Signals-From-Noise
What Sallen-Key Filter Articles Don't Tell You
Part II: The ac constraints that you need to know

by Dave Van Ess, Principal Application Engineer, Cypress Semiconductor

Last month’s column introduced the Sallen-Key filter. The topology discussed is shown in the figure below.

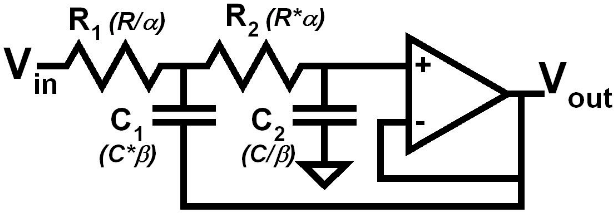

Fig. 1: Basic Sallen-Key Low-Pass Filter Topology

I included a seven-step process to specify the passive components to implement a filter with a particular roll-off frequency (**f_0**) and damping value (**d**). Also discussed was how the op amp dc parameters effect component selection. This TechNote will deal with the ac parameters and how they affect component selection.

As shown last column, the transfer equation for a unity-gain second-order low pass-filter is:

$$\frac{V_{out}}{V_{in}} = \frac{1}{\left(\frac{s}{2\pi f_0}\right)^2 + d\left(\frac{s}{2\pi f_0}\right) + 1} \qquad d := \frac{\alpha + \frac{1}{\alpha}}{\beta} \qquad f_0 := \frac{1}{2\pi RC}$$

This equation assumes the unity buffer is implemented with an ideal op amp, a device commonly found in university lecture halls, which has infinite gain, infinite bandwidth, and infinite input impedance. Fabricated from Utopian Nitrate and packaged in Impossiblium ideal op amps also have zero noise, use no power, cost nothing, and are available everywhere. Actually, the Ideal Op Amp is a model to help with design and analysis of op amp circuits. In many cases the op amp you select may be close enough to ideal. But understanding what effect each parameter has allows you to determine just how good is good enough.

Op Amp Bandwidth

Most commonly-used op amps have extremely high open-loop gain that is internally compensated to keep phase-shifted, high-frequency feedback from causing oscillations. The higher the frequency, the lower the open-loop gain. The frequency where the gain reaches unity is known as the gain bandwidth (**GBW**). At this frequency the op amp is incapable of supplying enough signal to feedback for unity-gain buffering. The transfer equation for an op amp configured as a function of the gain bandwidth (**f_{GBW}**) is:

$$\frac{V_{out}}{V_{in}} = \frac{1}{\sqrt{1+\frac{s}{2\pi f_{GBW}}}}$$

With this bandwidth-limited op amp model the new filter transfer function is:

$$\frac{V_{out}}{V_{in}} = \frac{1}{\left(1+\frac{s}{2\pi\cdot f_{GBW}}\right)\cdot\left(\left(\frac{s}{2\pi\cdot f_0}\right)^2+d\left(\frac{s}{2\pi f_0}\right)+1\right)+\left(\frac{\alpha^2+1}{d\cdot\alpha^2}\cdot\frac{s}{2\pi\cdot f_{GBW}}\frac{s}{2\pi f_0}\right)}$$

Kind of a messy equation! Fig. 2 shows a series of plots for a 10-kHz Butterworth filter (**f_0 = 10kHz, d=1.414, β = 1.414, α = 1**). The plots are for op amps with different bandwidths.

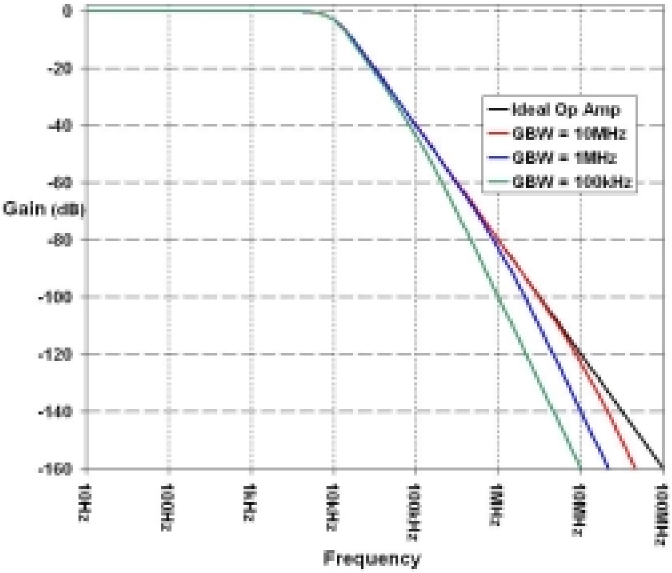

Fig. 2: Filter Response As A Function Of Op Amp Bandwidth

Clearly the higher the op amp bandwidth, the closer the transfer function is to ideal. The plot for the op amp with a GBW of 1 MHz is within 1 dB of the ideal response up to 500 kHz. A good rule of thumb is to specify a GBW at least 100 times the roll-off frequency. For a 1 kHz roll-off frequency most any op amp would work. For a 1MHz roll-off frequency an extremely fast op amp is required. Whatever bandwidth is selected, it is the ratio of the roll-off frequency and op amp GBW that determines actual response.

Op Amp Output Impedance

Op amp closed-loop output impedance is its open-loop impedance divided by the op amp gain. As open-loop gain decreases with frequency, the closed-loop output impedance increases. Impedances that increase with frequency are inductive. Fig. 3 shows a design of a 1 kHz Butterworth low-pass filter.

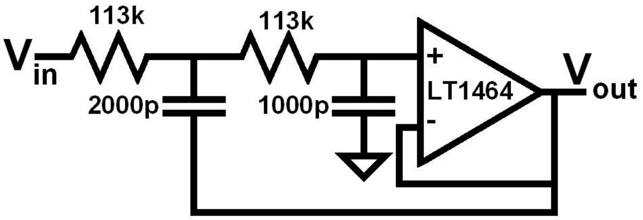

Fig. 3: 1 kHz Butterworth Low-Pass Filter

The op amp is a Linear Technology LT1464 which has a JFET input, with a gain bandwidth of 1 MHz. With the component values shown, the roll off frequency is 996 Hz and the damping value is 1.414. To simulate this circuit, I used LTSpice. It is a free version of Spice that Linear Technology provides from their web site. As circuit modeling software goes, it is pretty good, and for free it is excellent. The only downside is that the only op amp models provided are Linear Tech's. (Imagine that!) Still, all in all, it is a great tool for understanding the operation of analog circuitry. The response plot of this filter is shown below.

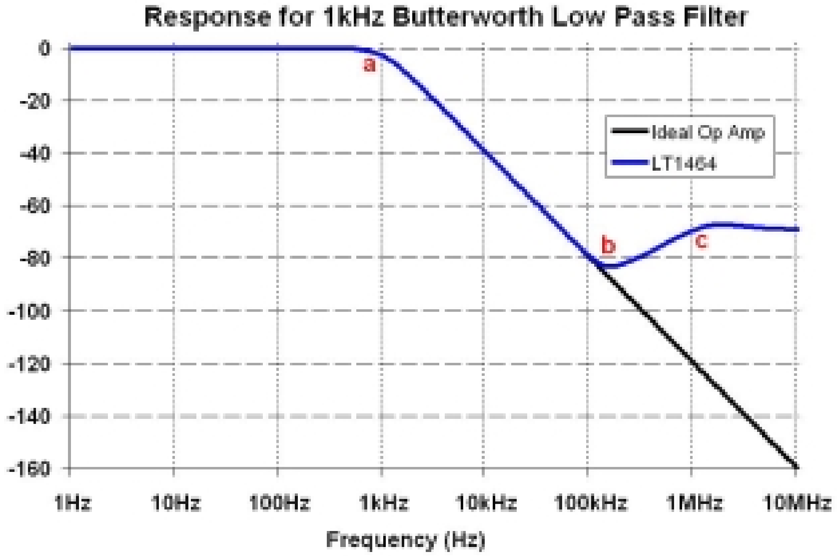

Fig. 4: Response For 1 kHz Butterworth Low-Pass Filter

The filter is at unity gain until it reaches the roll-off frequency (a). This point is specified by the resistor and capacitor values. At this point the response decreases at a rate of 40 dB/decade. All this time the output impedance of the op amp is increasing. This output feeds back to a capacitor that gets lower in impedance as the frequency increases. There comes a point (b) where the output impedance is greater than the capacitor impedance. At this point the feedback look primarily inductive and the response increases at a rate of 20 dB/decade. This continues until the frequency reaches the GBW of the op amp (c). At this point the output impedance is relatively constant and the response flattens to 0 dB/decade. So the filter response depends on the GBW, output impedance, and component values.

To make the output impedance look relatively smaller it is possible to increase the impedance value of the components. Fig. 5 shows plots of the filter where:

- All the components are made a decade smaller in value
- All the components remain as originally calculated
- All the components are made a decade larger in value

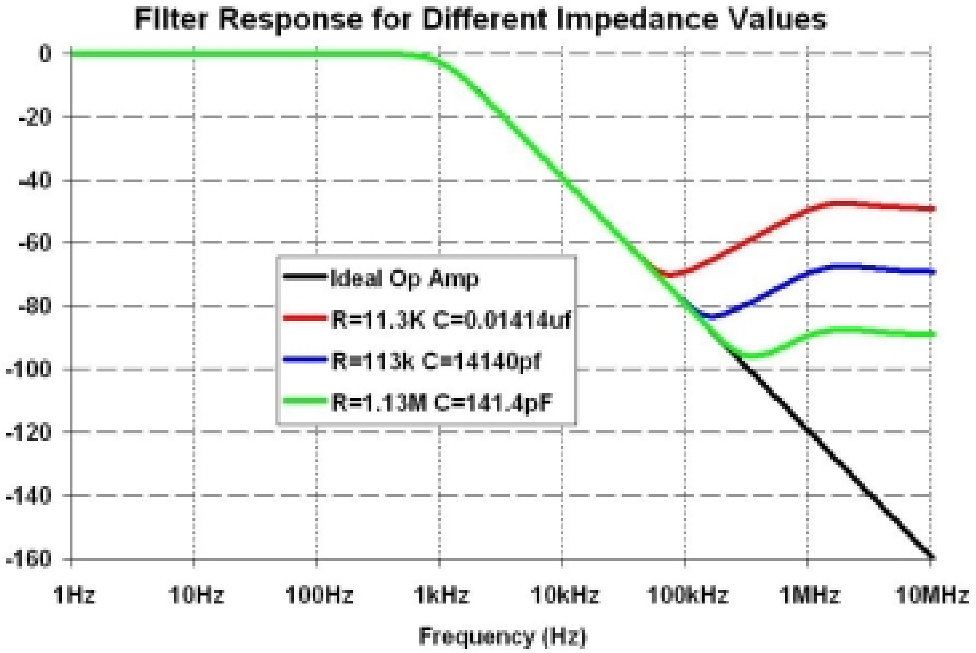

Fig. 5: Filter Response For Different Output Impedance Values

From this graph you can see that the smaller the impedance of the components, the sooner the op amp impedance exceeds the capacitor it feeds. For this op amp and these particular component values, the response levels out to –50 dB, -70 dB and –90 dB.

At higher frequencies the output impedance has a major effect on the output. It is possible to use this op amp only for the feedback and to use the unbuffered signal as the output. Another op amp can be used to buffer it and provide a low impedance output (Fig. 6).

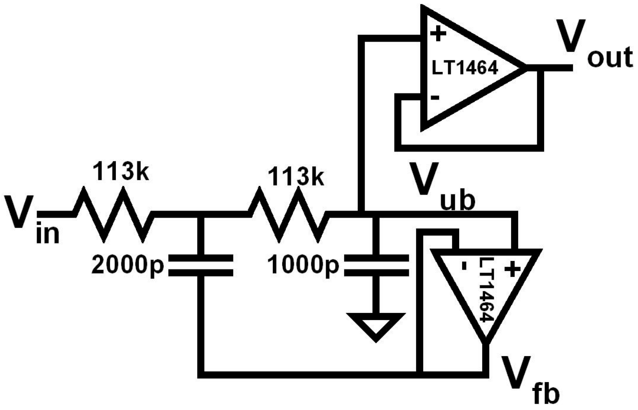

Fig. 6: Buffered Sallen-Key Low-Pass Filter Topology

The response of the feedback, unbuffered, and output voltages is shown in Fig. 7.

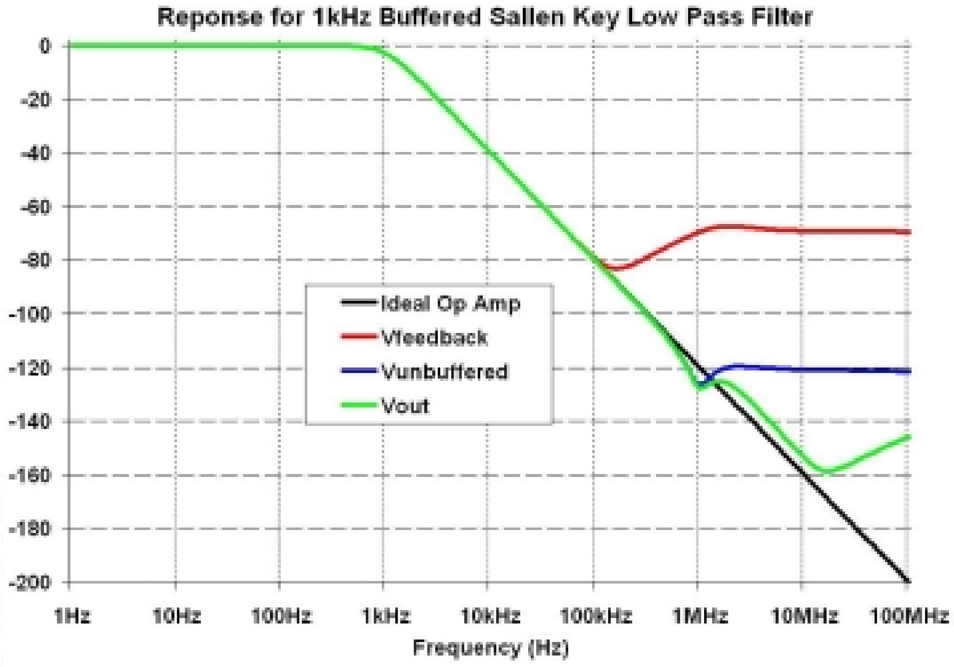

Fig. 7: Response For 1 kHz Buffered Sallen-Key Low-Pass Filter

The feedback voltage is the same as the output voltage of the standard Sallen-Key filter plot (Fig. 4, again). The unbuffered signal has none of the direct divider effects of the output impedance and its response settles out to 0 dB/decade value of –120 dB at 1 MHz. The new output buffer’s GBW allows the output to continue to decrease after the input has leveled off. This output stays within 3 dB of the ideal up to 630 kHz and is within 8 dB up to 14 MHz. All in all, this is not bad for op amps with a GBW of 1MHz.

That’s enough for now. I had meant to cover the effect of noise this month but the nice thing about having a column of my own is that I can spend as long as I need to on a subject. Unlike my deadline-driven day job, if the discussion goes on too long, we just cover it next month. That’s why I will finish this topic next month by looking at how component values affect:

- Op amp voltage noise
- Op amp current noise
- Resistor thermal noise

Postscript

It was good to meet some of you readers while I was at Embedded Systems in San José last month (April 2007). All were polite, and brutally honest, about what they liked and disliked about my column. Thank you for the feedback. Only one guy set out to prove he was way smarter than me. I gave him a certificate that said so. Anybody else want a certificate, or just want to talk shop? Write me at dwv@cypress.com.

About The Author

Dave Van Ess is a Principal Application Engineer at Cypress Semiconductor. He is an electrical engineer with experience in hardware, software, and analog design. Dave joined Cypress in 2000. He has nine patents for medical systems, signal processing design, and PSoC digital block enhancements. He has written numerous User Modules, application notes, and articles. He graduated sigma cum barely with his BSEE from the University of California, Berkeley, 1977.

An engineer by training, a poet by temperament, an outlaw in Nebraska, and a heck of a nice guy, Dave has worked in many different industries. His work experience includes test and measurement equipment, measurement and control systems for high energy physics research, and underwater acoustic transmitters and receivers deployed in open sea and artic ice fields. Electrons fear him! Women revere him!

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