HANDS-ON RADIO

Experiment 106
Effects of Gain-Bandwidth Product

Last month, we discussed gain-bandwidth product (GBW or GBP) and how it affects the ability of an op-amp to amplify signals of different frequencies. That's important, because op-amps are used as the active element in signal processing and filter circuits. What effect does GBW have in that kind of application? We'll use *LTspice* to illustrate the effects of GBW in a band-pass filter circuit as an example of the issues the circuit designer has to consider.

Gain and Q

In the experiment portion of the previous experiment, you built a simple amplifier circuit and substituted op-amps with different GBW to see the effect. Clearly, as GBW increased, so did the gain of the circuit at higher frequencies. What about circuit performance at much lower frequencies? Does GBW affect performance there, as well? Yes!

The effects are most easily seen in band-pass filters because requirements for steep filter "skirts" and narrow bandwidths require a lot of gain. Why do they require a lot of gain? Let's take a look at the multiple-feedback band-pass filter in Figure 1.[1] (This design was created by Jim Tonne, W4ENE, using the professional-level version of his *ELSIE* filter design software.[2]) It shows a two-pole band-pass filter with a center frequency, f_0, of 10 kHz and a bandwidth, BW, of 1 kHz. Thus, the filter's Q is

$$Q = f_0 / BW = 10\text{ kHz} / 1\text{ kHz} = 10$$

In this example, the software requires values for f_0 and BW, the capacitor values (using the equal C-method), and the order and type of filter response (second order Chebyshev in this case). Figure 1A is the filter design if an *ideal* op-amp is used. That means an op-amp with an infinite GBW and infinite dc gain. Each filter section has the same gain (A_V = 5.6 dB) and Q (18.24). The section's center frequencies are slightly different: $f_{0\text{-}1}$ = 9.56 kHz and $f_{0\text{-}2}$ = 10.46 kHz. Each section then acts as a narrow filter (Q = 18.24) tuned to a single f_0.

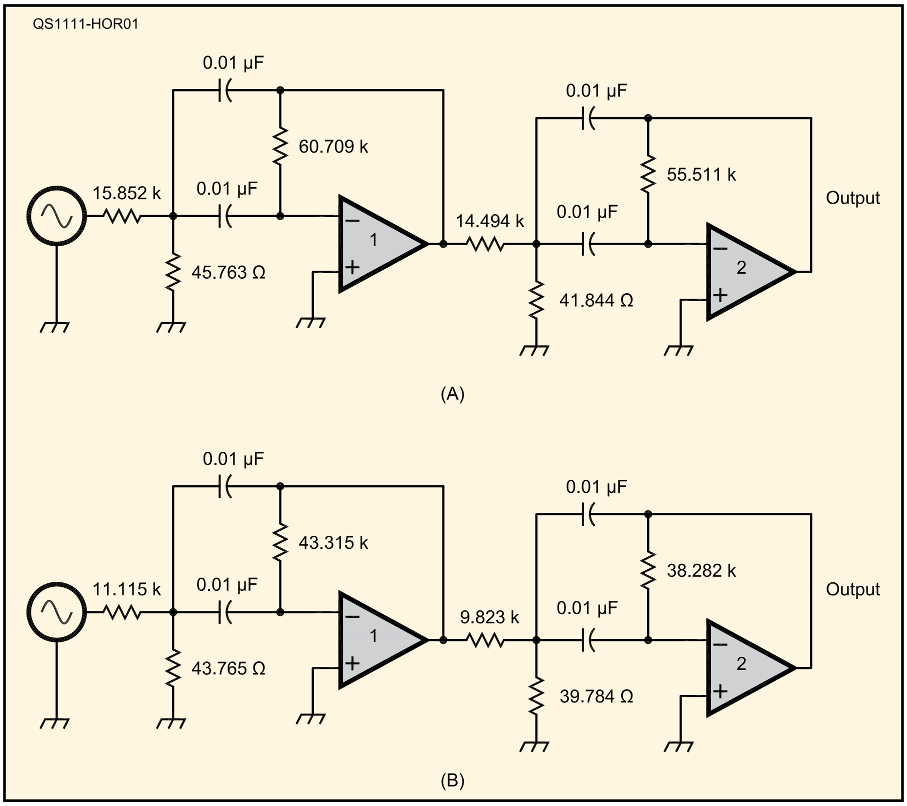

Figure 1 — Schematic of a two pole multiple feedback band-pass filter with a center frequency of 10 kHz and bandwidth of 1 kHz for a Q of 10. (A) shows the design for an ideal op-amp while (B) provides adjustments needed for practical op-amp performance (see text).

If the two filter sections are *cascaded* as shown, the result is the band-pass frequency response as shown in Figure 2. The *pole* for each section is shown by the small, red lines on the frequency axis to either side of 10 kHz. The extra gain is required because the individual filter sections work against each other away from their respective center frequencies. To create the passband of the filter the total response has to add up to 0 dB at the filter's overall center frequency of 10 kHz, which is between the two individual f_0 values. The result is that each filter has to have a gain of greater than 0 dB at its individual f_0.

All well and good, but it's kind of hard to buy an ideal op-amp. They are always out of them when I go to the store! Jim's software, though, allows you to specify the performance of the op-amp and compensates

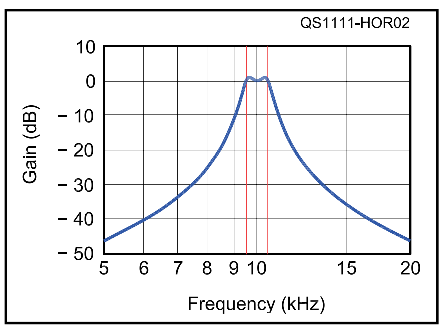

Figure 2 — Frequency response of the filter in Figure 1.

[1]Multiple-feedback band-pass filters are discussed in Hands-On Radio experiment #4. All previous experiments are available to ARRL members at **www.arrl.org/hands-on-radio**.
[2]Tonne Software, **www.tonnesoftware.com**.

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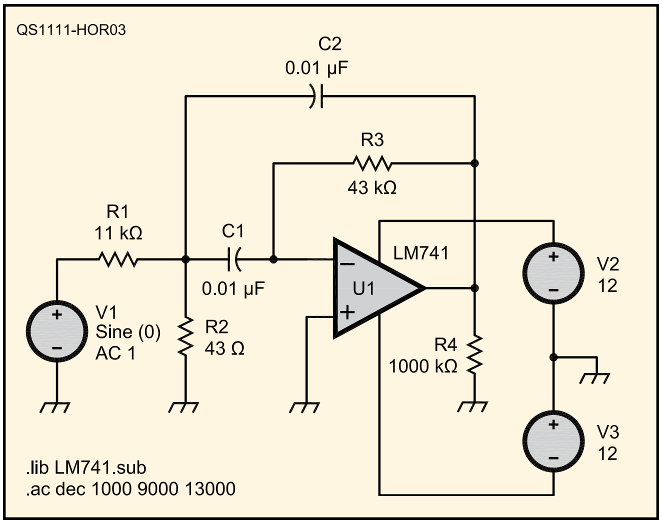

Figure 3 — *LTspice* schematic for Section 1 of the multiple-feedback band-pass filter.

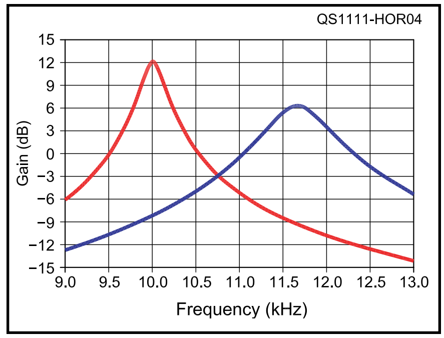

Figure 4 — Frequency response of the filter with an LM741 op-amp (red) and an LM318 op-amp (blue). The higher GBW of the LM318 results in performance that is closer to that of an ideal op-amp.

for its behavior. In this case, Jim used an op-amp with a dc gain of 100 dB (100,000 V/V), a GBW = 1 MHz and an input impedance of 1 MΩ. Figure 1B shows the result — the resistor values are a little smaller and the overall frequency response is the same.

Necessary Gain and Peaking

The non-ideal op-amp selected would seem to have plenty of gain at 10 kHz: 1 MHz / 10 kHz = 100. Each filter section has a gain of about 5.6 dB = 1.9 so we should be in good shape, right? Well, not really. From page 5.70 of the Analog Devices *Op-amp Applications* online book referenced last month: "A rule of thumb is that the open-loop gain of the op-amp should be at least 20 dB (×10) above the amplitude response at the resonant (or cutoff) frequency, including the peaking caused by the Q of the filter… A_0 = H Q, where H is the gain of the circuit."[3] (For a discussion of filter response peaking, see experiment #41.)

If each stage has a gain of 5.6 dB = 1.9 at f_0 and a Q of 18.24, then the op-amp must have a gain of 10 × (1.9 × 18.24) ≈ 348 at f_0. We're short of gain by a factor of about 3.5 to be able to ignore the effects of the op-amp's 1 MHz GBW. That's why the circuit values have to change a little bit.

Why does GBW make a difference at such a low frequency? What happens if the op-amp's GBW is too low? Quoting from page 5.106 of the *Op-amp Applications* book: "Without sufficient…gain, the op-amp virtual ground is no longer at ground. In other words, the op-amp is no longer behaving as an op-amp. Because of this, the [filter] no longer behaves like [a filter]." A virtual ground exists at the op-amp's inverting (–) input *only* if the op-amp's output signal causes all of the currents flowing into and out of those connections to balance. That allows the voltage at the inverting input to be the same as at the non-inverting (+) input, which is connected to ground. If the op-amp doesn't have enough "oomph" (gain and output drive capability) to keep those currents in balance, the inverting input is no longer at ground potential and that invalidates the assumptions on which the filter design equations are based. The circuit may provide some filtering function but it won't perform as designed.

Observing the Effects of GBW

You can simulate Section 1 of the circuit of Figure 1A to see the effects of GBW. Use the closest standard 5% series resistor values, such as 11 kΩ, 43 kΩ, 43 Ω, 10 kΩ, 39 kΩ and 39 Ω. This will shift the center frequency to nearly 12 kHz from the software's precision design. Retrieve the amplifier circuit you simulated for last month's experiment and add the necessary resistor and capacitors to make the multiple-feedback circuit as shown in Figure 3.

To change the values of the components, move the cursor over the symbol until it takes the shape of a hand, right click, then edit the value. (Use "u" for micro.) Start with the LM741 op-amp. You can change the op-amp library model by moving the cursor over the ".lib" library model identification line so that it becomes a text cursor, then right clicking and editing. Don't forget to change the op-amp part number as well, using the same process.

Because we want to see the frequency response of the circuit close to 10 kHz and not spread out from 1 kHz to 1 MHz, edit the simulation command line by right-clicking over the ".ac" line. I found that a span of 9 kHz to 13 kHz made it easy to see the effects of changing the op-amp. Figure 4 shows the result in red. (Click on the horizontal axis cursor to change the plot to linear and use 500 Hz tick marks. Click on the vertical axis cursor to turn off phase plotting.) Now change to the LM318 op-amp used for comparison last month and rerun the simulation. You'll get a response shown in blue in Figure 4 — quite a change!

First, the center frequency shifts from 10.1 kHz and a bandwidth of 300 Hz for the LM741 to 11.7 kHz and 800 Hz with the LM318. Gain also changes from 12 dB with the LM741 to 6 dB with the LM318. Because we're using standard values for the resistors, the design center frequency is now approximately 12 kHz, but the Q and gain values for the LM318 circuit are much closer to what is expected for an ideal op-amp.

You can see the effect even more clearly if you use one of the low cost high GBW op-amps available today, such as the LM7171 with a GBW of 200 MHz. (Download and use the model file as explained last month.) Another way to see big changes in performance is to increase the filter's center frequency. To change f_0 to 100 kHz, reduce the two capacitors by a factor of 100 kHz / 10 kHz = 10 for a value of 0.001 µF. The higher-speed op-amp is required to get anything close to expected performance.

The moral of this story is that sensitive circuits such as moderate- to high-Q filters can be very dependent on the performance of the components used to implement them. Although our junk boxes are full of op-amps with 1, 4 or 10 MHz GBW, they will probably give confusing results in circuits for which they are not suited, or if the tools we use to design the circuits make too many assumptions about their capabilities!

[3]**www.analog.com/library/analogDialogue/archives/39-05/op_amp_applications_handbook.html**