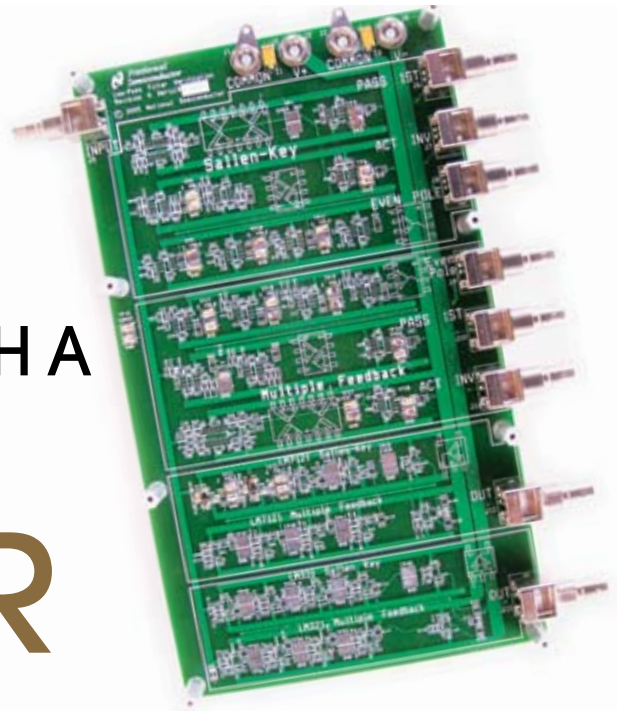


NOVEL DESIGN TECHNIQUES HELP REDUCE STOPBAND LEAKAGE IN YOUR FILTER DESIGNS.

ELIMINATE SALLEN-KEY STOPBAND LEAKAGE WITH A VOLTAGE FOLLOWER

BY MARTIN CANO • NATIONAL SEMICONDUCTOR



This filter board allows the evaluation of various Sallen-Key- and multiple-feed-back-topology filters (courtesy National Semiconductor).

The Sallen-Key lowpass filter is a form of the VCVS (voltage-controlled voltage-source) topology. Unfortunately, the interaction of the op-amp output impedance with the filter input degrades stopband performance (Figure 1). If the output impedance of the amplifier were zero, the stopband would continue to drop indefinitely with increasing frequency. This behavior corresponds to the ideal stopband response. The stopband-leakage effect has been the topic of various articles. This article details a method of decreasing or eliminating the stopband leakage by modifying the feedback loop of the filter section itself, rather than by adding more filter sections. You can achieve 50-dB decreases in stopband leakage without loading or modifying the output of the filter circuit.

The stopband feedthrough is a result of current injection into the output across capacitor C_1 (Figure 2). This current causes a voltage drop across the output impedance. The output impedance is inversely proportional to A_{OL} , the amplifier's open-loop gain over frequency. Because an amplifier's output impedance increases with frequency, the voltage drop across it, which the current injected through C_1 creates, becomes significant at higher frequencies.

You can estimate the general shape of the resulting stopband feedthrough by splitting the problem into two parts (Figure 3). One part is the forward-path response with no output impedance. In the other part, the forward path contributes nothing to the output, and the current injection into the output impedance generates all the output. This circuit approximates the interaction of the input with the impedance at the output. This interaction grows with frequency as the open-loop gain of the amplifier dictates. It does not include the nominal operation of the filter section. You can use the composite-gain plot of these two curves to approximate the stopband behavior (Figure 4). The first- and second-order pole locations, as well as the gain in the open-loop-

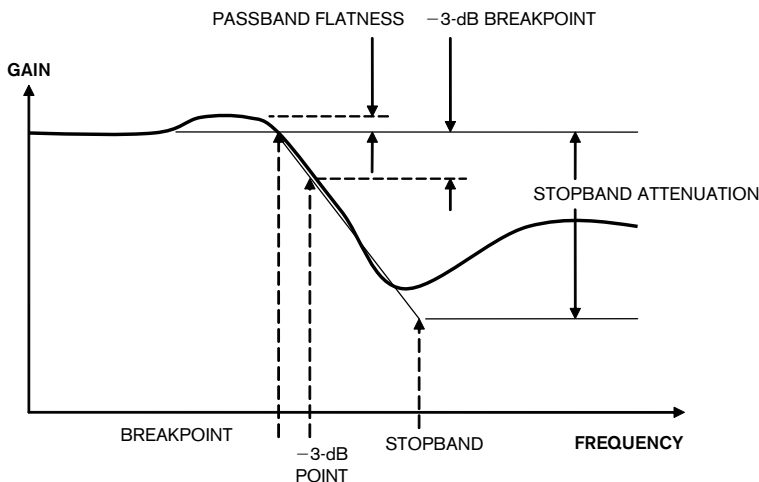


Figure 1 The Sallen-Key filter has peaking in the stopband. This well-known disadvantage limits the attenuation effectiveness and often fails your stopband specification.

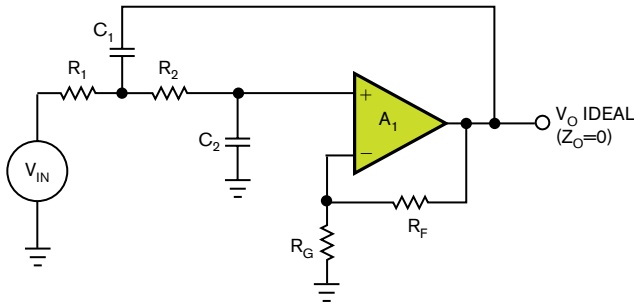


Figure 2 You make a conventional Sallen-Key filter using an op amp and two RC networks.

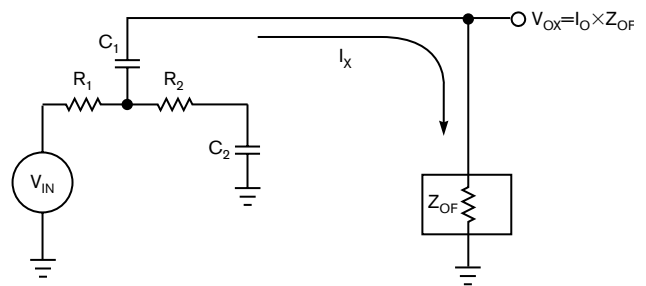


Figure 3 You can use an equivalent-circuit approximation to analyze the stopband-peaking effect.

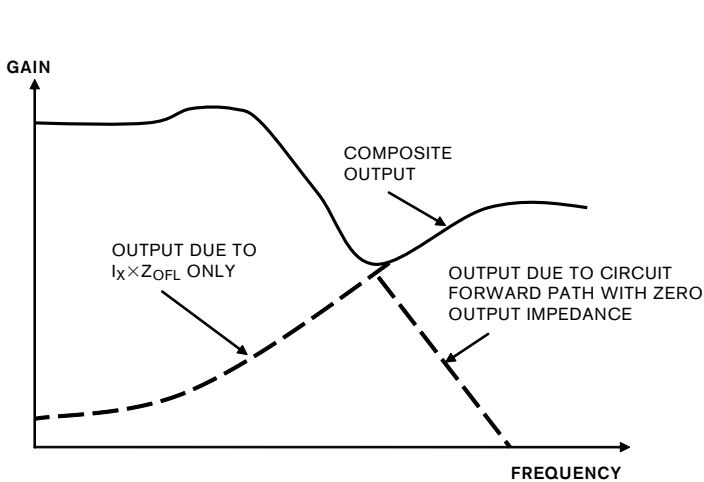


Figure 4 The observed peaking in the Sallen-Key section is a composite of two dominant effects. The ideal operation of the circuit combines with the interaction of the input reacting across the output.

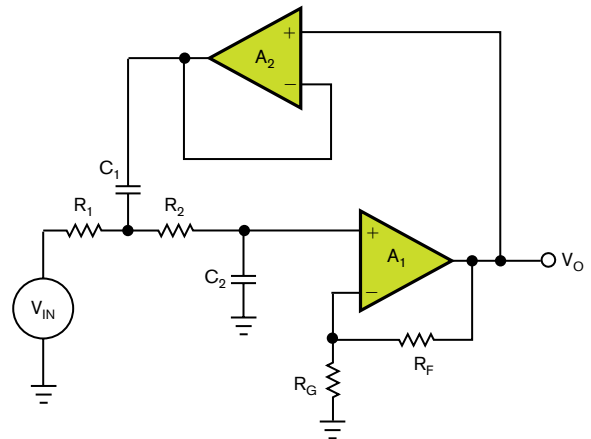


Figure 5 Adding a voltage-follower amplifier to the feedback loop does not affect the transfer function but does remove the interaction of the input with the amplifier's output impedance. This approach drastically reduces the stopband peaking.

transfer function of the op amp, play a role in determining the shape of the resultant feedthrough.

Experts have proposed various techniques for mitigating this effect, each with its advantages and disadvantages. One simple approach to this problem is to remove the interaction between the input current and the output impedance. You achieve this goal by adding a voltage-follower amplifier to the feedback path (**Figure 5**). This addition will extend the region of desired stopband behavior. The voltage drop across the output impedance due to input current through C_1 does not couple directly to the output impedance of the circuit. For this situation, it is helpful to visualize the buffer as a voltage source with the output impedance of A_2 in series connecting to C_1 . A voltage drop will occur across the output

impedance of A_2 , but it does not directly couple to the output. The effect of the output impedance is inductive in nature; that is, it rises as frequency increases. You drastically improve the stopband leakage, but it still occurs at a much higher frequency.

Carefully consider the amplifier characteristics of the buffer. Near the response breakpoint, the feedback path comes into play. In the passband, however, the ac characteristics of the amplifier are less significant. You should use a low-cost wideband amplifier that extends as much as possible the monotonic roll-off in the stopband. The dc offset of the amplifier is not important because C_1 blocks the dc feedback.

In deciding whether to use this approach, weigh its benefits against its performance requirements and design options. In some cases, it might be more

appropriate to use a different topology, such as the multiple-feedback filter. In some instances, you must use a noninverting configuration—for example, when the op amp that you use for the filter stage is a current-feedback amplifier. Because the multiple-feedback topology is incompatible with current-feedback op amps, a noninverting VCVS topology becomes more appropriate. You can then apply this technique to cure the stopband-leakage problem.

In this new configuration, the feedforward from the input capacitor to the output of the forward amplifier, A_1 , occurs at a higher frequency. The most likely culprit is the common-mode capacitance of A_1 , which creates a current path to the output of A_1 . A detailed analysis of the capacitances yields a simple model for predicting where the peaking will occur for this configuration. This approach is

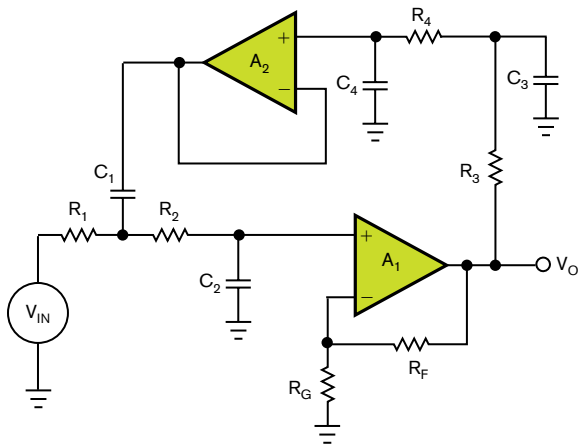


Figure 6 Lowpass filtering within the loop attenuates secondary stopband leakage at higher frequencies. Set R_3 , R_4 , C_3 , and C_4 to cut off about 100 times the filter-design frequency but less than the 3-dB bandwidth of A_2 .

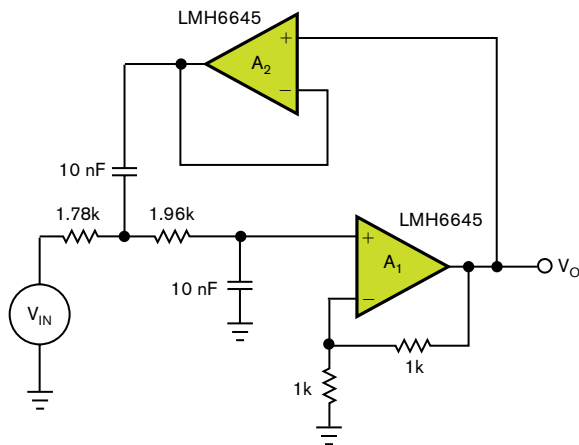


Figure 7 The experimental filter uses 55-MHz voltage-feedback amplifiers.

similar to the previous simplification that approximates the stopband leakage for the original circuit.

Amplifier-common-mode gain may have a significant effect on the response, so be sure that the amplifier you use has a good CMRR (common-mode-rejection ratio). If the buffer amplifier you select requires further reduction in stopband leakage, substitute different amplifiers and see what works best. You could also achieve significant attenuation by adding some high-frequency passive filtering between the output of A_1 and the input to the buffer (**Figure 6**).

The double-passive lowpass filter causes shunting to the current coming along the feedback path from the out-

put, sending it to ground. This high-frequency filtering occurs well within the stopband, and you should set it before the bandwidth of the buffer but far enough away from the stage-designed breakpoint so that it doesn't affect the intended low-frequency breakpoint and transfer function shape. Setting the two resistors and two capacitors two decades away from the filter-breakpoint frequency should not affect the filter shape. Also, you should set the scaling of the resistors relative to the capacitors so that the capacitors do not cause any ringing. A resistor of 200Ω to 1 kΩ should prevent ringing and oscillation due to the capacitors. For example, for a 10-kHz filter, setting the double breakpoint

at about 1 MHz with a 40-MHz buffer would be adequate.

For demanding applications, you can use separate packages for the forward amplifier and the feedback buffer. This approach prevents any paths that may couple signal through package crosstalk. This crosstalk always worsens with increasing frequency.

You can verify this theory by building the filters in real hardware. You can come up with component values and a filter configuration by using a filter-design tool, such as National Semiconductor's Webench filter designer. Once you have amplifier-part numbers and component values, you can build the filter in hardware. This test setup uses an Agilent/Hewlett-Packard (www.agilent.com/www.hp.com) 3562 dynamic signal analyzer along with an active filter-evaluation board. The filter uses 55-MHz voltage-feedback amplifiers (**Figure 7**). You can compare the results with those from the traditional VCVS by shorting out the feedback buffer, A_2 . The overlaid bode plots show significant improvement in stopband loss extending past 10 MHz (**Figure 8**). The filter-cut-off frequency is 10 kHz. **EDN**

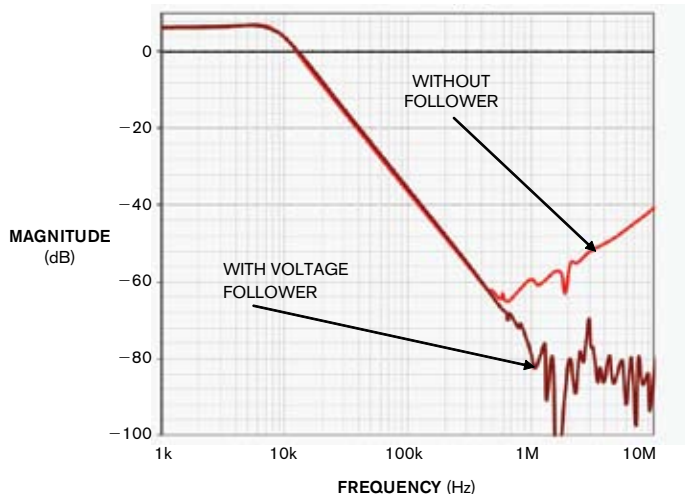


Figure 8 In the bench results for the circuit of **Figure 7**, the addition of A_2 improves the stopband performance by more than 40 dB at three decades past the 10-kHz breakpoint frequency.

AUTHOR'S BIOGRAPHY

Martin Cano most recently was a principal applications engineer at National Semiconductor, where he developed Webench tools and provided application support. He holds bachelor's and master's degrees in electrical engineering from Boston University's College of Engineering.