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Also: Ed Long On Crossover Design ◼ Testing Amplifiers with a Bridge ◼ Ralph West on Speaker Response Curves

Crossover Network Design

Edward M. Long *

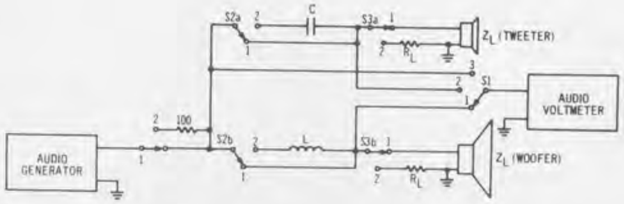
OVER THE YEARS, many articles, chapters of books and whole books have been written on the subject of crossover network design. While a practical crossover network is obviously intended for use with real loudspeaker drivers (woofers, tweeters, etc.), the design information usually treats such drivers as purely resistive load terminations. Often, very little, if any, attention is paid to the ultimate end use of the network: the blending and phasing of the acoustical output of the various drivers to produce a smooth total acoustical output from the loudspeaker system. This is not to say that such discussions are worthless, but they must be treated as only a good starting point. Many loudspeaker systems, in the past, were made up using only the simplest theoretical approach. For example, an 8 ohm woofer was matched to an 8 ohm tweeter, and, of course, both were connected to an 8 ohm crossover network. Asking a question like "When is an 8 ohm woofer really like an 8 ohm woofer?" would immediately stamp one as a trouble maker! In recent years however, this and other interesting questions have been raised with regard to one of the most important aspects of loudspeaker system design: the crossover network.

The proper design of a crossover network should proceed through three stages of development. The first stage treats the various loudspeaker driver impedances as if they were pure resistances, i.e. 4, 8, 16 ohms, etc. This is usually the only stage of development presented in almost all the available literature devoted to crossover network design. Since so much has been written elsewhere concerning this stage of crossover design, including various possible configurations and formulas for determining component values, we will pass on to the next stage of development.

In this second stage we must consider that the loudspeaker drivers are not pure resistances but complex and varying impedances. One author, while acknowledging this fact, continues his discussion of crossover networks using the convenient assumption that the terminating impedance is constant, with the admonition that a fair proficiency with computers is required to do otherwise.[1] There is a simple way out of this predicament. Assuming that a practical problem consists of designing the right crossover for a given set of loudspeaker drivers, one can use part of the problem in finding the solution! This is shown in Fig. 1. An audio signal generator acts as the function generator and a meter is used as the readout device. In essence we have an analog computer in which the loudspeaker drivers and their associated network components act as their own analog.

Using the setup shown in Fig. 1, one can plot the voltage appearing at the outputs of the high frequency and low frequency sections of the crossover network, both into the resistive load terminations and into the reactive load presented by the actual tweeter and woofer impedances. The impedance of the tweeter and woofer can also be plotted as well as the impedance of the network with resistive loading and the reactive loading presented to the network by the actual loudspeaker drivers.

The accompanying table shows the switch positions for the various tests. A simple, first order, constant resistance network is shown but higher order networks can easily be substituted. Figure 2 shows the results of crossover network electrical input and output measurements with both resistive and reactive (woofer and tweeter) loads. The actual system consists of a 10 in. woofer and a 3½ in. tweeter. It can be easily seen that the varying impedances of the woofer and tweeter do have a very definite effect upon the output of the crossover network. The rising impedance of the woofer, with increasing frequency, causes the voltage across the woofer to be higher than that obtained when a resistive load is substituted. Of course the actual power delivered to the woofer at



	TEST 1 Impedance of Woofer	TEST 2 Impedance of Tweeter	TEST 3 Output of Low Freq. Section R Load	TEST 4 Output of Hi Freq. Section R Load	TEST 5 Output of Low Freq. Section Z Load	TEST 6 Output of Hi Freq. Section Z Load	TEST 7 Impedance of Network R Load	TEST 8 Impedance of Network Z Load
S1	1	2	1	2	1	2	3	3
S2	1	1	2	2	2	2	2	2
S3	1	1	2	2	1	1	2	1
S4	2	2	1	1	1	1	2	2

Fig. 1—Test set-up for making crossover network measurements.

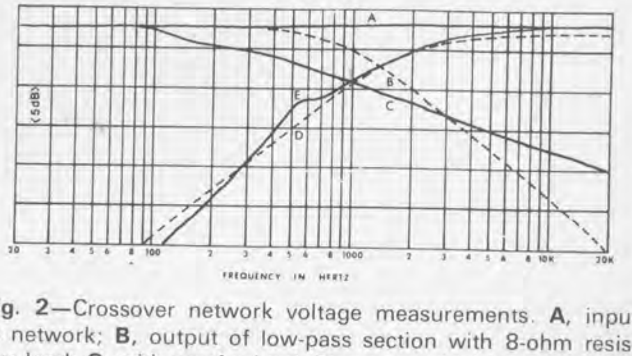


Fig. 2—Crossover network voltage measurements. **A**, input to network; **B**, output of low-pass section with 8-ohm resistive load; **C**, with woofer load; **D**, output of high-pass section with 8-ohm resistive load, and **E**, with tweeter load.

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* **Manager of Acoustics, Quadraflex Industries, Inc.**

any frequency is the result of the square of the voltage across the woofer divided by its impedance.

The previous two stages of development have allowed the preliminary crossover component values to be chosen and their effects to be measured, with both resistive and reactive loads. It is the final stage of development which is the most important, however. In this final stage, the acoustical output is measured. The microphone was placed 18 in. from the loudspeaker system and was located on a line between the woofer and tweeter. The woofer and tweeter were mounted flush to the face of the enclosure and as closely together as possible.

Figure 3 shows the acoustical output of the two-way system measured before and after changes made in the crossover network values. The dashed frequency response curve of Fig. 3A was obtained using the crossover network values calculated by assuming that the impedances of the woofer and tweeter were constant. The acoustical outputs of the woofer and tweeter were also assumed to be constant. Of course, practical loudspeakers do not exhibit perfectly flat frequency response characteristics. In this case, the frequency response of the system shows an excess of output through the midrange. By treating the crossover network and loudspeaker drivers as an electrical input, acoustical output combination, adjustments may be made to obtain the desired results. This may appear a bit facetious at first. Many times however, one will see a designer trying to correct an unsatisfactory speaker system design by selecting a different theoretical crossover frequency. Often, the desired results can be obtained by merely adjusting the network values selected initially, instead of redesigning the network for a new crossover frequency. The solid curve of Fig. 3B was obtained in this manner. Figure 3 also shows the loudspeaker system impedance characteristics with the modified (3D) and unmodified (3C) crossover networks into both resistive and reactive loads. The modified version might, more correctly, be called a low pass-high pass filter, since it is not truly a crossover network in the classical sense. Besides keeping the high frequencies from reaching the woofer and the low frequencies from reaching the tweeter, the modified network also acts to shape the response, thus achieving a flat acoustical output.[2] The midrange hump in the impedance curve of Fig. 3D is the result of this response shaping function of the crossover network. This hump causes a rejection of electrical input power by the network in the midrange and results in the solid frequency response curve of Fig. 3B. It should be mentioned here that the curves shown in Figure 2 were made after the modification of the crossover network and result in the acoustical output shown by the solid curve of Fig. 3B.

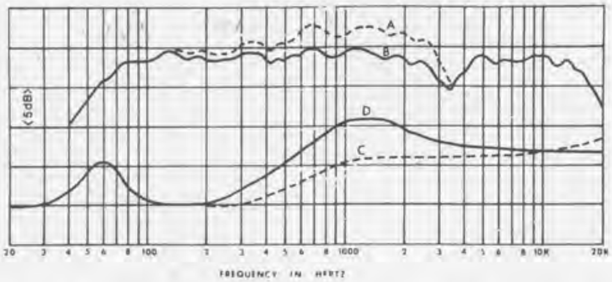


Fig. 3—A, frequency response of loudspeaker system with mathematically designed crossover network; **B**, modified network; **C**, impedance of system A, and **D**, impedance of modified system B.

Figure 4 shows the acoustical output of the woofer and the tweeter and the resulting combined acoustical output. There appears to be a small dip in the acoustical output at about 3kHz. Inspection of the frequency response curve of the tweeter output does not show any dip in the acoustical output at this frequency. The woofer is falling off rapidly at this frequency but since its output is at a much lower level than that of the tweeter, one would not expect such a dip to be the result of strictly amplitude effects. It has been determined that, as in the upper cutoff frequency region of a loudspeaker, the phase of its acoustical output begins to change and this will result in the acoustical output being 90° out of phase with the electrical input in the crossover region.[3,4] The first order network used in this design will cause the voltages across the woofer and tweeter to be 90° out of phase. By reversing the leads to the woofer and tweeter so that they are out of phase with respect to a d.c. voltage applied across their respective terminals, the acoustical output can be made to add properly.[5] This will be true throughout most of the overlap range of the woofer and tweeter. At about twice the crossover frequency there will be a small phase cancellation which is difficult to avoid completely. The spacing of the drivers will effect both the frequency and severity of this dip.

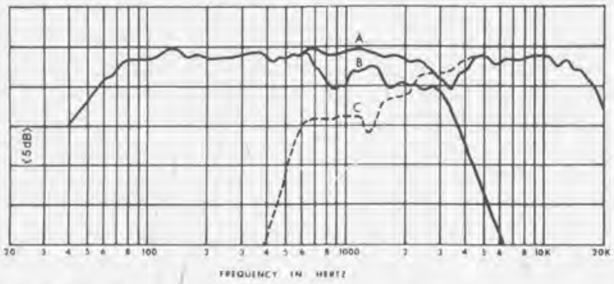


Fig. 4—A, frequency response of system; **B**, response of woofer; **C**, response of tweeter. All curves are with crossover network of Fig. 3D.

Figure 5 shows the effect of reversing the connections to the woofer and tweeter upon the acoustical output. The choice of connections is quite obvious. There are some who contend that such attention to phasing the acoustical output of the drivers has no real practical value since under reverberant conditions the total power output of the loudspeaker system will be the same regardless of phase. It is also contended that measurements made with a microphone, placed closely to a loudspeaker system usually show these effects of improper attention to phase and therefore the measurements should be made at a distance. It is the author's contention that a design which results in a loudspeaker system that produces a homogeneous plane wave radiation, without wierd phasing effects, as close to the face of the baffle as possible, is very desirable.

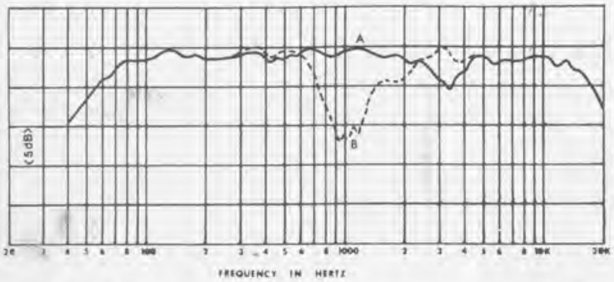
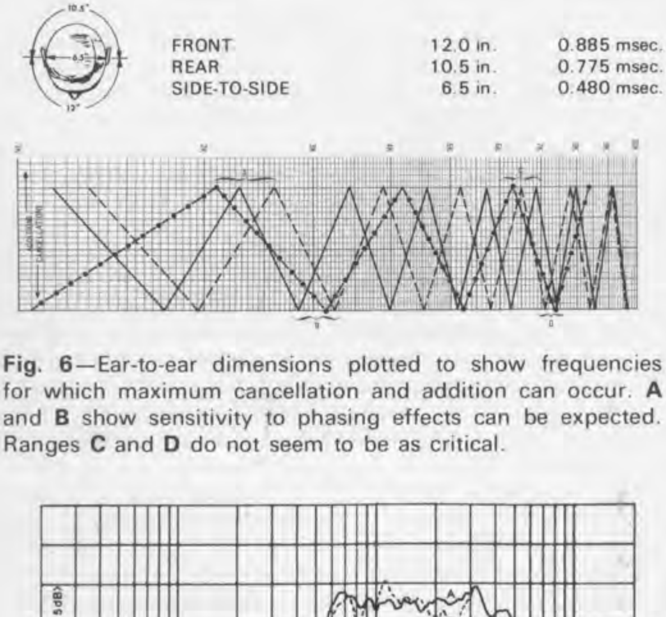


Fig. 5—Result of network-driver phasing. **A**, woofer and tweeter connected out of phase to d.c.; **B**, woofer and tweeter connected in phase to d.c.

Most discussions about what we can measure and what we can hear do not take into consideration a very basic distinction between the two processes. Measurements are usually made with a single microphone occupying a single point in space at any one time. The human listener has two ears which occupy two points in space with a finite distance between them. (Hopefully this distance is filled with more than space!)

Figure 6 shows a human head and three ear-to-ear dimensions. Each of these dimensions is also plotted in terms of maximum addition and cancellation of sound waves. The velocity of sound used in 1129 feet per second which yields a transit time for sound waves of 0.886 milliseconds per foot. When the sound enters one ear slightly before it enters the other ear, and this slight difference in arrival time represents one half wavelength at a particular frequency, then the listener can sense an out of phase condition. As the arrival time differential increases to one full wavelength, the listener will sense everything as being normal and comfortable. Of course, we are considering here only steady state and not transient conditions. To get an idea of the effects being discussed, one can connect a simple phase reversing switch to a pair of headphones. Although this is not an exact equivalent of what one experiences when listening to a loudspeaker system which exhibits phasing defects, it will give clues regarding how to listen for phasing effects between the drivers of a loudspeaker system. The interesting thing about the plots of frequency vs. addition and cancellation shown in Fig. 6, is the way the three ear-to-ear dimensions cause the additions to cluster in the 2100Hz - 2600Hz region (A) and the cancellations to cluster from 2850Hz to 3250Hz (B). Another cluster of additions and cancellations occurs in the 6300Hz - 6900Hz (C) and 7100Hz - 7400Hz (D) regions, respectively. The most critical for crossover phasing, based upon actual listening experiences, would appear to be the 2000 - 3500 Hz region. The frequencies of addition and cancellation for the shortest ear-to-ear dimension, through the head, is plotted for reference only since, hopefully, very little sound will pass directly through the head!



FRONT	12.0 in.	0.885 msec.
REAR	10.5 in.	0.775 msec.
SIDE-TO-SIDE	6.5 in.	0.480 msec.

Fig. 6—Ear-to-ear dimensions plotted to show frequencies for which maximum cancellation and addition can occur. **A** and **B** show sensitivity to phasing effects can be expected. Ranges **C** and **D** do not seem to be as critical.

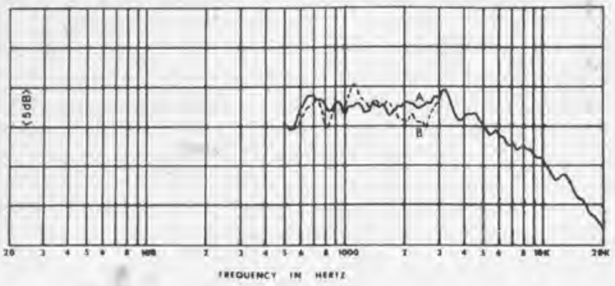


Fig. 7—Frequency response of loudspeaker system showing results of phasing. **A**, woofer, and tweeter out of phase to d.c.; **B**, woofer and tweeter in phase to d.c. See text for details of measurement.

A well-phased system can be listened to at close range as well as at a distance. A poorly phased system must be listened to at a distance and preferably in a fairly reverberent environment.

Figure 7 is an example of how even a measurement using a single microphone, under listening room conditions, can detect phase differences in a loudspeaker system. The microphone was placed 12 feet from the loudspeaker system. The loudspeaker system was placed with its back to the microphone and facing a wall! The reverberation (RT60) time measured under the same conditions was about 0.3 seconds through the 1000 to 3000 Hz range. The curves indicate that the microphone could measure the effect of reversing the phasing of the woofer and tweeter under these extreme conditions. Listeners could easily detect this phase reversing process.

In conclusion it must be mentioned that most loudspeaker systems designers are paying more attention to the acoustical phasing of various drivers than in the past.

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