Bandstop filters and the Bainter topology

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Many applications, such as tone-signaling, audio-signal, hearing-aid feedback, or mains rejection systems, require bandstop (notch) filters to eliminate undesirable signals. One can achieve these signal reductions by using active bandstop analog filters.

The bandstop filter circuit topologies considered in this article are Sallen-Key, multiple-feedback, and Bainter. Each circuit produces a second-order bandstop filter, with one pole and one zero in the transfer function

A starting point is to define the bandstop filter characteristics. In Figure 1, the bandstop filter disallows signals within a certain bandwidth (BW_P), while passing frequencies above and below the rejected frequency area.

This standard generic diagram highlights the key bandstop filter parameters; passband, stopband, f_0, BW_P, A_O, A_{SB}, BW_S, and R_P.

The three filter-response regions are the low-frequency passband, the stopband, and the high-frequency passband. In both of the passband frequency regions, signals pass freely from the input to the filter's output. In the stopband region, frequency signals are attenuated per the diagram in Figure 1. The notch filter's center frequency is f_0.

BW_P (passband bandwidth) defines the –3-dB bandwidth inside the bandstop filter. This bandwidth also defines the quality factor or Q (See Reference 1) of the filter, where $Q = (f_0 / BW_P)$. BW_S defines the stopband bandwidth. In the region below the BW_S point, the bandstop filter creates a notch, sometimes dipping –100 dB or more.

The stopband attenuation ranges from A_O to the A_{SB} (stopband magnitude). A_O (passband gain) and A_{SB} along with the specified stopband attenuation, defines the speed of the notch's attenuation. Finally, for Chebyshev approximations, the definition of the ripple magnitude is R_P.

The bandpass/notch filter requires pairs of poles and zeroes in the transfer function. The corner frequency of the poles and zeroes resides at or near f_0.

The transfer function of the bandstop/notch filter is:

$$H(s) = \frac{H_0\left(s^2 + w_z^{\,2}\right)}{s^2 + \frac{\omega_0}{Q}s + \omega_0^{\,2}} \quad (1)$$

For comparison purposes, the following discussion includes the Sallen-Key, multiple-feedback, and Bainter filter topologies to realize a bandstop filter.

Figure 1. Frequency response of the bandstop filter

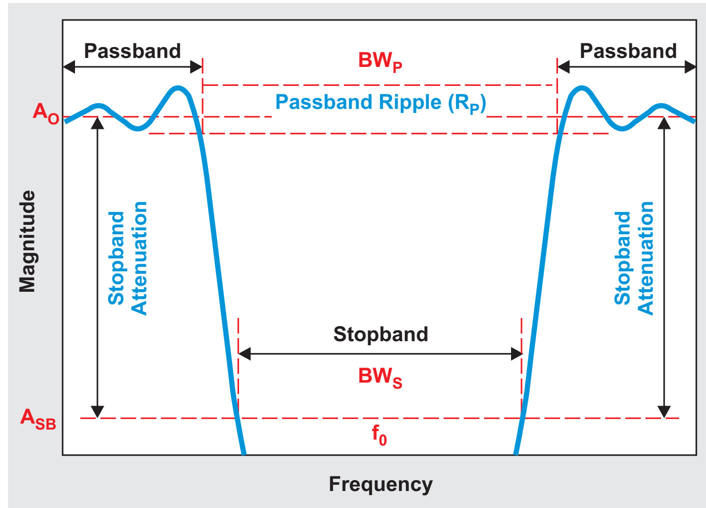
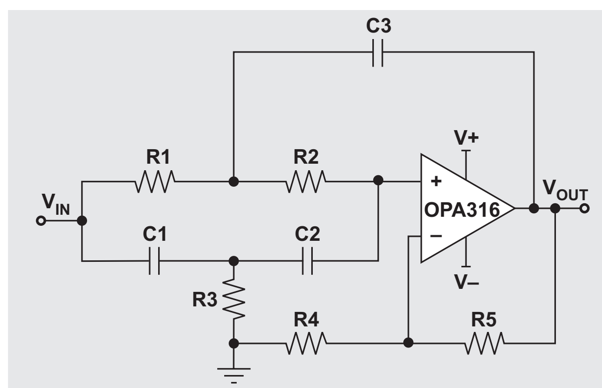


Figure 2. Second-order Sallen-Key bandstop or notch filter



Sallen-Key circuit topology

The Sallen-Key topology in Figure 2 implements a second-order bandstop filter. This particular circuit is valued for its simplicity, as it has one amplifier, five resistors, and three capacitors. One advantage of this circuit is that the ratio of the largest resistor to the smallest resistor is small, as well of the capacitor high and low values. This is beneficial to the manufacturability of the filter.

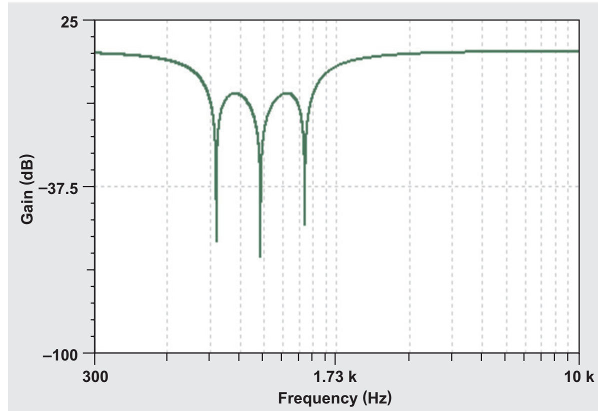
While the Sallen-Key filter is widely used in low-pass and high-pass filters, it has several serious drawbacks for bandstop filters. The Sallen-Key is not easily tuned because of the interaction of the component values on the center frequency (f_0) and Q. The open-loop output resistance also interferes while attempting to produce the ideal notch-filter characteristics (Figure 3). Additionally, f_0 cannot be easily adjusted because of component interaction.

A sixth-order filter is implemented by cascading three second-order filters (Figure 2) in series. Figure 3 shows the sixth-order, closed-loop response of a Sallen-Key circuit. This figure shows the Sallen-Key's circuit closed-loop gain response of 4.58 V/V with a linear phase 0.5° approximation type and f_0 equal to 1 kHz.

The construct of this sixth-order filter uses ideal resistors (15), capacitors (9), and amplifiers (3). With ideal components and devices in the circuit, the closed-loop frequency response has three spurs going down and shows that there is only about –15 dB of attenuation within the notch.

As a consequence of these shortcomings, the Sallen-Key notch filter is not a recommended topology for bandstop filter construction.

Figure 3. Closed-loop frequency response of sixth-order Sallen-Key notch filter



Multiple-feedback circuit topology

The multiple-feedback (MFB) topology in Figure 4 implements a second-order bandstop. The MFB circuit is also valued for its simplicity, having one op amp, three resistors, and two capacitors in the first stage. In the final stage, there is one op amp and three resistors. The second stage of this filter provides a summing function to add high-pass and low-pass responses at the end of the circuit. If it were a sixth-order filter, the final stage of this filter is at the end of the signal line, while there are three proceeding first stages.

While the MFB filter topology is widely used in low-pass, high-pass, and bandpass filters, it has several serious drawbacks for bandstop filters. The dependence of the transfer function on the op amp parameters is greater than the Sallen-Key realization. It is also hard to generate high-Q, high-frequency sections because of the limited open-loop gain of the amplifier at high frequencies.

Figure 5 shows the sixth-order, closed-loop response of a MFB circuit. A sixth-order filter is implemented by cascading three second-order filters (Figure 4) in series. In Figure 5, the MFB's circuit closed-loop gain of 4.58 V/V with an approximation type of linear phase 0.5° and f_0 equal to 1 kHz.

The filter in Figure 5 uses ideal resistors (12), capacitors (6), and amplifiers (4). With ideal components and devices in the circuit, the closed-loop frequency response shows that there is approximately –36.6 dB of attenuation within the notch. However, on either side of the notch, the filter gain increases by an undesirable amount of about 1.4 dB. These two humps are a consequence of the challenge to match the high-pass and low-pass filter in this system with the final-stage summing function.

Figure 4. A second-order multiple-feedback bandstop or notch filter

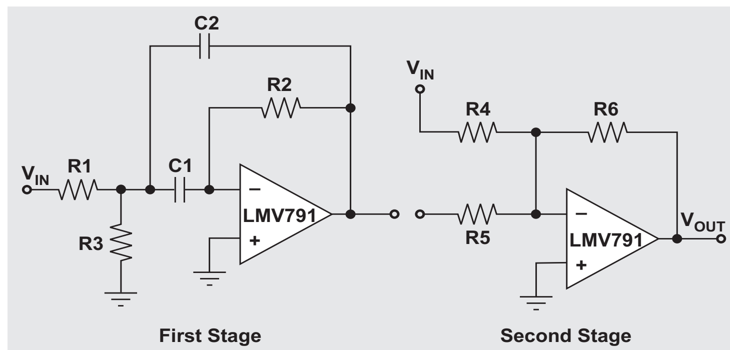
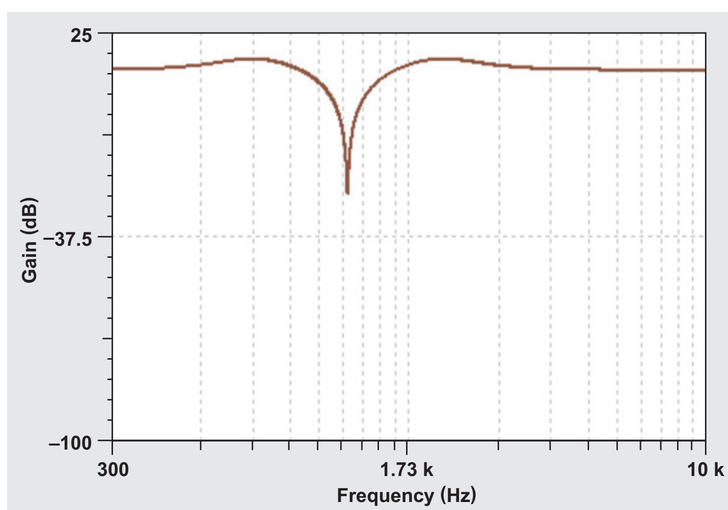


Figure 5. Closed-loop frequency response of sixth-order MFB notch filter



As a consequence of these shortcomings, the MFB notch filter is not a recommended topology for bandstop-filter construction.

Bainter circuit topology

As Figure 6 shows, the Bainter filter topology[2] has three simple amplifier circuit blocks with two feedback loops. The frequency response served at the output of A1 is a high-pass filter. The frequency response at the output of A2 is a low-pass filter, and A3 acts as a summer by providing the entire notch function at its output.

The circuit in Figure 6 has several fascinating properties. The Q of the notch is dependent on the gain of the amplifiers as opposed to component matching. Consequently, the notch depth is not sensitive to temperature drift or aging. The notch depth remains relatively constant even though the filter's frequency, f_0, may shift. Additionally, the component sensitivity of this filter is very low, about 0.5.

Figure 7 shows the sixth-order, closed-loop response of a Bainter circuit. A sixth-order filter is formed by cascading three second-order filters (Figure 6) in series. In Figure 7, the Bainter's circuit closed-loop gain is 4.58 V/V with an approximation type of linear phase 0.5° and f_0 equal to 1 kHz.

The construct of this filter uses ideal resistors (21), capacitors (6), and amplifiers (9). With ideal components and devices in the circuit, there is a less than –100 dB of attenuation for the closed-loop frequency response. Additionally, in contrast to the Sallen-Key and MFB filters, this is a very clean notch filter.

The Bainter notch filter is definitely a recommended topology for bandstop filter construction.

Figure 6. A second-order Bainter bandstop or notch filter

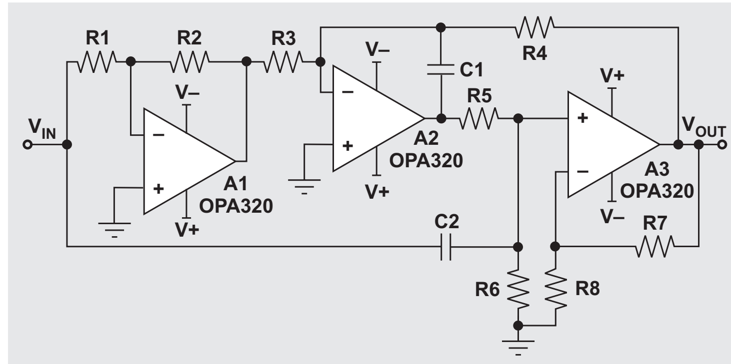
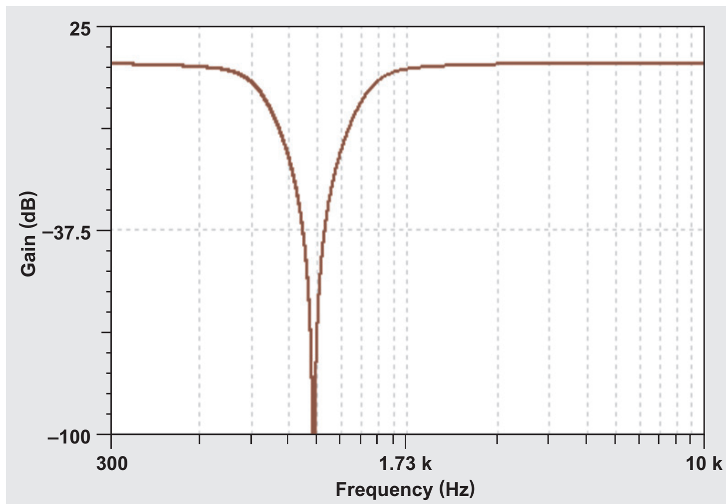


Figure 7. Closed-loop frequency response of sixth-order Bainter notch filter



Conclusion

When evaluating the correct topology for a bandstop filter, it is important to examine the closed-loop frequency response. Industry implementations of bandstop filters may use the Sallen-Key or MFB circuits. Both of these circuit topologies have their problems in the bandstop regions and in the passband regions with poor notch characteristics and unnecessary gain peaking in the passband region. The Bainter filter far surpasses the bandstop performance of these two filters by creating a clean notch filter.

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References

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2. "Active filter has stable notch, and response can be regulated," Bainter, James, Electronics, October 2, 1975. Available: **www.google.com/**

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