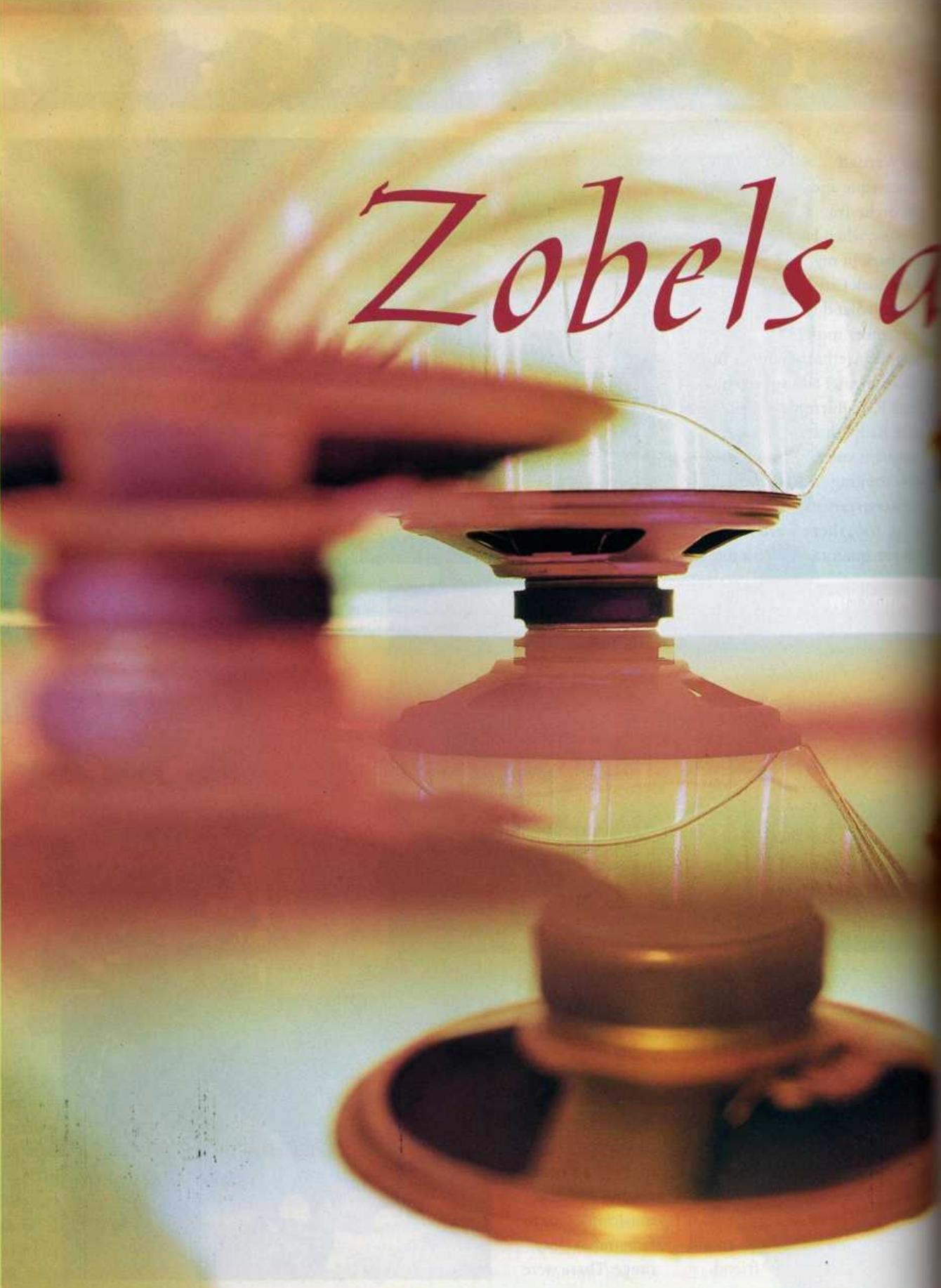


# Zobels a



PHOTOGRAPH: PITO COLLAS



# and All That

BY  
HANK ZUMBAHLEN

**W**hen designing a loudspeaker system, the crossover design is at least as important as the driver selection and enclosure design. The physics of sound reproduction make it very difficult for a single driver to handle all frequencies. Therefore, most speaker systems consist of multiple drivers, each reproducing a separate segment of the audio spectrum. A speaker driver can be thought of as a mass-controlled piston working into an acoustic load that derives its response curve from the cancellation of two opposing effects. The first effect is the cone excursion, which is inversely proportional to the square of the frequency. The second is the resistance of the acoustic load, which is directly proportional to the square of the frequency. These effects cancel each other out in the center of a speaker's response, creating a region of flat response.

At some high frequency, where the wavelength of the acoustic wave is less than the circumference of the driver, the acoustic resistance levels off, and the response of the speaker rolls off at 12 dB per octave. At the resonant frequency of

the driver, the excursion is dominated by the compliance of the suspension rather than by the mass of the cone. This causes a roll-off, which is also 12 dB per octave. Therefore, reproduction of low frequencies requires a driver that has a relatively large surface area, allowing it to move the large amount of air needed. The driver surface should also have relatively high stiffness so that it moves as a uniform piston and doesn't flex. This stiffness usually implies higher mass.

For high frequencies, the tweeter should have as little mass as possible so that it can respond to the input signal quickly. And even though designers would like a massless driver, it still needs stiffness so that it doesn't flex.

Typically, most loudspeaker drivers work well over a frequency ratio of about 10:1. This means that designers customarily use three drivers to cover the three decades of the audio spectrum of 20 Hz to 20 kHz. In the interest of

*Hank Zumbahlen is a Senior Field Applications Engineer in the Components Group Applications area of Analog Devices in Campbell, California. This article is adapted from "Speaker Crossovers," a section in Analog Devices' book entitled System Applications Guide.*

simplicity (and cost), designers sometimes try to cover the spectrum with two drivers.

This places greater demands on each driver and usually requires sharper cutoff rates in the crossover filter to limit the out-of-band signals from reaching the driver. It is especially important to limit the low-frequency energy to the tweeter in order to limit its excursion.

Since we have separate drivers covering separate sections of the audio spectrum, we need to divide up the input signal to direct the proper portions to the proper drivers. We accomplish this with crossovers, usually passive filters placed between the drivers and the power amplifier. Sometimes, however, the designer may want to implement the crossover at line level. There are some advantages, as well as disadvantages, to each approach, a situation every design engineer finds normal.

The passive crossover is simply a high-level passive filter. The driver is the load impedance of the network. The designer generally assumes the zero source impedance (as opposed to using a source termination), which ensures that maximum power is delivered to the load.

where  $V_{IN}$  is the input voltage,  $V_L$  is the low-pass output voltage,  $V_M$  is the band-pass output voltage, and  $V_H$  is the high-pass output voltage. Phase does not appear in this equation.

$$|V_L + V_M + V_H| = |V_{IN}| \quad (1)$$

It is not possible to pass a signal through a ladder network and preserve both magnitude and phase. Therefore, APCs are desirable because they do not introduce variations in the speaker's amplitude response.

The other popular network is the CPC, where the output power of the network is equal to the input:

$$|V_L|^2 + |V_M|^2 + |V_H|^2 = |V_{IN}|^2 \quad (2)$$

The use of the CPC type of crossover in commercial loudspeaker systems predates the APC's use by many years. It is interesting to note that odd-order systems are both APC and CPC.

The next thing that the designer must determine is the order (number of poles)

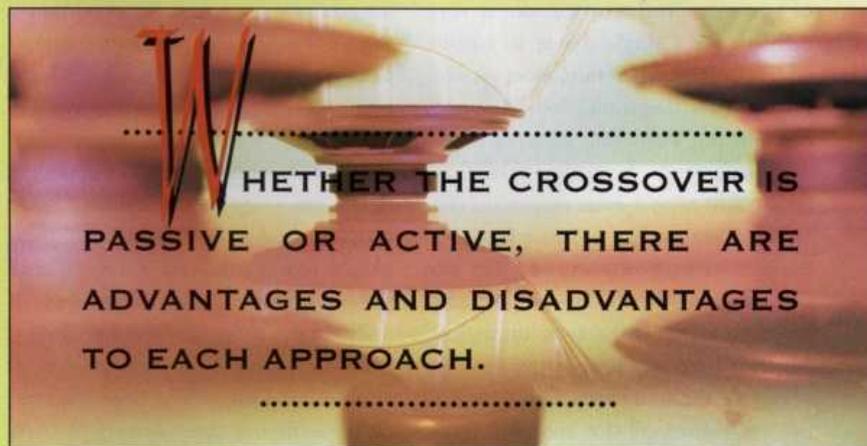
driver cancellation and more troublesome. (Inter-driver cancellation occurs when two drivers putting

out the same frequency are separated by an odd multiple of  $\frac{1}{2}$  of the wavelength of the signal.) A first-order system is a minimum-phase system as well.

Second-order systems are considered by many to be the lowest practical order for a crossover network. The number of components is still manageable, the required operational range is better controlled, and the phase shift of the network is still relatively low. In contrast to odd-order crossovers, second-order (and all other even-order) crossovers are relatively insensitive to system phase relationships.

Third-order systems are also very popular. Since they are odd-order, they are both APC and CPC. The number of components is still manageable, but the phase shift of the network is greater.

Fourth-order systems are sometimes used, generally where a high cutoff rate is required (often to reduce the excursion of a tweeter). The disadvantages of fourth-order systems are a high number of components, with a resulting high cost, and high phase shift in the network.



IMPEDANCE COMPENSATION

All design equations for crossover networks assume a constant load impedance. However, the impedance of a driver is anything but a constant (see Fig. 1). The designer should, therefore, add networks to try to equalize this impedance. Typically, this takes the form of a series RC paralleled across the driver terminals; it is called a Zobel network (see Fig. 2).

Unfortunately, this equalization is only an approximation, as the Zobel network only partially compensates for the driver's impedance variation. The impedance does not rise with frequency, as a series LR network does, but more closely approximates the  $R\sqrt{L}$ . This is sometimes referred to as a semi-inductor. The simple Zobel network, optimized at the crossover frequency, does a good job of flattening the impedance in the frequency range around the crossover, however, which is where we need it most (see Fig. 2).

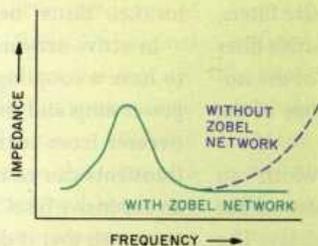
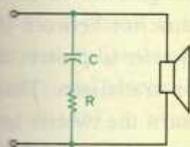
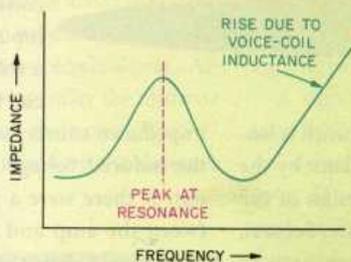
The first thing a designer determines is the crossover type. The two most often used are the all-pass configuration (APC) and the constant-power configuration (CPC).

The APC, introduced by Garde, seems to be the current favorite. When the outputs of the filter are combined, the resultant has the same magnitude as the input at all frequencies. This is shown in equation 1,

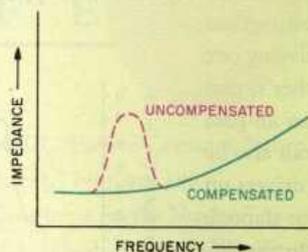
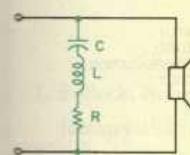
of the system. All-pole systems ultimately roll off at  $6n$  dB per octave, where  $n$  is the order.

First-order systems are attractive, because few components are required. However, because of the low roll-off rate, the response of the drivers must be flat well beyond the crossover frequency. As a practical matter, since the driver responses overlap so much, problems such as inter-

**Fig. 1—  
Speaker  
driver  
impedance.**



**Fig. 2—  
Zobel network.**



**Fig. 3—  
Resonance  
compensation.**

There is also an impedance peak at the resonant frequency of the driver, and this peak often has a fairly high Q. The designer can devise a series LRC network to equalize this peak, as shown in Fig. 3. However, as the frequency goes down, the size of the required inductor (in all respects: Electrical value, physical volume, and cost) gets large. While compensation of this type is therefore rare for woofers, it is more common (though not universal) for midrange drivers and tweeters, especially when the resonant frequency is situated within an octave of the crossover frequency. Since these are high-Q circuits, their transient response is not optimum, and they tend to ring.

The designer can add networks in series with the speakers to control response variations. These networks are usually parallel LR for rising response with frequency (Fig. 4), RC for falling response with frequency (Fig. 5), or LRC for a hump in the frequency response (Fig. 6).

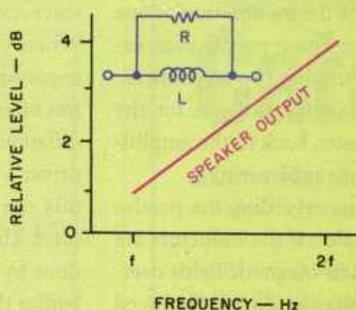
Figures 7 and 8 show how effective this Zobel and resonance compensation can be with a real midrange—three Audax HD12P25FSM drivers in parallel, actually.

One last function that should be accomplished in the crossover is to equalize the sensitivities of the drivers. This is commonly accomplished with an L-pad so that the level can be adjusted without affecting the load impedance seen by the network. An alternative is to use a resistor in series with the load. The total crossover load, using a series resistor, is then the sum of the pad resistor and the speaker, which should still be compensated by impedance equalization. This approach, while saving a resistor, doesn't allow the flexibility of adjustment offered by the L-pad.

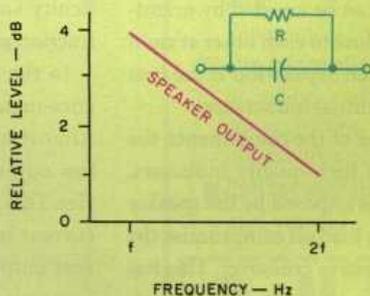
The quality of the components is crucial to good performance. Inductors should have low d.c. resistance because of the high peak currents that they will carry. These currents may actually be larger than the ones in the load and can approach tens

of amperes. Since the impedance of most crossovers is low, it doesn't take much resistance to turn an LC network into an LRC network. The formulas for passive crossovers assume ideal inductors with no series resistance. Therefore, the inductor should be wound with large wire. (Most crossover inductors are wound with AWG #16 or #14 wire.) Iron-core inductors should be designed so that they don't saturate, even under high peak-current conditions. Many audiophiles dislike iron-core inductors for their susceptibility to saturation, but they do allow higher inductance values for a given amount of wire, which translates to lower d.c. resistance.

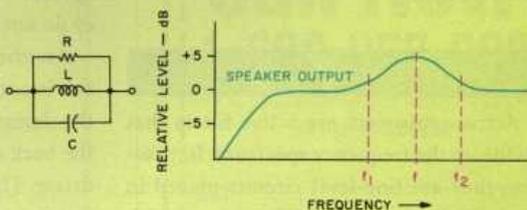
Capacitors for audio use should have a film dielectric. Electrolytic capacitors should be avoided whenever possible. Because there is no polarization voltage in



**Fig. 4—  
Compensation  
for rising  
response.**



**Fig. 5—  
Compensation  
for falling  
response.**



**Fig. 6—  
Compensation  
for a hump  
in response.**

the audio signal, a nonlinear response is caused by an electrolytic capacitor.

Also, the equivalent series resistance (ESR) and dielectric absorption (DA) of electrolytics are poor. Unfortunately, film caps are only available up to about 100  $\mu\text{F}$ , and at these values they are physically very large.

Resistors should be large enough to absorb at least the amount of power that is being delivered to the speaker. The square-section power resistors seem to be the best. They are inexpensive, fairly accurate, and stay resistive (rather than becoming reactive) throughout the audio range.

In wiring the drivers, it is desirable to run two separate wires (hot and common) to each set of drivers rather than running a common return for all drivers. This minimizes the inductance and impedance in the return and prevents the modulation of one driver by the other. Some people even extend this idea by running two separate cables, one for the woofer and one for the midrange and tweeter, back to the amplifier. This is referred to as bi-wiring.

Some final points regarding the passive crossover are in order. If the inductors are oriented so that their magnetic fields overlap, unwanted voltages may be induced from one inductor to the other by mutual inductance. This can be avoided by orienting coils that are close to each other at right angles to each other. Separation is the best way of avoiding mutual inductance.

The physical size of the components, the resistance of even high-quality inductors, and the limitations imposed by the speaker as the terminating load all compromise the accuracy of the passive crossover. This has tempted designers to go to active crossovers instead.

## ACTIVE CROSSOVERS

Active crossovers are active filters that divide up the frequency spectrum. In practice, they are line-level circuits placed in front of the power amplifiers. A separate power amp is therefore required for the driver in each frequency range, materially raising system cost, and this is the active crossover's chief disadvantage. There are, however, many advantages.

First, the active crossover network is isolated from the speaker's impedance by the power amp. This makes the design of the filter simpler and more accurate. Second, the impedance of the filter can now be scaled so that component values can be made more practical. Another advantage is that inductors are not used in active filters, and it is much easier to tune an active filter than it is a passive filter because of the isolation between the various sections of the active filter.

Another possible advantage, which can be implemented in an active crossover but not in a passive filter, is time delay. The acoustic center of a driver is usually located at a point approximately where the voice-coil attaches to the cone (or dome). When you mount different drivers on a common vertical baffle, their acoustic centers often do not line up. The resulting time difference can be cancelled by delaying one driver's output relative to another's, and this can be accomplished with an all-pass filter. This alignment of signals can also be done by mounting the different drivers on baffles that are physically offset or slanted. However, this increases manufacturing difficulty and may cause problems with diffraction around the baffle edges.

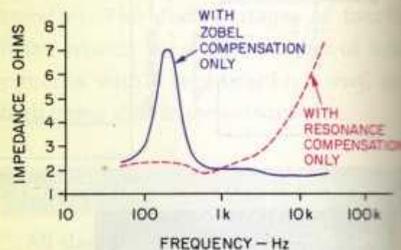
In the active crossover design, impedance-matching circuits may be eliminated. Almost all modern amplifiers have very low output impedances at audio frequencies. This means they will provide whatever current is required, within the amp's current output capability, to develop the correct voltage across the load. Therefore, speaker-impedance changes with frequency do not affect overall performance.

Another advantage is that since each driver is connected directly to an amplifier, the damping ratio of the amp can control the back electromotive force (EMF) of the driver. This is especially important for the woofer. A dynamic driver works by developing a voltage in a coil of wire—that is, the voice-coil—which then moves relative to a fixed magnet. Back EMF is produced by the voice-coil moving through a magnetic field due to the momentum of the

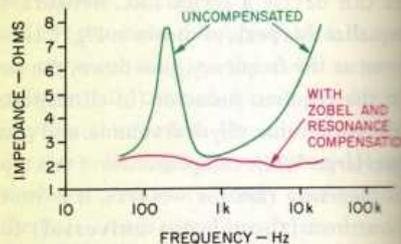
cone, not because of an input signal. This sets up a voltage in the coil. If the coil is connected to a low-

impedance source, such as a power amp, the induced voltage is effectively shorted out. If there were a passive crossover between the amp and the driver, this back EMF would distort the signal because of the finite driving impedance. Eliminating this effect results in better transient behavior (i.e., "faster" bass).

In active network designs, it is advisable to have a coupling capacitor between the power amp and the tweeter to protect the tweeter from turn-on transients. These transients can easily turn the tweeter into an expensive fuse! The capacitor should be chosen so that it does not affect the transfer function, and it is more than sufficient to have the corner frequency a decade or more below the upper crossover frequency. A high-quality film capacitor should be used in this application.



**Fig. 7—**  
Effects of Zobel and resonance compensation.



**Fig. 8—**  
Combined effect of Zobel and resonance compensation.

Subjective evaluations have indicated that active crossover networks sound better than their passive equivalents. Although active crossovers offer the ultimate in audio performance, their cost-effectiveness must be determined by the designer and the consumer.

#### DESIGNING BY COMPUTER

On a final note, computer programs have been written to aid in the design of crossovers. Robert M. Bullock's original work (a classic series of articles that appeared in *Speaker Builder* in January, February, and March 1985; January 1986, and April 1987) is available in the form of a BASIC program for two- and three-way designs. Several shareware programs have been written to spice up the presentation of the data, but these programs suffer in

particular from not being able to factor some of the terms in the higher order APC equations.

A significant advance in modelling allows the frequency response of the individual drivers to be factored into the crossover. Most simple computer programs, such as Bullock's, assume a flat response from the driver. Later programs, such as CALSOD (Computer Aided LoudSpeaker Optimization and Design), allow the designer to use the response of the driver as an input. Some programs can automatically take the response of the driver when used with the proper hardware.

Many programs exist for the design of active filters, running the gamut from simple spreadsheets to very elaborate graphics interface programs. A good source of audio-related software is the Madisound bulletin board (BBS) at 608/836-9473. A

## REFERENCES

1. Bullock, Robert M. III, "Passive Crossover Networks," *Speaker Builder*, "Part I," January 1985; "Part II," February 1985.
2. Koonce, G. R., "Crossovers for the Novice," *Speaker Builder*, May 1990.
3. Bohn, Dennis (ed.), "Floobydust," *Audio Handbook*, National Semiconductor Corp., 1977 (pp. 5-1 to 5-7).
4. Small, R. H., "Constant-Voltage Crossover Network Design," *Journal of the Audio Engineering Society*, January 1971.
5. Garde, P., "All-Pass Crossover Systems," *JAES*, September 1980.
6. Bullock, Robert M., "Loudspeaker-Crossover Systems: An Optimal Crossover Choice," *Loudspeakers, Vol. 2*, Audio Engineering Society, 1983 (pp. 332 to 341).
7. Bullock, Robert M., "How You Can Determine Design Parameters for Your Loudspeaker," *Speaker Builder*, January 1981.
8. Koonce, G. R., "Crossover Component Capabilities and Requirements, Part II: Crossover Voltage & Current Factors," *Speaker Builder*, April 1986.
9. Weems, David B., "Notch Filters," *Speaker Builder*, February 1986.
10. Harms, Wilfred F., "Evaluating the Zobel," *Speaker Builder*, April 1982.
11. Meraner, David J., "Is Driver Impedance Compensation Worthwhile?," *Speaker Builder*, March 1987.
12. Chin, Mike, "Magnetic Crosstalk in Passive Crossovers," *Speaker Builder*, May 1990.
13. Dickason, Vance, *The Loudspeaker Design Cookbook*, Marshall Jones, 1987.
14. Zumbahlen, Hank, "Mixed Signal Seminar," Analog Devices, Inc., 1991, Sec. 2.
15. Zumbahlen, Hank, "System Design Seminar," Analog Devices, Inc., 1993.



# FREE Stereo Catalog

- **Convenient shopping** — over 100 full-color pages covering hundreds of the latest stereos for your home and car, plus video and telephones
- **Quality you can count on** — Sony, Kenwood, Pioneer, JVC, Carver, Polk, Advent, Infinity, Bose, NHT, Panasonic, Mitsubishi, and more
- **The information you need** — including product descriptions, consumer tips, specifications, and our exclusive comparison charts
- **Call for your free copy!** You'll be glad you did

## Call Now!

### 1-800-955-9009

8 a.m. to Midnight (eastern time), 7 days a week  
or mail this coupon

Name \_\_\_\_\_

Address \_\_\_\_\_ Apt. # \_\_\_\_\_

City \_\_\_\_\_

State \_\_\_\_\_ Zip \_\_\_\_\_

## CRUTCHFIELD™

1 Crutchfield Park, Dept. AU, Charlottesville, VA 22906