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.

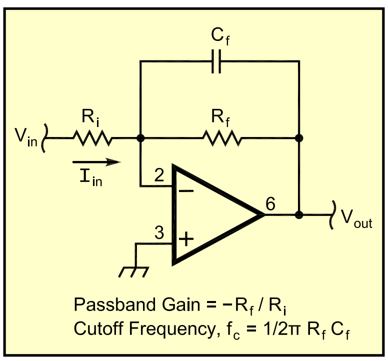

Figure 1—A low-pass filter.

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:

$$C_f = {}^1/_{2\pi f_c R_f} \text{ and } f_c = {}^1/_{2\pi C_f R_f} \qquad [1]$$

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, $C_f = {}^1/_{2\pi}$ (3 kHz)(10 kΩ) = 5.3 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_c 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 Ci 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:

$$C_i = {}^1/_{2\pi f_c R_i} \text{ and}$$
$$f_c = {}^1/_{2\pi C_i R_i} \qquad [2]$$

Gain in the passband is still the same, $-R_f/R_i$.

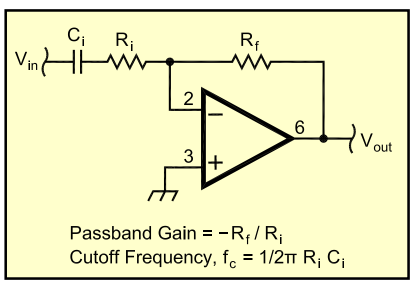

Figure 2—A high-pass filter.

Creating a Band-Pass Filter

Continuing with the communications audio theme, it's usually desired to attenuate frequencies below

H. Ward Silver, NØAX ♦ 22916 107th Ave SW, Vashon, WA 98070 ♦ n0ax@arrl.org

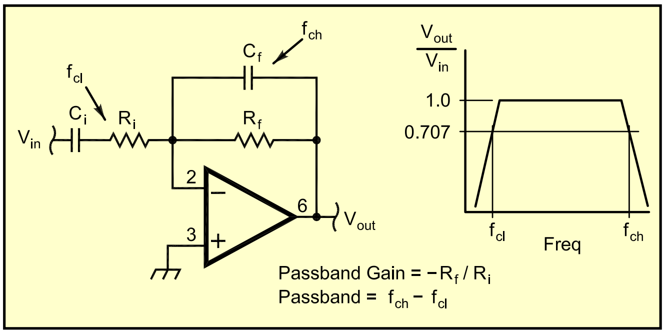

Figure 3—A band-pass filter.

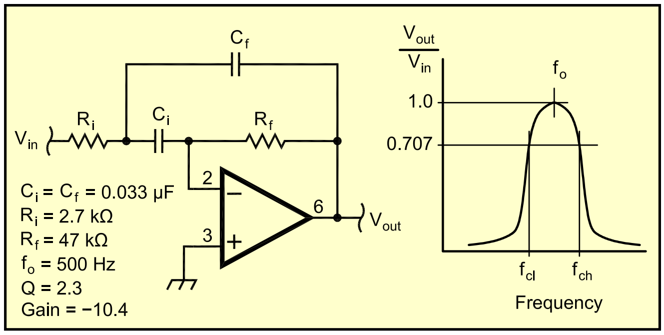

Figure 4—A multiple-feedback band-pass filter.

300 Hz. We can combine high-pass and low-pass functions as in Figure 3. This circuit has a cutoff frequency, f_{cl} and f_{ch}, at each end of the passband. We already have f_{ch} from our low-pass filter. For an f_{cl} of 300 Hz:

$C_I = {}^1/_{2\pi}(300\ \text{Hz})(10\ \text{k}\Omega) = 53\ \text{nF}$

We'll use the closest standard value of 56 nF. Let's build it!

Testing Band-Pass Filter #1

- Restore the low-pass filter circuit to its original configuration with two 10 kΩ resistors. Add the 56 nF capacitor in series with R_{in}.
- Measure input and output voltage between 10 and 5000 Hz. Determine the lower cutoff frequency as before.

A Better Band-Pass Filter

More advanced designs have a much steeper rolloff above and below the cutoff frequencies. The passband can be narrowed, amplification can be combined with filtering functions. There are a number of filter types that achieve these goals.

Band-pass filters have two additional parameters that define how the filter affects the input signals. The first is the filter's frequency of peak response, also called the "center frequency," and abbreviated f_o. The second is a measure, called "Q" of the filter's passband relative to f_o. (The symbol Q is also used in other related measurements, but it only refers to the shape of the filter passband here.)

$$Q = f_o / (f_{ch} - f_{cl}) \quad [3]$$

Higher values of Q mean that the filter's response is getting narrower or sharper. The quantity $f_{ch} - f_{cl}$ is the filter's bandwidth.

Figure 4 shows a "multiple feedback" band-pass filter, so-called because there are two feedback paths from the output through R_f and C_f. Although there are many methods of designing this circuit, we'll use the "Equal-C" method in which both C_i and C_f are given equal values. After f_o and Q are chosen, the resistor values are then calculated. The filter's gain is equal to $-2Q^2$. The circuit values shown set f_o to 500 Hz, Q to 2.3, and gain to −10.4.

Testing Band-Pass Filter #2

- Build the circuit and find f_o, f_{ch} and f_{cl} by measuring the input and output voltage of sine waves at frequencies from 50 to 5000 Hz. Calculate the filter's peak gain (V_{out}/V_{in}), bandwidth ($f_{ch} - f_{cl}$) and Q.
- Most filter responses are measured in decibels, or dB. Gain in dB = 20 log (V_{out}/V_{in}). Recalculate gain in dB. Gain at the upper and lower cutoff frequencies should be close to 3 dB below the gain of the filter at f_o.
- To change f_o, increase or decrease both capacitors, keeping their values the same. To increase f_o, decrease capacitance, and vice versa. f_o is directly proportional to the value of the capacitors.

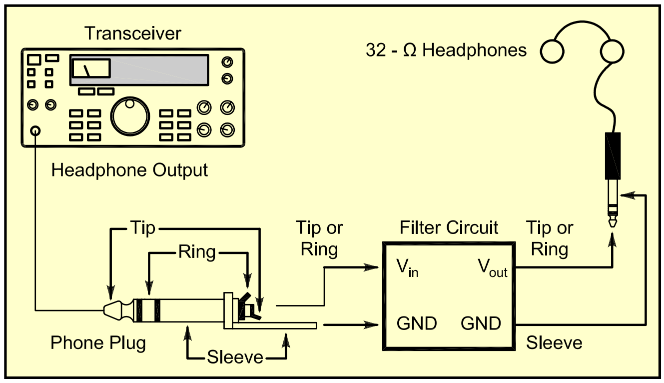

Figure 5—Listening to your filter circuit.

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, 10 kΩ (2 ea), 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 $V_{p\text{-}p}$ with 0.7 V_{RMS}. It should be 0.35 V_{RMS}. $V_{RMS} = 1/(2\sqrt{2})\ V_{p\text{-}p} = V_{p\text{-}p}/2\sqrt{2}$.

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!