Application Report
SBAA236 – August 2017

Compensation Methodology for Error in Multiple-Feedback Low-Pass Filter, Caused by Limited Gain-Bandwidth of Operational Amplifiers

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ABSTRACT

Analog active filters are essential signal-processing circuits, widely used to modify the frequency spectrum of an analog signal. The multiple feedback (MFB) filter is a widely applied topology used to realize a low-pass filter. During the design of the MFB filter, the active element is always modeled as an ideal operational amplifier (op amp), however all real op amps have a limited gain-bandwidth (GBW) product. The limited bandwidth of the op amp introduces errors into the amplitude and phase responses of the filter.

To diminish these errors, the normal solution is to choose an operational amplifier with a GBW more than 100x the –3 dB bandwidth of the filter. Only by choosing an op amp with a high GBW, relative to the bandwidth of the filter, can it be treated as an ideal op amp. However, the cost of high-GBW op amps may significantly increase the cost of the filter. For some applications, the GBW requirement can be so high that it can be difficult to identify a suitable, cost-effective op amp.

This application report provides a tutorial description of the error analysis for the MFB active low-pass filter. Additionally, the report introduces a new compensation method to reduce the errors caused by the limited GBW of an op amp. Simulation and test data are presented, which demonstrate the performance achieved by this compensation technique.

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1 Introduction

The Multiple Feedback (MFB) filter is a popular, active filter topology often applied in modern electronics. The MFB filter offers exceptional stop band rejection over other filter topologies. One benefit of the MFB topology is that it requires only one op amp to realize a filter pole pair. The required level of filter performance can be achieved by cascading several MFB stages. The pole response of the MFB is sensitive to the circuit RC elements, especially the GBW of the op amp.

This application report discusses the ideal MFB low-pass transfer function, and then analyzes the frequency response error contributed by the limited GBW of the op amp. The application report then introduces a new compensation methodology to reduce the error caused by the limited GBW. Lastly, a real-case MFB low-pass filter example is provided. Simulation and testing results confirm the effectiveness of this new compensation method.

2 Ideal Transfer Function and Error Analysis

Figure 1 shows a diagram of the low-pass MFB architecture.

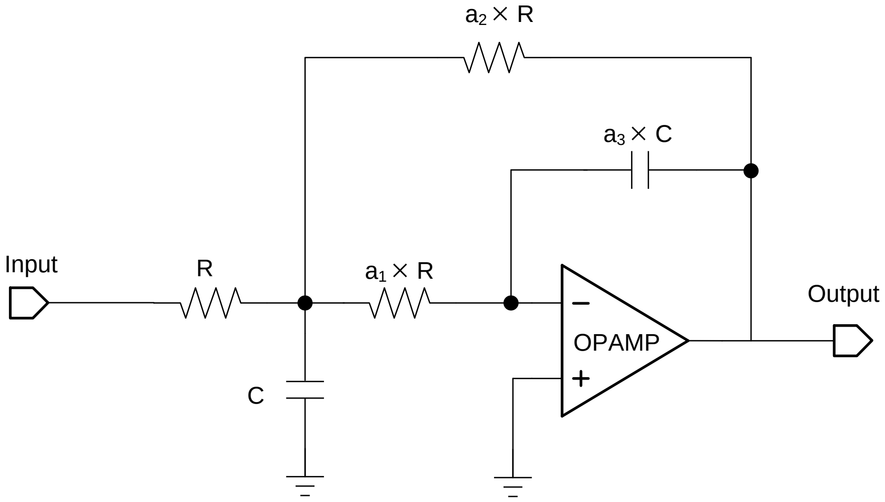


Figure 1. Low-Pass MFB Architecture

Equation 1 shows the Laplace transfer function for the circuit of Figure 1.

$$F(s) = \frac{-a_2}{s^2 \times (RC)^2 \times a_1 a_2 a_3 + s \times RC \times a_1 a_2 a_3 \left(1 + \frac{1}{a_1} + \frac{1}{a_2}\right) + 1} \quad (1)$$

DC gain (where s = 0, see Equation 2):

$$Av(DC) = -a_2 \quad (2)$$

Characteristic frequency (see Equation 3):

$$\omega_0 = \frac{1}{\sqrt{a_1 a_2 a_3}} \times \frac{1}{RC} \quad (3)$$

The quality factor (see Equation 4):

$$Q = \frac{1}{\sqrt{a_1 a_2 a_3}\left(1 + \frac{1}{a_1} + \frac{1}{a_2}\right)} \quad (4)$$

Equation 5 shows the ideal Laplace transfer function of MFB.

$$F(s) = \frac{-a_2}{s^2 \times \left(\frac{1}{\omega_o}\right)^2 + s \times \frac{1}{\omega_o Q} + 1} \tag{5}$$

When the filter performance requirements have been established, the resistance and capacitance values are determined by calculations, or by using filter synthesis software. In the real-filter case, the op amps used to construct the active filter have limited GBW, which alters the response of the filter, thereby causing it to deviate from the ideal.

If the limited GBW of the op amp is taken into consideration, the frequency response can be modeled as a 1-pole system.

The Laplace transfer function for a real op amp (see Equation 6):

$$A(s) = \frac{GBW}{s} \tag{6}$$

NOTE: GBW is specified in radians.

When the transfer function of the op amp has been introduced into the transfer function of the MFB, the equation becomes more complex (see Equation 7 and Equation 8):

$$F(s) = \frac{-a_2}{b_3 s^3 + b_2 s^2 + b_1 s + b_0} \tag{7}$$

$$\begin{pmatrix} b_0 \\ b_1 \\ b_2 \\ b_3 \end{pmatrix} = \begin{pmatrix} 1 \\ \frac{a_2}{GBW} + \frac{1}{GBW} + CRa_1a_3 + CRa_2a_3 + CRa_1a_2a_3 \\ \frac{CRa_2}{GBW} + \frac{CRa_1a_3}{GBW} + \frac{CRa_1a_2a_3}{GBW} + \frac{CRa_2a_3}{GBW} + C^2R^2a_1a_2a_3 \\ \frac{C^2R^2a_1a_2a_3}{GBW} \end{pmatrix} \tag{8}$$

This result indicates that when the transfer function of the op amp has been included, the filter order increases to that of a third-order response. Additionally, the qualify factor (Q) and the characteristic frequency of the filter have been affected by the GBW of the op amp. These changes are what alter the response of the filter.

It has been determined that the response errors introduced by the limited-GBW op amp can be effectively compensated for by adding a resistor, R_{comp}, in series with the a_3*C capacitor. Figure 2 shows the resulting revised MFB topology.

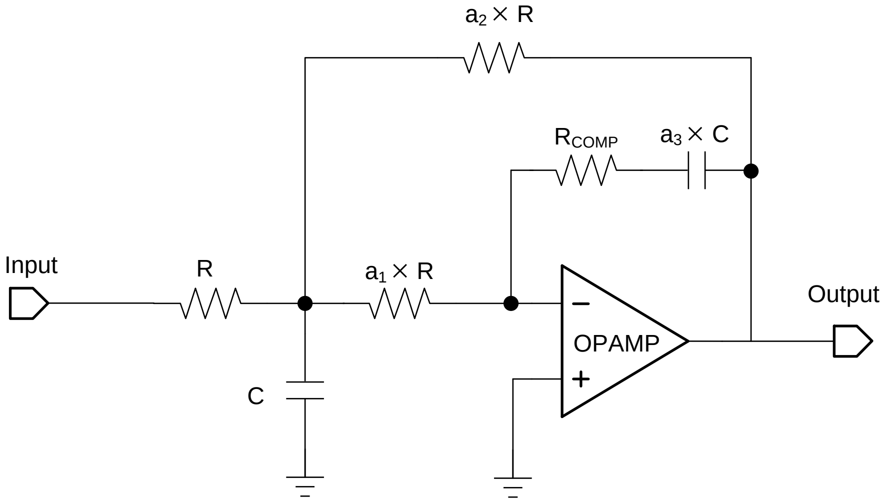


Figure 2. Modified Topology of MFB Incorporating Op Amp and GBW Compensation

R_{comp} is selected such that the corner frequency established by R_{comp} and a_3*C is equal the GBW of the op amp (see Equation 9).

$$R_{comp} = \frac{1}{GBWa_3C} \tag{9}$$

When R_{comp} is added to the standard MFB topology, the transfer function can be simplified as follows (see Equation 10 and Equation 11):

$$F(s) = \frac{-a_2}{b_2s^2 + b_1s + b_0} \tag{10}$$

$$\begin{pmatrix} b_0 \\ b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} 1 \\ \frac{a_2}{GBW} + \frac{1}{GBW} + CRa_1a_3 + CRa_2a_3 + CRa_1a_2a_3 \\ \frac{CRa_2}{GBW} + C^2R^2a_1a_2a_3 \end{pmatrix} \tag{11}$$

Characteristic frequency (see Equation 12):

$$\omega_0 = \frac{1}{RC\sqrt{a_1a_2a_3 + \frac{a_2}{CR \times GBW}}} \tag{12}$$

The quality factor (see Equation 13):

$$Q = \frac{\sqrt{\frac{a_2}{CR \times GBW} + a_1a_2a_3}}{\frac{a_2}{CR \times GBW} + \frac{1}{CR \times GBW} + a_1a_3 + a_2a_3 + a_1a_2a_3} \tag{13}$$

R_{comp} in conjunction with capacitor a_3*C adds a zero into the response that cancels the pole associated with the limited GBW of the op amp.

3 Simulation and Test Results

To verify the response of the revised MFB topology, a filter with a second-order, Butterworth low-pass response, with DC gain of 4 V/V (12 dB), and a characteristic frequency equal to the -3 dB bandwidth of the filter was selected.

The response requirements were entered into the WEBENCH® Filter Designer tool from TI, which generates the resistor and capacitor component values. FilterPro™ from TI could have been used as well. Both tools produce a schematic similar to that shown in Figure 3.

The MFB filter shown in Figure 3 realizes a Butterworth, second-order, low-pass response, with a –3 dB bandwidth of 300 kHz when an ideal op amp is used. However, Filter Designer indicates that to assure the correct filter response with an actual op amp, that it should have a GBW of at least 85 MHz. That is a high GBW requirement and would require using a high-speed op amp. High-speed op amps tend to be more costly than their lower-GBW op amp counterparts, so the goal here is to use a lower-GBW op amp and incorporate the proposed GBW compensation. The filter responses with and without the compensation can then be compared.

The TL081 is a popular JFET input op amp. Its GBW is 3 MHz – much less than the 85 MHz indicated by the filter programs. Despite this, the TL081 is selected to test the new GBW-compensation method.

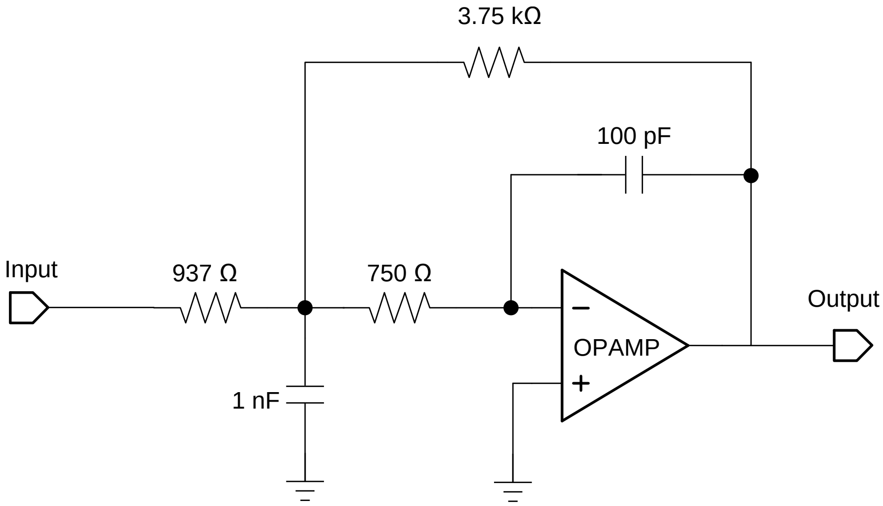


Figure 3. Schematic for 300-kHz MFB Low-Pass Filter

Figure 4 shows the AC transfer curves of the MFB low-pass filter using the TL081 along with an ideal op amp. Using the AC Analysis of TINA Spice, the AC Transfer Characteristic function makes it is easy to determine the –3 dB bandwidth of the filter. When the TL081 device is used in simulation the –3 dB bandwidth is 239 kHz, about 20% below the correct bandwidth achieved by the ideal op amp.

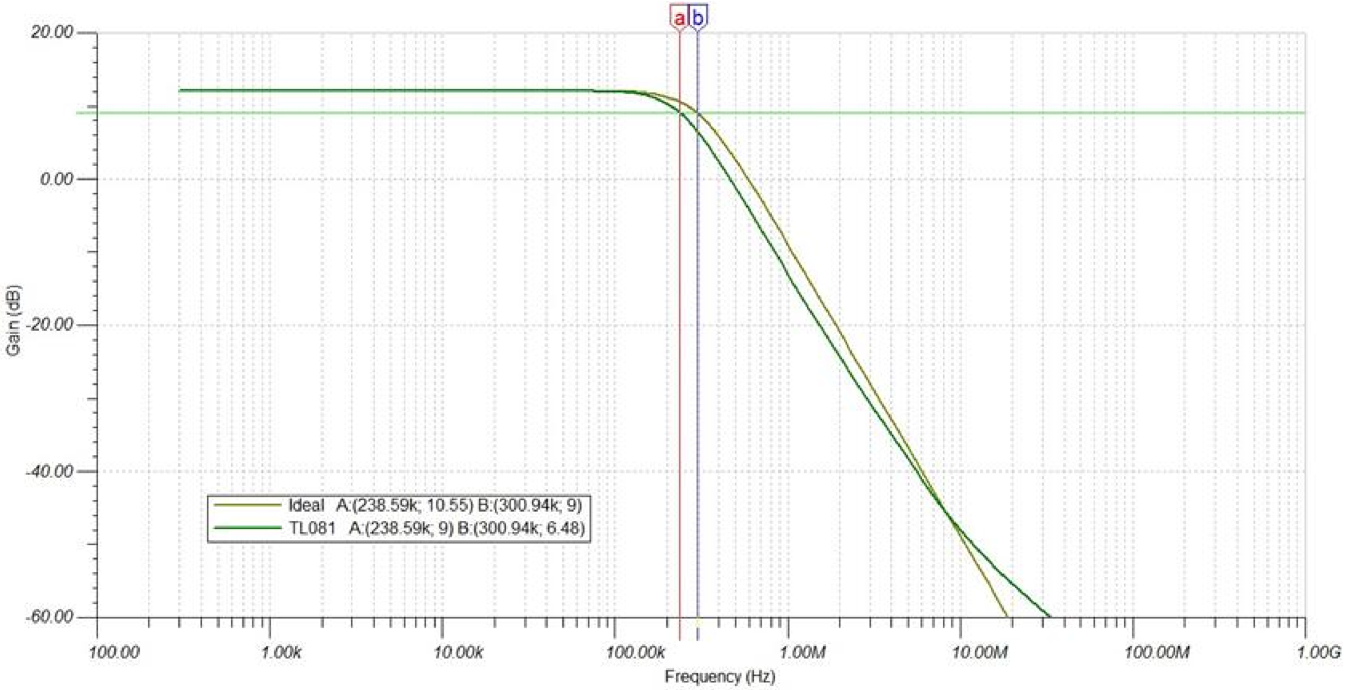


Figure 4. TINA Spice AC Simulation for Ideal Op Amp and TL081

Next, the GBW-compensation method is applied to the filter version using the TL081. Applying the 3-MHz GBW of the TL081 to Equation 9 results in a R_{comp} resistor of 520 Ω.

Lastly, the resistance connected directly in series with the op amp inverting input is recalculated using Equation 12 and Equation 13. Originally, in Figure 3, the resistor had a value of 750 Ω, but after recalculation it decreases to 320 Ω.

Figure 5 shows the original MFB filter schematic, now modified incorporating the two resistor changes.

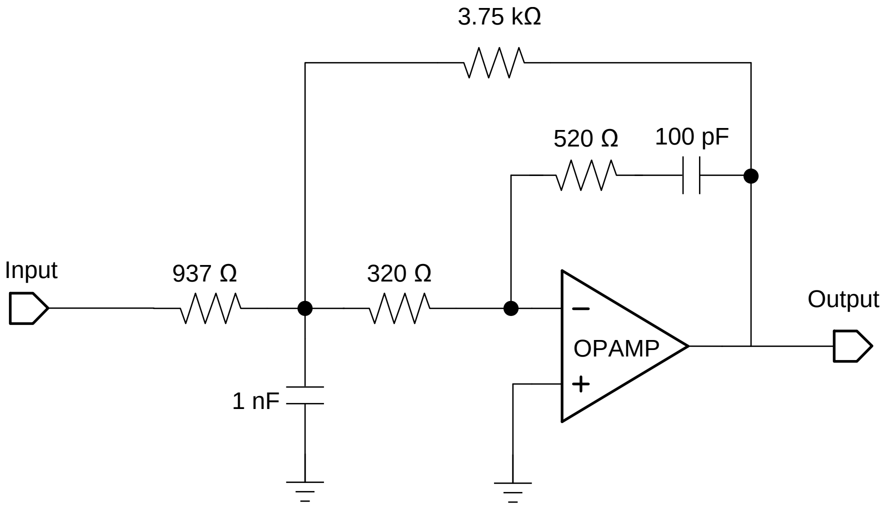
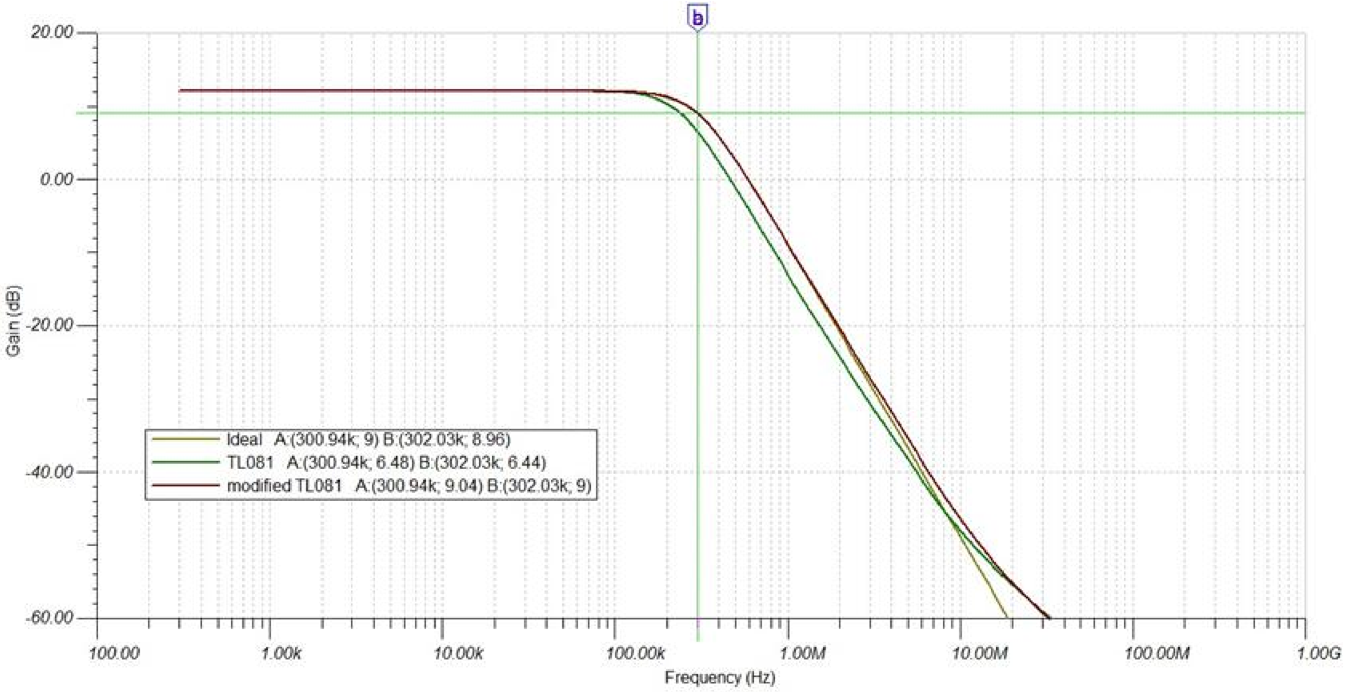


Figure 5. Schematic for Compensated 300-kHz MFB Low-Pass Filter

Figure 6 shows the simulation results for an ideal op amp, an uncompensated TL081, and the compensated TL081. It is evident from these plots that the ideal and compensated TL081 MFB circuits produce nearly identical gain versus frequency responses.

To further validate the compensation method, a network analyzer was used to determine the S21, forward voltage gain parameter, of the filter, which is equivalent to the AC transfer function of the filter.



(1) The ideal and compensated curves are nearly coincident.

Figure 6. TINA Spice AC Simulations for MFB Filter Using Ideal Op Amp, Standard TL081 Circuit and Compensated TL081 Circuit

Figure 7 shows the measured S21 result. The –3 dB bandwidth is 302 kHz, indicating that the original bandwidth target is supported by the TL081 with this new compensation technique applied.

Figure 7. S21 for Modified MFB Filter Using TL081

4 Conclusions

MFB low-pass filter response errors introduced by the limited gain-bandwidth of an operational amplifier have been analyzed. A new compensation method that reduces these errors was proposed. The method allows successful use of an op amp with a lower GBW than that recommended by filter synthesis programs or other means. The simulation and test results are in a close agreement with the theoretical analysis. Using this compensation method, designers can develop a MFB active low-pass filter for many applications using lower cost, lower bandwidth op amps.

5 References

- Texas Instruments, Using the Infinite-Gain, MFB Filter Topology in Fully Differential Active Filters, Technical Brief
- Texas Instruments, FilterPro™, User's Guide
- Texas Instruments, Design Methodology for MFB Filters in ADC Interface Applications
- Texas Instruments, TL081, Data Sheet

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