Stop-band limitations of the Sallen-Key low-pass filter

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We might expect the gain amplitude of an analog, low-pass anti-aliasing filter to continually decrease past the filter's cutoff frequency. This is a safe assumption for most filter topologies, but not necessarily for a Sallen-Key low-pass filter (Figure 1). The Sallen-Key filter attenuates any input signal in the frequency range above the cutoff frequency to a point, but then the response turns around and starts to increase in gain with frequency.

Figure 1. Second-order, active low-pass analog filters

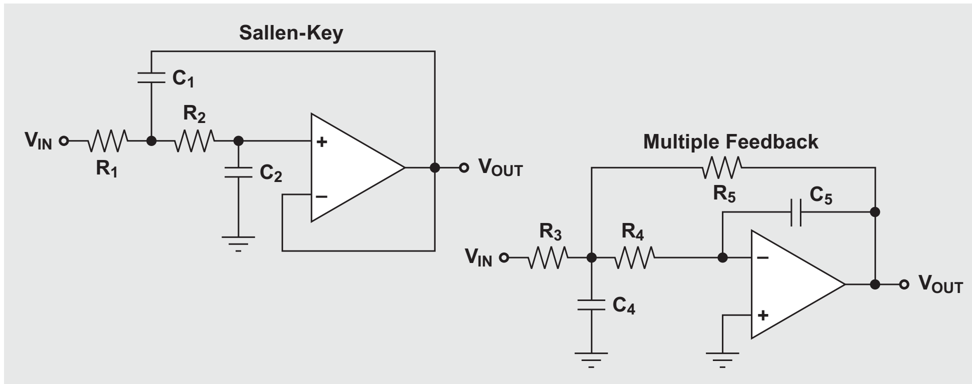


Figure 1 shows circuit diagrams for a second-order, Sallen-Key low-pass filter and a second-order, multiple-feedback (MFB) low-pass filter. In terms of the sign orientation of these two filters, the Sallen-Key filter produces a positive voltage from input to output without changing the sign. An MFB filter changes a positive input voltage into a negative voltage at the output of the filter. This difference provides the system designer added flexibility.

The relationships between the resistors and capacitors in both of these filters establish the filters' corner frequencies and response characteristics. The frequency responses of the two filters in Figure 1 are fundamentally the same. Theoretically, an input signal from DC to the filter's corner frequency passes to the output of the filter (V_{OUT}) without change. These two filters attenuate higher-frequency input signals that are above the cutoff frequency of the filter at a rate of 40 dB per frequency decade. Figure 2 illustrates the ideal transfer function of these two filters in the frequency domain. This figure shows a Butterworth, or maximally flat, response. Chebyshev and Bessel responses will be different.

The filter-response DC gain in Figure 2 is equal to 0 dB. The corner frequency of this low-pass filter occurs at 1 kHz, and the gain magnitude at 1 kHz is equal to –3 dB. Following this corner frequency, the filter response falls off at a rate of –40 dB/decade. Theoretically, the attenuation continues to occur as the frequency increases.

Figure 2. Ideal transfer function of low-pass filter with 1-kHz corner frequency

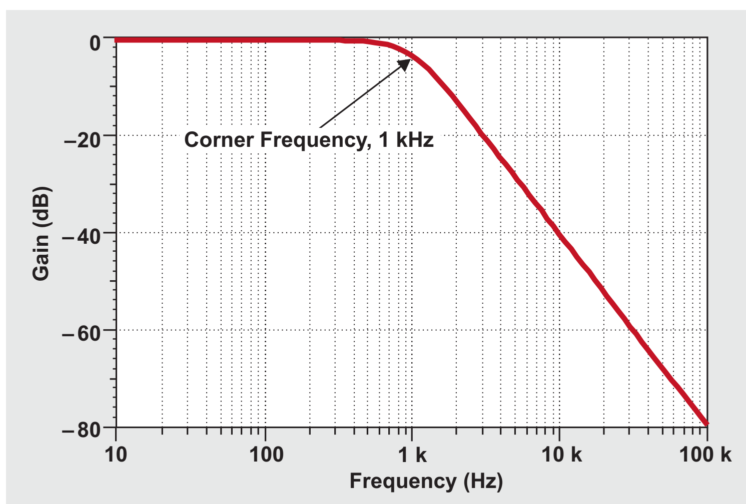
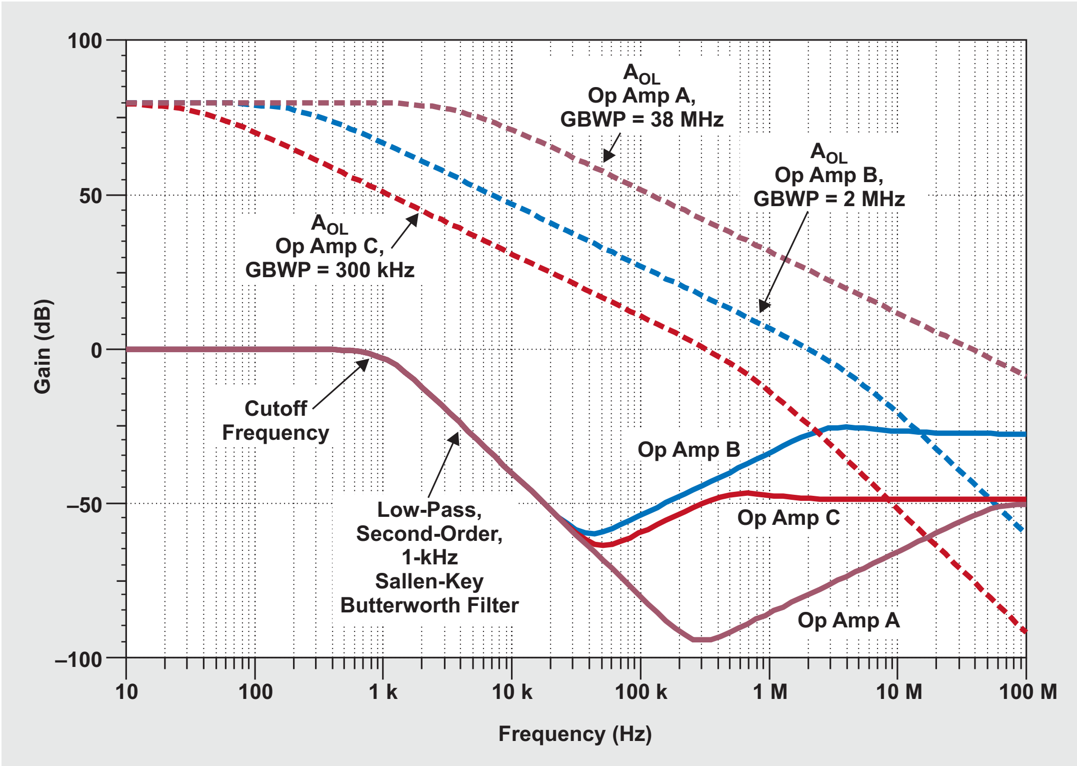


Figure 3. Frequency response of three low-pass filters and amplifier open-loop gain



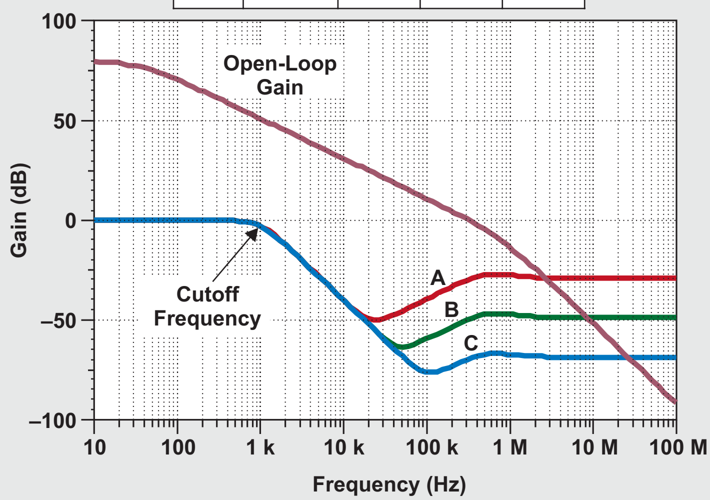
The MFB filter closely matches the theoretical attenuation of the filter in Figure 2. We would expect the Sallen-Key filter to follow suit, but it does not. Figure 3 shows the behavior of three Sallen-Key low-pass filters. The amplifier gain curves start at the top of the diagram at 80 dB, and the filter curves start at a gain of 1 V/V or 0 dB. The top three curves in Figure 3 show the open-loop gain, A_{OL}, of each amplifier as the response crosses 0 dB. The configuration for amplifiers in the top three curves is a simple gain of 10,000 V/V or 80 dB. In the diagram, the gain bandwidth product (GBWP) of these operational amplifiers—A, B, and C—are 38 MHz, 2 MHz, and 300 kHz, respectively.

The three lower curves in this figure show the frequency response of second-order, Sallen-Key low-pass filters for each amplifier. The resistor and capacitor values for the Sallen-Key filter (see Figure 1) are R_1 = 2.74 kΩ, R_2 = 19.6 kΩ, C_1 = 10 nF, and C_2 = 47 nF. These resistors and capacitors, combined with the amplifier, form a Butterworth, maximally flat response. After the cutoff frequency (Figure 3), the responses of all three of the filters show a slope of –40 dB/decade. This is the response we would expect from a second-order low-pass filter; then at some point the filter gain ceases to decrease and starts to increase at a rate of 20 dB/decade. The difference in the frequency response, where the three amplifiers change to a positive slope, depends on the individual amplifier's output impedance as it relates to the resistance values in the circuit. As the open-loop gain of the amplifier decreases, the closed-loop output impedance of the amplifier increases. An op amp's closed-loop output impedance is its open-loop impedance divided by the op amp's gain.

We can reduce the impact of the upward trend in the filter's response by preceding or following the offending active filter with a passive, R-C, second-order low-pass filter. The caveat to preceding or following the second-order active filter with a passive filter is that it may interfere with the phase response of the intended filter, which may cause additional ringing in the time domain. It will also create a stage whose input is not high-impedance or whose output is not low-impedance. Both solutions will possibly add offset and noise to the circuit. Finally, these solutions will add to the overall cost of the application circuit.

Figure 4. Second-order filter response with different R-C values

Second-Order Filter Values				
Filter	R_1 (kΩ)	R_2 (kΩ)	C_1 (nF)	C_2 (nF)
A	0.274	1.96	100	470
B	2.74	19.6	10	47
C	27.4	196	1	4.7



At the frequency where the amplifier's output impedance is greater than the impedance of the resistor (R_1), the feedback looks inductive and the response increases at a rate of 20 dB/decade. The curves in Figure 4, which show the response of a second-order circuit using the OPA234, exaggerate this effect. In Figure 4, the values of the resistances from A to C increase by 10×, and the values of the capacitors from A to C decrease by 10×. With these changes, the general filter response does not change until after the lower three curves pass 0 dB. The corner frequency, where the filter response starts to increase, is dependent upon the relationship between the closed-loop output impedance of the amplifier and the magnitude of R_1.

Eventually each filter's response flattens at the 0-dB crossing frequency of the op amp's open-loop gain. It is no coincidence that the flattening of the filter response occurs at this crossing. As the frequency increases beyond this point, the open-loop gain of the amplifier has no gain.

Needless to say, if a Sallen-Key low-pass filter is used, some characterization is in order. This discussion about analog filters may be discouraging, but we can use alternative filters to solve the problem presented without increasing the filter resistances or adding a passive R-C filter. When an inverting filter is an acceptable alternative, an MFB topology can be used. The MFB configuration does not display this reversal in the gain response at higher frequencies and has the advantage of not taxing the input stage's transistors through their common-mode range.

References

1. Bonnie Baker, *A Baker's Dozen: Real Analog Solutions for Digital Designers* (Amsterdam: Elsevier, 2005), ISBN 0-7506-7819-4.
2. Dave Van Ess. Signals-from-Noise: What Sallen-Key Filter Articles Don't Tell You, Parts I to III. *ConnectivityZONE* [Online]. Available: www.en-genius.net (search Sallen-Key)

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