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### Devices Connected/Referenced

AD8622	Dual, Low Power, Precision Rail-to-Rail Output Op Amp
ADA4062-2	Low Power JFET-Input Op Amp

## 8-Pole Active Low-Pass Filter Optimized for Precision, Low Noise, and High Gain Using the AD8622 and the ADA4062-2 Op Amps

### CIRCUIT FUNCTION AND BENEFITS

This circuit is a precision, low noise, low power, 8-pole active low-pass filter with a gain of 40 dB. It uses the Sallen-Key topology with the Butterworth response.

Rather than simply constructing the filter with a quad op amp, the selected combination of dual op amps offers a more optimized solution. The AD8622 low noise (0.2  $\mu\text{V}$  p-p, 0.1 Hz to 10 Hz), low offset voltage (10  $\mu\text{V}$  typical) op amp is used for the input and gain stages. The AD8622 offers the lowest offset voltage and noise in the industry for its power (215  $\mu\text{A}$ /amplifier @  $\pm 15$  V). The ADA4062-2 JFET-input op amp is used for the last two stages and also offers low power (165  $\mu\text{A}$ /amplifier). The low input bias current of the ADA4062-2 allows the use of larger resistors and smaller capacitors in the last two stages, thereby reducing the passive component board area.

The filter offers the industry's lowest power solution (760  $\mu\text{A}$  total quiescent current using  $\pm 15$  V supplies) that yields not only precision and low noise but high gain. Using two duals rather than a single quad op amp also provides flexibility and ease in the PCB layout. The ADA4062-2 is also available in a 1.3 mm  $\times$  1.6 mm LFCSP package (smaller than an SC-70), making it the smallest JFET-input op amp in the industry. The smaller size is ideal if designers are concerned about board space when using two duals instead of a quad.

Low-pass filters are often used as antialiasing filters in data acquisition systems or as noise filters to limit high frequency noise. The Butterworth filter is a maximally flat magnitude response filter with no ripple in both the pass band and the stop band. However, this is achieved at the expense of a wider transition band in the frequency response, as compared to other

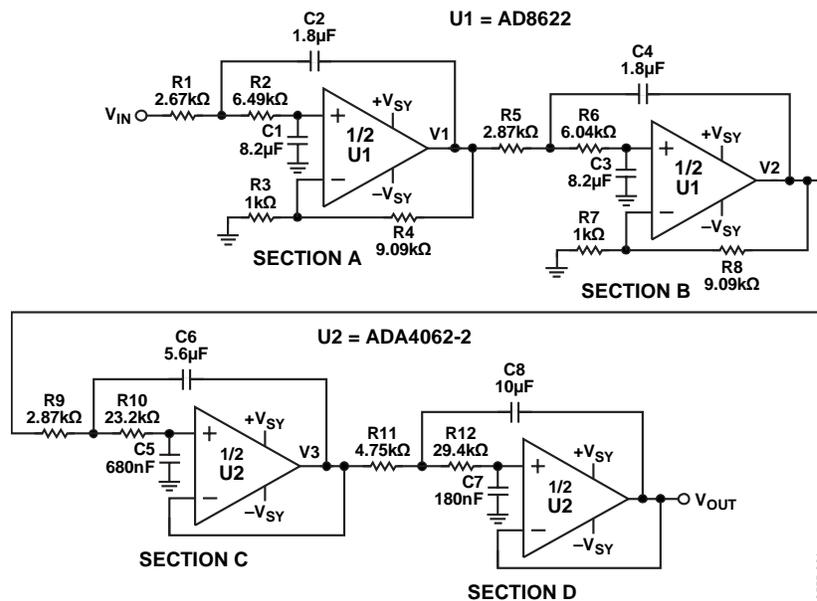


Figure 1. 8-Pole Sallen Key Butterworth Low-Pass Filter Using the AD8622 and ADA4062-2,  $V_{SY} = \pm 15$  V (Decoupling Not Shown)

### Rev. 0

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responses that have ripple. Therefore, higher order Butterworth filters are often required. An active filter design is more complex than a passive filter because both the topology and the proper op amps must be selected. However, the active design allows signal gain, and also eliminates the need for large inductors and capacitors required to implement a low frequency passive filter.

The Sallen-Key topology, also known as the voltage controlled voltage source (VCVS), has been widely used in the industry due to its simple design with few circuit elements. The filter shown has a cutoff frequency,  $f_c$ , of 10 Hz and overall gain of 100 V/V, or 40 dB. The design can be easily scaled to other frequencies using standard filter design techniques.

### CIRCUIT DESCRIPTION

The 8-pole low-pass filter with four complex conjugate pole-pairs is implemented by cascading four 2-pole Sallen Key low-pass filters. Sections A and B are configured as 2-pole low-pass filters with a gain of 10 each, while sections C and D are configured as unity gain filters. The arrangement of the cascade is very important. If gain is required, it should be developed in the early stages to reduce total noise at the output.

Another excellent guideline to avoid saturation or clipping in the op amps is to arrange the stages in order of increasing Q (quality factor). Table 1 shows the Q requirements and pole position associated with each stage of the Butterworth filter. Also, refer to Chapter 8 (“Analog Filters”) in *Linear Circuit Design Handbook* for pole locations on the s plane and Q requirements for filters of different order.

**Table 1. Design Table for 8-Pole Butterworth Low-Pass Filter**

Section	Poles	Q
A	$-0.9808 \pm j 0.1951$	0.5098
B	$-0.8315 \pm j 0.5556$	0.6013
C	$-0.5556 \pm j 0.8315$	0.9000
D	$-0.1951 \pm j 0.9808$	2.5628

To reduce cost and board space, a quad amplifier is generally used to implement an 8-pole filter. However, using two duals instead of a quad should be considered because of the added benefits. With two dual op amps, PCB layout is easier, and the number of board layers can sometimes be reduced. Traces can be spread out, thereby reducing parasitic capacitances and crosstalk. With different gain, bandwidth, noise, and dc precision requirements for each stage, it is important to choose the appropriate amplifier for each stage of the filter.

A low noise and low offset voltage op amp should be used for the first stage of the filter because noise and offset from the first stage is multiplied by the noise gain of all four stages. The AD8622

is a dual, low power, precision op amp. At supply voltages of  $\pm 15$  V, the 0.1 Hz to 10 Hz voltage noise is  $0.2 \mu\text{V p-p}$ , and the typical offset voltage is only  $10 \mu\text{V}$ . The AD8622's dc precision and low noise makes it a good choice for the first two stages of the filter. Smaller resistors are chosen for the first two stages to reduce their thermal noise contribution to the overall noise of the filter. When the total filter gain occurs in the the first two stages, the noise requirement for op amps in the remaining stages is not as important. This allows a lower cost, less precise op amp to be used.

The low power ADA4062-2 is selected for Sections C and D. The ADA4062-2 has JFET differential pair inputs with high input impedance and very low bias current. Because the noise requirement is reduced for the last two stages, and the ADA4062-2 has very low bias current, larger resistor values can be used with smaller capacitors. The low input bias currents of the JFETs contribute minimal dc errors to the circuit.

The cutoff frequency,  $f_c$ , and Q for an individual 2-pole low-pass filter can be calculated with the following equations:

$$f_c = \frac{1}{2\pi\sqrt{R1 \times R2 \times C1 \times C2}} \quad (1)$$

$$Q = \frac{\sqrt{R1 \times R2 \times C1 \times C2}}{R1 \times C1 + R2 \times C1 + R1 \times C2 (1 - \text{Gain})} \quad (2)$$

As a general rule, the gain-bandwidth product of the op amp chosen should be at least 100 times greater than the product of the  $f_c$ , Q, and gain of the filter for the equations to be accurate.

For sufficient full power bandwidth, slew rate is also a concern. Slew rate is given by the general equation:

$$\text{Slew Rate} = \pi \times f_c \times V_{OUT P-P} \quad (3)$$

For a 10 Hz cutoff frequency, the AD8622 and ADA4062-2 both have sufficient slew rate to avoid slew rate limiting.

It is also important to choose appropriate resistor and capacitor values. Selecting a large resistor causes an increase in thermal noise. Although smaller capacitors can then be used to achieve a particular  $f_c$ , the input capacitance of the amplifier may now be significant. The capacitors should be at least 100 times greater than the input capacitance of the amplifiers. The resistors and capacitors are very important in determining the performance over manufacturing tolerances, time, and temperature. At least 1% or better tolerance resistors and 5% or better tolerance capacitors are recommended. Bypass capacitors (not shown in figure) are also needed. In this case, a  $10 \mu\text{F}$  tantalum capacitor in parallel with  $0.1 \mu\text{F}$  ceramic capacitor should be placed on each power pin of each dual op amp. Details of proper decoupling techniques can be found in [Tutorial MT-101](#).

Figure 2 shows the actual measured frequency response of the low-pass filter where:

$V_1$  is the output of the first stage.

$V_2$  is the output of the second stage.

$V_3$  is the output of the third stage.

$V_{OUT}$  is the final filter output.

$V_1$  shows a 40 dB/decade roll-off;  $V_2$  an 80 dB/decade rolloff; and  $V_3$  a 120 dB/decade roll-off. The desired output at  $V_{OUT}$  shows a 160 dB/decade roll-off with a sharp transition band. As noted, the transition band gets sharper as the order of the filter increases.

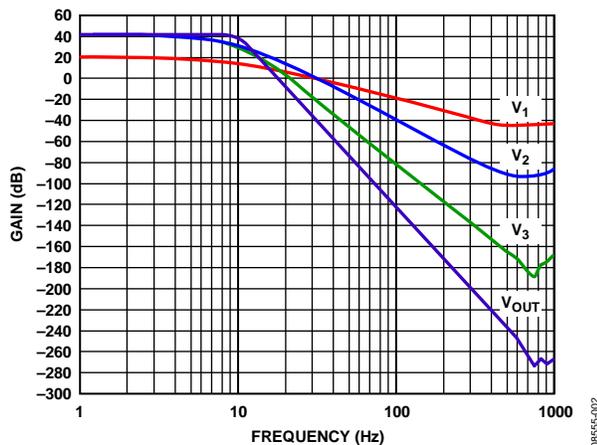


Figure 2. Measured Frequency Response of the 8-Pole Active Filter

Analog Devices has a [Filter Wizard](#) design tool that helps users not only design the active filter but also select the appropriate op amp. The tool will guide users through the filter application design process. These steps include entering filter criteria, reviewing recommended parts, active filter synthesis, and finally generating a bill of materials and/or the op amp SPICE netlist.

### COMMON VARIATIONS

As mentioned earlier, a less stringent requirement is imposed on the selection of op amps for the last two stages. The ADA4062-2 can be replaced with a variety of other amplifiers. For instance, the OP07D is lower cost and can be used but at the expense of higher supply current. For lower supply voltages, consider the ADA4665-2. If a quad op amp is required for the design, the AD8624 is also available. However, when selecting amplifiers, always make sure that the input common-mode voltage range is not violated.

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### LEARN MORE

- [AN-202 Application Note, An IC Amplifier User's Guide to Decoupling, Grounding, and Making Things Go Right for a Change](#). Analog Devices.
- [AN-214 Application Note, Ground Rules for High-Speed Circuits](#), Analog Devices.
- [AN-345 Application Note, Grounding for Low- and High-Frequency Circuits](#), Analog Devices.
- [AN-347 Application Note, Shielding and Guarding: How to Exclude Interference-Type Noise](#), Analog Devices.
- [AN-358 Application Note, Noise and Operational Amplifier Circuits](#) Analog Devices.
- [AN-649 Application Note, Using the Analog Devices Active Filter Design Tool](#), Analog Devices.
- [AN-940 Application Note, Low Noise Amplifier Selection Guide for Optimal Noise Performance](#), Analog Devices.
- Jung, Walt. *Op Amp Applications*, Analog Devices. Also available as *Op Amp Applications Handbook*, Elsevier.
- MT-047 Tutorial, *Op Amp Noise*. Analog Devices.
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### Data Sheets

- [AD8622 Data Sheet](#)
- [AD8624 Data Sheet](#)
- [ADA4062-2 Data Sheet](#)
- [ADA4665-2 Data Sheet](#)
- [OP07D Data Sheet](#)

### REVISION HISTORY

1/10—Revision 0: Initial Version