CROSSOVER BASICS

Knowing crossover characteristics can help you predict a speaker system's sound

It's hard to know what a speaker sounds like without hearing it. You can get some idea if you know something about its drivers. For example, a big speaker with two 15-inch woofers is likely to have better bass than a small speaker with one 6-inch woofer.

Drivers aren't the only parts in a speaker, however. When a speaker has different drivers to handle different parts of the frequency range, something else is necessary—a *crossover network.*

A crossover network divides the audio signal coming from a receiver or amplifier and sends the right parts of it to the right drivers. In a three-way speaker, it sends the lows to a woofer, middle frequencies to a midrange, and highs to a tweeter (see Figure 1). To know what frequencies each driver handles, you have to know the speaker system's *crossover frequencies*—the point(s) at which a rising or falling note will *cross over* from one driver to another. In addition to crossover frequency, other important features of crossover networks are the rate and shape of its attenuation *slopes*, which determine how the frequencies fade out from one driver and fade in to the next.

Because crossovers are designed for specific drivers in multiway speakers, they are usually built into each speaker. But they can also be purchased as separate components, especially for three-piece satellite/subwoofer systems or for biamplified and triamplified systems.

Whether a crossover comes with the speaker or is separate, knowing its characteristics can tell you something about the speaker's sound before you hear it. Different types of crossovers have different advantages and disadvantages. Some are hard on drivers (making them handle a wide range of frequencies), while others have problems with phase coherence (giving two drivers the same signal out of phase) or time alignment (causing the drivers to produce the same sounds at slightly different times).

Sonic Effects of Crossovers

Many multiway speakers have level controls for the midrange and the tweeter that act like broadband tone controls. The so-called *turnover points* of these controls are the crossover frequencies. Obviously, adjusting these controls can dramatically change the sound of a speaker.

A more subtle crossover effect is caused by the different distortion characteristics of different drivers. A crossover frequency that is too low or too high can send signals to a driver that it can't reproduce without distortion, and this distortion will get worse at higher volumes.

The amount of overlap a crossover network allows between drivers—that is, when a signal is reproduced by two drivers because its frequency is in the high part of one driver's range and in the low part of the other's—can also make a difference in the system's sound. Some speakers, such as those made by Bose, are touted for their large overlap (nearly an octave in the Bose 601 III's), while others, such as the JSE Infinite Slopes, are touted for their minimal overlap (with slopes over 100 dB per octave).

Crossovers and Drivers

Typically, there is a crossover output for each driver in a speaker. Since the limiting factor is driver capability, a speaker designer's selection of drivers dictates his choice of crossover frequencies.

For example, sending too much low-frequency energy to a tweeter is an easy way to send the tweeter to an early grave. The tweeter can't move far enough to reproduce very low-bass frequencies. And even if it could survive that much motion, its voice coil will burn out first because of the excessive energy levels.

Another driver limitation that affects crossover design is how evenly a driver disperses sound. If a woofer has wide dispersion and a tweeter has narrow dispersion, the speaker may sound weird and "beamy." If the dispersion patterns of the drivers don't match well, stereo imaging is likely to be lousy, especially for the overlap frequencies produced by both drivers.

How Crossovers Work

A crossover network is nothing more than a collection of electrical filters. A two-way speaker needs a *highpass* filter to pass highs to the tweeter while holding back the lows and a *lowpass* filter to pass lows to the woofer while holding back the highs. A three-way speaker will also need a *bandpass* filter to pass the middle frequencies to the midrange driver while holding back both the highs and the lows.

Figure 2 shows the output curves of the filters in a typical three-way crossover network. Notice how the lowpass filter lets the low frequencies, up to about 200 Hz, go through untouched while reducing the level of the higher frequencies, so that a note at, say, 4,000 Hz reaches the woofer at a level about 24 dB lower than a bass note. As the frequency increases, the output level from this filter steadily decreases.

The highpass filter works the opposite way, allowing its output level to increase as the frequency increases until about 10,000 Hz, above which it passes the high-frequency signals to the tweeter unchanged. In the middle of the network, the bandpass filter attenuates both lows and highs while leaving middle frequencies unchanged.

A system's crossover frequencies are determined by the *cutoff frequencies* of its crossover filters, which are the points at which their output level is 3 dB below the maximum output (which would produce a sound only half as loud). Signals beyond the cutoff frequency—above it for a lowpass filter, below it for a highpass filter, and either way for a bandpass filter, which has two cutoff frequencies—are still allowed to go through, but at a decreasing level as the frequency changes.

In Figure 2, the cutoff frequency of the lowpass filter and the lower cutoff of the bandpass filter are just over 400 Hz, while the upper bandpass cutoff and the highpass cutoff are just over 4,000 Hz. These two points, therefore, are the crossover frequencies of the speaker system.

Crossover Types

Ideally, the acoustic output of a speaker with more than one driver should be the same as the output of a speaker with just one perfect full-range driver. In practice, however, it is difficult to make different drivers work together in perfect harmony. The speaker's designer must choose the right crossover frequencies as well as the right shapes and rolloff rates for the filter slopes if the system is going to sound anything like the ideal.

A crossover filter's characteristics are described mathematically in an equation that represents a curve like those in Figures 2 through 6. Filter curves have three parts: the *passband* section, which is where the curve is level (or flat) because the filter is passing all signals in that frequency range; the *stopband* section, which is the part of the curve beyond the cutoff point that appears as a straight line with a certain constant angle, or slope; and the *transition region* between the passband and the stopband, which is the part that is truly curved.

The slope of a filter is the *rate* at which it rolls off, or attenuates, its output beyond the cutoff point given a constant-level input. It is usually expressed in decibels per octave, and for mathematical reasons the figures are almost always multiples of six. As the slope of a filter gets steeper and steeper, it approaches the ideal limit of a so-called "brick-

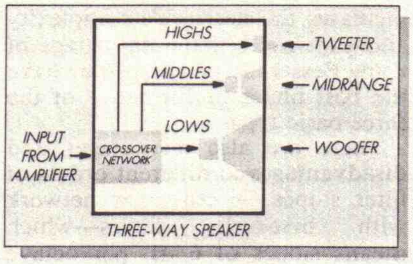

Figure 1. The crossover network in a three-way speaker system needs three filters: a highpass filter to send the high frequencies to the tweeter, a bandpass filter to send the middle frequencies to the midrange driver, and a lowpass filter to send the bass frequencies to the woofer. Different types of crossovers will provide more or less overlap between the signals sent to drivers in adjacent ranges.

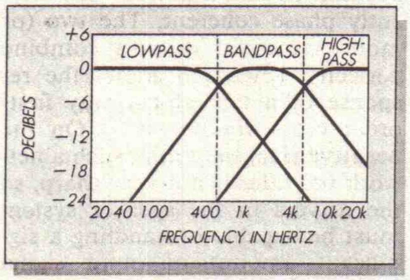

Figure 2. Response curve for the crossover network in a typical three-way system. Each of the three filters lets a certain range of frequencies pass through to its associated driver unaltered while rolling off the unwanted frequencies beyond its range. The crossover points for the system are where the filter outputs are 3 dB down from their maximum levels.

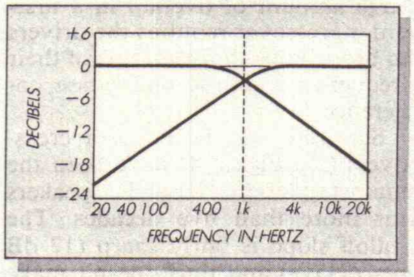

Figure 3. Response of a first-order crossover for a two-way system. The slope beyond the crossover point is a gentle 6 dB per octave, creating a wide overlap in the frequency ranges sent to each driver.

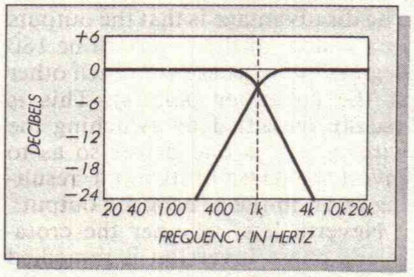

Figure 4. Response of a two-way, second-order Butterworth crossover. The rolloff slope is 12 dB per octave.

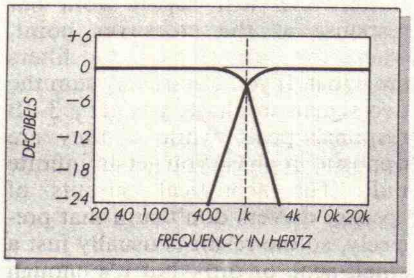

Figure. 5. Response of a two-way, third-order Butterworth crossover, with a slope of 18 dB per octave.

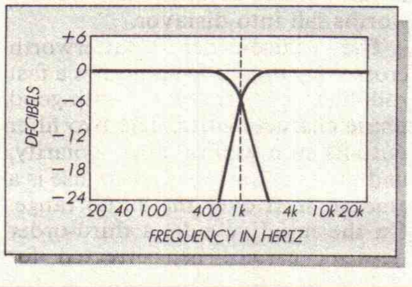

Figure 6. Response of a two-way, fourth-order Linkwitz-Riley crossover. In this special case of a Butterworth crossover, the rolloff curve is sharper and the crossover point is at −6 dB instead of the usual −3 dB. Beyond the crossover point, the slope is the same 24 dB per octave as with any fourth-order filter.

wall filter," in which the attenuation is so sharp that the curve representing it seems to drop straight down from the passband like a wall.

Crossover slopes are also sometimes described as being of a certain *order*, namely, the mathematical order of the equation describing the filter. To convert the order of a crossover into a decibel-per-octave slope, simply multiply the number of the order by six. Thus, a *second-order* crossover has a filter slope of 12 dB per octave, and a *third-order* crossover has a slope of 18 dB per octave.

Just as important in characterizing a crossover as its filter slope (or order) is the shape of the crucial transition region between the passband and the stopband. The equations defining these curves are called *transfer functions*, and the different types are named after the mathematicians who identified them. The filters most commonly used for speaker crossovers are described, respectively, by *Butterworth*, *Chebychev*, *Bessel*, and *Linkwitz-Riley* transfer functions (the last being a special case of the Butterworth type). Each function can be of any order, but only the first through fourth orders are commonly used for audio filters, and even among these only a few of the possible combinations are practical for speaker crossovers.

Design Tradeoffs

The various types and orders of crossover filters have different characteristics in practice, and these present advantages and disadvantages to the designer of a speaker's crossover network. For instance, Butterworth filters have the flattest passband response of the three main types. That is, the frequencies that should be passed through to the driver unchanged are least affected by going through the filter circuit.

Chebychev filters, on the other hand, have the advantage of rolling off faster than Butterworth filters with the same slope. That is, the transition from the passband to the stopband is sharper. The disadvantage is that the frequency response of Chebychev filters is not as flat in the passband as that of Butterworth filters, and for this reason they are not used very often.

Bessel filters do not roll off as fast as either Butterworth or Chebychev filters, which means that in most speaker crossovers a Bessel filter would have to have at least a fourth-order slope to be effective. That increases the network's complexity and expense, but the advantage of using Bessel filters is that they have the best phase performance of the three basic types.

There are also advantages and disadvantages to different orders of filter slopes. A crossover network with first-order filters—which means slopes of 6 dB per octave beyond the cutoff points—is inherently phase coherent. The two (or more) crossover outputs combine perfectly. (Figure 3 shows the response of a typical two-way first-order crossover network.) On the negative side, the rolloff such a network provides is not very sharp, so the drivers in the speaker system must be capable of handling a significant amount of input signal beyond the crossover points. The large amount of overlap in a first-order crossover requires the drivers to be well matched in terms of their frequency response and phase coherence.

Second-order Butterworth crossovers (see Figure 4) have been the mainstay of theater-style speakers for more than five decades. The rolloff slope is fairly sharp (12 dB per octave) and thus doesn't make ridiculous demands on the drivers. The disadvantage is that the outputs in a system of this type will be 180 degrees out of phase with each other at the crossover point(s). This is usually remedied by switching the wires going to one driver so as to invert the phase of its input, resulting in an in-phase acoustic output.

Nevertheless, whether the crossover's phase inversion is remedied or not, a speaker using second-order Butterworth will depart from flat response at the crossover point, where the outputs from the filters are equal. If you electrically sum the two signals in phase, you get a 3-dB response peak, while if they are opposite in phase you get an infinite null. The acoustical outputs of speaker drivers don't sum that precisely, so the result is usually just a small peak or dip—but it's enough to have made second-order Butterworths fall into disfavor.

The third-order Butterworth crossover (Figure 5) combines a fast rolloff (18 dB per octave) with good phase characteristics. The two filter outputs sum well in either polarity, and the resulting phase response is a gradual shift over the audio range. On the negative side, a third-order network cannot be corrected for speaker time-offset effects (when the drivers are not aligned in the same acoustic plane) by using a time-delay circuit.

The fourth-order Butterworth crossover suffers from the same problem as the second-order Butterworth: the outputs are 180 degrees out of phase at the crossover points. The 24-dB-per-octave slope of a fourth-order filter greatly minimizes interaction between the drivers in the crossover region, but this advantage is overshadowed by the large phase shift. Moreover, while the types of crossover previously discussed can all use passive (unamplified) filters, the complexity of a fourth-order network makes it economically impractical to produce a passive design.

A special case of the fourth-order Butterworth crossover is the fourth-order Linkwitz-Riley crossover (Figure 6). Again, its slope is 24 dB per octave, but the outputs of the individual filters are down 6 dB at the crossover point, instead of the standard 3 dB. Although the crossover point is 3 dB lower, this does not cause an audible dip in the frequency response because of the phase characteristics of the two drivers.

Simple in concept and elegant in performance, the fourth-order Linkwitz-Riley offers the best set of compromises of all the designs we've discussed. Its outputs sum neatly for a flat frequency response, they are in phase at the crossover frequency, and their phase relationship permits time correction for drivers that are not in the same acoustic plane. The third-order Butterworth and the fourth-order Linkwitz-Riley are the filters of choice for most speaker crossovers, although some first-order filters are still being used in inexpensive speakers for reasons of economy.

Whatever type of crossover is used in a speaker system, the success of the overall design can only be judged by listening to how the speaker sounds. Any speaker design represents various tradeoffs. Understanding the basics of crossovers, however, will help you to narrow your selection to the speakers that are most likely to satisfy your listening tastes, budget, and system requirements. □