Noise from active filters: An unwelcome surprise

My birthday is this month; every year I remind my friends how much engineers HATE surprises. Whether it's a surprise in our social lives or a surprise in a project, anything unexpected is unwelcome. In analog circuits, a very unwelcome surprise is the noise produced by active filter circuits. After all, active filters are supposed to remove noise!

All active circuits produce some amount of noise and filters are no different. We can uncover the source of this noise by looking at their noise gain. Noise gain is a term used to describe the amount of amplification that a circuit applies to its intrinsic noise source(s). In a typical op amp circuit, the noise gain is measured from the non-inverting input.

Figure 1 shows the TINA-TI™ simulation circuit I used to measure the noise gain of two 2nd-order, Butterworth, 1kHz low pass filters. One circuit uses the Sallen-Key (SK) topology and the other uses a multiple feedback (MFB) topology. To measure the noise gain of an active filter, the signal input is grounded and a signal source is inserted in series with the op amp non-inverting input.

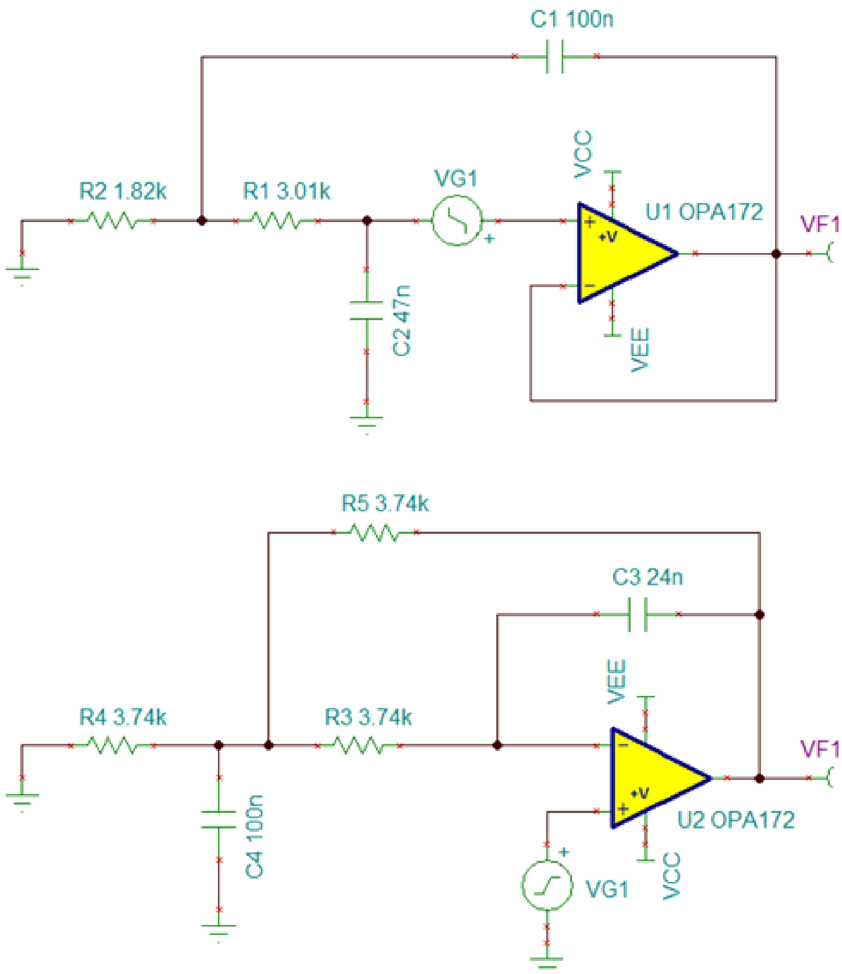


Figure 1: Circuit configuration for measuring the noise gain of Sallen-Key (top) and multiple feedback (bottom) active filters.

Performing an AC transfer characteristic analysis on the two circuits reveals their noise gain:

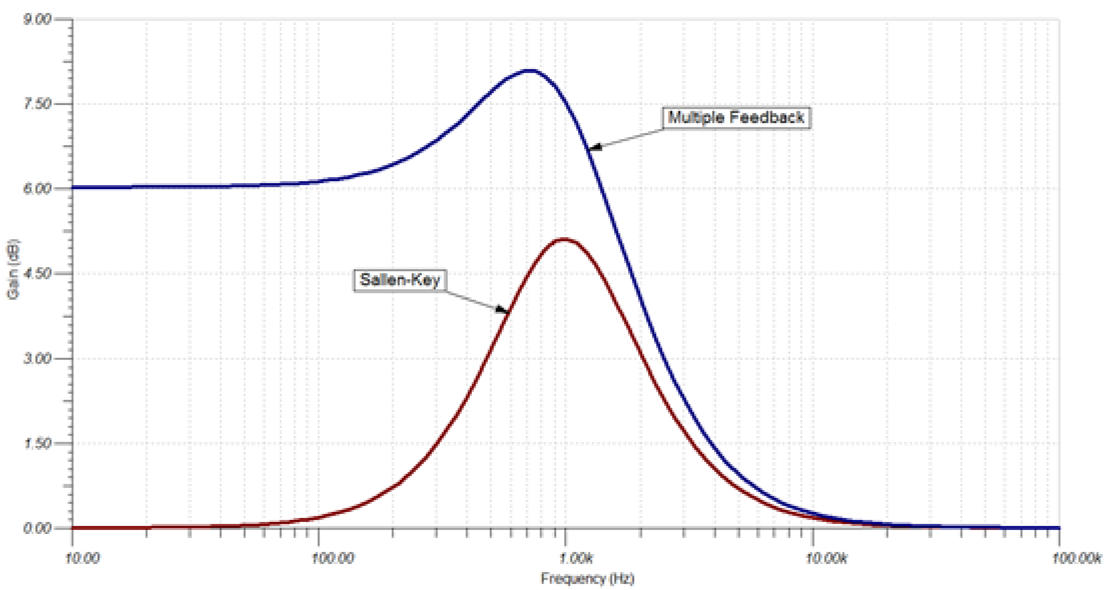


Figure 2: The noise gain of 1kHz, Butterworth lowpass filters. An MFB filter is shown in Blue and the SK filter is shown in red.

Although these two circuits have identical filter characteristics (signal gain and attenuation, Q, corner frequency), their noise gain is quite different! Notice that the MFB filter has a noise gain of 6dB in the pass band because the op amp is in an inverting configuration.

Also notice the increase in the noise gain which occurs near the filter's corner frequency. The magnitude of this noise gain "hump" is proportional to the quality factor, or Q, of the filter. To illustrate that point, we can compare several SK filters with the same signal gain and corner frequency, but different Q values.

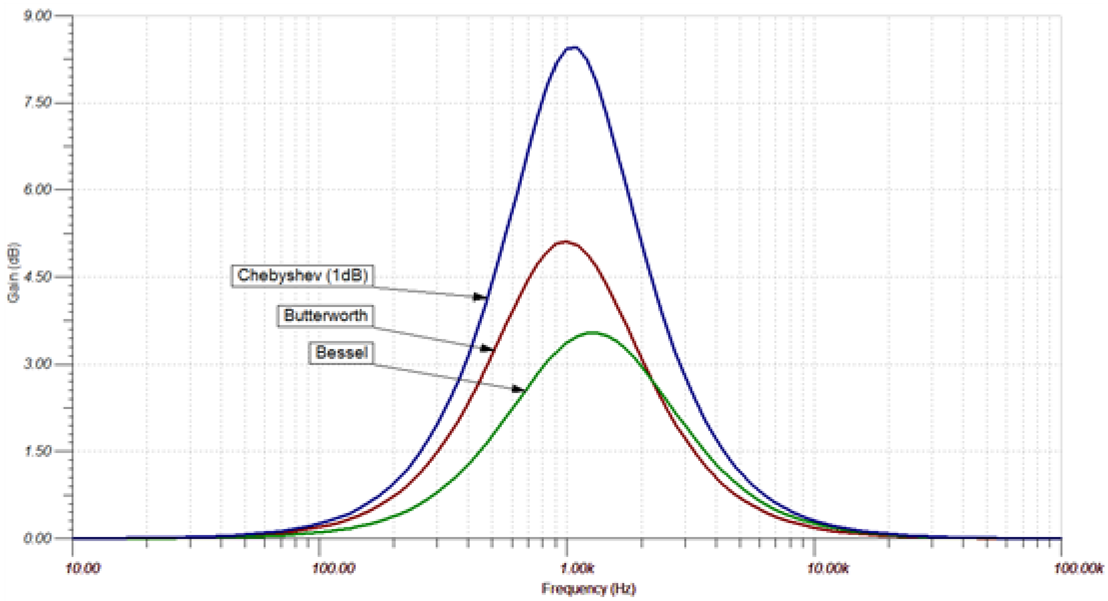


Figure 3: Noise gain comparison of SK low pass filters of differing Q values

Higher Q filters have substantially greater noise gain near their corner frequency and this affects the total integrated noise. I used TINA-TI to simulate the total integrated noise of 3 SK low pass filters in a 10kHz bandwidth, all built with the OPA172. The corner frequency of the filters was identical (1kHz) but their Q values were different. The results are summarized in Table 1.

Table 1: Total integrated noise in a 10kHz bandwidth of SK filters with different Q values.

Filter Characteristic	Q	Total Integrated Noise (10kHz bandwidth)
Bessel	0.580	709 nVrms
Butterworth	0.707	771 nVrms
Chebyshev (1dB)	0.957	981 nVrms

Engineers often select higher Q filters for their greater attenuation, without considering the increase in noise from the filter itself!

Here is a list of my basic rules for low noise filter design. I tried to implement all these design practices in my most recent TI Precision Design: An Analog, Active Crossover Network for Two-Way Loudspeakers.

Basic Rules for Low Noise Filter Design

- Use the Sallen-Key topology if possible.
- Avoid high Q filters if a low Q filter can do the job.
- Use the lowest resistor values possible as long as you:

    1. Use high quality capacitor types (film or NP0/C0G ceramics). Other types of capacitors may produce distortion, as I show here and here.

    2. Avoid excessively loading the op amp or other circuits.

- Pay attention to the source impedance presented to the op amp. A FET input op amp may provide lower noise when the filter resistor values are large.
- Place low pass filters at the end of the signal path to attenuate the noise of preceding circuits.

Following these rules can help avoid some of the unwanted surprises we engineers have to cope with on a daily basis!

Soufiane Bendaoud Very nicely done and yes this is often overlooked. Thanks John

Stephen Power Hi John

I would like to add the following comments regarding the unity gain 2-pole low pass Sallen-Key topology.

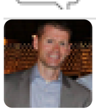
(a) For the unity gain SK, with regard to fc and Q, I believe that it makes no difference which of the resistors is closest to the signal source since fo= 1/(2*pi*sqrt(R1*R2*C1*C2)) and Q = sqrt(R1*R2/(R1+R2). However, if a step input is applied to the filter then it is better to have the larger resistor closest to the signal source. I believe the reason is due to the increase in op amp output impedance with frequency. When a step signal is applied a spike appears at the output of the filter. By putting the larger resistor closest to the signal source the attenuation is higher and the spike is reduced. Note that this is only true for the unity-gain SK.

(b) Capacitor Dielectric Absorption (DA) is a problem with active filters. I believe that DA is voltage dependent, with the problem getting worse as the voltage across the capacitor increases. Looking at the unity gain SK, the capacitor to GND sees the full signal while the feedback capacitor has approximately 0V across it. Generally in SK filter design the caps are not equal with one value several times the other. For low frequencies the cap values might need to be quite large (perhaps several hundred nF) and it may be difficult to get the right cap types (NP0 or PPS for SMD, polypropylene for TH). Hence, I believe that if you have to choose then it is better to make the cap to GND the smaller value, higher quality, capacitor and the feedback capacitor the higher value lower quality part (Of course, best if both are of high quality).

regards

Steve

Stephen Power Of course I forgot the sqrt (n) bit in the Q formula, where n is the ratio of caps.

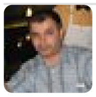


John Caldwell Stephen,

You bring up really great points about the location of the passive components within the Sallen-Key filter circuit. I will have to do some investigating on how they affect the filter output with a step input (maybe a future blog post?).

b) My two articles listed in the Basic Rules section (rule 3, item 1) examine the effects of capacitor voltage coefficient on signal distortion, but not dielectric absorption. In his book The Design of Active Crossovers, Douglas Self confirms your recommendation for using a high quality capacitor to ground with a comparison of polyester and polypropylene capacitors. However, when I repeated this investigation using ceramic capacitors, the results with mixed dielectric types (C0G and X7R) were still unacceptable, so I avoid recommending that customers try it unless their signal levels are extremely low or they have no other option.

Thanks for reading my blog post and providing some high quality input! I hope you'll come back to the Precision Designs Hub in the future!



Ahmet Cetin Thank you for given information. Higher Q cause higher noise output. If transfer function is the same effect to both signal and noise, Is S/N ratio change for higher Q? or is noise gain diffirent from signal gain? Regards.

Kendall Castor-Perry A quick comment on Stephen P's post below. If the values of the two resistors aren't the same, you can put them in either order and you'll get the same filter frequency response for sure. But the noise properties will be different - easily shown in simulation. There's a great paper by Peter Billam on optimizing for this - if you can't track it down, mail me at filterwizard@cypress.com and I'll try to dig out my own copy. Noise - and offset - in filters is a fascinating topic, I've covered some facets of it in my Filter Wizard columns.

John Caldwell Ahmet, noise gain is different than signal gain because it is always measured from the non-inverting input of the amplifier as I show in Figure 1. In these two circuits, the noise gain is measured from the point where I have inserted the voltage sources (VG1 in both circuits) however the signal gain would be measured from the filter input (where R2 and R4 are grounded).