Application Brief

How to Design MFB Filters with Amplifier Bandwidth Limitations

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Introduction

Active filters are popular because board size and cost can be reduced, and active filters are capable of dealing with very low frequencies that become unrealistic for filters that require inductors, as the inductors can become quite large and costly. Of these, the multiple feedback topology is a commonly used design. One limitation of active filters is very-high frequency applications due to the bandwidth limitation of the amplifier. Many free filter design software simply recommend selecting devices with a GBWP that is 100 times greater than the filter bandwidth to avoid gain errors in the frequency response. With higher bandwidth filters, finding an amplifier that meets the criteria can be difficult and sometimes impossible. Instead, adjusting passive component values can provide a frequency response much closer to the desired filter shape.

MFB Filter Design Criteria for Ideal Amplifier

The MFB low pass active filter topology shown in Figure 1 is used to demonstrate how to calculate the passive component values and the effects a non-ideal amplifier has on the filter characteristics.

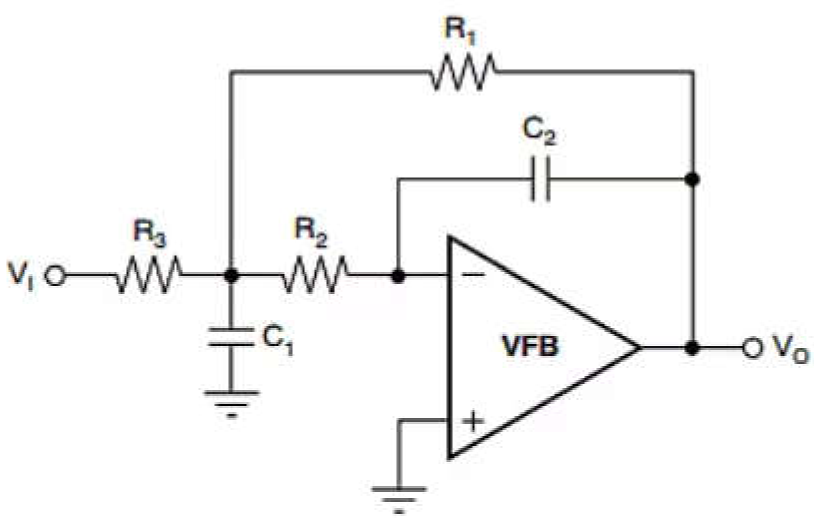

Figure 1. MFB Filter Topology

Using an MFB active filter topology, there are five passive component values to determine and three filter characteristics. Using an equal-R design approach Equation 1, a constraint for R_2 can be found:

$$R_2 = \frac{-2kT}{{i_n}^2}\left(\frac{1 + A_v}{1 + 3Av}\right) + \frac{1}{2}\sqrt{\left(\frac{4kT}{{i_n}^2}\right)^2\left(\frac{1 + A_v}{1 + 3Av}\right)^2 + 4\left(\frac{e_n}{i_n}\right)^2\left(\frac{1 + A_v}{1 + 3Av}\right)} \tag{1}$$

This equation returns the maximum value of R_2 for the resistor noise terms to be equal to the amplifier noise voltage. Selecting a lower value of R_2 improves noise. However, take careful consideration when selecting R_2 as very low values start to load the output stage driving into the filter and the filter amplifier output stage. If needed, R_2 can be set higher to lighten loading with the drawback of higher total output noise. Once R_2 is selected, the remaining passive components can be calculated using the following equations:

$$C_2 = \frac{1}{\omega_0 R_2 Q(2A_v + 1)} \tag{2}$$

$$C_1 = \frac{Q}{\omega_0 R_2 (1 - Q\omega_0 R_2 C_2 (1 + 4))} \tag{3}$$

$$R_3 = \frac{1}{A_V \omega_0{}^2 R_2 C_1 C_2} \tag{4}$$

$$R_1 = R_3 A_V \tag{5}$$

Where A_v represents the desired gain of the filter, Q factor represents the peaking in the Bode magnitude plot, and ω_o is the characteristic frequency of the filter (in radians).

MFB Filter Transfer Function for Nonideal Amplifier

The above characterizations of the MFB active filter were found using the assumption that an ideal amplifier was being used, meaning no additional poles affected the frequency response of the filter. However, one of the biggest design roadblocks is accounting for the effects of a nonideal amplifier. A nonideal amplifier can be represented by a single pole model with the following transfer function, A(s):

$$A\left(s\right) = \frac{A_{ol}\omega_a}{s + \omega_a} \tag{6}$$

Where A_{ol} is the amplifier open loop gain at DC and ω_a is the dominant pole frequency. ω_a can be found for a specific device using Equation 7.

$$\omega_a = GBWP \times \frac{2\pi}{A_{ol}} \quad [radians] \tag{7}$$

Factoring in this single pole model of the amplifier adds a pole to the transfer function of the MFB filter. The transfer function then takes the following form:

$$H\left(s\right) = \frac{V_o(s)}{V_i(s)} = \frac{G}{s^3 + B_2 s^2 + B_1 s + B_0} \tag{8}$$

Where...

$$G = \frac{A_{ol}\omega_a}{C_1 C_2 R_2 R_3} \tag{9}$$

$$B_2 = \frac{1}{R_2 C_2} + \frac{1 + \frac{R_1}{R_2 \,||\, R_3}}{R_2 C_1} + \omega_a (1 + A_{ol}) \tag{10}$$

$$B_1 = \frac{1 + \frac{R_1}{R_3}}{R_1 R_2 C_1 C_2} + \omega_a\left(\frac{1}{R_2 C_2} + \frac{A_{ol} + 1}{R_1 C_1}\left(1 + \frac{R_1}{R_2 \,||\, R_3}\right)\right) \tag{11}$$

$$B_0 = \frac{\omega_a \left(A_{ol} + 1 + \frac{R_1}{R_3}\right)}{R_1 R_2 C_1 C_2} \tag{12}$$

From here a cubic solver is used to determine the complex pole pair and the real solution. The complex pole solution takes the form of:

$$P_{1,2} = a \pm jb \tag{13}$$

The characteristic frequency can be found from Equation 14.

$$\omega_o, actual = \sqrt{a^2 + b^2} \quad [radians] \tag{14}$$

And the Q factor can be found using Equation 15.

$$Q_{actual} = \frac{1}{2cos\left(tan^{-1}\left(\frac{b}{a}\right)\right)} \tag{15}$$

Adjusting Passive Component Values for Nonideal Amplifier

When designing an active filter, designers must understand how to overcome the limitations of a nonideal amplifier. As shown in MFB Filter Design Criteria for Ideal Amplifier, we can calculate the passive component values for an active MFB filter, but the frequency response differs depending on the behavior of the selected amplifier. Using the equations shown in MFB Filter Transfer Function for Nonideal Amplifier, we can determine the actual filter behavior and use that to adjust passive components to get a frequency response closer to the desired filter shape.

When choosing an amplifier with a GBWP 100 times greater than the filter bandwidth is not feasible, a passive component adjustment algorithm can be used to lower gain errors in the frequency response and get a frequency response much closer to the desired filter shape. To adjust passive component values, one method is to determine the error between the actual Q factor and the desired Q factor to determine a new adjusted Q factor to be used in recalculating the passive component values. The same process must be followed for the characteristic frequency as well. The adjusted Q factor and adjusted characteristic frequency can be found from the following equations:

$$Q_{adjusted} = \frac{{Q_{target}}^2}{Q_{actual}} \tag{16}$$

$$\omega_o, adjusted = \frac{{\omega_{o,target}}^2}{\omega_{o,\ actual}} \tag{17}$$

Plugging the adjusted characteristic frequency and Q factor values into the equations in MFB Filter Design Criteria for Ideal Amplifier for the target characteristic frequency and Q factor produces new passive component values that improve the filter shape.

Design Example

To illustrate the effects of bandwidth limiting and passive component adjustment on the filter frequency response, a second order lowpass MFB filter is designed using the OPA2863A. The OPA2863A has a GBWP of 50MHz. Three filters with varying characteristic frequencies are designed to show the limitations bandwidth imposes. All three filters have a target Q factor of 1 and DC gain of 2V/V. Table 1 shows the results of designing a lowpass MFB filter without any RC adjustment.

Table 1. MFB Filters Without RC Correction

Desired Cutoff Frequency	R1 (Ω)	R2 (Ω)	R3 (Ω)	C1 (pF)	C2 (pF)	Q Factor	Actual Cutoff Frequency	Percent Error
500kHz	2000	1000	1000	1010	81	1.003	491.45kHz	1.71%
5MHz	2000	1000	1000	101	8.1	1.005	4.29MHz	14.2%
20MHz	2000	1000	1000	25.3	2.02	0.8953	12.38MHz	38.1%

Then the RC adjustment method was used to reduce the error in the frequency response by accounting for the limited amplifier bandwidth. The results are shown in Table 2.

Table 2. MFB Filters With RC Correction

Desired Cutoff Frequency	R1 (Ω)	R2 (Ω)	R3 (Ω)	C1 (pF)	C2 (pF)	Q Factor	Actual Cutoff Frequency	Percent Error
500kHz	2000	1000	1000	989	79.7	1.000	499.85kHz	0.03%
5MHz	2000	1000	1000	85	6.86	0.9961	4.95MHz	1.00%
20MHz	2000	1000	1000	17.3	1.11	0.8697	16.55MHz	17.25%

Figure 2, Figure 3, and Figure 4 show the frequency response of each filter design with and without the passive component value correction method.

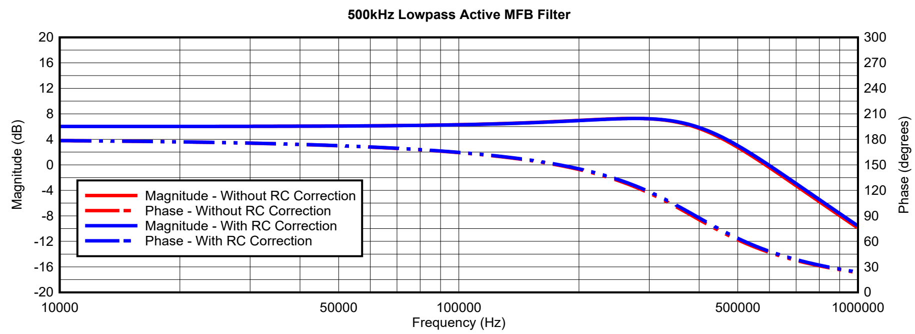

Figure 2. 500kHz Low-Pass Active MFB Filter

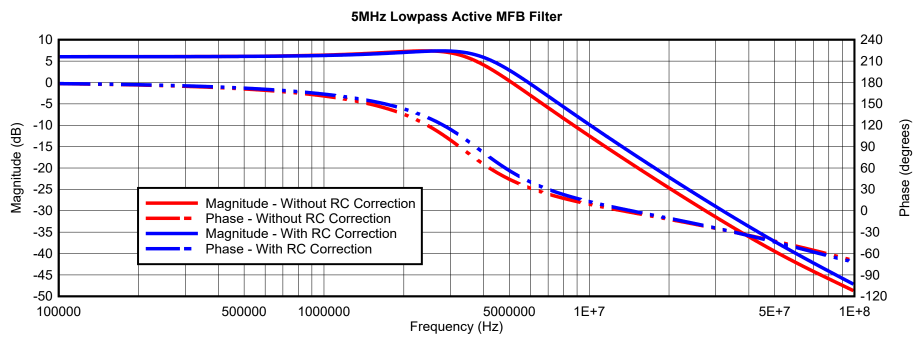

Figure 3. 5MHz Low-Pass Active MFB Filter

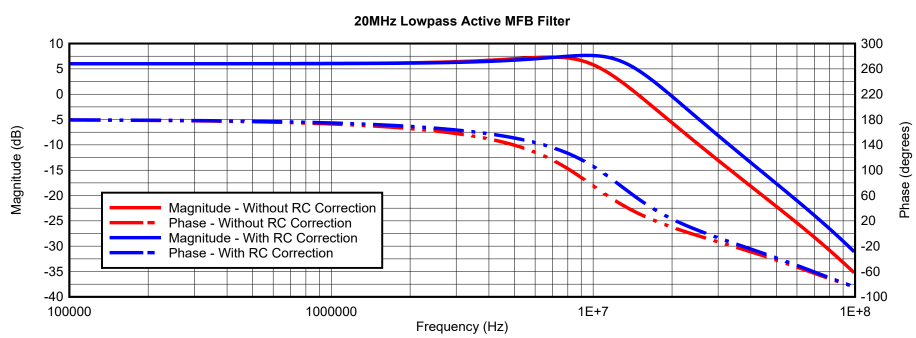

Figure 4. 20MHz Low-Pass Active MFB Filter

Factors Not Considered

The analysis done throughout this article left a few topics unconsidered. First, any parasitic capacitance on the inverting input pin of the amplifier was disregarded. Reference 4 covers this topic in more detail. Another factor that needs to be considered but was not covered in this application brief is the possible variation in GBWP from device to device. Depending on temperature and from part-to-part, possible GBWP variation is conservatively estimated around ±20 to ±30% depending on the amplifier architecture. The values of passive components calculated in this article are ideal values and not always standard resistor and capacitor values. Some error is introduced from selecting the closest standard component value to the ideal value. Also, standard resistor and capacitor values have variation in value as well, although small variation (around 0.5% to 1%) are more readily available today.

Summary

One of the most common questions asked when designing an active filter is what minimum GBWP is needed to achieve the desired filtering. Many softwares recommend an amplifier with a GBWP that is 100 times greater than the filter bandwidth. This, however, can add excess cost and higher power requirements to the system. Instead, using a passive component adjustment method can significantly decrease the GBWP margin from the 100 times that many filter design softwares use. As shown in the design examples, designing an active filter where the GBWP was only 2.5 times greater than the filter bandwidth produced an error from the target filter characteristics of about 17%. This provides for a wider array of amplifier choices, even for higher-frequency filters, due to a lower GBWP margin being needed.

References

- Texas Instruments,*Design Methodology for MFB Filters in ADC Interface Applications* application report.
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