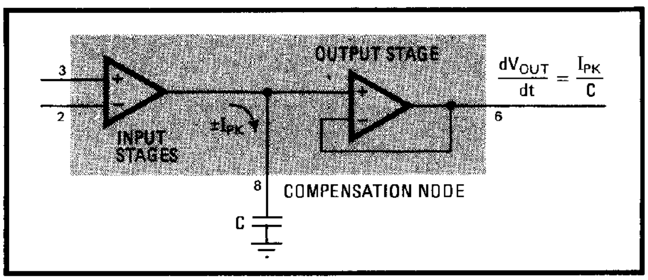
by Barrie Gilbert
Analog Devices Semiconductor, Wilmington, Mass.

A circuit that rejects impulse signals but passes low-slew-rate signals without attenuation or phase shift can be made by connecting a capacitor to the compensation terminal of an operational amplifier. This nonlinear low-pass filtering is useful in the reduction of noise (particularly impulse noise) and in the control of glide rate between notes in electronic music equipment.

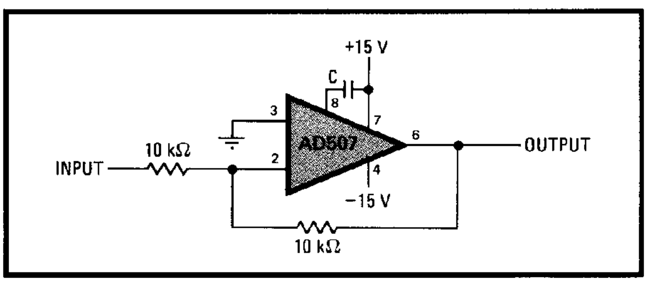
Figure 1 shows the basic configuration required of the op amp. It must have a compensation node into which it drives a stable current, I, during slewing. For optimum performance, this current should have the same magnitude in either slew direction. An external capacitor tied to the node then limits the slew rate to any value below the maximum specified for the particular op amp, because V_{out} is the voltage across the capacitor, and therefore

$$dV_{out}/dt = I/C$$

Not all op amps have the necessary configuration,



1. Nonlinear filter. An operational amplifier that has a compensation terminal with a well-controlled peak current, such as the AD504 or AD507, becomes a nonlinear low-pass filter when a capacitor is connected as shown. Because the slew rate of this circuit is limited, impulse signals and noise are strongly attenuated while low-slew-rate signals are passed without a change of amplitude or phase.



2. How to do it. The actual working circuit for the nonlinear low-pass filter shown here has the performance illustrated by wave forms in Fig. 3. Capacitor C has various values, depending on application.

and of those that do, only a few have a sufficiently well-controlled value for the peak current from the compensation node, I_{pk}. The AD507 is ideally suited to this application, having an I_{pk} that varies little from device to device or with temperature or supply-voltage variations. Its nominal value of ±200 microamperes, which may be either measured or calculated from the compensated slew rate, gives a slew-rate of 1 volt per microsecond for a C of 200 picofarads, and reliable accuracy up to slew-rates of 10 V/μs.

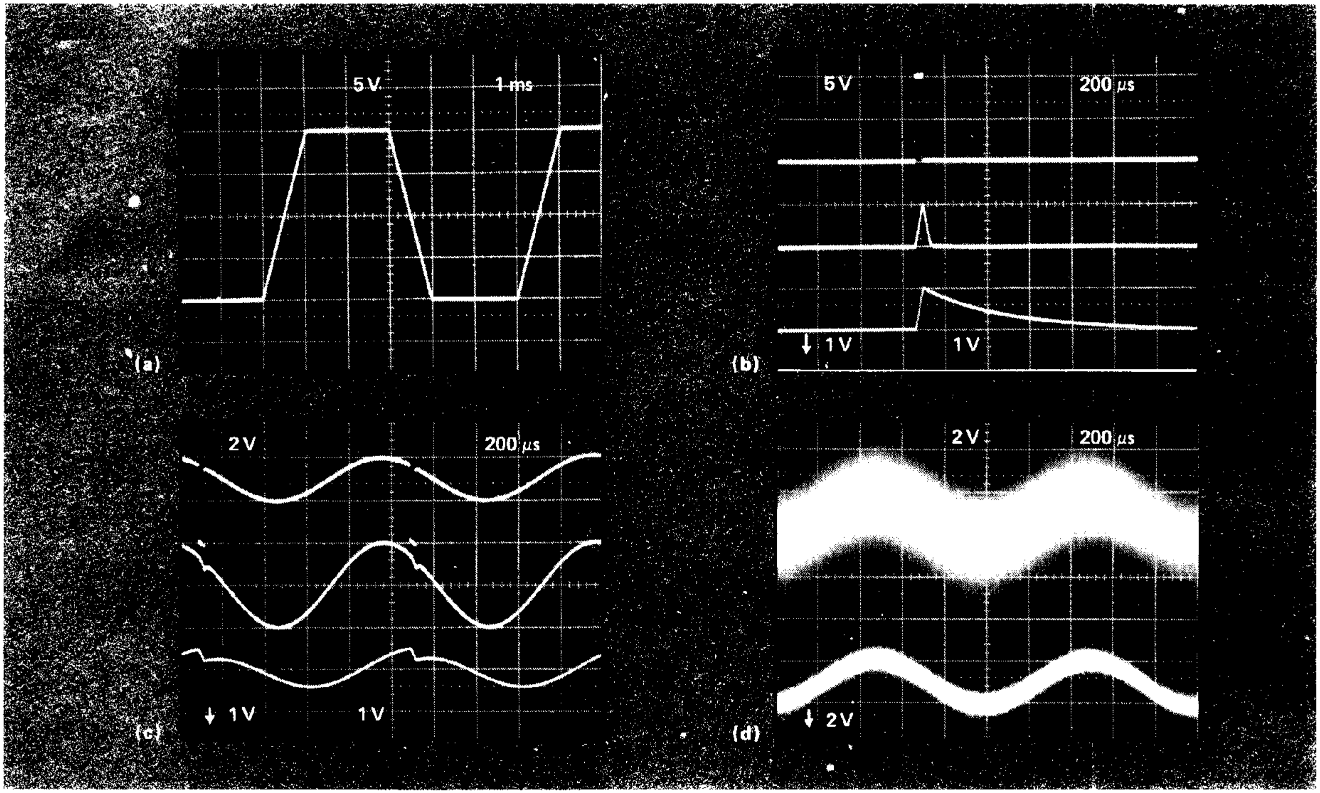
Figure 2 shows a unity-gain inverting amplifier using the AD507; with C = 0.01 microfarad the slew-rate is 0.02 V/μs. The response to a ±10-V square wave, shown in Fig. 3a, demonstrates this slew rate. Notice that C provides adequate loop stabilization, so the capacitor normally connected from pin 6 to pin 8 may be omitted. The small-signal response of this filter is determined by C, but is much higher than the full-power response; for the capacitor shown the figures are 20 kilohertz to −3 decibels (signal level of ±100 mV), and 320 hertz for ±10 V, respectively. Gains other than unity may be achieved simply by altering the ratio R_2/R_1, and the amplifier may be used equally well in the noninverting mode. The slew-rate is unaffected by the absolute value of the resistors, the gain, or the mode.

The usefulness of the filter can be judged by the other wave forms in Fig. 3. In Fig. 3b a 40-μs pulse of 10-V amplitude is shown in the top trace, and the output from the nonlinear filter with C = 0.008 μF is shown in the center trace, which for clarity has been inverted and expanded vertically. The nonlinear op-amp filter has reduced the pulse to a 1-V triangle lasting 80 μs. For comparison, the response of a single-pole linear filter having a time-constant of 400 μs is shown in the lower trace. Although the amplitude has been reduced to 1 V, a tail in the response extends beyond 1 millisecond.

The capacity to reject impulse signals while passing signals of low slew rate with neither attenuation nor phase error is shown more clearly by the wave forms in Fig. 3c. Here the input is a 1-kHz sine wave of 1-V amplitude, on top of which rides a 40-μs pulse of amplitude 3.5 V representing a noise spike. The center trace is the output of the nonlinear filter and shows that the pulse has been almost eliminated while the wave form of the sine wave is preserved.

In contrast, the linear low-pass filter (again a single 400-μs RC network) more than halves the sine-wave amplitude and introduces about 60° of phase lag. Furthermore, the pulse is stretched and actually distorts the wave form, as the lower trace demonstrates.

Nonlinear filters may also be used to reduce the Gaussian noise content of a signal, since it contains occasional high peaks (there is a 0.37% probability that the amplitude exceeds three times the rms value). Fig. 3d illustrates this. Again the input is a 1-kHz sine wave with an amplitude of 1 V, to which has been added 1 V rms of white noise. The output shows an undistorted



3. Get the picture? Performance of nonlinear low-pass filter is shown and compared with that of a linear low-pass (RC) filter. In (a) the input signal is a square wave; with C = 0.01 µF, the circuit slews the output at 20 V/ms. Both (b) and (c) show impulse inputs, response of nonlinear filter with C = 0.008 µF, and response of a linear low-pass (RC) filter. Noise reduction is demonstrated in (c).

sine wave, with only 0.3-V rms noise. Subjectively (if this were an audio signal) the improvement is slight, and more care is needed in selecting the optimum slew rate to effectively reduce white noise.

Unlike in linear filters, no change in response results from cascading stages of equal gain and slew rate. Also, if stages of different gain or slew rate are used, the one having the lowest slew rate is in the driver's seat. A high-pass nonlinear filter can easily be made by subtracting the low-pass signal from the direct input. In fact, the voltage at the summing node of the op amp in Fig. 2 is the high-pass function of the input.

Bandpass filters also can be constructed, by cascading a low-pass section with a high-pass section. When these have the same slew-rate the center frequency of the bandpass filter is inversely proportional to input amplitude. The practical value of the high-pass and bandpass nonlinear filters has not been established. □