

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

By Bonnie C. Baker

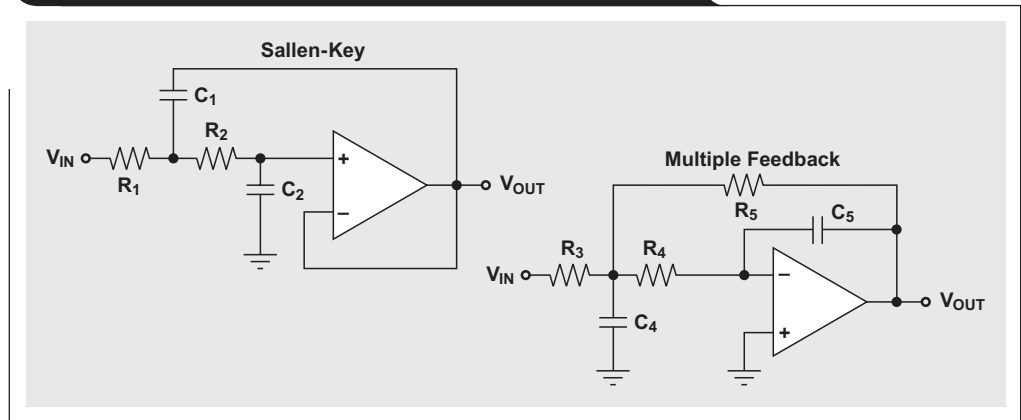
Senior Applications Engineer, Data Acquisition Products

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 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.

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



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

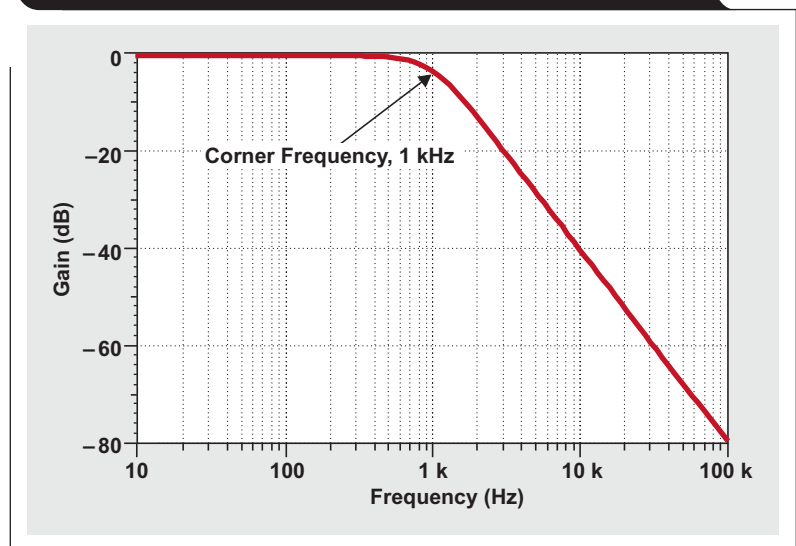
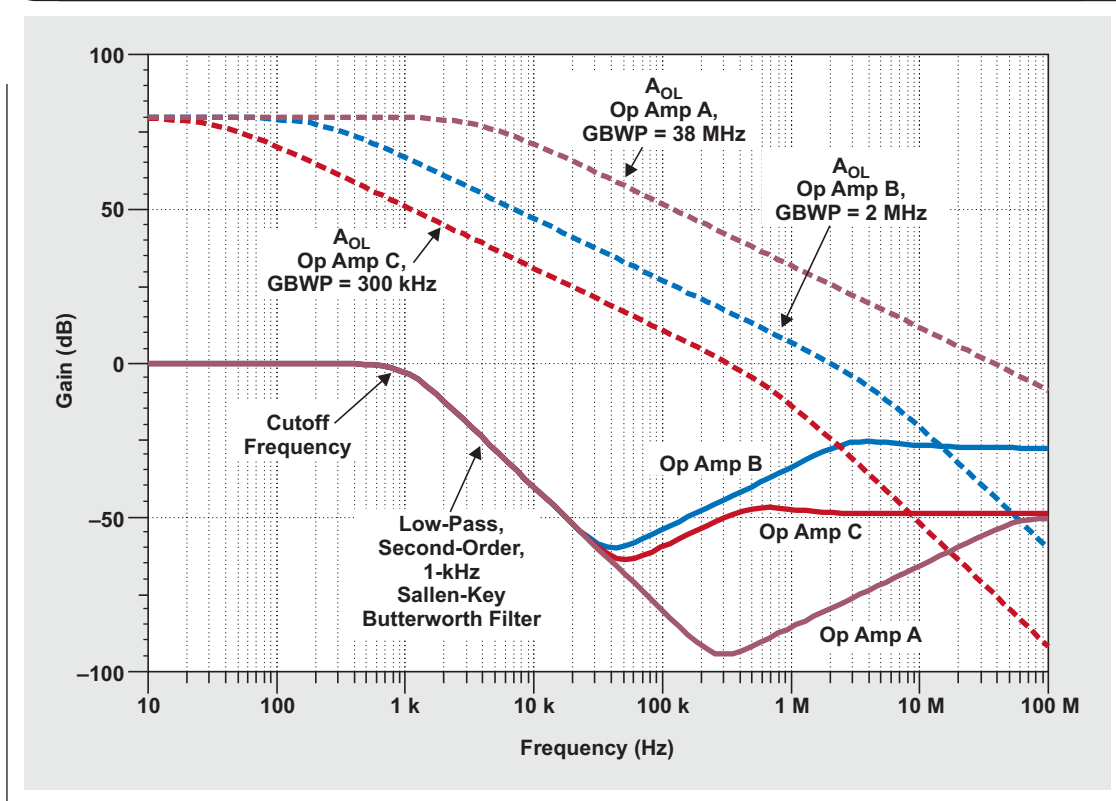


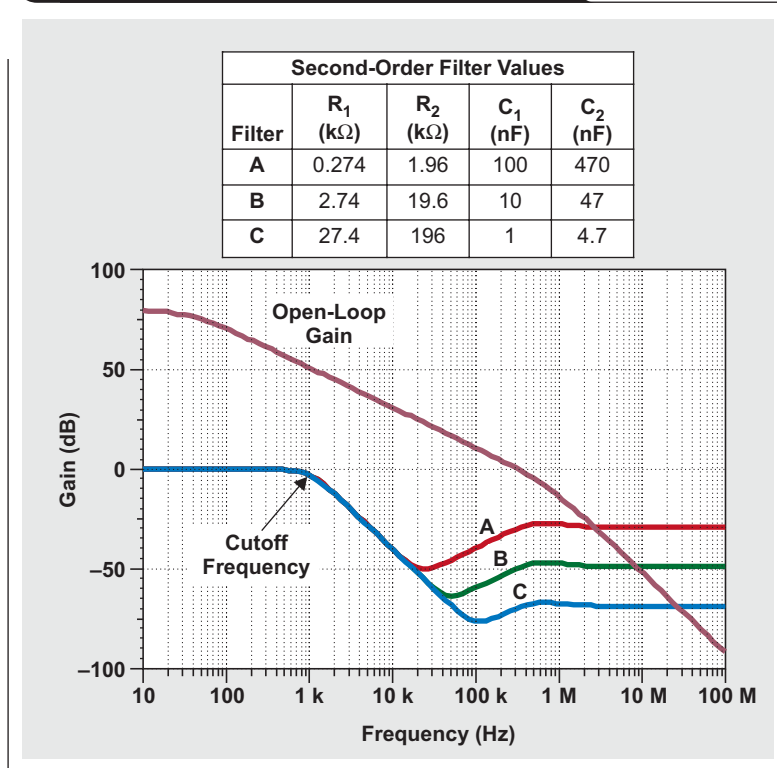
Figure 3. Frequency response of three low-pass filters and amplifier open-loop gain


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 $R_1 = 2.74 \text{ k}\Omega$, $R_2 = 19.6 \text{ k}\Omega$, $C_1 = 10 \text{ nF}$, and $C_2 = 47 \text{ nF}$. 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

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 \times , and the values of the capacitors from A to C decrease by 10 \times . 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 alterna-

tive 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)

Related Web sites

dataconverter.ti.com
www.ti.com/filterpro
www.ti.com/sc/device/OPA234

IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, modifications, enhancements, improvements, and other changes to its products and services at any time and to discontinue any product or service without notice. Customers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All products are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its hardware products to the specifications applicable at the time of sale in accordance with TI's standard warranty. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by government requirements, testing of all parameters of each product is not necessarily performed.

TI assumes no liability for applications assistance or customer product design. Customers are responsible for their products and applications using TI components. To minimize the risks associated with customer products and applications, customers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any TI patent right, copyright, mask work right, or other TI intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information published by TI regarding third-party products or services does not constitute a license from TI to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. Reproduction of this information with alteration is an unfair and deceptive business practice. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI products or services with statements different from or beyond the parameters stated by TI for that product or service voids all express and any implied warranties for the associated TI product or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

TI products are not authorized for use in safety-critical applications (such as life support) where a failure of the TI product would reasonably be expected to cause severe personal injury or death, unless officers of the parties have executed an agreement specifically governing such use. Buyers represent that they have all necessary expertise in the safety and regulatory ramifications of their applications, and acknowledge and agree that they are solely responsible for all legal, regulatory and safety-related requirements concerning their products and any use of TI products in such safety-critical applications, notwithstanding any applications-related information or support that may be provided by TI. Further, Buyers must fully indemnify TI and its representatives against any damages arising out of the use of TI products in such safety-critical applications.

TI products are neither designed nor intended for use in military/aerospace applications or environments unless the TI products are specifically designated by TI as military-grade or "enhanced plastic." Only products designated by TI as military-grade meet military specifications. Buyers acknowledge and agree that any such use of TI products which TI has not designated as military-grade is solely at the Buyer's risk, and that they are solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI products are neither designed nor intended for use in automotive applications or environments unless the specific TI products are designated by TI as compliant with ISO/TS 16949 requirements. Buyers acknowledge and agree that, if they use any non-designated products in automotive applications, TI will not be responsible for any failure to meet such requirements.

Following are URLs where you can obtain information on other Texas Instruments products and application solutions:

Products		Applications	
Amplifiers	amplifier.ti.com	Audio	www.ti.com/audio
Data Converters	dataconverter.ti.com	Automotive	www.ti.com/automotive
Clocks and Timers	www.ti.com/clocks	Broadband	www.ti.com/broadband
DSP	dsp.ti.com	Digital control	www.ti.com/digitalcontrol
Interface	interface.ti.com	Medical	www.ti.com/medical
Logic	logic.ti.com	Military	www.ti.com/military
Power Mgmt	power.ti.com	Optical Networking	www.ti.com/opticalnetwork
Microcontrollers	microcontroller.ti.com	Security	www.ti.com/security
RFID	www.ti-rfid.com	Telephony	www.ti.com/telephony
RF/IF and ZigBee® Solutions	www.ti.com/lprf	Video and Imaging	www.ti.com/video
		Wireless	www.ti.com/wireless

Mailing Address: Texas Instruments
Post Office Box 655303
Dallas, Texas 75265

TI Worldwide Technical Support

Internet

TI Semiconductor Product Information Center Home Page

support.ti.com

TI Semiconductor KnowledgeBase Home Page

support.ti.com/sc/knowledgebase

Product Information Centers

Americas	Phone	+1(972) 644-5580
Brazil	Phone	0800-891-2616
Mexico	Phone	0800-670-7544
	Fax	+1(972) 927-6377
	Internet/Email	support.ti.com/sc/pic/americas.htm

Europe, Middle East, and Africa

Phone	
European Free Call	00800-ASK-TEXAS (00800 275 83927)
International	+49 (0) 8161 80 2121
Russian Support	+7 (4) 95 98 10 701

Note: The European Free Call (Toll Free) number is not active in all countries. If you have technical difficulty calling the free call number, please use the international number above.

Fax	+ (49) (0) 8161 80 2045
Internet	support.ti.com/sc/pic/euro.htm

Japan

Fax	International	+81-3-3344-5317
	Domestic	0120-81-0036
Internet/Email	International	support.ti.com/sc/pic/japan.htm
	Domestic	www.tij.co.jp/pic

Asia

Phone	
International	+91-80-41381665
Domestic	<u>Toll-Free Number</u>
Australia	1-800-999-084
China	800-820-8682
Hong Kong	800-96-5941
India	1-800-425-7888
Indonesia	001-803-8861-1006
Korea	080-551-2804
Malaysia	1-800-80-3973
New Zealand	0800-446-934
Philippines	1-800-765-7404
Singapore	800-886-1028
Taiwan	0800-006800
Thailand	001-800-886-0010
Fax	+886-2-2378-6808
Email	tiasia@ti.com or ti-china@ti.com
Internet	support.ti.com/sc/pic/asia.htm

Safe Harbor Statement: This publication may contain forward-looking statements that involve a number of risks and uncertainties. These "forward-looking statements" are intended to qualify for the safe harbor from liability established by the Private Securities Litigation Reform Act of 1995. These forward-looking statements generally can be identified by phrases such as TI or its management "believes," "expects," "anticipates," "foresees," "forecasts," "estimates" or other words or phrases of similar import. Similarly, such statements herein that describe the company's products, business strategy, outlook, objectives, plans, intentions or goals also are forward-looking statements. All such forward-looking statements are subject to certain risks and uncertainties that could cause actual results to differ materially from those in forward-looking statements. Please refer to TI's most recent Form 10-K for more information on the risks and uncertainties that could materially affect future results of operations. We disclaim any intention or obligation to update any forward-looking statements as a result of developments occurring after the date of this publication.

E093008

ZigBee is a registered trademark of the ZigBee Alliance. All other trademarks are the property of their respective owners.