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## TUTORIAL 4422

# Integrated solutions make analog filter design easy

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*Abstract: This application note explains advances of switched-capacitor analog filters for anti-aliasing and noise filtering for ADCs (analog-to-digital converters), as well as "reconstruction" post-filtering for DACs (digital-to-analog converters). The article summarizes the unique benefits of the MAX74xx series filter vs. continuous-time active filters and provides application examples.*

A similar version of this article appeared in the October 2009 issue of *Electronic Products* magazine.

Analog filters play an important part in electronic signal-synthesis subsystems, providing functions such as anti-aliasing and noise filtering for ADCs, and reconstruction post-filtering for DACs.<sup>1</sup> Different design specifications and requirements dictate the use of the particular filter configurations. The most popular filters include Bessel, Butterworth, and elliptic.

Bessel lowpass filters provide a linear phase response with a ripple-free passband and monotonic rolloff. These characteristics make Bessel filters ideal for time domain applications. Butterworth lowpass filters have a maximally flat frequency response in the passband with a monotonic rolloff that is much sharper than the Bessel filter. Their phase response varies nonlinearly with frequency. These characteristics present no problems for amplitude-based applications. Finally, elliptic lowpass filters have a nearly flat passband response with an extremely sharp rolloff characteristic. Elliptic filters are ideally suited to amplitude-based anti-aliasing applications.

Design and construction of continuous-time active filters pose substantial design challenges and require the use of multiple high-performance op amps surrounded by many matched tight-tolerance passive components. Design challenges include selection of the optimal filter configuration, as well as the use of specialized software for filter synthesis.<sup>2</sup> A simpler approach might include the use of highly integrated SCFs (switched-capacitor filters)—such circuits can reduce the number of components, make it easier to tune the filter, and trim system power. This article will examine a filter implementation, first using a continuous-time filter and then with an SCF approach to show the differences in performance and complexity.

As mentioned previously, due to their characteristics, Bessel filters are ideal for time domain applications, as they have no distortion in the oscilloscope/analyzer type measurements. However, the cost for the perfect characteristic filter is that the designer must construct a higher order Bessel filter (having more poles than a Butterworth or elliptic filter) to achieve a suitable level of stopband attenuation.

**Figure 1** shows a schematic for a 5th-order, 1.0kHz, lowpass Bessel filter. This design is based on Sallen-Key architecture, is optimized for minimum component count, and uses standard-value 1%-tolerance resistors and 5%-tolerance ceramic capacitors. To determine the component values, the design was created using FilterPro™ software and "tested" using PSPICE simulation tools.

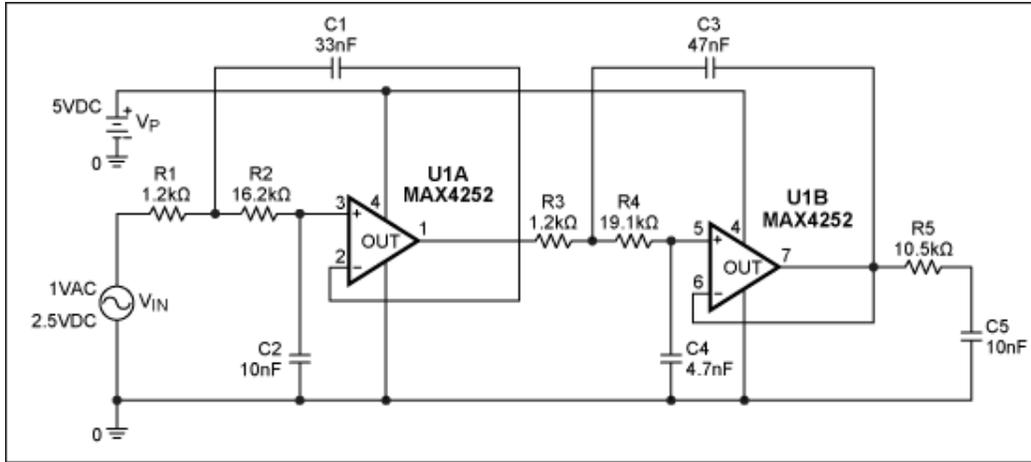


Figure 1. Two op amps and a handful of passive parts comprise this 5th-order, 1.0kHz, lowpass Bessel filter.

In many cases, input and output RC filters also require additional op amp buffers, particularly if the signal source impedance is relatively high (above a few hundred ohms) and the output of the filter is connected to the relatively low impedance circuit (below several hundred kilohms).

SPICE simulations run on the Bessel filter circuit are shown in **Figure 2**. These frequency response plots are the result of a Monte Carlo run of 100 different virtual manufacturing builds for the same filter. The SPICE simulator randomly varies the component values within their specified tolerances to account for manufacturing variances. The results of the simulation demonstrate a passband variation around  $f_C = f_{IN} -3dB \pm 0.6dB$  due to capacitor and resistor values spread in their tolerance ranges.

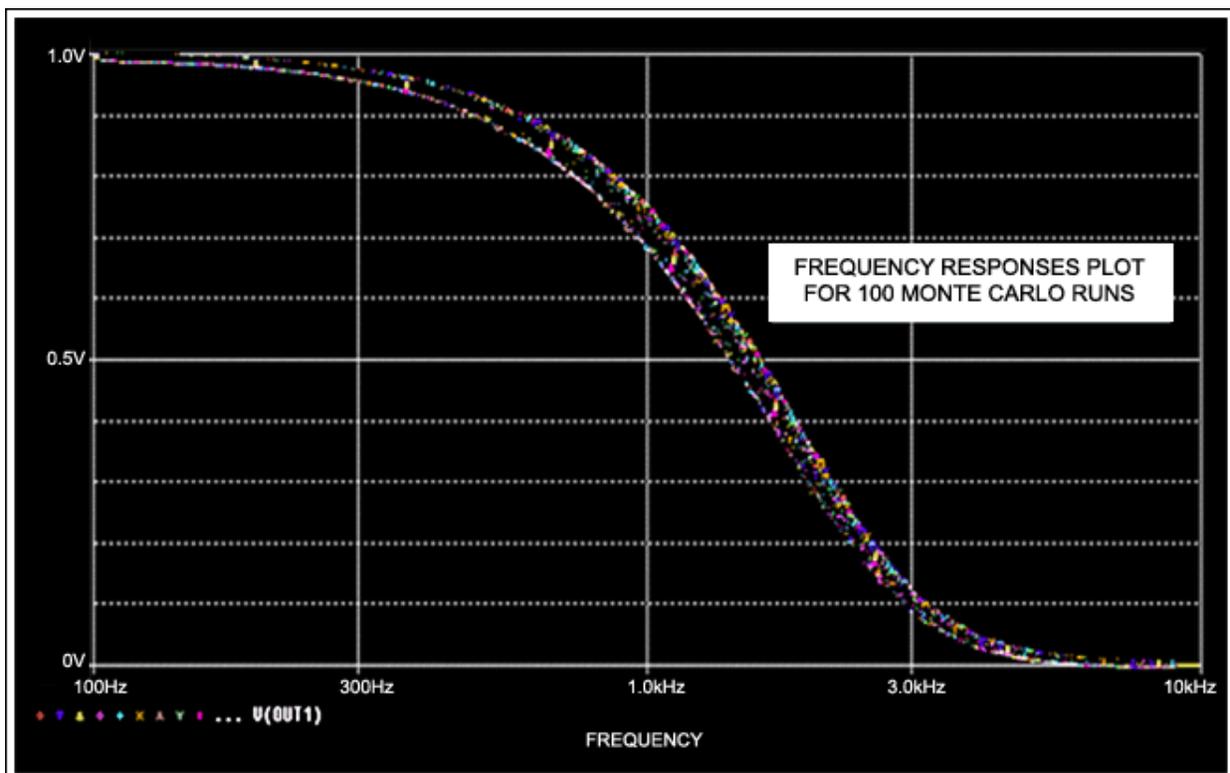


Figure 2. These frequency response plots show the results of SPICE simulations of the five-pole Bessel filter.

To achieve acceptable filter characteristics at 1kHz to 15kHz cutoff frequencies (for 80dB dynamic range or better), designers must use components with even tighter tolerances and better temperature stability. For example:

- a. Amplifiers must exhibit a required unity gain of 0.5MHz to 6.5MHz for 1kHz to 15kHz cutoff frequencies and a THD+N (total harmonic distortion plus noise) factor of better than 0.005%.
- b. Capacitors should be precision ceramic or film capacitors. These capacitors should hold their nominal value over wide temperature and voltage ranges.
- c. Resistors should be the metal film type with  $\pm 1\%$  or better tolerances and a low temperature coefficient.
- d. To ensure that the components deliver the desired characteristics, they should be acquired from reputable sources such as Panasonic, Rohm, Vishay, Kemet, and AVX.

Preliminary estimates show that component cost of the 5th-order, 1kHz to 15kHz cutoff frequency, lowpass Bessel filter could be in the range \$1.50 to \$2.00 (1000-up pricing). This does not include incremental time expenses for design, test, PCB layout, assembly, components procurement, and so on; these expenses are difficult to quantify and will vary from company to company. For more detailed information regarding component-variation sensitivity for high-order, continuous-time filters, see application note 738, "[Minimizing Component-Variation Sensitivity in Single Op Amp Filters.](#)"

Maxim offers a much more efficient, less complex approach by providing an integrated solution based on switched-capacitor technology, which allows most of the filter function to be integrated on a single silicon IC. (Application note 733, "[A Filter Primer](#)," provides additional information regarding SCF operations.) All that the designer must do to set up a particular filter characteristic is to use a single, inexpensive external capacitor or external clock. The result is a compact, reliable, predictable, cost-effective filter design that is less susceptible to temperature and other variations.

**Figures 3 and 4** show the simple circuit implementations for 5th-order, low-pass Bessel filter based on SCF chips (the [MAX7409/MAX7413](#)). The decoupling,  $0.1\mu\text{F}$  capacitors could be the generic, low-cost ceramic type (dielectric type X7R or Z5U). However, for  $C_{\text{CLK}}$  in Figure 4, a COG (NPO) dielectric type is recommended.

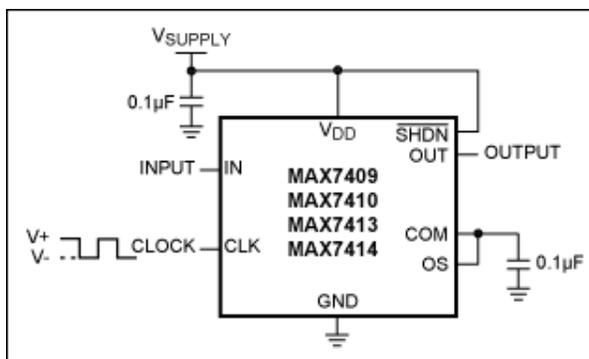


Figure 3. Setting  $f_c$  (cutoff frequency) for a switched-capacitor filter circuit can be done by using an external clock with a  $50\% \pm 10\%$  duty cycle.

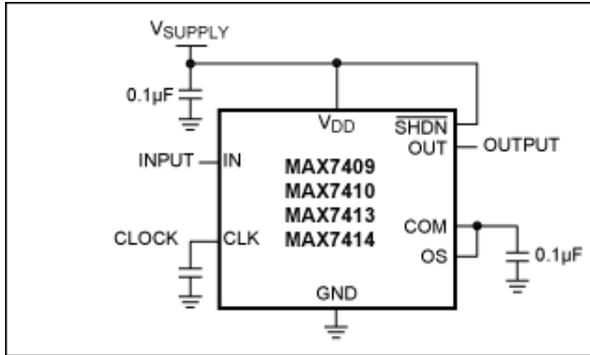


Figure 4. Setting  $f_C$  by using the switched-capacitor filter's internal oscillator requires connecting the  $C_{CLK}$  capacitor between CLK and ground. At  $C_{CLK} = 300\text{pF}$ ,  $f_C = 1\text{kHz}$ .

Simulations and test results (shown in **Figure 5**) indicate an improvement in passband variation for a MAX7409/MAX7413-based design vs. a continuous-time, op-amp-based design. Another advantage of these two integrated solutions is easy tunability. The cutoff frequencies are clock tunable with two clocking options available: self-clocking or external clocking. In comparison, changing the cutoff frequency in the op-amp-based design often requires fundamental redesign.

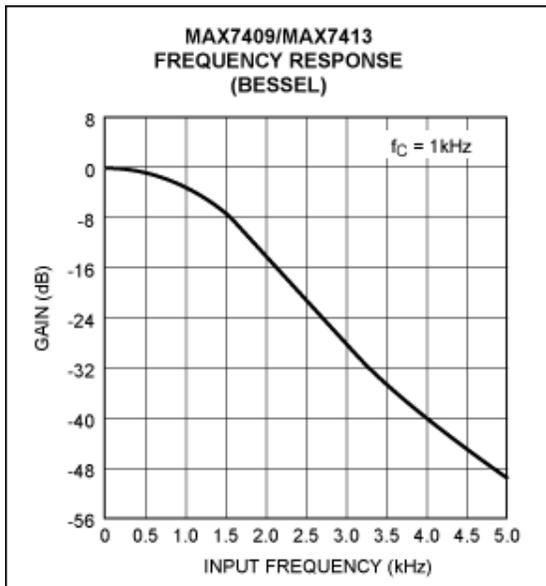


Figure 5. Passband variation at  $f_C = f_{IN}$  is only  $-3\text{dB} \pm 0.4\text{dB}$  over temperature and voltage.

**Tables 1** and **2** illustrate a few of the many integrated filter solutions from Maxim that consume little power, yet deliver high-order-filter characteristics.

**Table 1. Maxim's family of low-power, 5th-order filters**

Part	Supply Voltage (V)	Filter Type	Filter Characteristics
MAX7411	+5	Elliptic	Steepest rolloff, 37dB of stopband rejection
MAX7415	+3	Elliptic	Steepest rolloff, 37dB of stopband rejection
MAX7408	+5	Elliptic	Steep rolloff, 53dB of stopband rejection
MAX7412	+3	Elliptic	Steep rolloff, 53dB of stopband rejection
MAX7409	+5	Bessel	Linear phase response
MAX7413	+3	Bessel	Linear phase response

MAX7410	+5	Butterworth	Maximally flat passband and stopband response
MAX7414	+3	Butterworth	Maximally flat passband and stopband response

**Table 2. Maxim's family of low-power, 8th-order filters**

Part	Supply Voltage (V)	Filter Type	Filter Characteristics
MAX7400	+5	Elliptic	Steepest rolloff and 83dB of stopband rejection
MAX7401	+5	Bessel	Linear phase response
MAX7403	+5	Elliptic	Steep rolloff and 60dB of stopband rejection
MAX7404	+3	Elliptic	Steepest rolloff and 83dB of stopband rejection
MAX7405	+3	Bessel	Linear phase response
MAX7407	+3	Elliptic	Steep rolloff and 60dB of stopband rejection

## References

1. Application note 3494, "The Basics of Anti-Aliasing: Using Switched-Capacitor Filters."
2. Application note 738, "Minimizing Component-Variation Sensitivity in Single Op Amp Filters."

FilterPro is a registered trademark of Texas Instruments.

Related Parts		
MAX7400	8th-Order, Lowpass, Elliptic, Switched-Capacitor Filters	<a href="#">Free Samples</a>
MAX7401	8th-Order, Lowpass, Bessel, Switched-Capacitor Filters	<a href="#">Free Samples</a>
MAX7403	8th-Order, Lowpass, Elliptic, Switched-Capacitor Filters	<a href="#">Free Samples</a>
MAX7404	8th-Order, Lowpass, Elliptic, Switched-Capacitor Filters	<a href="#">Free Samples</a>
MAX7405	8th-Order, Lowpass, Bessel, Switched-Capacitor Filters	<a href="#">Free Samples</a>
MAX7407	8th-Order, Lowpass, Elliptic, Switched-Capacitor Filters	<a href="#">Free Samples</a>
MAX7408	5th Order, Lowpass, Elliptic, Switched-Capacitor Filters	<a href="#">Free Samples</a>
MAX7409	5th-Order, Lowpass, Switched-Capacitor Filters	<a href="#">Free Samples</a>
MAX7410	5th-Order, Lowpass, Switched-Capacitor Filters	<a href="#">Free Samples</a>
MAX7411	5th Order, Lowpass, Elliptic, Switched-Capacitor Filters	<a href="#">Free Samples</a>
MAX7412	5th Order, Lowpass, Elliptic, Switched-Capacitor Filters	<a href="#">Free Samples</a>
MAX7413	5th-Order, Lowpass, Switched-Capacitor Filters	<a href="#">Free Samples</a>
MAX7414	5th-Order, Lowpass, Switched-Capacitor Filters	<a href="#">Free Samples</a>
MAX7415	5th Order, Lowpass, Elliptic, Switched-Capacitor Filters	<a href="#">Free Samples</a>

## More Information

For Technical Support: <http://www.maximintegrated.com/support>

For Samples: <http://www.maximintegrated.com/samples>  
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