Experiment #4—Active Filters

Amplifiers are great, but where op-amps really prove their worth is in more advanced circuits that are difficult to execute with discrete transistors. A ham’s radio shack is full of filters, many of which are based on the op-amp. This month, we’ll take a look at two of the simplest filters and one that’s a little more complex.

Terms to Learn

- **Cutoff Frequency**—The frequency, \( f_c \), at which the filter output voltage falls to \( 1/\sqrt{2} \) or 70.7% of its peak output. At this frequency, the power of the output signal has been cut in half.
- **Low, High and Band-Pass Filters**—Low-pass filters attenuate signals with frequencies above the cutoff frequency. High-pass filters do the opposite (attenuate below cutoff). Band-pass filters pass a range of signal frequencies, but attenuate signals outside that range, called the passband.
- **Q**—The ratio of a filter’s center frequency to the bandwidth of its passband. Higher-Q means a narrower passband for a given center frequency.
- **Roll-off**—The gradual reduction in signal amplitude beyond a filter’s cutoff frequency.

The Low-Pass Filter

The amplifier circuits we built last month can amplify signals all the way from dc to the limits of the op-amp, more than 1 MHz. But what if we don’t want to amplify all those frequencies—perhaps just those in the communication audio range below 3 kHz? That requires an amplifier whose gain changes with frequency, or a low-pass filter.

We’ll start with the unity-gain amplifier (refer to Figure 3 in last month’s column). Remember that the op-amp output must balance the input current \( (V_{in}/R_i) \) with an equal current through the feedback component, \( R_f \). What if \( R_f \) was replaced with components whose impedance changed with frequency? Then the op-amp’s output voltage would also have to change with frequency to keep the currents balanced.

That’s just what is happening in Figure 1, where capacitor \( C_f \) has been placed across \( R_f \). The reactance of \( C_f \) \( (X = 1/2\pi f_c) \) gets smaller with frequency. That means the impedance of the feedback path between the op-amp’s inverting terminal and output also gets smaller with frequency. The lower impedance means that less output voltage is required to balance the input current and the circuit’s output will decrease for high-frequency signals. This is a low-pass filter.

We only want to amplify communications audio, so the cutoff frequency, \( f_c \), should be about 3 kHz. In this circuit, \( f_c \) is reached when the impedance in the feedback path (the parallel combination of \( R_f \) and \( C_f \)) is one-half of the input resistance, \( R_i \). This occurs when the reactance of \( C_f \) equals \( R_f \). The design equations for our low-pass filter are:

\[
C_f = \frac{1}{2\pi f_c R_f} \quad \text{and} \quad f_c = \frac{1}{2\pi C_f R_f}
\]

Let’s try it!

Testing the Low-Pass Filter

- Design the amplifier to have a passband gain of 1, so \( R_f = R_{in} \). Use a value of 10 kΩ. For an \( f_c \) of 3 kHz, \( C_f = \frac{1}{2\pi (3 \text{ kHz})(10 \text{ k}\Omega)} = 5.3 \text{ nF} \). Use the closest standard value of 5.6 nF, which will result in an \( f_c \) of 2.8 kHz. (Don’t forget the power supply bypass capacitors when building the circuit.)
- Confirm that the filter has unity-gain at dc by using a 1 kΩ potentiometer to apply a variable dc voltage as in the previous experiment. Use a ±12 V power supply across the potentiometer.
- Use the function generator to apply a 1 V p-p sine wave at 10 Hz to the filter input. If you are using a DMM to measure signal voltage, this is 0.35 V RMS. Measure the input and output voltage at 10, 20, 50, 100, 200, 500, 1000, 2000 and 5000 Hz.
- Find \( f_c \) by varying the signal frequency until output voltage is 0.7 V p-p (or 0.25 V RMS). It’s unlikely that \( f_c \) will be exactly 2.8 kHz because the actual values of \( R_f \) and \( C_f \) are somewhat different than their labeled values.
- Change the filter’s passband gain to 2.2 by increasing \( R_f \) to 22 kΩ. Measure the output voltage from 1000 to 5000 Hz. What happened to \( f_c \)? As \( R_f \) increases, the frequency at which the reactance of \( C_f \) balances \( R_f \) decreases. To restore \( f_c \), \( C_f \) will have to be decreased by the same amount as \( R_f \) increased— to 5.6 nF / 2.2 = 2.5 nF. Replace \( C_f \) with the closest standard value of 2.7 nF and see if \( f_c \) is back where it belongs.

High-Pass Filters

You can also make gain “roll off” at low frequencies with components that cause the balancing function of the op-amp to reduce its output voltage below the cutoff frequency as shown in Figure 2. As frequency decreases, the reactance of \( C_i \) increases, reducing input current. Balancing current thus takes less output voltage and the filter’s output will decrease along with input frequency. Following similar reasoning, the design equations for the high-pass filter are:

\[
C_i = \frac{1}{2\pi f_c R_i} \quad \text{and} \quad f_c = \frac{1}{2\pi C_i R_i}
\]

Gain in the passband is still the same, \(-R_f / R_i\),

Creating a Band-Pass Filter

Continuing with the communications audio theme, it’s usually desired to attenuate frequencies below...
Listening to Your Filters

All this measuring is fine, but it’s more fun to actually use your circuits for a practical purpose. Figure 5 shows how to route your rig’s received audio through the filter circuit so that you can hear the effect of the filter using headphones from a portable music player. Set your rig to use its widest filter (usually “AM”) and then listen to the filter output. The op-amp can’t drive a very big load, so keep the audio output level low to avoid distortion.

Suggested Reading

The 2003 ARRL Handbook, pp 16.1-16.2, 16.28-16.29; Horowitz and Hill, The Art of Electronics, chapter 5, sections 5.01-5.05. One of the best books for hobbyists on active filters is Don Lancaster’s Active Filter Cookbook.

The ARRL Web site for this series is www.arrl.org/tis/info/html/hands-on-radio/.

Shopping List

• 741 op-amp
• ¼-W resistors of the following values: 2.2 kΩ (2 ea), 10 kΩ, 22 kΩ, 47 kΩ
• 1 kΩ potentiometer (single or multi-turn)
• 56 nF, 33 nF (2 ea), 5.6 nF, and 2.7 nF film or ceramic capacitors (1 nF = 1000 pF = 0.001 µF)
• 2—10 µF capacitors with a voltage rating of 25 V dc or higher

Errata

Experiment #2 mistakenly equated 1 Vpp with 0.7 Vrms. It should be 0.35 Vrms: Vrms = 1/(2√2) Vpp = Vpp/2√2.

Next Month

Next month, we’ll take a look at the popular “555” timer and use it as an oscillator, a pulse generator and maybe even as a timer!