High-speed notch filters

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Low-Power Wireless Applications

Introduction

Active notch filters have been used in the past for applications like elimination of 50- and 60-Hz hum components. They have proven to be somewhat problematic from the standpoints of center frequency (f_0) tuning, stability, and repeatability. The advent of high-speed amplifiers opens the possibility of higher-speed notch filters—but are they actually producible? This article will show what is presently possible and what design trade-offs a designer will face with real-world components.

As a review, the reader should remember some characteristics of the notch filter:

- The depth of the notch obtainable in simulations like that shown in Figure 1 is *not* the depth that can be achieved with real-world components. The best that the designer can hope for is 40 to 50 dB.
- Instead of focusing on notch depth, the designer should focus on center frequency and Q. The Q for a given notch filter is the –3-dB point, *not* the notch depth or a point 3 dB above the notch depth, as shown in Figure 2.

Remember that the designer's objective is not a notch filter but the rejection of a specific interfering frequency. Any filter that does not reject that interfering frequency because it misses the frequency or has too little rejection at that frequency is not much use.

The best way to avoid missing the interfering frequency is to select the best values of R and C from the start. The RC Calculator under "Filter Design Utilities" in Reference 1 should be used to find the correct values of R_0 and C_0 for the circuits in the following discussion.

Topology

A number of notch-filter topologies were explored. Some design goals are a topology that:

- produces a notch (as opposed to band rejection);
- uses a single op amp;
- can be easily tuned with independent adjustments for center frequency and Q;
- can operate from a single-supply voltage; and
- can be adapted to fully differential op amps.

Unfortunately, it was not possible to achieve all of these, although some desirable circuits can be constructed that can meet some of these goals.

Figure 1. Simulated notch depth

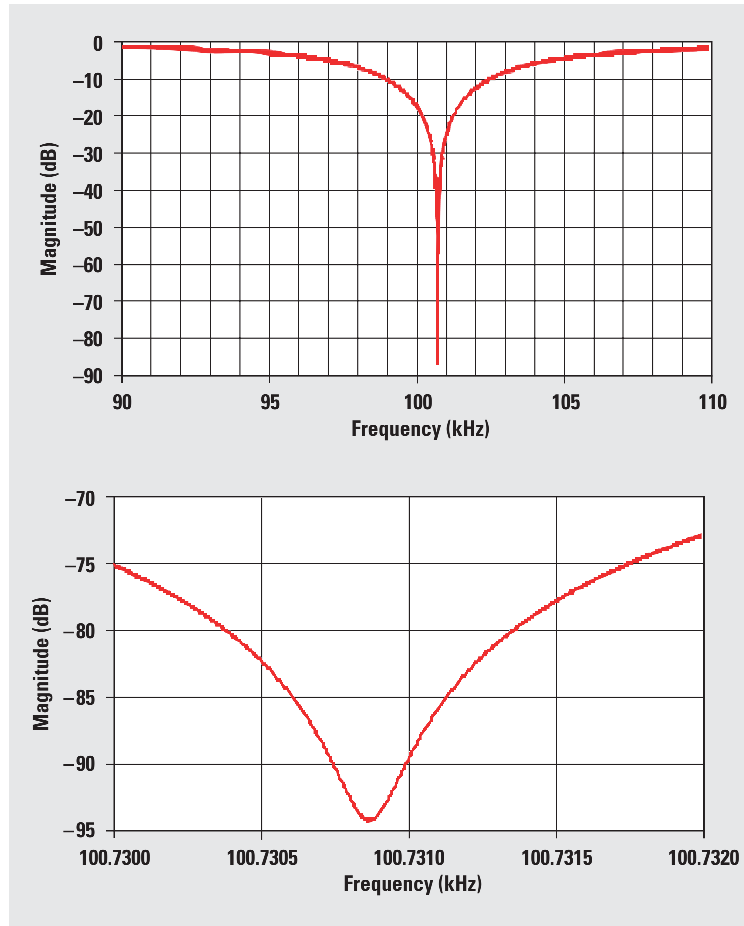
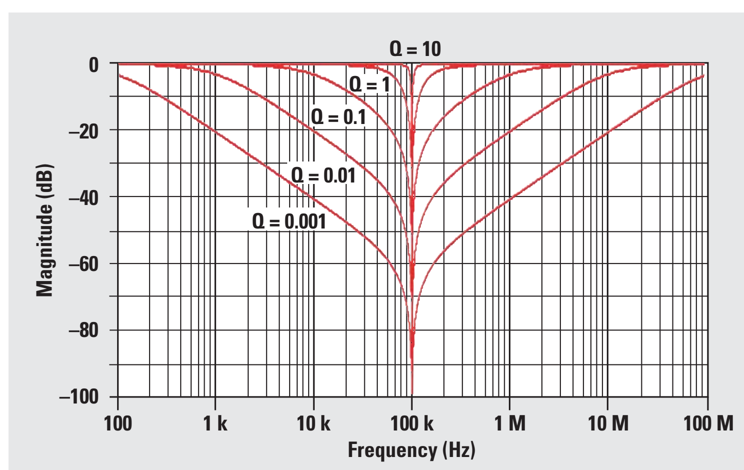


Figure 2. The Q of a notch filter



Twin-T notch filter

The twin-T topology of Figure 3 deserves an honorable mention here, because a notch filter can be implemented with a single op amp. It is not as flexible as one would hope, because the center frequency is not easily adjustable. Trimming the center frequency involves simultaneous adjustment of the three R_0 resistors. This is a concern because triple potentiometers are large, expensive, and may not track very well—especially the section that has to be one-half the value of the other two. Mismatches in the R_0 resistors will very quickly erode notch depth to less than 10 dB.

The circuit has some other disadvantages as well:

- It requires six high-precision components for tuning, and two of those are ratios of the others. If the designer wants to get away from ratios, eight precision components are required. $R_0/2$ = two R_0 in parallel, and $2 \times C_0$ = two C_0 in parallel.
- The twin-T topology is not easily adaptable to single-supply operation and cannot be used with a fully differential amplifier.
- The spread of resistor values becomes large due to the requirement of $R_Q << R_0$. The spread of the resistor values has a bearing on the depth of the notch and on center frequency.

Nevertheless, for applications where only a single op amp can be used, the twin-T topology is quite usable if the designer matches components or buys very high-precision components.

Fliege notch filter

The Fliege notch topology is shown in Figure 4. The advantages of this circuit over the twin-T are as follows:

- Only four precision components—two Rs and two Cs—are required for tuning the center frequency. One nice feature of this circuit is that slight mismatches of components are okay—the center frequency will be affected, but not the notch depth.
- The Q of the filter can be adjusted independently from the center frequency by using two noncritical resistors of the same value.

Figure 3. Twin-T notch filter

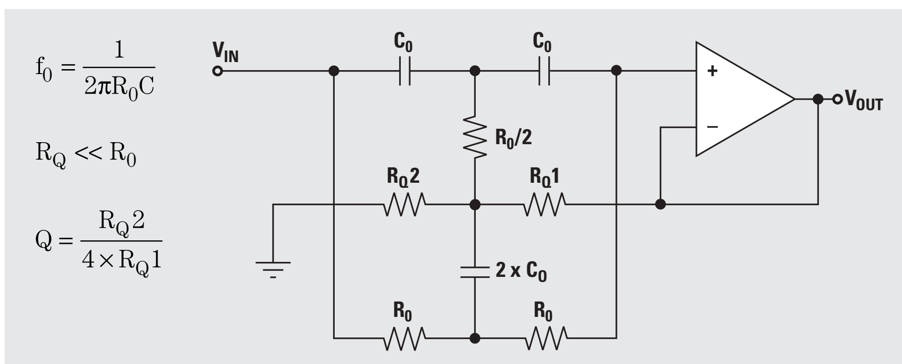


Figure 4. Fliege notch filter

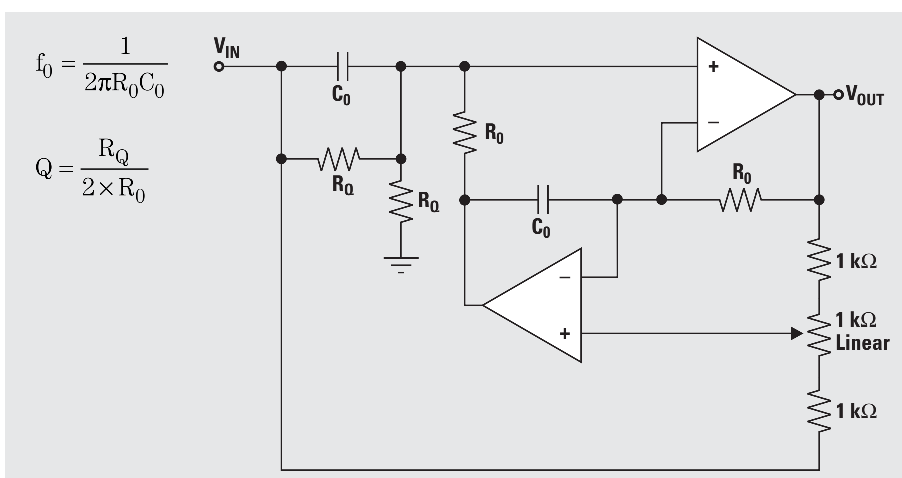


Table 1. Component values for the Fliege notch filter

Q	1 MHz			100 kHz			10 kHz		
	R_0 (kΩ)	C_0 (pF)	R_Q (kΩ)	R_0 (kΩ)	C_0 (nF)	R_Q (kΩ)	R_0 (kΩ)	C_0 (nF)	R_Q (kΩ)
100	1.58	100	316	1.58	1	316	1.58	10	316
10	1.58	100	31.6	1.58	1	31.6	15.8	1	316
1	1.58	100	3.16	1.58	1	3.16	15.8	1	31.6

- The center frequency of the filter can be adjusted over a narrow range without seriously eroding the depth of the notch.

Unfortunately, this circuit uses two op amps instead of one, and it cannot be implemented with a fully differential amplifier.

Simulations

Simulations were first performed with ideal op amp models. Real op amp models were later used, which produced results similar to those observed in the lab. Table 1 shows the component values that were used for the schematic in Figure 4. There was no point in performing simulations at or above 10 MHz because lab tests were actually done first, and 1 MHz was the top frequency at which a notch filter worked.

A word about capacitors: Although the capacitance is just a value for simulations, actual capacitors are constructed of different dielectric materials. For 10 kHz, resistor value spread constrained the capacitor to a value of 10 nF. While this worked perfectly well in simulation, it forced a change from an NPO dielectric to an X7R dielectric in the lab—with the result that the notch filter completely lost its characteristic. Measurements of the 10-nF capacitors used were close in value, so the loss of notch response was most likely due to poor dielectric. The circuit had to revert to the values for a Q of 10, and a 3-MΩ R_Q was used. For real-world circuits, it is best to stay with NPO capacitors.

The component values in Table 1 were used both in simulations and in lab testing. Initially, the simulations were done without the 1-kΩ potentiometer (the two 1-kΩ fixed resistors were connected directly together and to the non-inverting input of the bottom op amp). Simulation results are shown in Figure 5.

There are actually nine sets of results in Figure 5, but the curves for each Q value overlie those at the other frequencies. The center frequency in each case is slightly above a design goal of 10 kHz, 100 kHz, or 1 MHz. This is as close as a designer can get with a standard E96 resistor and E12 capacitor. Consider the case of 100 kHz:

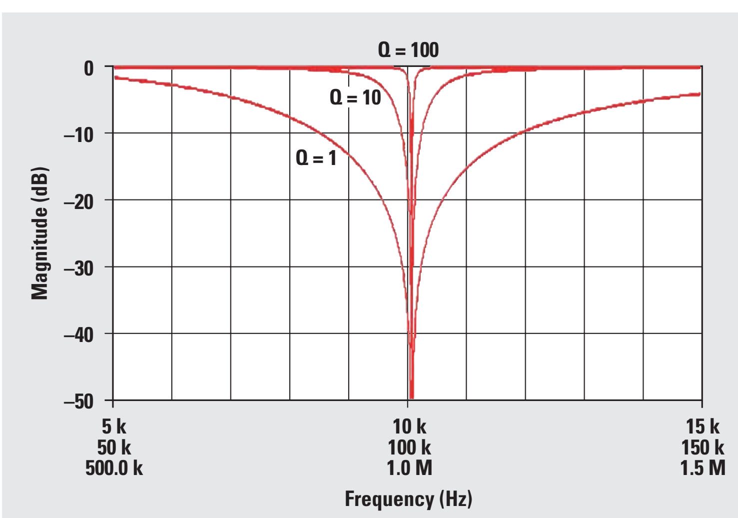
$$f_0 = \frac{1}{2\pi R_0 C_0} = \frac{1}{2\pi \times 1.58\ \text{k}\Omega \times 1\ \text{nF}} = 100.731\ \text{kHz}$$

A closer combination exists if E24 sequence capacitors are available:

$$f_0 = \frac{1}{2\pi R_0 C_0} = \frac{1}{2\pi \times 4.42\ \text{k}\Omega \times 360\ \text{pF}} = 100.022\ \text{kHz}$$

The inclusion of E24 sequence capacitors can lead to more accurate center frequencies in many cases, but procuring the E24 sequence values is considered an expensive (and

Figure 5. Simulation results before tuning



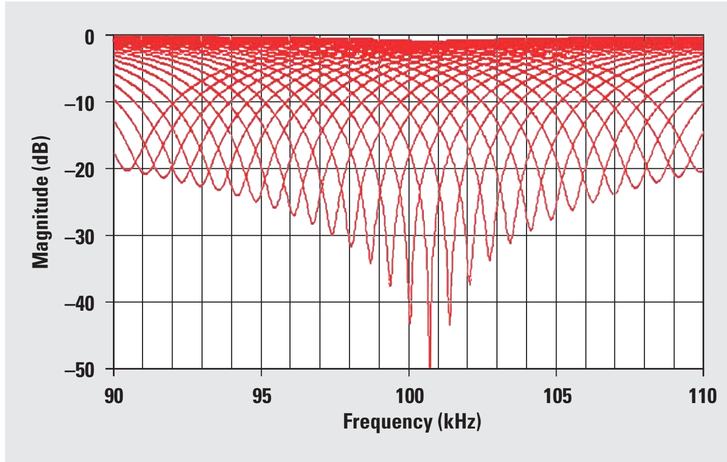
unwarranted) expenditure in many labs. While it may be easy to specify E24 capacitor values in theory, in practice many of them are seldom used and have long lead times associated with them.

There are easier alternatives to selecting E24 capacitor values. Close examination of Figure 5 shows that the notch misses the center frequency by only a small amount. At lower Q values, there is still substantial rejection of the desired frequency. If the rejection is not sufficient, then it becomes necessary to tune the notch filter.

Again considering the case of 100 kHz, we see that the response near 100 kHz is spread out in Figure 6. The family of curves to the left and right of the center frequency (100.731 kHz) represents filter response when the 1-kΩ potentiometer is inserted and adjusted in 1% increments. When the potentiometer is exactly in the middle, the notch filter rejects frequencies at the exact center frequency. The depth of the simulated notch is actually on the order of 95 dB, but that is not going to happen in the real world. A 1% adjustment of the potentiometer puts a notch that is greater than 40 dB right on the desired frequency. Again, this is best-case with ideal components, but lab results are close at low frequencies (10 and 100 kHz).

Figure 6 shows that it is important to get close to the correct frequency with R_0 and C_0 from the start. While the potentiometer can correct for frequency over a broad range, the depth of the notch degrades. Over a small range (±1%), it is possible to get a 100:1 rejection of the undesirable frequency; but over a larger range (±10%), only a 10:1 rejection is possible.

Figure 6. Tuning for center frequency



Lab results

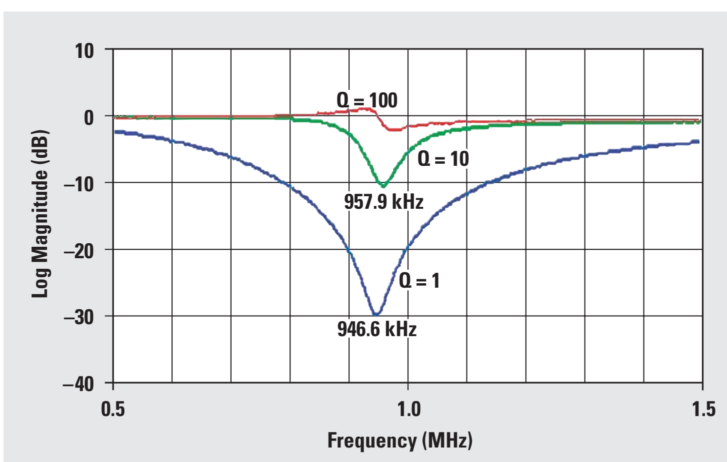
A THS4032 evaluation board was used to construct the circuit in Figure 4. Its general-purpose layout required only three jumpers and one trace cut to complete the circuit. The component values in Table 1 were used, starting with those that would produce 1 MHz. The intention was to look for bandwidth/slew-rate restrictions at 1 MHz and test at lower or higher frequencies as necessary.

Results at 1 MHz

Figure 7 shows that there are some very definite bandwidth and/or slew-rate effects at 1 MHz. The response curve at a Q of 100 shows barely a ripple where the notch should be. At a Q of 10, there is only a 10-dB notch, and a 30-dB notch at a Q of 1. Apparently notch filters cannot achieve as high a frequency as one would hope, but the THS4032 is only a 100-MHz device. It is reasonable to expect better performance from parts with a greater unity-gain bandwidth. Unity-gain stability is important, because the Fliege topology has fixed unity gain.

If the designer wishes to estimate what bandwidth is required for a notch at a given frequency, a good place to

Figure 7. Lab results at 1 MHz



start is the gain/bandwidth product given in the datasheet, which should be 100 times the center frequency of the notch. Additional bandwidth will be required for higher Q values. There is a slight frequency shift of the notch center as Q is changed. This is similar to the frequency shift seen for bandpass filters. The frequency shift is less for notch filters centered at 100 kHz and 10 kHz, as shown in Figure 8 and later in Figure 10.

Results at 100 kHz

Component values from Table 1 were then used to create 100-kHz notch filters with different Qs. The results are shown in Figure 8. It is immediately obvious that viable notch filters can be constructed with a center frequency of 100 kHz, although the notch depth appears to be less at higher values of Q.

Remember, though, that the design goal here is a 100-kHz—not a 97-kHz—notch. The component values selected were the same as for the simulation, so the notch center frequency should theoretically be at 100.731 kHz; but the difference is explained by the parts used in the lab. The mean value of the 1000-pF capacitor stock was 1030 pF, and of the 1.58-kΩ resistor stock was 1.583 kΩ. When the center frequency is calculated with these values, it comes out to 97.14 kHz. The actual components, however, could not be measured (the board was too fragile).

As long as the capacitors are matched, it would be possible to go up a couple of standard E96 resistor values to get closer to 100 kHz. Of course, this is probably not an option in high-volume manufacturing, where 10% capacitors could come from any batch and potentially from different manufacturers. The range of center frequencies will be determined by the tolerances of R_0 and C_0, which is not good news if a high Q notch is required. There are three ways of handling this:

- Purchase higher-precision resistors and capacitors;
- lower the Q requirement and live with less rejection of the unwanted frequency; or
- tune the circuit (which was explored next).

At this point, the circuit was modified to have a Q of 10, and a 1-kΩ potentiometer was added for tuning the center frequency (as shown in Figure 4). In real-world design, the potentiometer value selected should slightly more than cover the range of center frequencies possible with worst-case R_0 and C_0 tolerances. That was not done here, as this was an exercise in determining possibilities, and 1 kΩ was the lowest potentiometer value available in the lab.

Figure 8. Lab results at 100 kHz

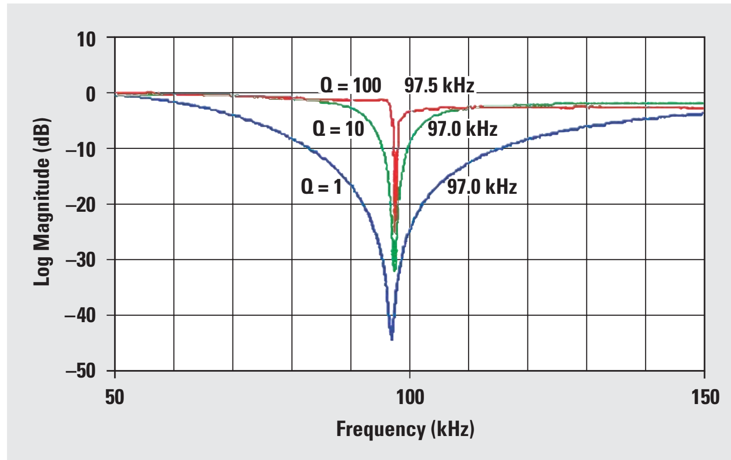
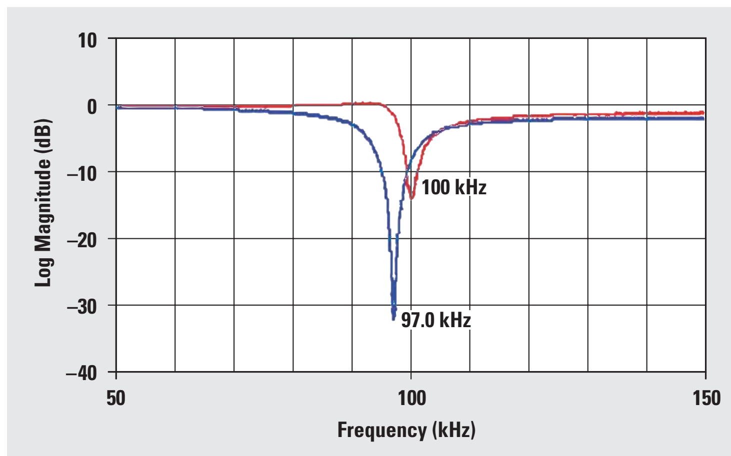


Figure 9. Tuning for exact center frequency



When the circuit was tuned for a center frequency of 100 kHz as shown in Figure 9, the notch depth degraded from 32 dB to 14 dB. Remember that this notch depth could be greatly improved by making the initial f_0 closer to ideal. The potentiometer is meant to tune over only a small range of center frequencies. Still, a 5:1 rejection of an unwanted frequency is respectable and may be sufficient for some applications. More critical applications will obviously need higher-precision components.

Op amp bandwidth limitations, which will also degrade the tuned notch depth, may also be keeping the notch depth from being as low as possible. With this in mind, the circuit was retuned for a center frequency of 10 kHz.

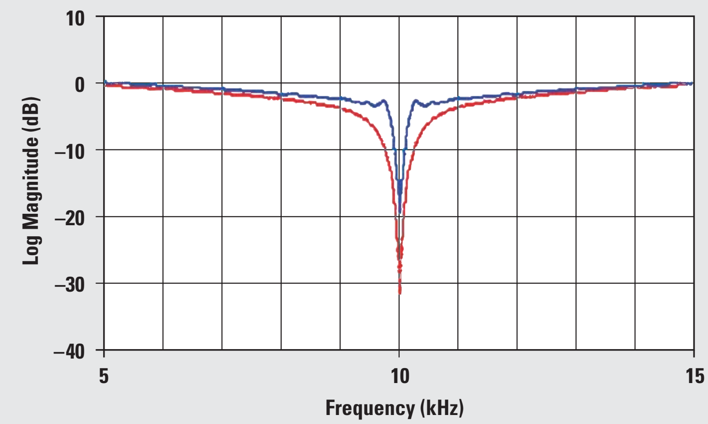
Results at 10 kHz

Figure 10 shows that the notch depth for a Q of 10 has increased to 32 dB, which is about what one would expect from a center frequency 4% off from the simulation (Figure 6). The op amp was indeed limiting the notch depth at a center frequency of 100 kHz! A 32-dB notch is a rejection of 40:1, which is quite good.

So even with components that produced an initial 4% error, it was possible to produce a 32-dB notch at the desired center frequency. The bad news is that to escape op amp bandwidth limitations, the highest notch frequency possible with a 100-MHz op amp is somewhere between 10 and 100 kHz. In the case of notch filters, "high-speed" is therefore defined as being somewhere in the tens or hundreds of kilohertz.

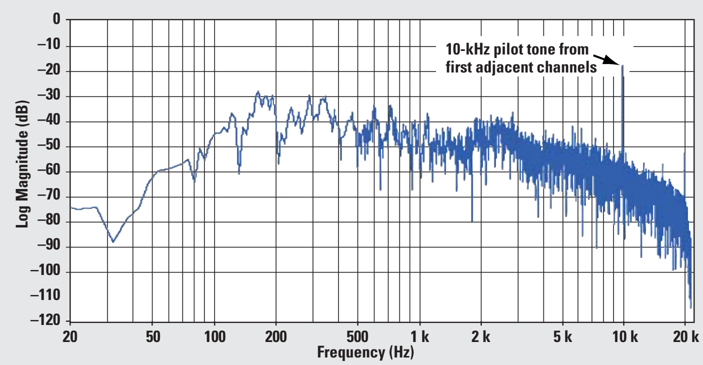
A good application for 10-kHz notch filters is AM (medium-wave) receivers, where the carrier from adjacent stations produces a loud 10-kHz whine in the audio, particularly at night. This can really grate on one's nerves when listening is prolonged. Figure 11 shows the received audio spectrum of a station before and after the 10-kHz notch was applied. Note that the 10-kHz whine is the loudest portion of the received audio (Figure 11a), although the human ear is less sensitive to it. This audio spectrum was taken at night on a local station that had two strong stations on either side. FCC regulations allow for some variation of the station carriers. Therefore, slight errors in carrier frequency of the two adjacent stations will make the 10-kHz tones heterodyne, increasing the unpleasant listening sensation. When the notch filter is applied (Figure 11b), the 10-kHz tone is reduced to the same level as that of the surrounding modulation. Also visible on the audio spectrum are 20-kHz carriers from stations two channels away and a 16-kHz tone from a transatlantic station. These are not a problem, because they are attenuated substantially by the receiver IF. A frequency of 20 kHz is inaudible to the vast majority of people in any event.

Figure 10. Lab results at 10 kHz*

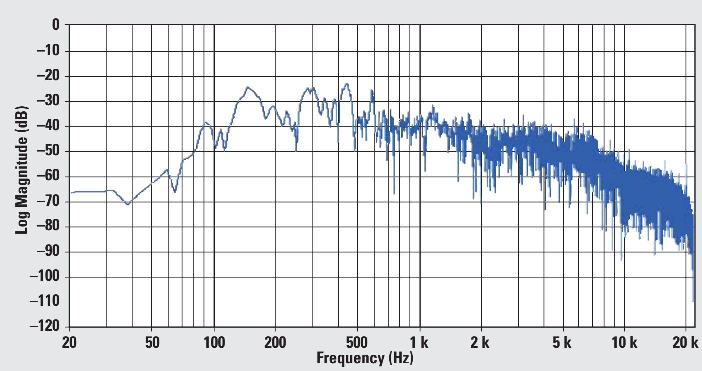


*Some artistic liberties were taken with this plot. The laboratory instrument displays values only down to 10 kHz, so the left-hand portion of the plot is a mirror image of the right-hand portion. The laboratory instrument also has some roll-off at frequencies below 100 kHz, which was artistically eliminated from this plot.

Figure 11. AM reception with and without notch filter



(a) Without notch filter

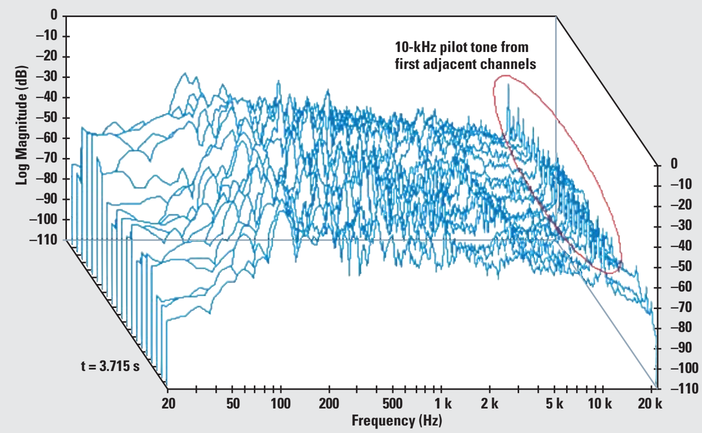


(b) With notch filter

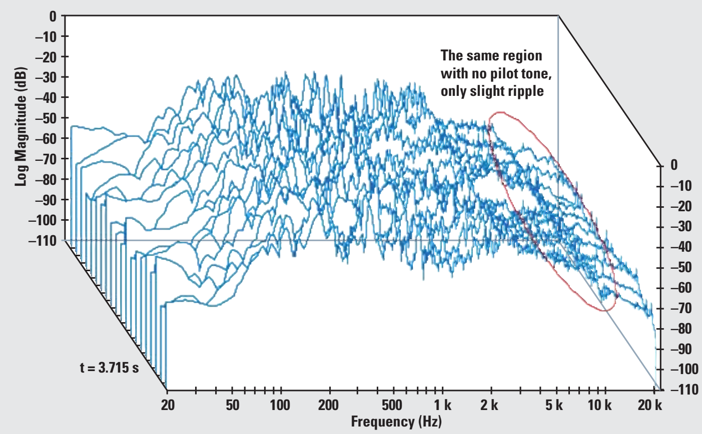
Figure 12 shows the same spectrum on a waterfall diagram. In this case, the sample window is widened, and the 10-kHz carrier interference is shown as a string of peaks that vary in amplitude. When the notch is applied, the 10-kHz peaks are eliminated, and there is only a slight ripple in the received audio where 10 kHz has been notched out.

For European readers who want to have a more pleasing medium-wave listening experience, the component values are C_0 = 330 pF, R_0 = 53.6 kΩ, and R_Q = 1 MΩ. Shortwave listeners will benefit from a two-stage notch filter, one stage being the 10-kHz previously described, and the other stage being a 5-kHz notch filter with component values of C_0 = 270 pF, R_0 = 118 kΩ, and R_Q = 2 MΩ.

Figure 12. Heterodyning and notch filter effects



(a) Heterodyning effect



(b) Notch filter effect

Applicability

Although testing described in this article was performed on the THS4032, the application circuits are usable with all single-ended, unity-gain, voltage-feedback op amps. A key specification is unity-gain bandwidth, which should be from 100 to 1000 times the center frequency. The Fliege notch filter cannot be constructed from current-feedback amplifiers or from fully differential op amps.

Conclusion

High-speed op amps have been used to produce low-pass and high-pass filters up to the tens of megahertz with fairly good success. Narrow band-pass filters and notch filters are much less understood and much more critical applications. While the tolerance of a capacitor might change the cutoff frequency of a low-pass filter or produce ripple in the passband, that same tolerance can produce dramatic changes in the center frequency and notch depth of a notch filter.

With a Fliege notch topology, the number of critical components is reduced to four—two identical Rs and two identical Cs. Fortunately for the designer, there is an inherent matching that occurs when devices are manufactured at the same time, so it is possible to construct notch filters from them even if the tolerance given in the datasheet does not imply matching. There is good, independent control over the center frequency and Q, with the possibility of tuning over a narrow range, which compensates for the initial tolerance errors.

A 1-MHz, Q = 1 notch filter constructed with a 100-MHz op amp showed poor performance at higher values of Q. The same op amp did better at 100 kHz but still showed degradation at higher Q values, particularly when the center frequency was tuned. It was not until the center frequency was decreased to 10 kHz that performance close to simulation results was obtained. Limiting the notch filter to high tens to low hundreds of kilohertz (for faster parts) eliminates many applications. These frequencies, however, represent the state of the art in design for these unusual filters.

Reference

1. "Amplifiers and Linear Engineering Design Utilities," www.ti.com/amplifier_utilities

Related Web sites

amplifier.ti.com
www.ti.com/sc/device/THS4032

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