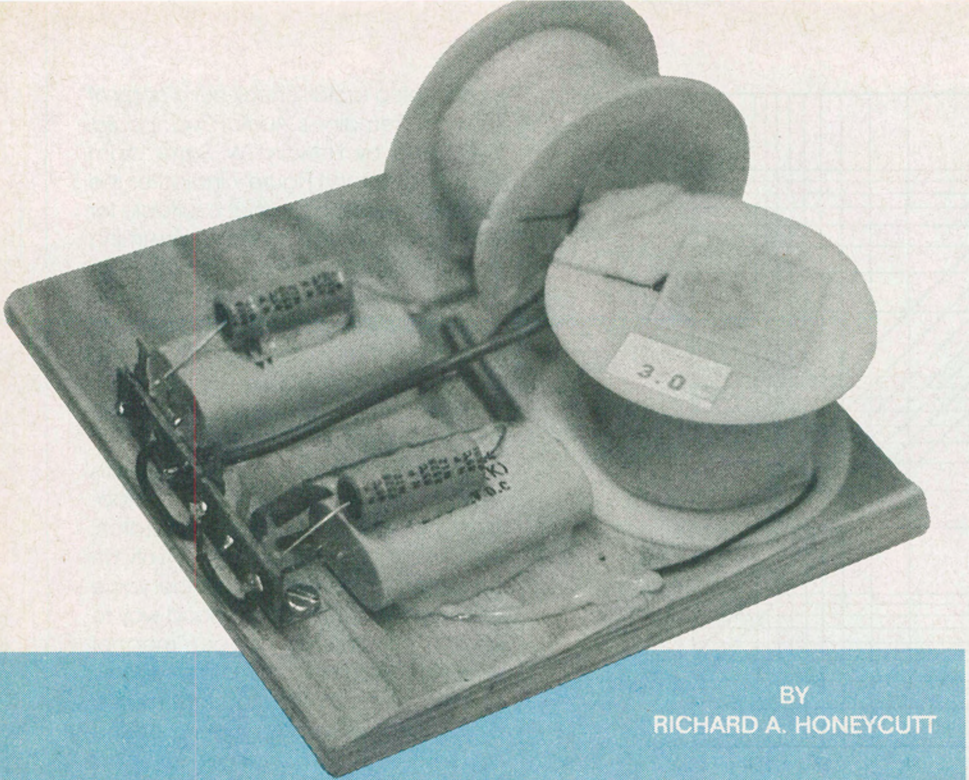

BY
RICHARD A. HONEYCUTT

Own Speakers

$$C = \frac{1}{2\pi f Z_T}$$

You can use this equation to find the size capacitor you need, or you can use the graph shown in Fig. 2.

There is a "gotcha", though, even in this simple design, and we may as well deal with it now. Speaker impedance is not constant with frequency. Therefore, your "8-ohm" speaker may have an impedance of 10 or 12 ohms or more at the crossover frequency. Thus you must determine the speaker's impedance at that frequency.

Fortunately, there's an easy way to measure the speaker's impedance. All you need is a signal generator, a voltmeter, and an ammeter. If you don't have an ammeter you can use a 1k resistor and a voltmeter instead.

The test setup with the ammeter is shown in Fig. 3A. After wiring up the circuit, you adjust the audio generator to produce the desired crossover frequency, and read the voltage and current from the meters. The impedance will be the voltage divided by the current.

The setup without the ammeter is shown in Fig. 3B. You adjust the audio generator as before and read the voltages as shown. To determine the impedance divide the value of the voltage across the speaker (V_s) by the resistor voltage (V_r) and multiply by 1000.

We are not quite through yet: When you go looking for capacitors at your local electronic emporium, you'll find that you need to know more than just the value. There's a voltage rating to be reckoned with, too. The rating you choose will determine the maximum power that your system can handle. The voltage can be calculated by using:

$$V = \sqrt{2PZ}$$

where P is the maximum power your amplifier can produce, and Z is the highest speaker impedance into which the amplifier can produce full power (usually 8 ohms for home stereos and 4 ohms for car units). Alternatively, you can read the voltage from Fig. 4. I always buy at least 100-WVDC capacitors, allowing a theoretical maximum of a 600-watt amplifier. That provides a comfortable safety margin.

Another choice you'll have is the type of capacitor. The cheapest way to go is to use a non-polar electrolytic. Standard electrolytics, including Tantalums, require a DC polarizing voltage, but a non-polar electrolytic has two standard units inside, connected "back-to-back" (*i.e.* the two positive leads connected together).

Many smaller stores have only polarized units, especially in values above about 2 µF, but you can make a non-polar capacitor by wiring two polarized capacitors back to back as mentioned. Each capacitor must have twice the capacitance that you want the non-polar unit to have.

While electrolytic capacitors can be used in crossovers, they do have a tendency to soak up some of the speaker's power at high frequencies, so that you don't get maximum performance from the tweeter. The technical name for that fault is "dielectric absorption."

Polyester film capacitors, or better yet, polypropylene film units, have almost no dielectric absorption in the audio range. The difference between electrolytics and film capacitors is audible, unless you've sacrificed your hearing to too much loud stuff.

They are available in values up to about 12 µF, and they can be wired in parallel to obtain larger values. (Capacitor values add when capacitors are wired parallel to one another.) In fact, if the values you need are over 6 µF, it's often cheaper to buy smaller capacitors and parallel them than to buy a single large unit.

Adding a Low-Pass Filter. If you choose to add a low-pass filter for the woofer, it can be just a simple coil (or inductor). A coil's reactance is proportional to the frequency it handles:

$$X_L = 2\pi f L$$

where L is the inductance in henrys. Putting a coil in series with the woofer causes the woofer to get progressively less power as the frequency is increased. The correct coil inductance can be found by using:

$$L = \frac{Z_W}{2\pi f}$$

where Z_W is the woofer impedance at the crossover frequency. Alternatively, you can use the chart in Fig. 5. The circuit with the coil added is shown in Fig. 6.

Coils can be bought at many electronics stores and from mail-order houses. Again, you have some choices

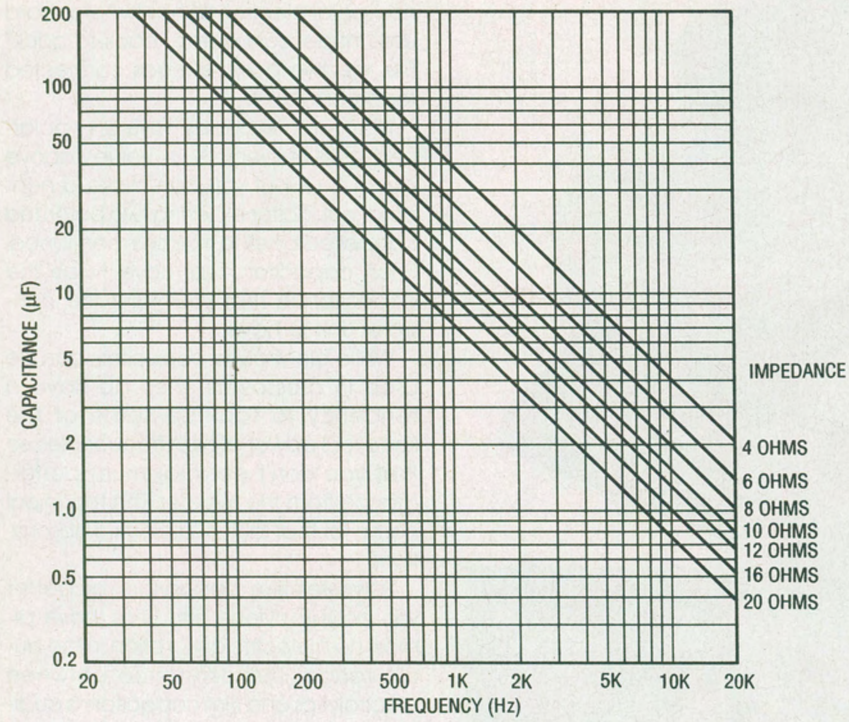

Fig. 2. Select capacitor values for two-way speaker systems from this easy-to-use graph.

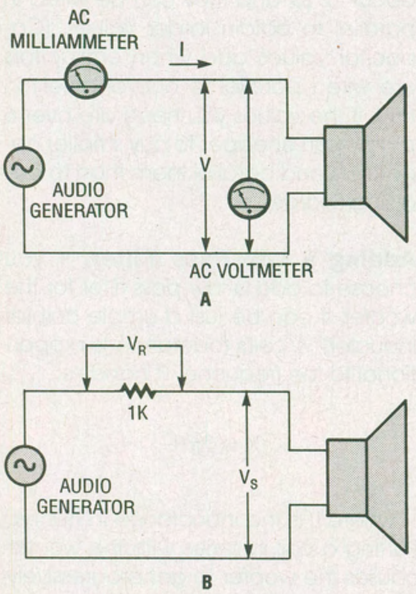

Fig. 3. Measuring speaker impedance is easy. You only need a signal generator, a voltmeter, and an ammeter (A). If you don't have an ammeter, you can use a resistor and voltmeter instead (B).

to make, the first of which is whether you want to use an iron- or air-core coil. Iron-core coils are commonly available because it takes fewer turns of wire to make them. Unfortunately, the magnetic characteristics of iron are not very linear, so those coils introduce some distortion. However, in a well-designed iron-core coil the distortion will usually be under 1% or so, as long as you do not exceed the rated power. However, at excessive power levels, an iron-core coil will make your system sound really raunchy.

Your other choice is to use an air-core coil. They do not introduce distortion, but unless large enough wire is used to wind them, they can degrade your system's damping factor. (For a discussion of damping factor, check out a copy of Howard Tremaine's *Audio Cyclopedia*, published by Howard W. Sams, from your local library.) Figure 7 indicates the minimum wire gauge that is suitable for coils of various inductances, assuming a nominal 8-ohm speaker. For a 4-ohm speaker, use coils wound with wire three sizes larger. The graph is based on a coil resistance that is not over 5% of the speaker's DC resistance (*e.g.* 0.3 ohm for an 8-ohm speaker with a 6-ohm DC resistance).

Unlike the capacitor (unless you're *really* adventurous), a coil is a component that you can make from scratch. Being able to "roll your own" is only an advantage if you can't find the value you need; it may not be a good way to save money. You see, copper "magnet wire" for winding coils costs roughly one-fifth as much when bought in 50-lb bails as it does when bought a pound at a time. So a coil maker can sell you a prewound, tested coil at a healthy profit while still charging you no more than you would have to pay for the wire alone, unless you have a friend who's into motor rewinding. (Those are the guys who buy most of the 50-lb bails.) How to wind crossover coils is a subject for another article, though.

The frequency response of a simple coil-and-capacitor crossover network is shown in Fig. 8. Notice that at frequencies a little beyond the crossover frequency, the response falls off at a rate of 6-dB-per-octave (an octave is a dou-

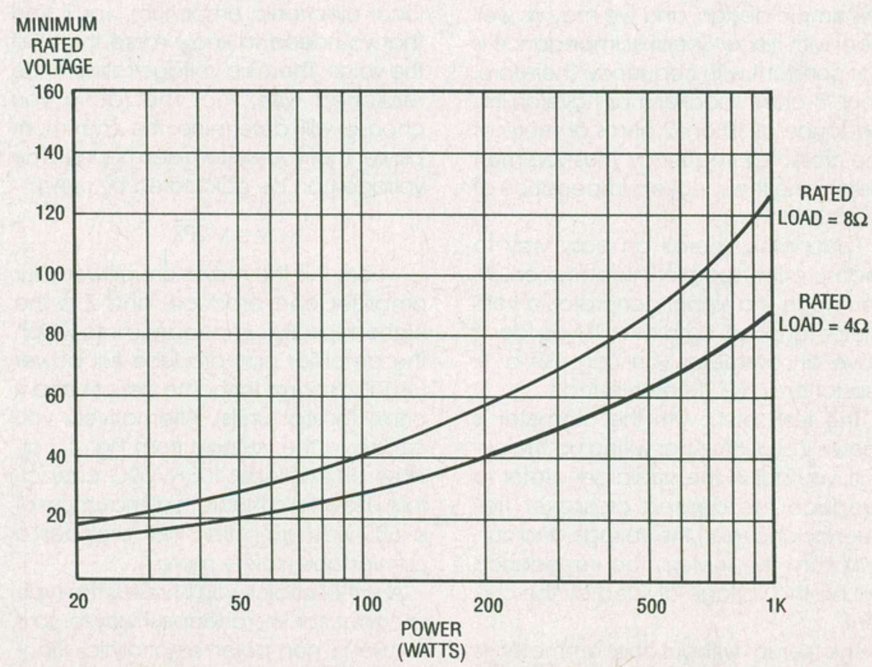

Fig. 4. You can determine the capacitor voltage rating if you know your amplifier's maximum output power by using this graph.

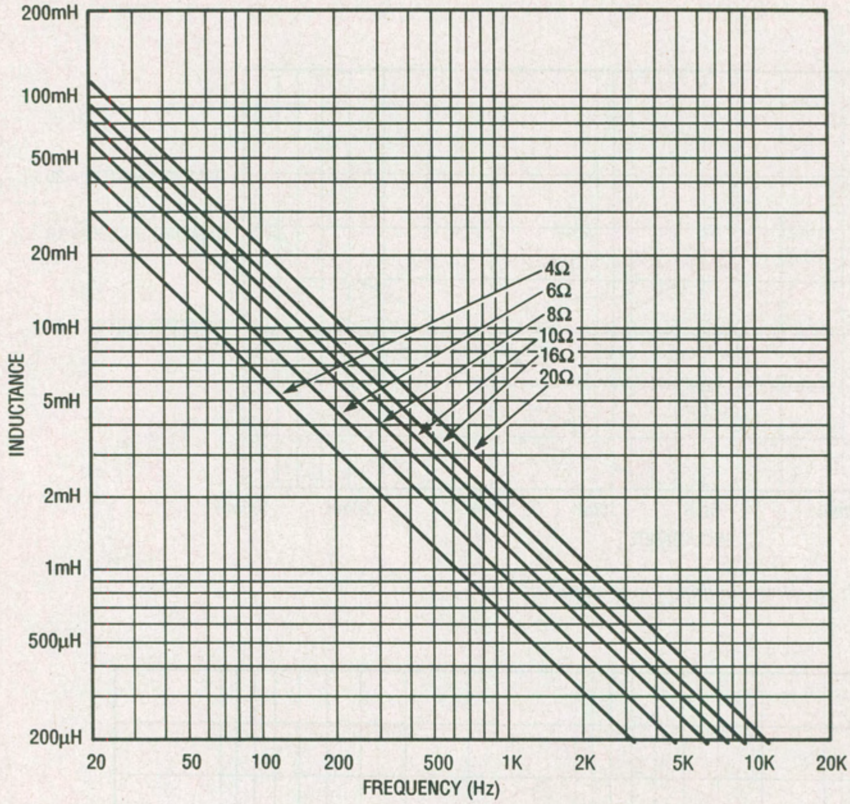

Fig. 5. Inductors can be selected from this graph if you know the frequency and load requirements of your speaker system.

bling or halving of frequency). That is characteristic of "first-order filters," which are filters that have only one reactive device (whether it's a coil or capacitor). Since the woofer's low-pass filter has only the coil, and the tweeter's high-pass filter has only the capacitor, each is a first-order filter, and this is a first-order network.

Adding a Midrange. We could add a midrange speaker to our system, using another coil and capacitor as shown in Fig. 9. The additional components form a band-pass filter. The values of the components can be determined from:

$$C1 = \frac{1}{2\sqrt{2}\pi f_H Z_T}$$

$$C2 = \frac{f_H - f_L}{\pi Z_{ML} f^2_M}$$

$$L1 = \frac{Z_{MH}}{4\pi(f_H - f_L)}$$

$$L2 = \frac{\sqrt{2}Z_W}{2\pi f_L}$$

where the various impedances are indicated by a subscript: W for woofer, T for tweeter, and M for midrange, and L and H denote the values at the low and high crossover-frequencies, respectively. (For example, two impedances are needed for the midrange driver: Z_{ML} at the low crossover frequency, and Z_{MH} at the high frequency.) The frequency f_M is the "geometrical center frequency" of the midrange section, and it is given by $f_M = \sqrt{f_H f_L}$. A peculiar feature of many 3-way crossovers is that they boost the midrange about 2 dB above the woofer and tweeter. That is no real problem, but it does mean that the midrange should be made about 2 dB less sensitive than the other two speakers (more on that later).

A Two-way, Second-Order Crossover. Figure 10A shows a 2-way second-order crossover network and Fig. 10B contains its response curves. Notice that at frequencies a little distance from the crossover frequency, each of its curves falls off at a rate of 12 dB per octave. The first-order filter's response is also shown (dashed lines) for comparison.

You might be wondering why you would want to use a second-order filter, since it requires twice as many components. There are two possible reasons: In high-power systems, the woofers can often stand 200 watts or more. Tweeters, however, can only handle a small fraction of that power. Thus it becomes very important to cut off the high-energy low frequencies as sharply as possible.

For example, let's say a first-order system is built with a crossover frequency of 1000 Hz, and a 100-watt, 500-Hz sinewave is fed into the system. The tweeter will have to handle about 50 watts. With a second-order crossover, the tweeter would only have to handle about 25 watts.

The second reason for using a higher-order crossover is that whenever two speakers are reproducing the same frequency at roughly the same levels,

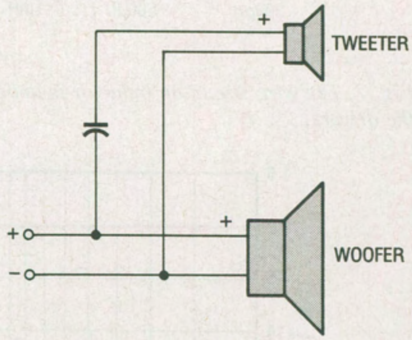

Fig. 6. This is a simple two-way first-order crossover. It prevents the woofer from receiving a significant amount of high-frequency energy.

there will be interference between them, reinforcing some frequencies and cancelling others. By using a higher-order crossover, you can reduce the range of frequencies in which such overlap is possible. To choose the values for a 2-way second-order crossover, use these equations:

$$C1 = \frac{1}{4\pi Z_T f_H}$$

$$C2 = \frac{1}{4\pi Z_W f_L}$$

$$L1 = \frac{Z_T}{\pi f_H}$$

$$L2 = \frac{Z_W}{\pi f_L}$$

Notice that the tweeter in Fig. 10A is connected with opposite polarity than the one in Fig 6. This is necessary because of the phase shift introduced by the second-order network. In order for the woofer and tweeter to pump air in phase at the crossover frequency (where they're both working), they have

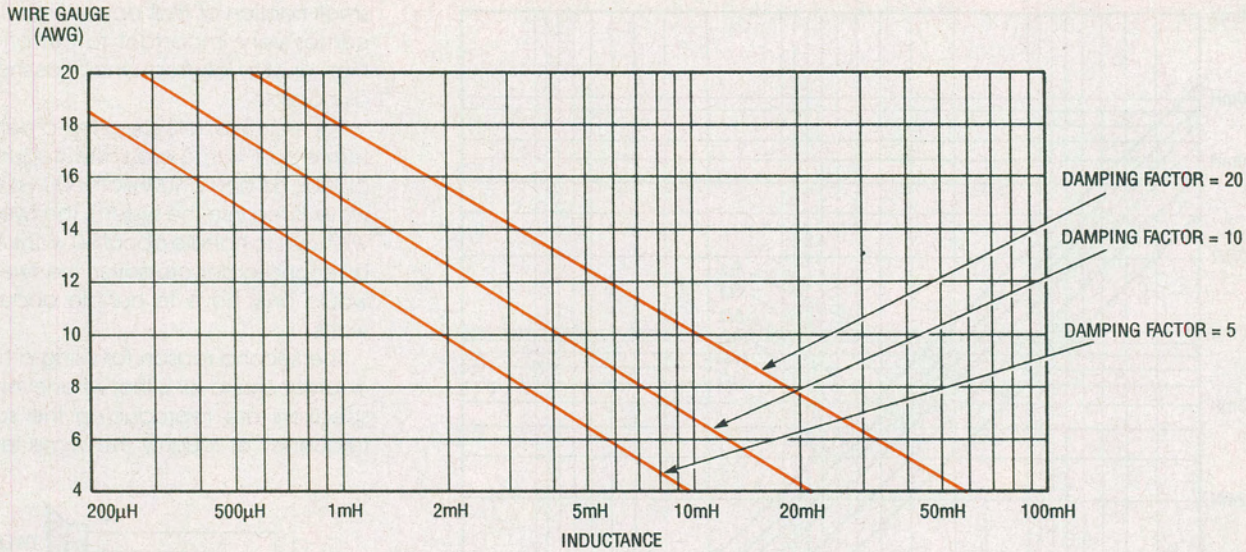

Fig. 7. The wire size of an inductor is important. It restricts the dampening capability of the drivers.

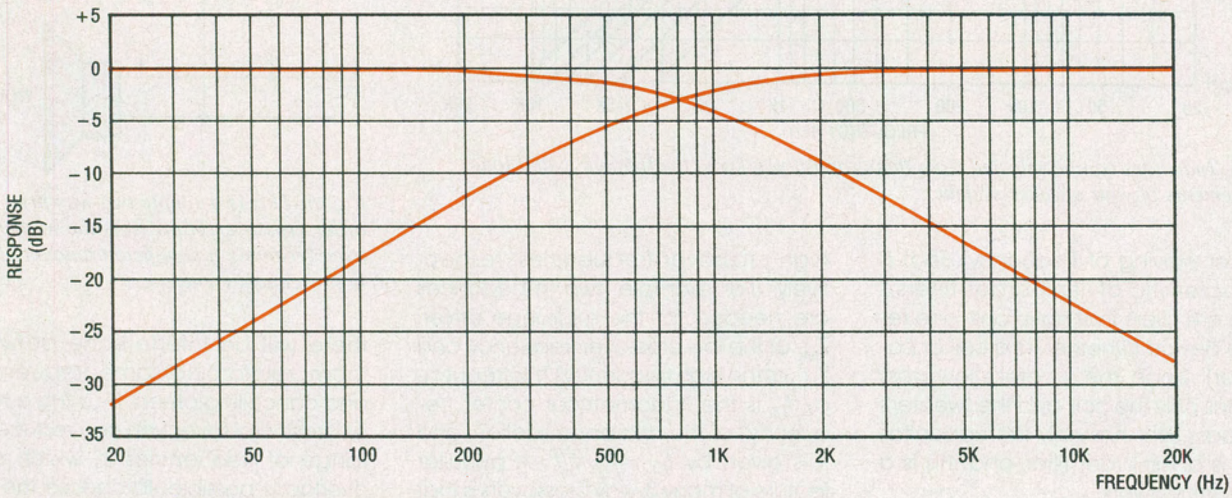

Fig. 8. This is the typical response of a first-order two-way crossover network. Note the shape decline in response beyond the crossover frequency.

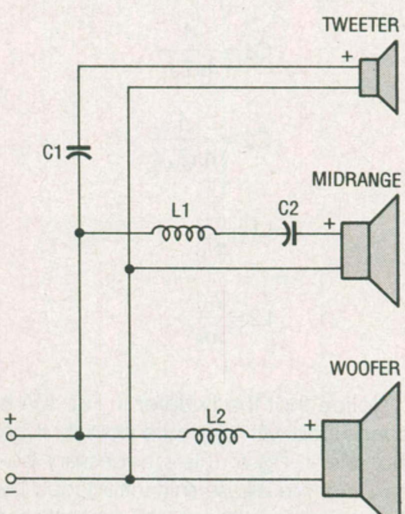

Fig. 9. This three-way first-order crossover can greatly enhance the sound quality of a speaker system.

to be connected as shown. Otherwise, their outputs will cancel and produce a response dip at the crossover point.

A Three-Way, Second-Order Crossover. Figure 11 shows a 3-way second-order crossover network. Note the tweeter is wired with the same polarity as the woofer, but now the midrange is reversed. Calculate the parts value as follows:

$$C1 = \frac{1}{4\pi Z_T f_H}$$

$$C2 = \frac{f_H - f_L}{2\sqrt{2}\pi Z_{ML} f^2_M}$$

$$C3 = \frac{1}{2\sqrt{2}\pi Z_{MH}(f_H - f_L)}$$

$$C4 = \frac{1}{4\pi Z_W f_L}$$

$$L1 = \frac{Z_T}{\pi f_H}$$

$$L2 = \frac{Z_{MH}}{\sqrt{2}\pi(f_H - f_L)}$$

$$L3 = \frac{Z_{ML}(f_H - f_L)}{\sqrt{2}\pi f^2_M}$$

$$L4 = \frac{Z_W}{\pi f_L}$$

A Practical example. As an example, let's see what components we would need to make a typical speaker system. We'll use a 12-inch woofer and a horn tweeter with stated impedances

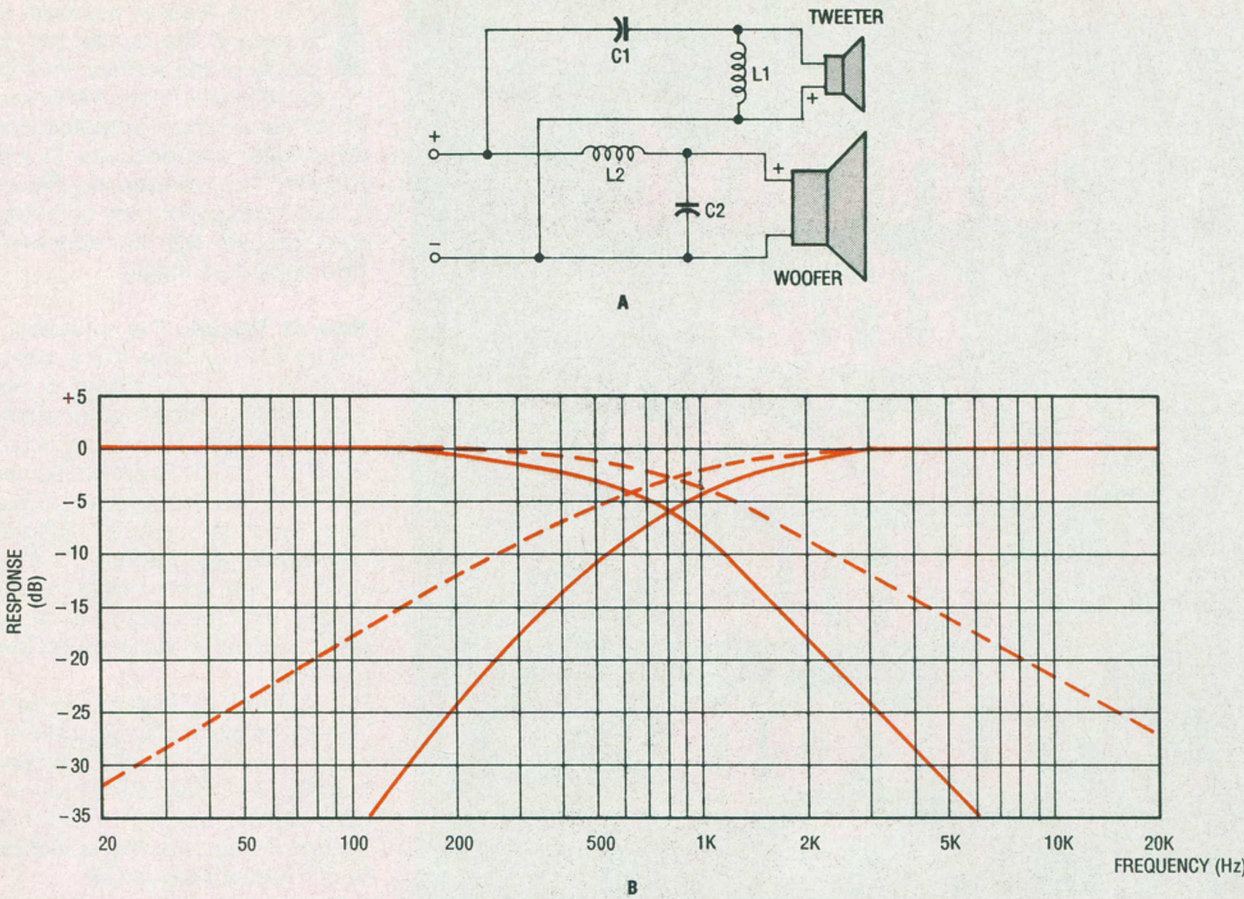

Fig. 10. A two-way second-order network is a more frequency-selective circuit (A). As you can see the response declines at 12 dB per octave (B).

of 8 ohms. We'll choose a 2-kHz crossover frequency. Measuring the actual speaker impedances, we find that Z_W is 20 ohms and the Z_T is 9 ohms at 2 kHz. If we only use a simple capacitor crossover, the capacitor's value would be:

$$C = \frac{1}{2\pi f Z_T} = \frac{1}{2 \times \pi \times 2000\text{Hz} \times 9\Omega} = 8.8\mu\text{F}$$

Moving on to a two-way first-order crossover will require adding a coil whose inductance is:

$$L = \frac{Z_W}{2\pi f} = \frac{20\Omega}{2 \times \pi \times 2000\text{Hz}} = 1.6\text{mH}$$

If we decide to improve performance and increase tweeter protection by using a second-order network, we'll cut the capacitor value in half and double the inductor value. Thus we will need two 4.4-µF capacitors and two 3.2-mH coils.

Perhaps, after looking more closely at the response curves for our woofer and tweeter, we decide that our system could be improved if we used a midrange speaker also. We decide on crossover frequencies of 500 and 4,000 Hz. Measuring impedances, let's say we find that the woofer presents 18 ohms at 500 Hz, the midrange has 8.9 ohms at 500 Hz and 12.6 ohms at 4,000 Hz, and the tweeter has a load of 9.8 ohms at 4,000 Hz. Plugging those numbers into the equations for a second-order, three-way network, we find:

$$f_M = \sqrt{4000\text{Hz} \times 500\text{Hz}} = 1414\text{Hz}$$

$$C1 = \frac{1}{4\pi Z_T f_H} = \frac{1}{4 \times \pi \times 9.8\Omega \times 4{,}000\text{Hz}} = 2\mu\text{F}$$

$$C2 = \frac{f_H - f_L}{2\sqrt{2} \times \pi Z_{ML} f^2_M} = \frac{4000\text{Hz} - 500\text{Hz}}{2\sqrt{2}\pi \times 8.9\Omega \times (1414\text{Hz})^2} = 22.1\mu\text{F}$$

$$C3 = \frac{1}{2\sqrt{2}\pi Z_{MH} f_H - f_L} = \frac{1}{2\sqrt{2} \times \pi \times 12.6\Omega \times (4{,}000\text{Hz} - 500\text{Hz})} = 7\mu\text{F}$$

$$C4 = \frac{1}{4\pi Z_W f_L} = \frac{1}{4 \times \pi \times 18\Omega \times 500\text{Hz}} = 8.9\mu\text{F}$$

$$L1 = \frac{Z_T}{\pi f_H} = \frac{9.8\Omega}{\pi \times 4{,}000\text{Hz}} = 0.78\text{mH}$$

$$L2 = \frac{Z_{MH}}{\sqrt{2}\pi(f_H - f_L)} = \frac{12.6\Omega}{\sqrt{2} \times \pi \times (4000\text{Hz} - 500\text{Hz})} = .9\text{mH}$$

$$L3 = \frac{Z_{ML}(f_H - f_L)}{\sqrt{2}\pi f^2_M} = \frac{12.6\Omega \times (4000\text{Hz} - 500\text{Hz})}{\sqrt{2} \times \pi \times (1414\text{Hz})^2} = 1.2\text{mH}$$

$$L4 = \frac{Z_W}{\pi f_L} = \frac{18\Omega}{\pi \times 500\text{Hz}} = 11.4\text{mH}$$

Many years ago, I built a three-way speaker system using prime-quality

(Continued on page 100)

SPEAKERS

(Continued from page 39)

components and well-designed, well-built crossovers and cabinets. The system sounded harsh at the top end, however. Measurements using sine-wave signals did not reveal the problem. After quite a lot of head-scratching, I determined that the problem was tweeter resonance. I was crossing from the midrange into the tweeter at 2500 Hz using a second-order crossover. The tweeter's resonant frequency was 1600 Hz. What was actually happening was that the tweeter was receiving enough energy at 1600 Hz to make the voice coil move far beyond its linear range. As a result, the tweeter was producing a lot of distortion whenever the music had frequencies around 1600 Hz. Figure 12 shows a notch-filter circuit that can be added to the crossover across the tweeter to block energy at the tweeter's resonant frequency. The design equations are:

$$C_N = \frac{1}{2\pi R_E Q_{es} f_s}$$

$$L_N = \frac{Q_{es} R_E}{f_s}$$

$$R_N = R_E + \frac{Q_{es} R_E}{Q_{ms}}$$

where R_E is the speaker's DC resistance, Q_{es} and Q_{ms} are the electrical and mechanical Q's of the speaker, and f_s is the speaker's resonant frequency.

Those characteristics should be available from the speaker's manufacturer, but you can measure measure R_E, using a digital multimeter, for yourself. You can also find f_s by using the test setup shown back in Fig. 3. Adjust the signal generator's frequency for the lowest current (voltmeter-ammeter method) or the highest voltage across the resistor (resistance-voltmeter method). "Guess" values of Q_{es} and Q_{ms} would be about 1.2 and 0.7, respectively, for typical dome tweeters. Fortunately, guessing wrong on the Q's will not seriously affect the circuit's operation.

The notch-filter circuit can also be used with the midrange driver, but it is seldom needed there unless a dome-type midrange is used. Cone and horn midrange units usually have very well-damped resonances that don't cause problems.

If a second-order network is better than a first-order one, wouldn't a third (or fourth or fifth) be better still? Perhaps marginally so, but each time you add an inductor in series with a speaker, you add some resistance and reduce the damping factor, so there's a point of diminishing returns. Many designers believe that if you need more than a second-order crossover, you should use an active circuit; once again, active crossovers are a subject for another time.

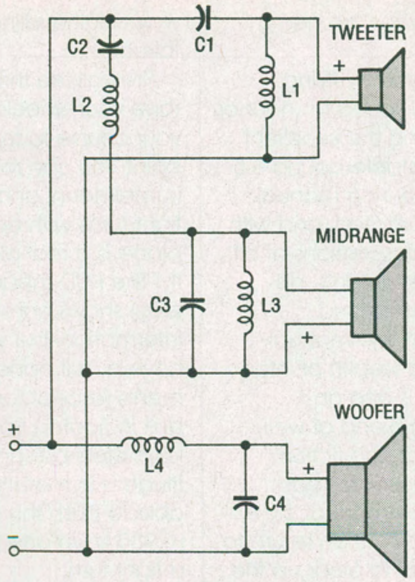

Fig. 11. A three-way second-order crossover has a pretty impressive name but it's pretty easy to build. Note the reversed midrange polarity.

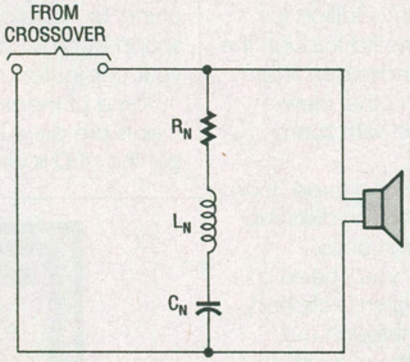

Fig. 12. A notch filter like this one can be used to stop annoying resonance.

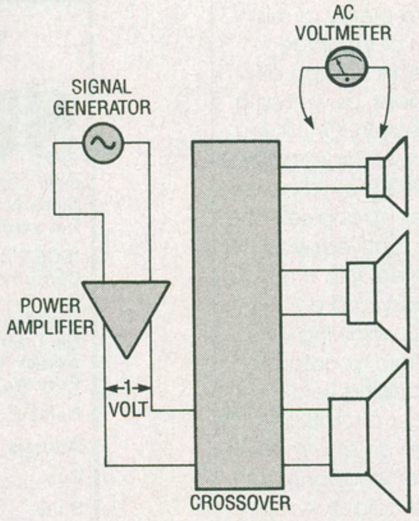

Fig. 13. This crossover test setup is easy to arrange and use. Be sure your power amplifier is supplying no more than one volt before connecting the crossover.

Selecting Drivers. We've left one of the most important concerns for last: how do you choose a woofer, midrange, and tweeter that will sound good together? First, you make sure that the three have overlapping responses. Preferably, you will have published response curves at your disposal that you can use to verify this, but at least you can check the stated response specifications. Then you can place the crossover frequencies in the middle of the overlaps. (It should go without saying that you don't want speakers with published response curves that have serious humps or dips in the middle.)

Second, the woofer and tweeter should have the same sensitivity ratings (given in dB at 1 watt from a distance of 1 meter). As mentioned earlier, the midrange should be 2 dB less sensitive than the woofer and tweeter, because three-way crossover networks actually have a 2-dB gain in their midrange section.

Finally, all three speakers should be rated for at least the minimum power you plan on using. Midrange and high-frequency speakers often have two power ratings: an actual power rating and a "system" power rating. As an example, a tweeter rated for use in a 100-watt system may have an actual power rating of about 6 watts, provided that a second-order crossover of 300 Hz or higher is used.

Building and Testing. When you build a crossover network, mount the components on a plywood board that can be screwed to the inside of the speaker cabinet, preferably with some sponge weatherstrip underneath the board to suppress rattles. You can mount the components using hot-melt glue or silicone "bathtub caulk." Always mount adjacent coils at right angles to each other to prevent magnetic interaction.

Once you have built the crossover network, it pays to make a few measurements before you hook up the stereo for a sound check. Figure 13 shows a test setup that you can use to make the test. What you're trying to verify is that the crossover works as expected.

While slowly varying the frequency from one half to two times the low crossover frequency, measure the AC voltage at the woofer terminals. That voltage should start dropping just below the crossover frequency, and should drop rapidly above it. Do the same with the midrange. It should have a low voltage at half the lower crossover frequency, rising as the frequency increases, then leveling out above the crossover frequency. Check the midrange and tweeter sections in the same way, but this time varying the frequency from half to twice the upper crossover frequency. Any wiring errors you may have made can be discovered by these tests. (I once blew an amplifier by mis-wiring a crossover network so that it presented too low an impedance to the amp; a 15-minute test is cheap insurance.)

If you are really interested in crossover design, there has been a lot of valuable work published in the *Journal of the Audio Engineering Society* in the last few years. Much of this is summarized in Vance Dickason's *Loudspeaker Design Cookbook*, published by the Marshall Jones Company of Francestown, N.H. There's also some good info in Badmaieff/Davis', *How to Build Loudspeaker Enclosures*, published by Howard Sams.

Well, I guess you're wondering about my young friend and his girl's ex-speaker system. Once he found out what the problem was, he decided to use a simple capacitive crossover like the one that was originally in the system, but he did buy 100-volt capacitors. Then he decided to add midrange units. He wasn't very good with a saber saw. Oh well .... ■

"Why can't you be obsessed with cars like a normal man?"