PROJECT NOTES / ENGINEERING BRIEFS

ELECTRICAL VERSUS ACOUSTICAL PARAMETERS IN THE DESIGN OF LOUDSPEAKER CROSSOVER NETWORKS

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The current interest in distortionless crossover network design prompts the following observations. First, while Ashley and Henne [1] mention that listening tests do not necessarily agree with theoretical criteria, neither their paper nor Small's [2] suggests the practical step of measuring the combined acoustical output from the system rather than the electrical input to the loudspeakers as a guide to what is "ideal" and what is not. In this way, Small's requirement that the two loudspeakers be equalized to have identical amplitude and phase characteristics through the crossover region is not an absolute necessity, since the needed equalization becomes an integral part of the network design.

Second, a factor that helps explain the discrepancy between the theory and audible results is the relation of direct on-axis sound to total radiated acoustic power through the crossover region. This deserves more detailed discussion than is supplied in Small's otherwise excellent analysis.

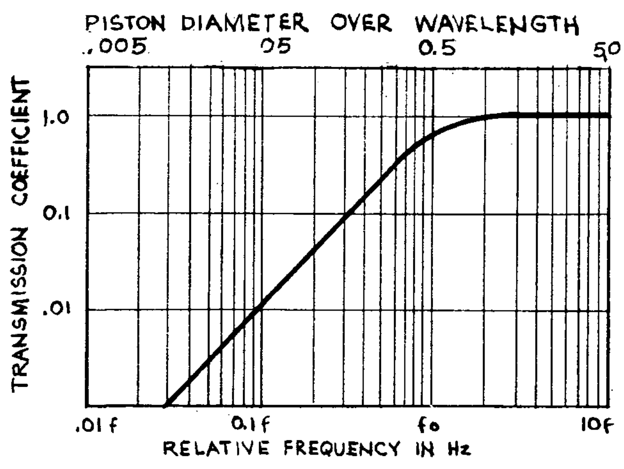

Fig. 1. Transmission coefficient versus frequency for circular piston in very large flat baffle.

Fig. 1 is derived from the familiar graph of the radiation resistance seen by a circular piston operating in a very large flat baffle. Following the example of Locanthi [3], the effect is shown as transmission coefficient, drawn as a simple 6-dB per octave rolloff below f_0. f_0 is the frequency of ultimate loading, which is assumed to be that frequency at which the diameter of the piston is $\lambda/2$. (These are simplifications, but sufficiently accurate for our purpose.)

A mass-controlled piston operating below f_0 exhibits uniform on-axis response and uniform power response. Above f_0, on-axis response remains uniform, but power response rolls off because the device becomes more and more directional. A "resistance-controlled" (constant velocity) piston exhibits uniform power response above f_0, but on-axis response rises because of increasing directionality unless a dispersive device, such as an acoustic lens, is used. Practical loudspeakers generally fall somewhere between the two categories [3].

Fig. 2a represents a loudspeaker mounted in a very large flat baffle and radiating into a semireverberant listening room. An auditor is located on the axis of the loudspeaker at some arbitrary point at least several diameters away. For a voltage $\bar{e}$ across the voice coil terminals, a sound pressure $\bar{p}$ is produced at the auditor's location. This sound pressure is made up of a direct component plus a reverberant component. In a typical home listening situation, the reverberant component predominates.

In Fig. 2b a second identical loudspeaker has been added. The two are connected in parallel (the simplest network of all) and mounted as close together as possible, following Small's dictum that ". . . it is the only way to ensure uniform addition of the driver outputs for both direct and reflected sound throughout the listening area." The sound pressure at the auditor's location is the vector sum of the pressures produced by the two loudspeakers.

Fig. 2c shows the same two loudspeakers separated by a distance equal to several wavelengths. The axes of the two loudspeakers intersect at the auditor's location, and

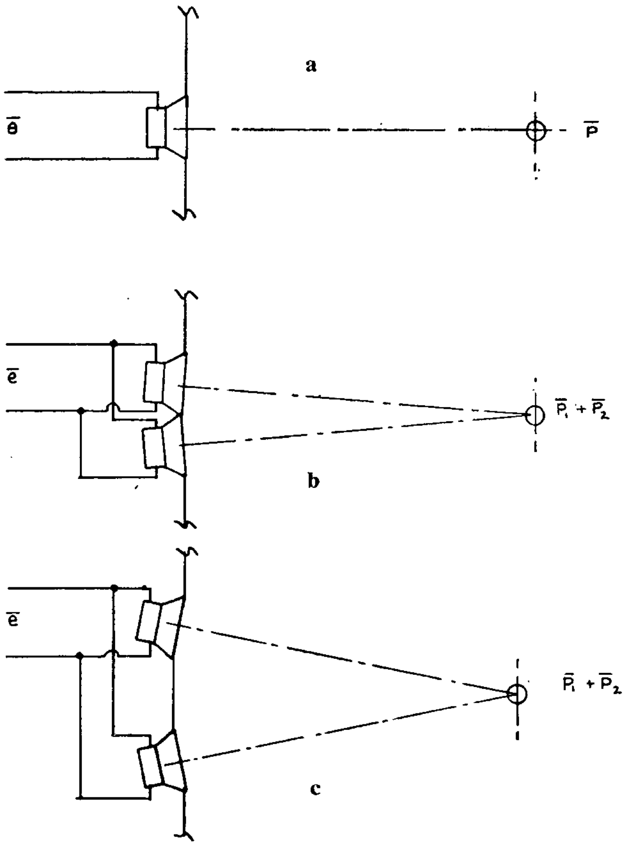

Fig. 2. Comparison of the performance of **a**, a single loudspeaker with **b** two such loudspeakers mounted very close together and **c** mounted several wavelengths apart.

the distance from the auditor to either speaker is the same as in the preceding examples.

Suppose that, in all three situations, the loudspeakers are operated at frequencies well below f_0. In Fig. 2b their outputs combine in phase through a full 180° solid angle. By connecting two speakers in parallel we have doubled the electrical power input, yet the acoustical power output has gone up 6 dB, or a factor of four. This is explained by the fact that the combined radiating area of the two pistons moves f_0 down a half-octave and correspondingly raises the transmission coefficient 3 dB. In this instance, therefore, both direct and reverberant sound pressures are raised 6 dB compared with a single speaker.

However, if the speakers are widely separated as in Fig. 2c, the transmission coefficient remains unchanged. Therefore, although $\bar{p}_1 + \bar{p}_2 = 2\ \bar{p}$ for direct sound at the auditor's location, sound pressures throughout the listening room add in random phase, and total acoustic power is doubled, compared with a single speaker . . . the change in reverberant sound pressure is 3 dB less than the change in direct sound pressure.

What happens if the loudspeakers are operated at frequencies above f_0? Keeping our attention at Fig. 2c, there are no changes in the relationships. Compared with a single speaker, direct sound pressure increases 6 dB, but reverberant sound pressure increases only 3 dB.

In the situation of Fig. 2b, even though the speakers are mounted as close together as possible, there can be no increase in the transmission coefficient beyond unity. Again, therefore, direct sound pressure increases 6 dB while reverberant sound pressure increases only 3 dB. It seems that close spacing, by itself, is not enough.

The implications for practical crossover network design are discouraging. For most "constant-voltage" networks to produce the intended results, not only must the two loudspeakers have identical characteristics through the crossover region and be mounted very close together, they also must be small compared with any wavelength through the crossover region. Consider a 12-inch woofer and 3-inch midrange radiator; if we allow only one octave on either side of crossover rather than the two octaves recommended by Small, the highest permissible crossover frequency is still only about 250 Hz.

While a 250-Hz crossover is not common, it is certainly possible. But, maintaining the same philosophy in the high-frequency range requires closely coupled direct radiators having diameters less than 1 inch. Even if one assumes this to be within the realm of possibility for a home loudspeaker system, there remains the problem of high-quality high-power loudspeaker systems for theatres and auditoriums, where requirements dictate that transducers (whether direct radiators or horns) be operated above f_0.

A possible answer to the dilemma is to drive high- and low-frequency loudspeakers in quadrature. Under this condition, referring again to Fig. 2, for frequencies

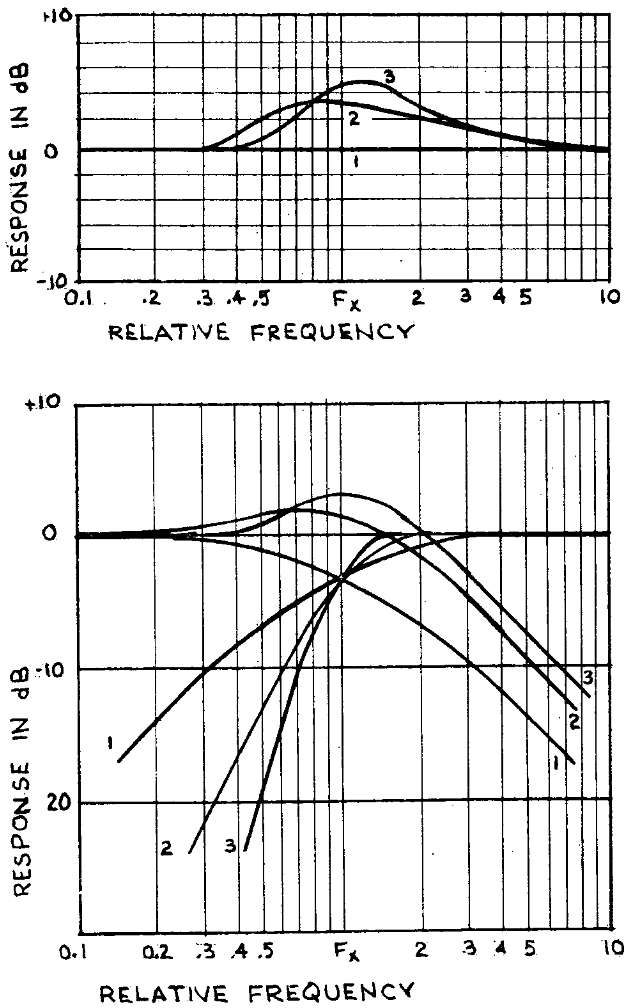

Fig. 3. Frequency response of asymmetrical constant-voltage crossover networks. **a.** In terms of power response as arithmetic sum of both channels. **b.** In terms of two channels independently [1].

above *or* below f_0, both direct and reverberant sound pressures are 3 dB greater than for a single speaker. It would seem, then, that for uniform response with practical loudspeakers, an ideal network not only should meet criteria for constant-voltage transfer and phase linearity, but also should provide a constant 90° phase difference between the two outputs and unity power transfer when the outputs are summed arithmetically. Which somehow brings us back to the good old first order 6-dB per octave constant-resistance configuration.

For example, Fig. 3 compares the response of the first-order constant-resistance network (curve 1 in both graphs) with that of second- and third-order asymmetrical constant-voltage networks. When the higher order networks are used with loudspeakers operating above f_0, one can expect a hump in perceived response through the crossover region because reverberant response sums as the total power from the two channels.

One might consider making use of the 90° phase relationship (mentioned by Small) between a resistance-controlled horn-type tweeter and a mass-controlled cone-type woofer. By connecting these to a second-order constant-resistance network, the 90° difference between transducer outputs should combine with the 180° difference between network outputs to achieve the desired quadrature shift. (Whether by accident or design, several commercial loudspeaker systems are made up of these three types of components.) Unfortunately, the added 90° phase difference increases, rather than compensates for, the inherent delay distortion of the network.

If one must make a choice, experience suggests that the ear is far more sensitive to a small change in level than to a small departure from phase linearity (delay distortion). This is confirmed by the experiments of Ashley and Henne. An interesting listening comparison between phase-linear and non-phase-linear network response can be set up quite simply by making use of another unique property of the first-order constant-resistance network. By reversing the phase of one set of outputs, delay distortion is introduced without affecting any of the other properties of the network.

Of course, one can reverse the phase of any crossover network, and often with substantially different results. For example, Small states that the second-order constant-resistance network has a null at crossover. Analytically yes, but this circuit is normally used with the phase of one channel reversed, giving (vectorially) a 3-dB bump rather than a null. Small and Ashley both indicate that the phase shift of the third-order constant-resistance network varies from 0° to 360°. But if one channel is reversed, the maximum phase shift is only 180° and delay distortion is similarly halved.

These effects are illustrated in Fig. 4. Frequency has been plotted linearly so that delay at any frequency is proportional to the slope of the curve at that frequency. For clarity the curves have been separated vertically and do not repreesnt absolute phase relationships. It is interesting that, when connected in reverse phase, all three networks have a maximum phase shift of 180°, or ± 90° from the crossover frequency. When outputs are summed vectorially, first- and third-order networks provide uniform voltage transfer, in contrast to the 3-dB peak of the second-order circuit. By definition, all three circuits provide constant (arithmetic) power transfer.

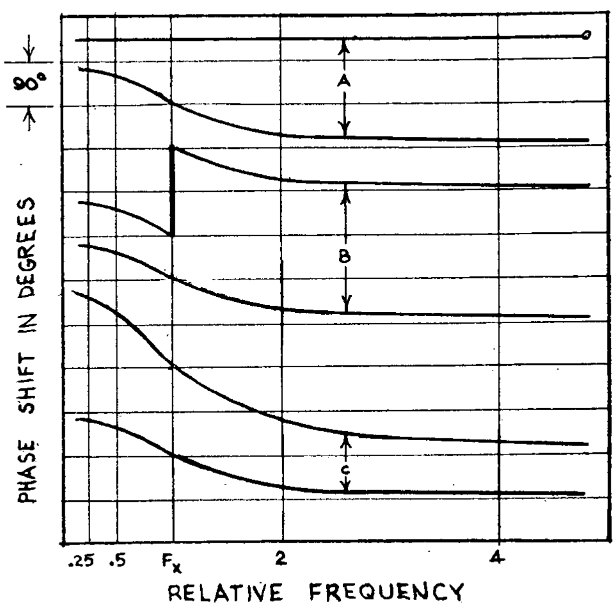

Fig. 4. Phase shift of summed outputs of constant-resistance networks. Lower curves show effect of phase reversal in one channel. **a.** First-order network. **b.** Second-order network. **c.** Third-order network.

In conclusion, because of the importance of the reverberant field in most listening situations, it is highly desirable that the crossover network provide uniform sound pressure level through the crossover region, for both direct and reverberant sound at the normal listening location. Therefore, when transducers have similar characteristics, first- and third-order constant-resistance networks give the greatest promise of achieving an imperceptible crossover; in the case where the transducers add a 90° phase shift, the second-order circuit probably is a better choice. Using operational amplifiers, higher order networks are quite practical and may prove to be even more desirable.

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About the Author: George L. Augspurger received his B.A. degree from Arizona State University at Tempe, M.A. from UCLA, and has done additional postgraduate work at Northwestern University. After working in sound contracting and television broadcasting, he joined James B. Lansing Sound, Inc. in 1958 where he served as Technical Service Manager and, later, as Manager of the company's newly-formed Professional Products Department. In 1968 he was appointed JBL's Technical Director.

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