Using the infinite-gain, MFB filter topology in fully differential active filters

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Active filters are commonly employed in analog signal-conditioning applications. Some of the more common applications include tailoring a signal's bandwidth to reduce noise. One example of this is a low-pass anti-aliasing filter in front of an analog-to-digital converter (ADC); another is an anti-imaging filter that follows the output of a delta-sigma digital-to-analog converter (DAC) to remove unwanted high-frequency content. These filters—most commonly low-pass, high-pass, and band-pass filters—are often used to manage the amplitude response within a particular frequency range. The amplitude response may be tailored to track a particular pass-band or stop-band characteristic such as one provided by a Butterworth, Chebyshev, or Bessel filter. Filter-synthesis software is available from several sources, including Texas Instruments (TI). The synthesis programs and various on-line calculators allow for quick realization of practical filter designs. TI's FilterPro™ software accommodates all of the filters just mentioned.

Differential-amplifier and differential-input mixed-signal circuits such as ADCs are recognized for their inherent ability to reject common-mode signals and noise.[1] This ability provides a distinct advantage over the performance of single-ended-input/output ADCs, where unintended noise and signals may be processed along with the intended signal. Both the circuit complexity and the passive component count increase for a differential circuit, but maximizing system performance may easily justify the increased complexity. Like the basic differential-amplifier stages, differential active filters reject common-mode signals.

Designers often need to filter a signal as it is processed through the circuit's signal chain. In most instances the application calls for a low-pass filter. Other filters such as the band-pass, high-pass, band-reject, or an all-pass (used to create a specific time delay) are sometimes needed, but not nearly as often as the low-pass filter.

The Sallen-Key and infinite-gain, multiple-feedback (MFB) filter topologies are well-documented in filter literature, books, and on-line resources. Their popularity may stem from the fact that they require only one operational amplifier per second-order stage. Alternate topologies are available that provide a very precise filter response and offer lower component sensitivity; but they require two to four operational amplifiers per second-order stage, plus several additional precise passive components. Using one or more cascaded Sallen-Key or MFB stages often provides the necessary level of filter performance without resorting to more complex topologies.

The MFB configuration is one of the few topologies that readily lends itself to an application requiring a fully differential active filter because typical feedback paths run from the amplifier output back to only one input circuit—the inverting input circuit. The noninverting input is either biased at a common-mode potential or grounded, and no feedback is applied to it in its most common connection. The basic single-ended MFB filter topology can be used as the basis for developing a differential filter that has equivalent response characteristics. Nearly all other filter topologies require one or more feedback paths to each input of the operational amplifiers and are therefore more difficult to apply.

Transforming a single-ended-input/output filter into a fully differential filter

Filter handbooks and software don't always include topologies for differential filters, so knowing how to convert a single-ended-input/output filter to a fully differential filter when needed can save design time. For example, TI's FilterPro includes a provision for selecting a fully differential low-pass or high-pass filter but not a fully differential band-pass filter. Suppose the latter is needed. A basic single-ended MFB filter created with FilterPro can be used as a starting point. The 10-kHz second-order Butterworth filter (Q = 0.707) shown in Figure 1 is used here as an example. Butterworth filters have a maximally flat pass-band response, which is a desirable trait for most analog signal paths. A higher-order Butterworth filter further flattens the pass-band response and provides higher attenuation in the stop band. The second-order filter used in this example provides an amplitude roll-off rate of –40 dB/decade, beyond the –3-dB cutoff frequency. For now, a value of 100 nF is selected for C2, and all the other components are allowed to float to their calculated values. FilterPro allows the designer to enter a capacitor value or a seed value for the input resistor; in this case, C2's value of 100 nF is entered. Once the filter requirements are entered into the program, the resulting values are displayed within a schematic of the filter.

A helpful FilterPro feature is that it selects standard capacitance values and then calculates the required resistances that meet the filter response. Often the resistor values are within the range of resistors with 1% tolerance. Capacitors with a tolerance of better than 5%, such as 2 or 1%, have limited availability. Resistors, by comparison, are commonly available with a tolerance of 1% and even 0.1%. Therefore, most of the filter component values can be covered without resorting to parallel or series combinations; but keep in mind that components with tight tolerances are required if a precise filter response is to be achieved.

The 10-kHz Butterworth low-pass filter shown in Figure 1 uses an OPA211 precision operational amplifier, which is well suited for this application because of its wide bandwidth and high gain at the filter's critical frequencies. Other operational amplifiers will also work but must have sufficient gain bandwidth (GBW) to support the filter's performance. More will be mentioned about this later.

Transforming the single-ended-input/output low-pass filter to a fully differential filter is really quite simple. The procedure is as follows: (1) Create a mirror of the single-ended filter circuit; (2) combine the circuit elements that connect to ground; and (3) replace the operational amplifier and its mirror with a fully differential operational amplifier. Viewing the circuit in Figure 2, which shows the single-ended low-pass filter and its mirror, aids understanding of this procedure.

The fully differential amplifier does not require the ground reference that a conventional operational amplifier uses, so the ground points in the circuit are no longer needed. Also, when the mirror was created, an extra input-voltage source and output meter were created; they

Figure 1. A 10-kHz single-ended Butterworth MFB input/output low-pass filter

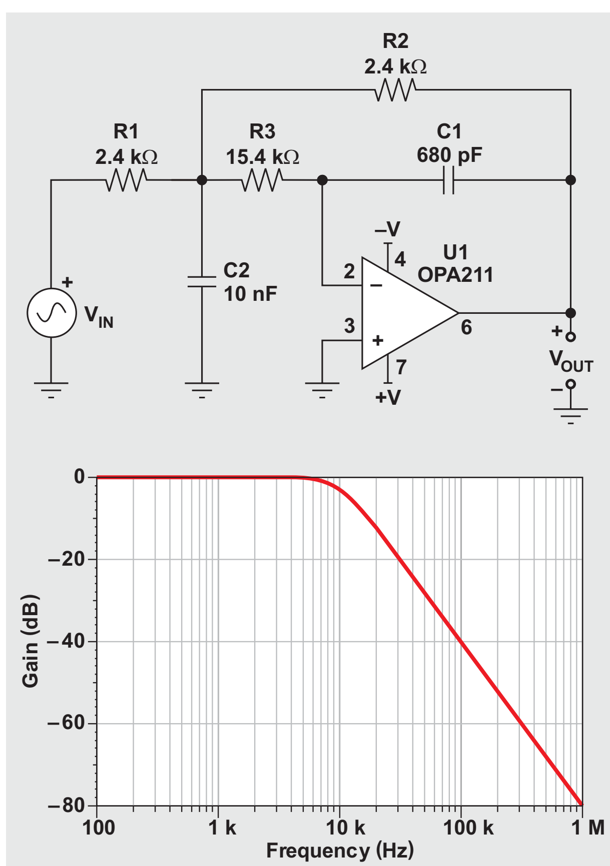
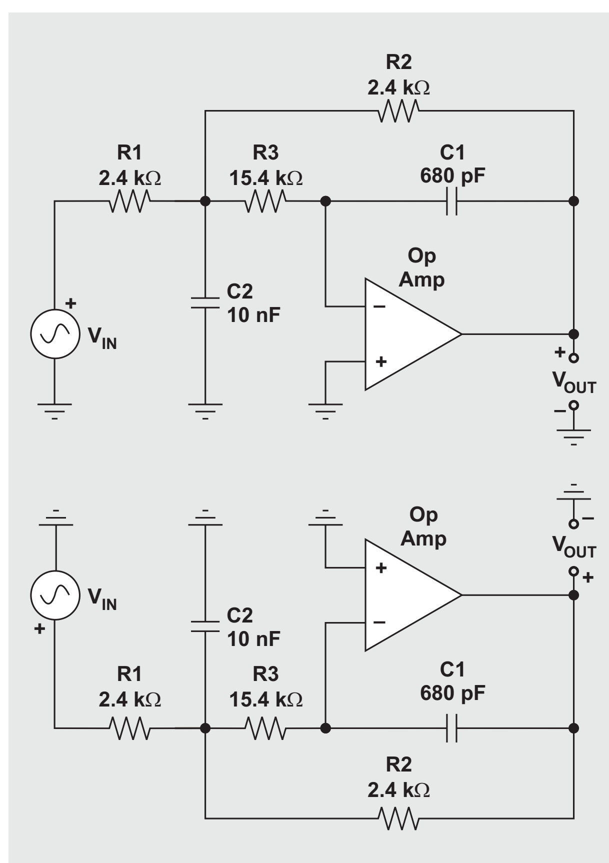


Figure 2. Mirroring the single-ended MFB input/output low-pass filter



are redundant and not required either. The capacitor C2 and the mirrored C2 are required, but their individual reactances can be combined in one capacitor. Once their ground connections are removed and they are connected together, they form a series connection. Therefore, C2 becomes common to both sides of the filter's input circuit, and its value is half of the original value. In the original low-pass filter, C2 had a value of 10 nF, but once the filter has been transformed, C2's final value is 5 nF. Lastly, the two conventional operational amplifiers are removed and replaced with one fully differential operational amplifier. In this case, a high-performance audio OPA1632 is selected. The transformed fully differential second-order low-pass filter is shown in Figure 3. A plot of gain versus frequency shows that the response is exactly the same for the fully differential and the single-ended filters.

By now it may be apparent why the value of C2 was preset to 10 nF. When a low-pass filter undergoes the transformation process, the capacitor ends up at half the original value. Selecting a capacitor value of 10 nF or 20 nF results in a transformed capacitor value of 5 nF or 10 nF, respectively. All of these are standard capacitor values. If C2 had originally been 4.7 nF, the transformed value would have been 2.35 nF, which isn't a standard value. Fortunately, when FilterPro synthesizes a fully differential filter, it always selects standard capacitor values and adjusts the resistor values to provide the correct response.

The transformation procedure may be just as easily applied to high-pass and band-pass filters. The resistors and capacitors of these filters lie in different positions within the MFB circuit than do those of low-pass filters. As a result, instead of the one capacitor and its mirror being reduced to one capacitor, a resistor and its mirror are combined into one resistor. That resistor requires twice the resistance of that used by the single-ended filter.

Figure 3. A transformed 10-kHz fully differential second-order Butterworth low-pass filter

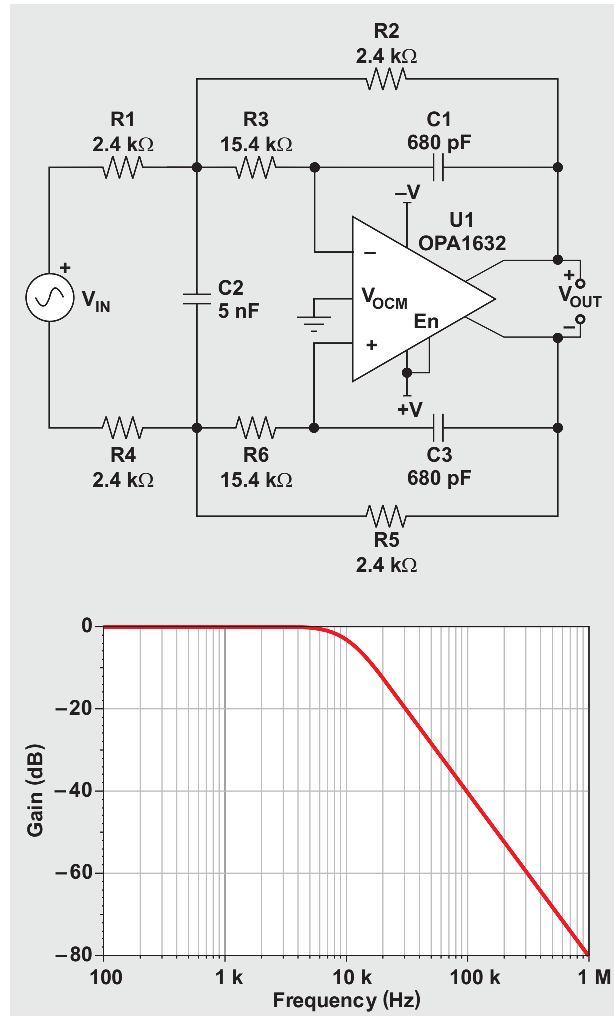


Figure 4. A 10-kHz (Q = 10) fully differential second-order Butterworth band-pass filter

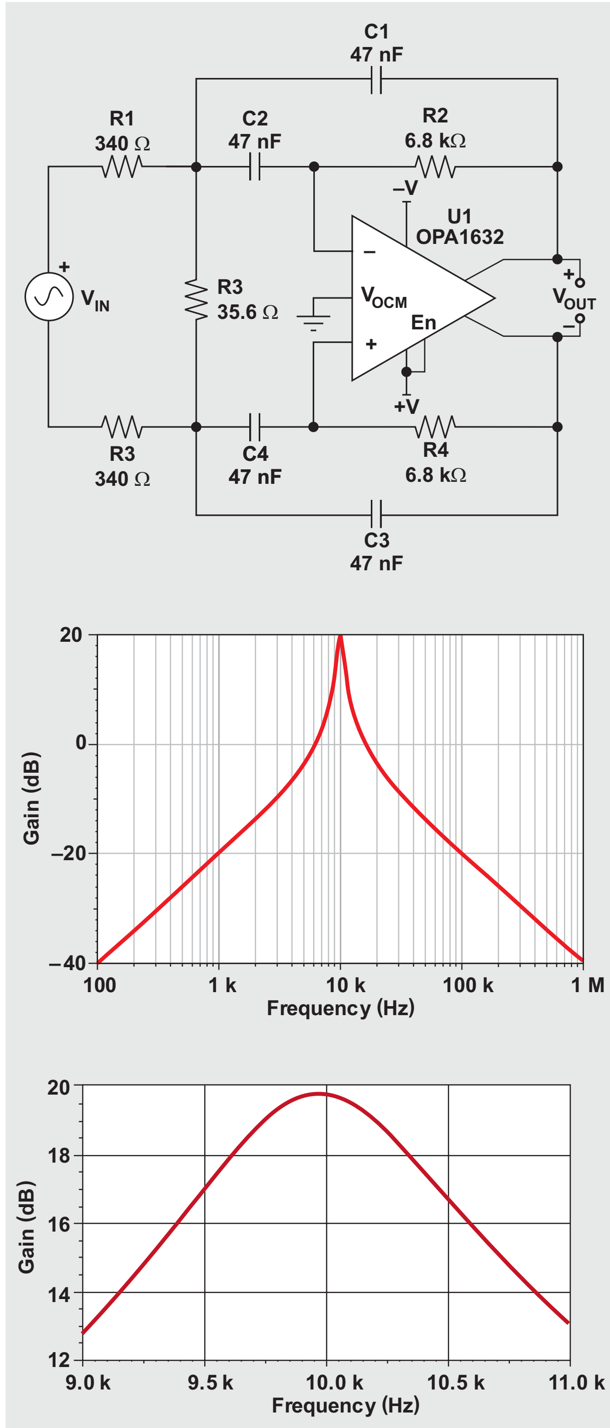


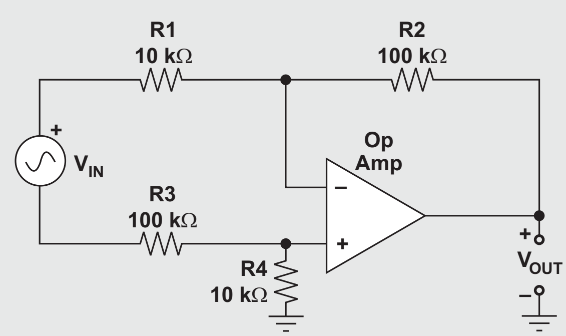
Figure 4 provides an example of a band-pass filter with a center frequency of 10 kHz, a –3-dB bandwidth of 1 kHz, and a gain of 10 V/V, with $Q_{bp} = 10$ ($f_C/BW_{-3\ dB}$). This filter was transformed via the same steps described earlier for the low-pass fully differential filter. Keep in mind that R3 is double the resistance required in a single-ended filter.

The differential-input, single-ended-output active filter

Up to this point, single-ended-input/output and fully differential active filters have been discussed. There are times, however, when an application requires a filter function provided by a differential input but requires only a single-ended output. System applications sometimes are configured with the input transducer or sensor entering the circuit differentially, while the remainder of the circuitry after the input stage operates in a single-ended fashion. Certainly the fully differential filter could be employed with one or the other output, but the amplifier involved likely offers more capability than is needed. Numerous fully differential operational amplifiers are available, but their parametric variety is limited when compared to the vast selection offered by conventional operational amplifiers. Thus, for the differential-input, single-ended-output filter, a conventional operational amplifier is a logical and often lower-cost option.

The differential-input, single-ended-output filter can be viewed as having similarities to the difference amplifier, which is comprised of a single operational amplifier and four resistors or impedances. An example schematic for a difference amplifier is shown in Figure 5. Note the differential inverting and noninverting inputs and the single-ended output. The ratios of R2 to R1 and R3 to R4 are

Figure 5. The basic difference amplifier

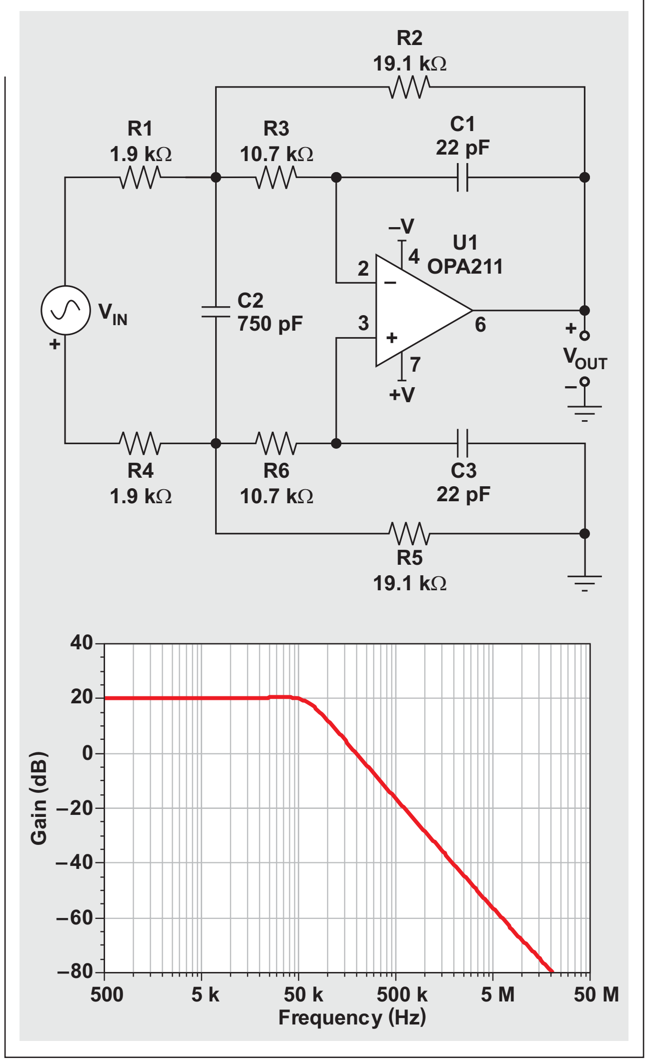


$$V_{OUT} = V_{IN} \times \left[\frac{-R2}{R1} + \frac{R4}{R3 \times R4} \times \left(1 + \frac{R2}{R1}\right)\right]$$

precisely matched such that the rejection of common-mode signals is maximized, and the amplification of differential signals is achieved with high gain accuracy. When it comes to the filter's case, the components are arranged to provide the differential filter function and to maintain input balance, just as the difference amplifier does.

The procedure for transforming the single-ended filter to the differential-input, single-ended-output filter is the same as it was for creating the fully differential filter. A conventional operational amplifier replaces the fully differential operational amplifier and, since there is a single output, the circuit is connected a little differently. Instead of connecting from a differential output back to the noninverting input, the lower feedback network simply connects to ground. Viewing Figure 6 makes the connection easy to understand. The circuit and response are shown for a 50-kHz differential-input, single-ended-output, second-order 0.5-dB Chebyshev filter that has a gain of +10 V/V. The differential-input, single-ended-output configuration can be just as easily applied to band-pass and high-pass filters.

Figure 6. A 50-kHz, differential-input, single-ended-output, second-order 0.5-dB Chebyshev low-pass filter (A_V = +10 V/V)



Considerations for practical active filters

Using filter software such as FilterPro can make designing filters straightforward and easy, but be aware that the component values resulting from such software or even from manual calculations may not always be completely satisfactory. The resistor and capacitor values derived may place impractical loading on the sensors that drive the filter, or on the operational amplifiers used in and/or around the filter circuit. This includes the input and feedback resistors in the filter. When using fully differential operational amplifiers such as the OPA1632, the designer should review the data sheet before using the feedback resistor value returned by a filter program or calculation. The OPA1632 is a very low-noise operational amplifier with a noise spectral density of about 1.3 nV/$\sqrt{Hz}$ (10 kHz). There may be the temptation to use large-value resistors to minimize capacitances, but those resistors can easily produce noise on their own that exceeds that of the OPA1632. The capacitance associated with amplifier input in conjunction with a large feedback resistance creates a pole in the response that degrades the amplifier's closed-loop bandwidth and phase margin. Therefore wideband amplifiers like the OPA1632 most often use small-value feedback resistors to preserve the amplifier's bandwidth. The same precautions must be observed whether the operational amplifier is conventional or fully differential.

Circuit designers are sometimes surprised to find that the filter response of the actual filter is not as expected. The filter exhibits inexact gain, incorrect cutoff or center frequencies, or incorrect pass-band or stop-band response characteristics. Most often this is the result of the operational amplifier having insufficient closed-loop gain at frequencies critical to the filter's performance. Surprisingly high GBW may be required of the operational amplifier, especially when a filter's operating frequency is increased, the stage gain is high, and the filter must accurately reproduce the pass-band ripple characteristics. For best MFB performance, it is recommended that any one stage's filter Q be 10 or less.

FilterPro performs a GBW calculation for both the low-pass and high-pass filters. The GBW returned is a simple approximation based on the following:

$$GBW_{Section} = G \times f_n \times Q,$$

where G is the section or stage gain (V/V), f_n is the section's natural frequency, and Q is related to the stage-damping factor, Q = 1/(2ζ). FilterPro provides the G, f_n, Q, and GBW product (listed as "GBP") in a table that summarizes the filter characteristics of each stage. This simple approximation may be used as a starting point for the other filter responses as well. More exacting GBW results may be obtained from the formulas listed in Reference 2.

Fortunately, some operational amplifiers have SPICE simulation models that accurately model the AC and transient behaviors. That is the case for both the OPA211 and OPA1632 mentioned in this article. Once the particular filter has been defined and synthesized, the filter components and operational amplifiers can be tested with a simulator such as TI's TINA-TI™ or one of the many other SPICE-based simulators.

The test run should provide an accurate account of a particular filter's true AC and transient behaviors. Any unexpected distortions in the filter performance should become evident from the simulations. Using the simulation approach is a good place to start before the actual filter is built and bench tested. All of the filter responses shown in this article were obtained from TINA-TI SPICE simulations.

References

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Document Title	**TI Lit. #**
1. Jim Karki, "Fully differential amplifiers remove noise from common-mode signals," *EDN* (November 9, 2000), pp. 149–156.	—
2. Ron Mancini, Ed., "Op Amps for Everyone," Design Reference, Section 16.8.4, pp. 16-53–16-54	slod006

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