Crossover Networks
from A to Linkwit-Riley

by

Richard Chinn

Rick Chinn is a working sound engineer who has been involved in all facets of recording, sound reinforcement and acoustical design for the past fifteen years. He has written articles for <u>Modern Recording and Music</u>, <u>Music and Sound Output</u> and <u>A/V Video</u> and has worked for TAPCO and Kaye-Smith studios.

Crossover Networks form A to Linkwitz-Riley

Crossover networks have been with us for quite a while.1 Considering how long they've been around, you'd think that we had them figured out by now. As you will see, this is hardly the case. In recent years, new research has brought additional facts to light. With each new bit of knowledge, another piece of the puzzle falls into place.

What Is A Crossover?

It is hard to make a loudspeaker that is capable of handling the entire audio spectrum. It is more difficult to make one that does this well. It is much easier to make a loudspeaker capable of only handling a limited portion of the audio spectrum.

The earliest multi-way systems used only two loudspeakers (drivers). They were called two-way systems because the audio spectrum was split into two-parts and fed to two drivers. You can still find large two-way systems in use today in movie theatres and in sound reinforcement. Two-way systems are by no means the be-all and end-all of high-fidelity. You can find commercially made speaker systems that range from one-way to five-way and beyond. More is not necessarily better. It's interesting to note that in most recording studios, the control-room monitor speakers are still two- or three-way designs, based on the old theatre systems of the 1930s. The multiple-driver approach is the basis of contemporary loudspeaker system design.

The crossover network's (okay, from now on, we're just going to call it the crossover.) role in all of this is to divide the incoming audio signal into sub-ranges of the entire audio spectrum. Typically, there is one crossover output for each loudspeaker in a multi-way design. Since the limiting factor is the capability of the drivers used to make up the system, the drivers dictate the choice of crossover frequency(s).

For example, sending excessive low-frequency (bass) energy to a tweeter (high-frequency speaker), is usually an easy way to send it to its grave. The tweeter's cone is not capable of moving far enough to reproduce the lower frequencies. If the tweeter's cone isn't damaged by the excessive movement, then the voice coil may burn up because of the extra energy content of the lower frequencies.

There's more to the choice of crossover frequency than just the capabilities of the drivers involved, but for now, this will suffice.

1. J. K. Hilliard, "Loudspeaker Dividing Networks," Electronics, January, 1941.

How Do They Work?

A crossover is nothing more than a pair (more if we aren't talking about a two-way system) of electrical filters. These filters are known as highpass and lowpass filters. Systems other than two-way use bandpass filters for the intermediate ranges of the audio spectrum.
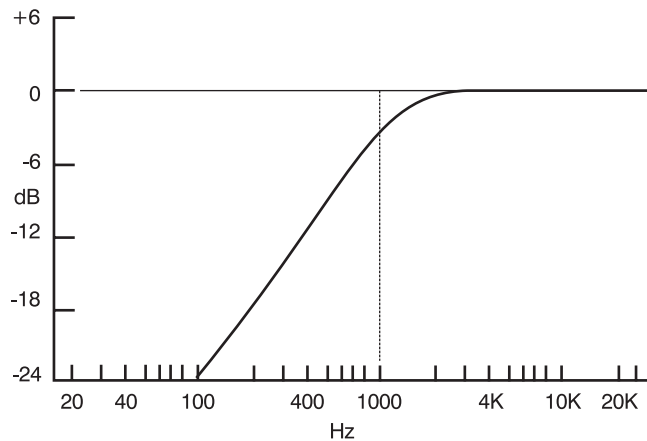
Figure 1. A 1000 Hz highpass filter

A highpass filter's output is shown graphically in Figure 1. As you can see, the output is zero at DC (0 Hz) and rises progressively at higher frequencies. The cutoff frequency of the filter is the frequency where the output is 3 dB down from the output in the level region of the graph. The cutoff frequency for our example is 1000 Hz. As you can see, the output progressively decreases as frequency decreases. If you were to listen to this signal, it would sound like a loud, tinny, transistor radio. A common misconception is the belief that there is no output below the cutoff frequency of the filter. A filter of this type is known in engineering circles as a "brick wall filter." A brick wall filter is a mathematical impossibility to achieve. Figure 2 shows the frequency response of such a filter.
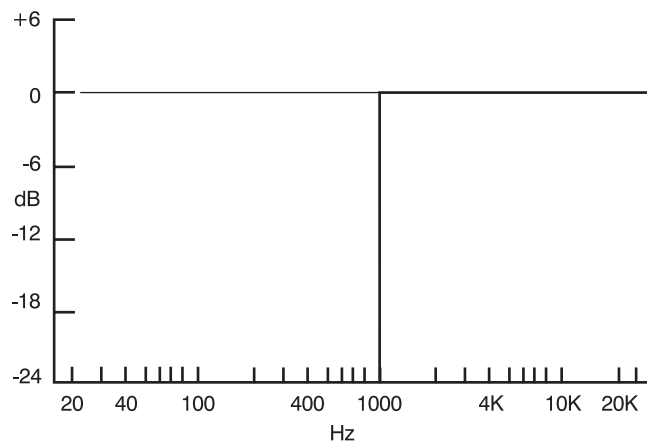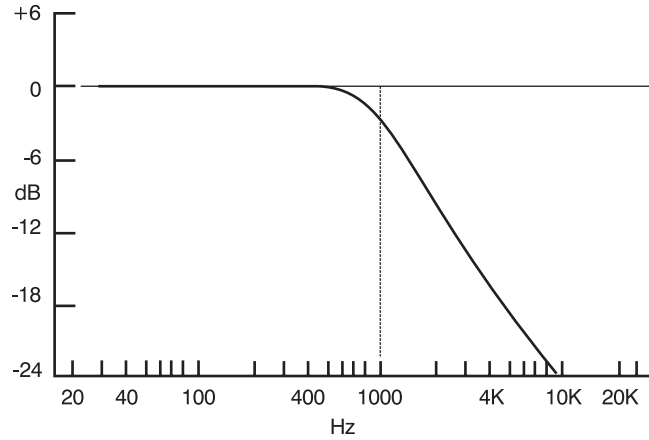
Figure 2. A brick wall filter

Figure 3. A 2000 Hz lowpass filter

Figure 3 shows a 1000 Hz lowpass filter. It's output is the inverse of the filter shown in Figure 1. If these two filters were used as a crossover network, what the crossover frequency would be? If you said 1000 Hz, you're right. The crossover frequency is the frequency where the two curves cross each other. Figure 4 shows the two curves overlaid on each other.
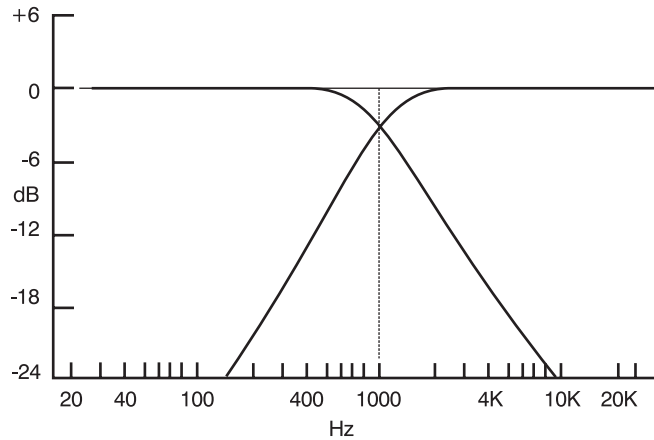

Figure 4. A 1000 Hz crossover

A bandpass filter is simply a lowpass filter followed by a highpass filter. The cutoff frequencies aren't necessarily the same, in fact they're usually quite different (like 500 Hz and 5000 Hz). Figure 5 shows a three-way crossover using the above frequencies. Figure 6 shows how these filters are connected to the loudspeakers.
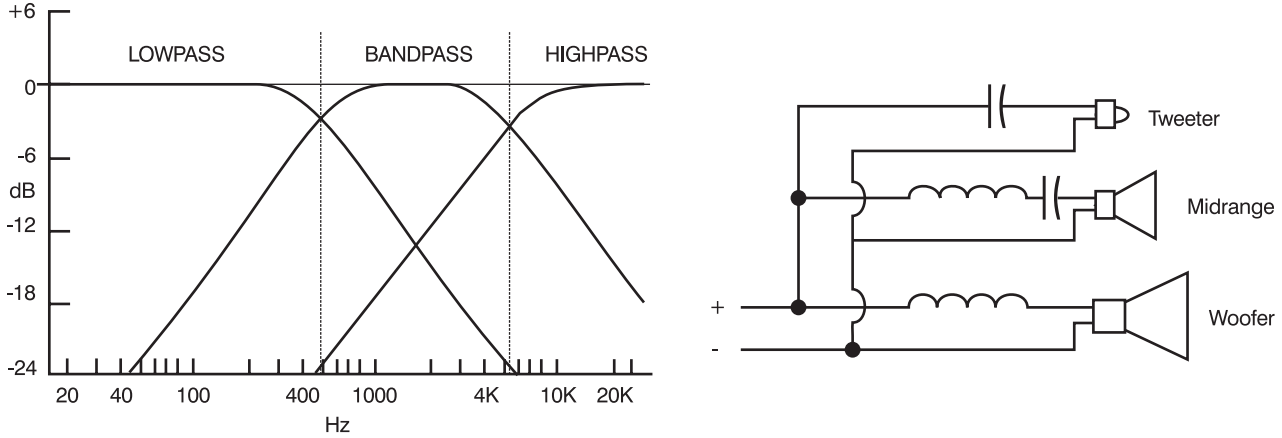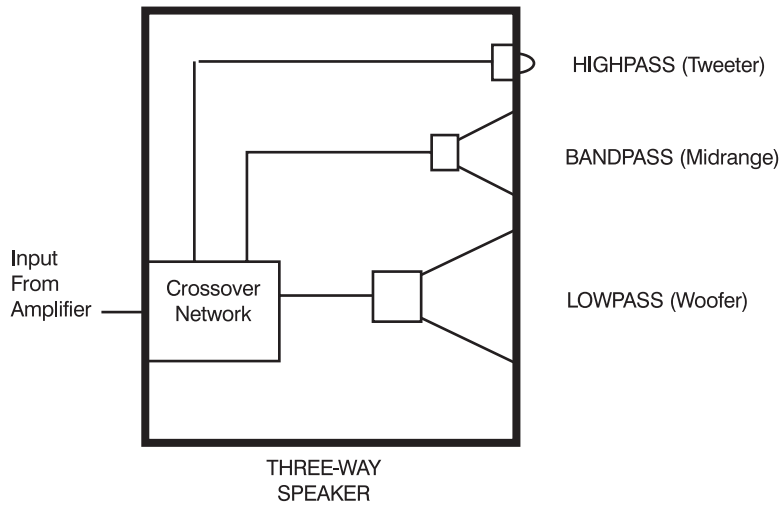

Figure 5. A three-way crossover

Figure 6. Connecting the crossover into the system

Types of Crossovers

Theoretically, the acoustical output of the crossover/speaker system should be the same as the output of a single perfect loudspeaker. This is not as simple as it sounds.

There are many different types of crossovers. Now in this context, the word type refers to something distinctly different than just the number of audio sub-ranges that the unit is capable of providing. What we're referring to here is the slope and roll off characteristic of each crossover output. This is equally applicable to a two-way as well as a five-way crossover design.

Crossover slope

The slope of a crossover (actually, the slope of the output of the filters that make up the crossover) is the rate of change of the output voltage for a given change in the input frequency, with the input voltage held constant. Typically the slope is stated in terms of dB/octave. For a number of mathematical reasons, the slope of a filter is almost always a multiple of 6 dB/octave. Let's put it another way. It's much more difficult to design for a slope that isn't a multiple of 6 dB/octave. Sometimes, the slope of the crossover is stated by describing it as "nth" order. In this case, the "order" is the order of the equation that describes the filter's characteristics. You can convert this to the slope by multiplying the order by 6 dB/octave. Thus, a second-order crossover has a slope of 12 dB/octave.

The effect of larger (steeper) slope characteristics is to make the individual filter characteristic look more and more like a brick wall filter. In more practical terms, it means less output in the region beyond the crossover frequency.

Crossover cutoff characteristic

In addition to slope, another attribute is the cutoff characteristic. Simply stated, this is the shape of the input/output curve as it makes the transition from the passband (level portion) to the stopband (where the slope is measured).

Although there are many different cutoff characteristics, there are enough similarities to group the different types into families based on the mathematical formula that defines the filter. This formula is known as the filter's transfer function. For one reason or another, mankind has chosen to name these different families after the mathematicians who identified them. The most common filters used for crossover filters have Butterworth, Tchebychev, or Bessel transfer functions. Here is a synopsis of each of them:

• Butterworth filters are maximally flat in their passband. The have the flattest passband response of the three types mentioned.

• Tchebychev filters roll off faster than Butterworth filters of the same slope. They do this at the expense of the flatness of the passband response. For this reason, they are not terribly popular as crossover filters.

• Bessel filters do not roll off as fast as either the Butterworth or Tchebychev filters. For most loudspeaker crossovers, fourth-order is a practical minimum if you want to use a Bessel filter. On the other hand, this filter has the best phase performance of the three.

An Overview of Crossover Networks

Now that you have had a glimpse of the world of crossovers, it's time to explore a few of the various types, and their advantages and disadvantages.

First-Order Networks

The first-order network produces a roll off characteristic of 6 dB/octave. It is inherently phase coherent, and the two crossover outputs combine perfectly. A typical circuit and some curves are shown in Figure 7.
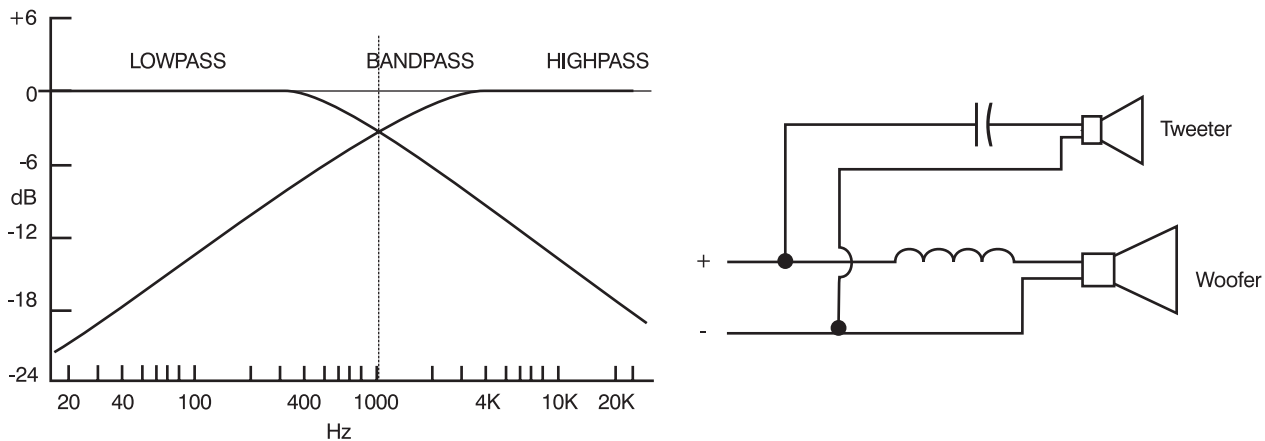

Figure 7. A first order crossover network

On the negative side, the first-order network's roll off is not very sharp, and the drivers must be capable of delivering (as well as handling) significant output below the crossover point. Furthermore, the large amount of overlap requires the drivers to match fairly well, both from a frequency response standpoint as well as from a phase shift standpoint. This is a tall order.

Second-order Butterworth Networks

The second-order Butterworth crossover has been the mainstay of theatre-style speakers for over 5 decades. The roll off characteristic is fairly sharp (12 dB/octave), and doesn't make ridiculous demands on the drivers. Figure 8 shows a typical second-order Butterworth crossover.
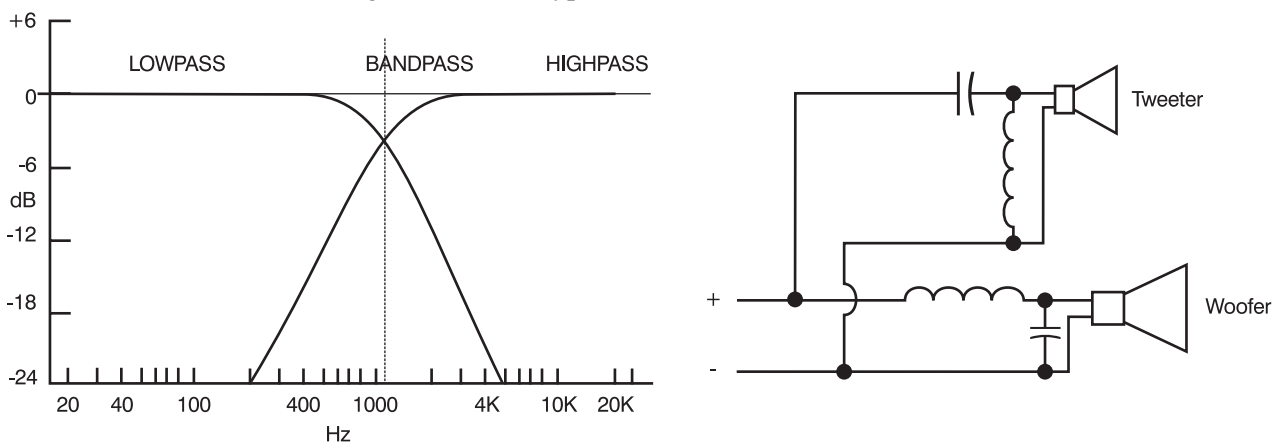

Figure 8. A second-order Butterworth crossover

On the other hand, at the crossover point, the two outputs are 180 degrees out of phase with each other. A common cure for this is to reverse the phase of the high-frequency driver by interchanging the two connecting wires. (Note that the net result is to place the high-frequency driver in-phase with the low-frequency driver.) Electrically speaking, if you sum the two outputs out-of-phase, you get an infinite null. Fortunately, loudspeakers don't sum acoustically that well, so the differences are either a small peak, or a small dip at the crossover frequency. Nevertheless, the second-order Butterworth crossover has fallen into disfavor.

Third-order Butterworth Networks

The third-order Butterworth crossover combines a fast roll off characteristic (18 dB/octave) with good phase characteristics. The two crossover outputs sum together well in either polarity, and the resultant phase response is a gradually changing shift over the audio range. Figure 9 shows a typical third-order Butterworth crossover.
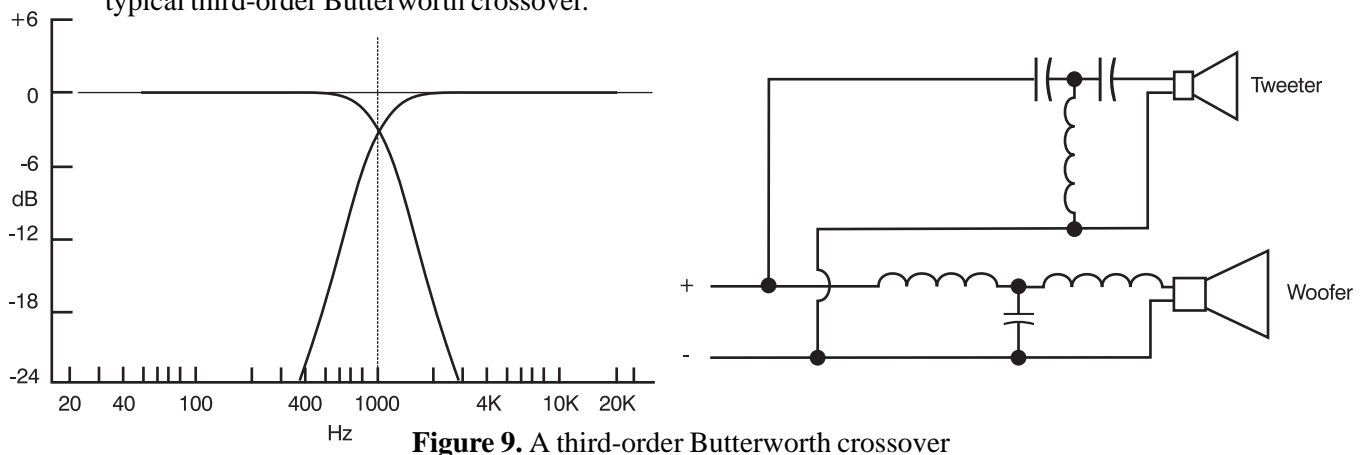

Figure 9. A third-order Butterworth crossover

On the negative side, the third-order network can not be corrected using time delay for the case where the loudspeakers do not radiate from the same vertical plane (which is the usual case!). This notion is discussed further a bit later in this paper.

Butterworth and Linkwitz-Riley fourth-order crossovers

The fourth-order Butterworth crossover suffers from the same problem that the second-order Butterworth crossover suffers from...the outputs are 180 degrees out-of-phase at the crossover frequency. True, the 24 dB/octave slope greatly minimizes the interaction between the drivers in the crossover region, but the phase problem overshadows this. Although the previous figures have shown passive networks, the complexity of a fourth-order network make it pretty economically unfeasible for a passive, high-level (speaker level) crossover. Figure 10 shows a typical active fourth-order Butterworth crossover.
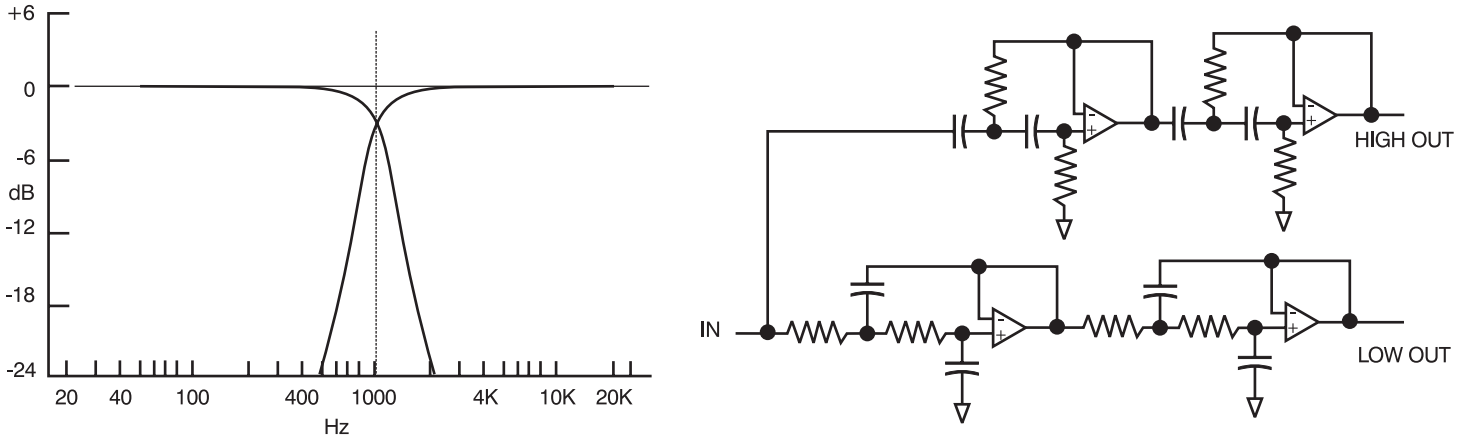
Figure 10. A fourth-order Butterworth crossover

A special case of the fourth-order Butterworth crossover is the fourth-order Linkwitz-Riley crossover. The slope is still 24 dB/octave, like the fourth-order Butterworth crossover, but the individual filter outputs are 6 dB down at the crossover point. This is what makes this crossover different from all the others. The usual implementation of this crossover is a simple series connection of two second-order Butterworth filters (two for the high-pass channel, and two more for the low-pass channel). Figure 11 shows a Linkwitz-Riley crossover.
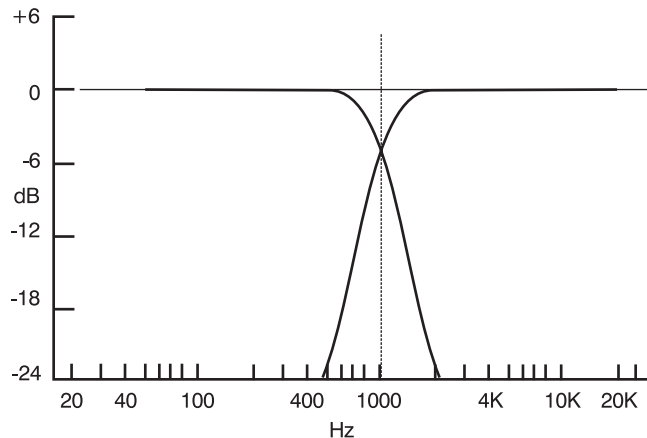

Figure 11. A Linkwitz-Riley crossover

Simple in concept, elegant in performance, the Linkwitz-Riley crossover achieves what all the others set out to do:

• The outputs will sum with flat frequency response.

• The outputs are in-phase at the crossover frequency.

• The phase relationship of the output allows time correction for drivers that are not in the same acoustic plane.

The Effects of Phase Shift

An unavoidable consequence of highpass, lowpass, or bandpass filter design is phase shift. It's way beyond the scope of this discussion to do anything but touch upon the subject. In a nutshell, any network that affects the amplitude of a signal will also affect its phase in a predictable manner. What is phase anyway? In a nutshell it is the time relationship of two signals. You've probably encountered a very basic phasing problem in connecting two loudspeakers in a stereo system. If the two systems aren't in-phase, the bass output partially cancels and the result is a thin sounding system. Reversing the wires to one of the speakers corrects the problem by inverting the phase of the signal going to that speaker. This is an example of a 180 degree phase shift. In crossovers, we're dealing with phase shifts that may start at 0 degrees, and gradually change to well over 360 degrees.

How does phase shift affect a crossover? Good question, because if we ignored the phase shift, the rest would be easy. The phase shift caused by the crossover filters affects two things:

• The ability of the crossover/loudspeaker system to reproduce transient-type (pulse) waveforms.

• The flatness of the combined acoustical output of the two (or more) drivers.

• The radiation angle of the loudspeaker's output. Different crossovers cause differences in the angle at which the combined output of the various drivers reaches a maximum. Figure 12 illustrates the concept of radiation angle. The change in radiation angle is also frequency sensitive. At frequencies near the crossover point, both drivers contribute to the total acoustic output. The change in radiation angle occurs because of the frequency sensitive phase shift that occurs in the crossover region. At frequencies far removed from crossover, the radiation patterns shifts to that of the individual drivers.
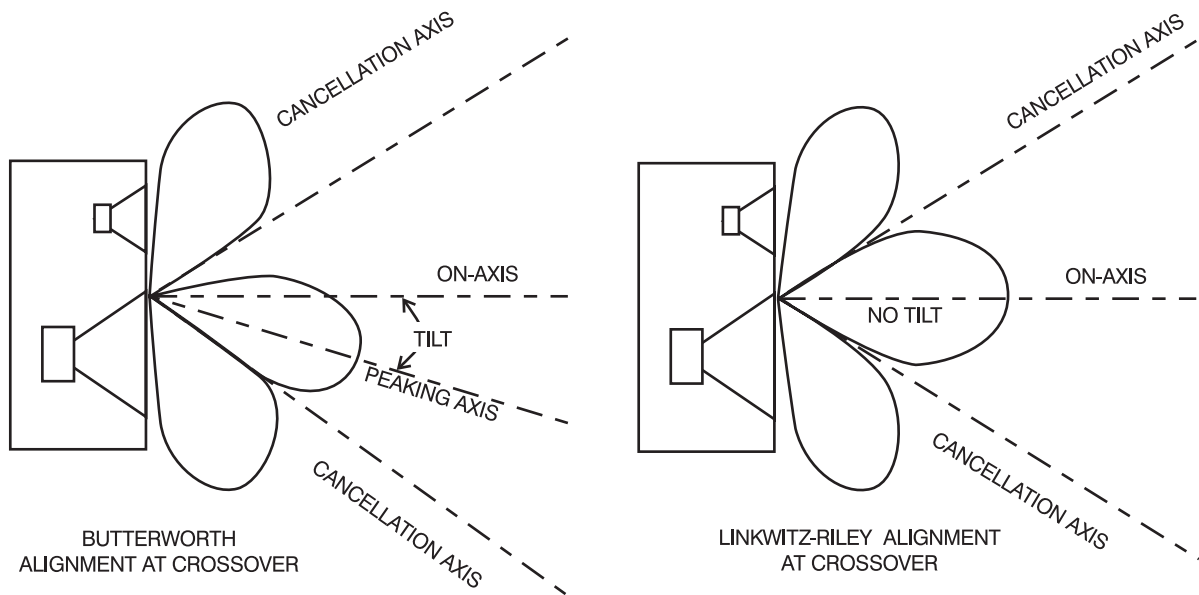

Figure 12. The radiation angle of a loudspeaker

The bottom line: The choice of crossover slope and cutoff characteristics is governed by:

• System design considerations

• The degree to which the combined acoustical output of the various drivers is flat

• The effect of crossover phase shift on the angle of radiation

• The effect of crossover phase shift and driver placement on the transient response of the system.

Crossover and loudspeaker phase alignment

In order for a loudspeaker system to accurately reproduce a pulse waveform, the wavefronts from each driver must arrive at the listener's ears at the same time. Optimizing this characteristic of a loudspeaker's performance is known as phase alignment or time alignment. Figure 13 should make this concept clearer.
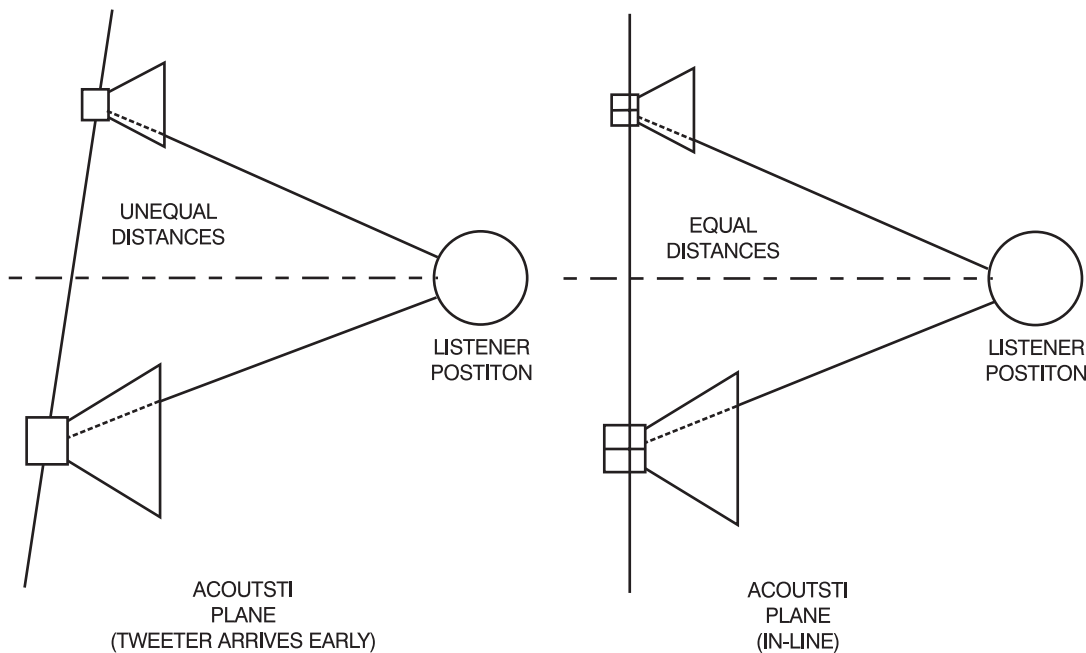

UNEQUAL DISTANCES

LISTENER POSTITON

ACOUTSTI PLANE (TWEETER ARRIVES EARLY)

EQUAL DISTANCES

LISTENER POSTITON

ACOUTSTI PLANE (IN-LINE)

Figure 13. Vertical Driver Alignment

Since sound travels at approximately 1100 feet/second in air, a distance of about 12 inches represents a delay of approximately one millisecond (0.00l sec) at 1000 Hz (it's actually .885 ms/ft). The problem of phase alignment is worst at the crossover frequency, because both drivers are contributing to the overall acoustical output of the system. Thus, any time delay between the sources (woofer and teeter) results in uneven frequency response in the region around the crossover frequency.

A simple way of minimizing this problem is to physically adjust the vertical alignment of the various loudspeakers until their acoustic centers are in alignment. This makes the driver-to-listener distance the same for each driver, which then puts them on the same acoustic plane.

Putting It All Together

Currently, three different sorts of crossovers are popular with loudspeaker designers:

- First-order crossovers still find application because they are inexpensive. The crossover outputs do sum properly, but the 6 dB/octave slope puts ridiculous demands on the drivers.

- The third-order filter is popular because it at least sums flat and for many applications (like subwoofer crossovers) is more than adequate. Although its phase response makes it impossible to align the loudspeakers for optimum phase response, the steep slope is still a decided advantage in terms of the demands made on the drivers.

- The fourth-order Linkwitz-Riley crossover offers the best set of compromises of all of the crossover types we've discussed. Except for the first order crossover, the Linkwitz-Riley crossover allows the drivers to be aligned for optimum phase response by either physical alignment or by means of electronic phase delay. In bi-amplified systems, where the crossover point is above 250 Hz, this is the best choice.

References:

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