

Stereophonic Earphones and Binaural Loudspeakers*

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Stereophonic sound is recorded for reproduction over spaced-apart loudspeakers. When earphones are substituted for loudspeakers the stereophonic space perspective is incorrectly portrayed. This paper describes two electrical networks which allow earphones to be used in place of loudspeakers without substantial loss of space perspective. One of them is designed to work from low impedance sources and feed into high impedance earphones. The second, which is a dual of the first, is more suited to medium impedance sources and low impedance earphones.

It is pointed out that these networks can also be used to convert a binaural program for reproduction over a stereophonic loudspeaker system. This is done by reversing the phase of one amplifier channel and of the corresponding loudspeaker.

INTRODUCTION

STEREOPHONIC sound is recorded for reproduction over spaced-apart loudspeakers. When earphones are substituted for loudspeakers the stereophonic space perspective is distorted. This paper describes two electrical networks which allow earphones to be used in place of loudspeakers without substantial distortion of space perspective.

BINAURAL VS STEREOPHONIC SYSTEMS

To bring the problem into sharper focus, the difference between a binaural system and a stereophonic system is shown in Fig. 1. In the binaural system, at left, two pressure responsive microphones are placed about 8 in. apart on a dummy head or baffle, at *A*. The microphones are connected through suitable lines and amplifiers to corresponding earphones worn by an observer at a remote location, *B*. The sounds from a performer at the extreme left, for example, reach the microphones at unequal times, and this is portrayed on the upper phasor diagram by the sound pressure *L* leading the sound pressure *R* by a corresponding phase angle ϕ . At the same time, the magnitude of *L* is apt to be somewhat larger than that of *R* because of the baffle effect of the head. It should be noted that the *L* and *R* phasors portray correctly the relationship between sound pressures that would have been experienced by an observer located at *A*. The microphones produce voltages which correspond to *L* and *R*, and these voltages (after suitable amplification) produce corresponding pressures *L* and *R* at the observer's earphones at *B*. Thus, leaving aside the question of freedom of head motion and front-rear recognition, the observer at *B* receives an identical sound pressure pattern as if he had been located at *A*.

The stereophonic transmission system might be of the type shown at right in Fig. 1. In this particular system several microphones are placed near the performers in a broadly spaced array and are suitably distributed between the two transmission channels. Again, for example, consider the performer at the extreme left. The left channel will carry most of the signal *L* and the right channel signal *R* will approach zero. At the observer location *B*, sounds will emanate predominantly from the left loudspeaker, and therefore a similar pressure pattern will be produced at the ears of the observer as if he had been located at *A*, except for the added reverberation at the listener location *B*, which is assumed to be small.¹

In comparing the three phasor diagrams, it becomes clear that each of the resulting pressure-phasor relationships is just what is required for the correct perception of direction for the particular performer being considered. These desired relationships are obtained when earphones are used in a binaural system or when spaced-apart loudspeakers are used in a stereophonic system. The above analysis may be proven to hold similarly for other performers in the array; it may also be proven to hold for the "Stereosonic" and M-S systems of microphones sometimes employed in stereophonic recording.

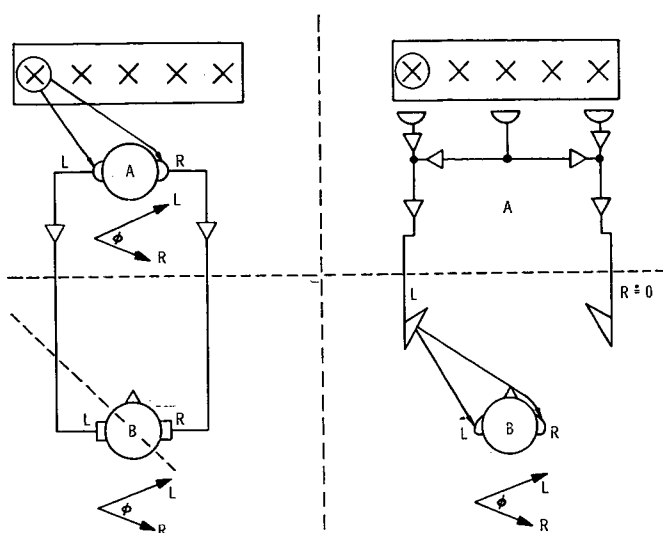
An important observation here is that proper space perspective requires a precisely determined cross-feed between the two ears. With the binaural arrangement this occurs at the microphones in the dummy head. With a stereophonic arrangement it occurs at the observer's ears.

INTERCHANGING LOUDSPEAKERS AND EARPHONES

We will now examine what happens when spaced-apart loudspeakers are used with a binaural program, or when

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¹ The author is indebted to Professor F. V. Hunt of Harvard University for his observations relating to this reverberation problem.

FIG. 1. Binaural *vs* stereophonic system.

earphones are used with a stereophonic program. The former instance is shown at the left in Fig. 2. The microphones of the dummy head send signals of appropriate magnitude and phase position as before, but now each loudspeaker in turn produces its own pressure pattern at the ears of the observer. Starting with the left loudspeaker, the left and right ear pressures will be L_l and R_l respectively. The right loudspeaker produces pressures R_r and L_r . Adding up the two corresponding pressure phasors, it is seen that the total left phasor L leads the total right phasor R by a very small angle γ , and in addition R is now larger than L . These two effects will be somewhat compensatory and as a result the observer will perceive a virtual image practically directly midway between the loudspeakers. Therefore, if loudspeakers are used for reproduction of a binaural program, much if not all of the directional information is lost. This is because of the existence of a double cross-feed, one at the microphones and the other at the loudspeakers.

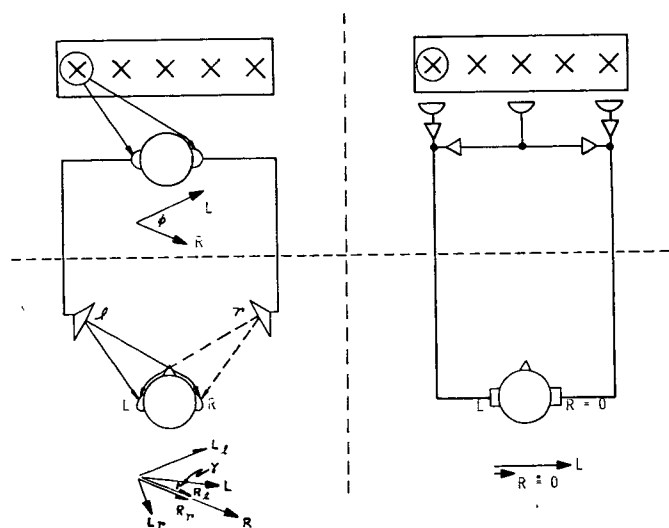


FIG. 2. Incorrect perspective resulting from use of loudspeakers with a binaural program and earphones with a stereophonic program.

In the stereophonic case, using earphones at right, since only the left signal L is present sound pressure is developed in the left ear of the observer only. This is a most unusual type of sensation which has no counterpart in real-life hearing situations, except when the observer places his ear very close to or directly against a source of sound. Stereophonic programs heard in this manner provide the sensation that the extreme left or right sounds originate directly outside the observer's ears, resulting in a gross distortion in space perspective. The reproduction is almost bizarre, with a sensation that the various instruments form a "musical hat" on the observer's head.

This, evidently, is caused by the lack of suitable cross-feed between the two ears.

STEREOPHONIC EARPHONES

To design a suitable cross-feed network for earphones, we begin by inquiring into the pressure distribution which occurs at the left and right ears from the loudspeakers in a stereophonic reproducing system. Weiner² has obtained the

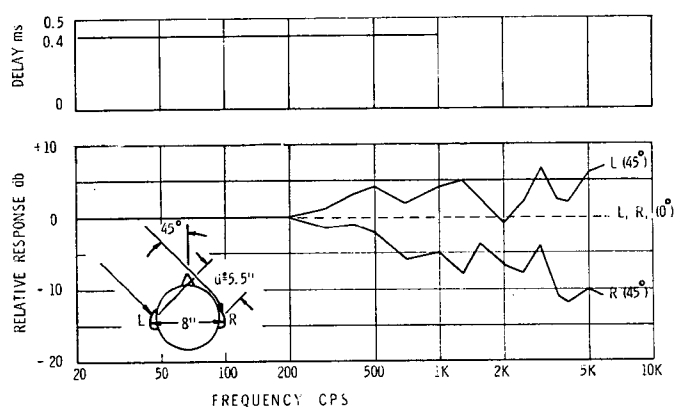


FIG. 3. Relative response for the nearest and the farthest ears for 45° incidence (from Weiner).

applicable pressure distribution during his studies on the diffraction of sound around a human head, and from his data we have constructed the relative left and right pressure functions for loudspeakers placed at a 45° orientation with respect to the observer; shown in Fig. 3, with the "head-on" (0°) function shown as relatively "flat." For the sounds arriving from the left loudspeaker, the pressure L increases from a relative 0 db at 200 cps to an average of about 5 db at 3 kc, while the right pressure drops to an average of -10 db in the same interval.

Obviously a similar situation exists with respect to sounds originating from the right loudspeaker if the L and R curves are reversed. As to time delay data, which Weiner does not give, an assumption is made here that the delay corresponds to a 5.5 in. projected distance, which is equivalent to 0.4 ms. Above 1 kc stereophonic perception appears to be a function

² Francis M. Weiner, "On the Diffraction of a Progressive Sound Wave by the Human Head," J. Acoust. Soc. Am., 19, 143-146 (1947).

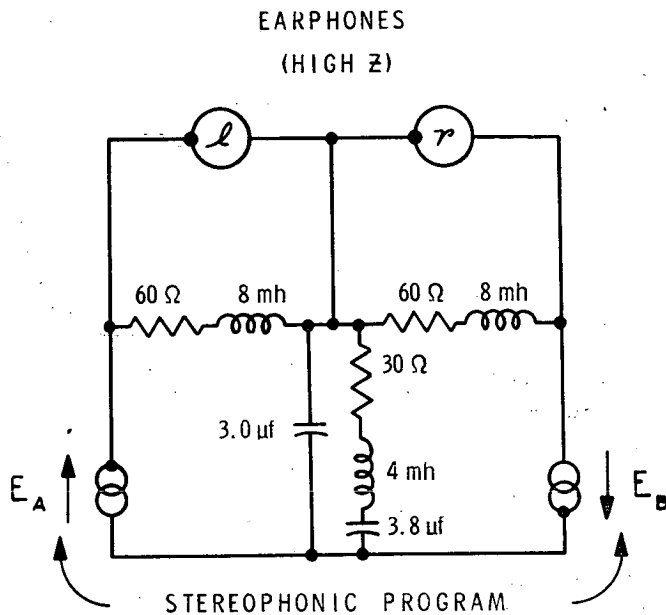


FIG. 4. Circuit for high impedance stereophonic earphones.

of relative intensity, and small values of delay do not appear to have special significance.

The next step is to design a symmetrical network interconnecting the two earphones that will cause the prescribed amount of signal modification and cross-feed delay between the right and left signals. One such network which is moderately simple and quite effective was developed using the CBS Laboratories analogy computer, and it is shown in Fig. 4. The program sources E_A and E_B , as well as the earphones, are connected in a series-additive mode, so that in-phase signals will produce in-phase pressures from both earphones. The network, with the circuit values shown, is designed for operation from low impedance program sources (say, 4 ohm or less) and to feed high impedance earphones (say, 2,000 ohm or more). Similar networks may be designed for other values of amplifier or earphone impedance. For low impedance earphones, the dual of the above circuit shown in Fig. 5 is more conveniently used. It should be noted that here the earphones, as well as the amplifiers, are connected in a parallel-additive mode.

The electrical performance of the networks is shown in Fig. 6. The curves from Fig. 3 have been transferred here in dotted lines to indicate a "design objective." The actual

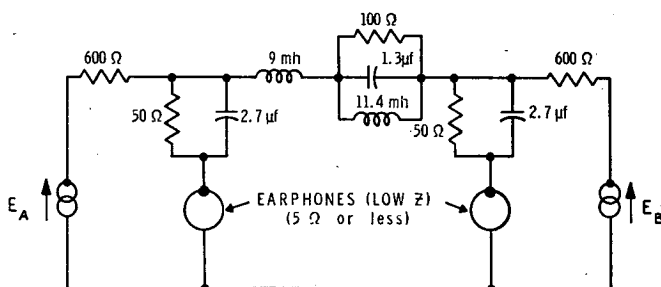


FIG. 5. Circuit for low impedance stereophonic earphones.

transmission and delay of the networks is given in solid lines. The delay time is well achieved up to 1 kc, which is the frequency range where delay is most effective. Above 1 kc the amplitude function is most important, and it is moderately well duplicated. A more complicated network could have been devised to better follow the prescribed functions. However, the additional complexity did not appear to be warranted in view of the considerable deviation in the data from one observer to another reported by Weiner.

It should be noted that with two identical L and R (i.e., center) signals these networks will provide a "flat" transmission characteristic, corresponding to the 0° incidence response in Fig. 3.

Actual listening tests using these stereophonic earphones, against a stereophonic loudspeaker system, have shown a satisfactory match in performance. A precise A-B test, of course, could not be made since one had to remove the earphones to listen to the loudspeakers and vice-versa. However, the experimental arrangement included a switching system which allowed the earphones to be disconnected and the loudspeakers to be switched on when the observer lifted the earphones from his ears. A remarkable similarity of space perspective was noted in this manner between earphones and loudspeakers.

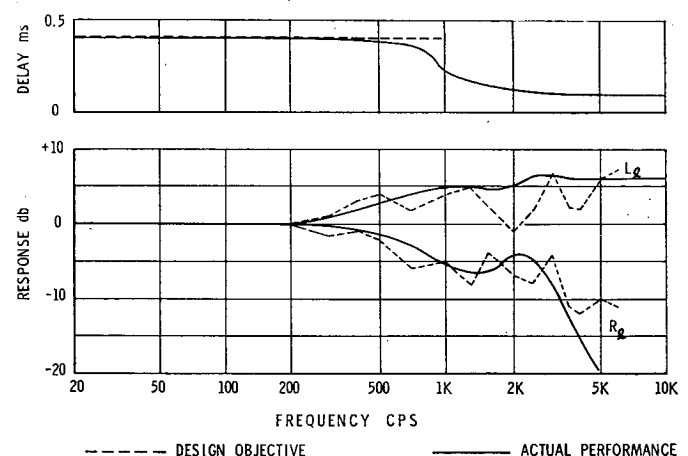


FIG. 6. Performance of circuits in Figs. 4 and 5 vs the design specifications (Fig. 3).

BINAURAL LOUDSPEAKERS

It may be pointed out that this study also helps solve a converse problem: how to properly reproduce a binaural program over a stereophonic loudspeaker system. Just as to convert from stereophonic to binaural program a certain amount of cross-talk of appropriate amplitude and phase has to be provided from each channel to the other, so it would seem that to convert from binaural to stereophonic program a similar amount of cross-talk must be eliminated from each channel. This operation may be performed with similar networks, but with the phase of one channel reversed. As an example, in Fig. 7 the network of Fig. 4 is shown again, but here the two binaural channels are connected in a parallel additive (series subtractive) sense and

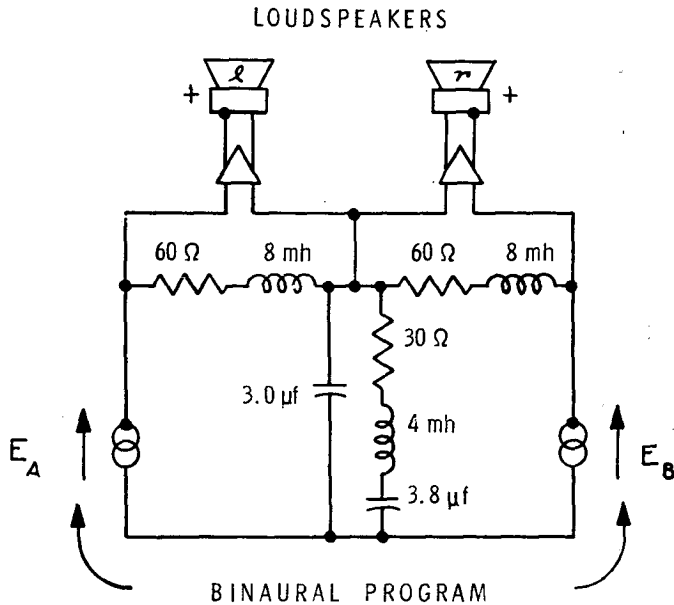


FIG. 7. Circuit for binaural loudspeakers.

the loudspeaker polarity is appropriately reversed so as to reproduce in-phase signals in an additive manner. This scheme might be useful, for example, if one attempted to convert a program previously recorded binaurally for stereophonic reproduction.

If one were to assume that the output-voltages e_l and e_r in Fig. 4 are equivalent to the voltages produced in a binaural microphone system, then relative to the voltages E_A and E_B in a stereophonic system,

$$(1) \quad e_l = K_1 E_A + K_2 E_B$$

$$(2) \quad e_r = K_1 E_B + K_2 E_A$$

where the K 's are a function of impedance elements. If e_l and e_r are introduced in place of the voltages E_A and E_B in Fig. 7, the two outputs into the loudspeaker amplifiers will be

$$(3) \quad e'_l = K_1 (K_1 E_A + K_2 E_B) - K_2 (K_1 E_B + K_2 E_A) = (K_1^2 - K_2^2) E_A$$

and

$$(4) \quad e'_r = (K_1^2 - K_2^2) E_B.$$

Therefore e'_l and e'_r will be free of cross-talk from the opposite channel but will require a complex multiplicand $1/(K_1^2 - K_2^2)$ for proper operation. This hypothesis has not been subjected to an experimental verification.

CONCLUSION

In conclusion, networks have been developed which allow for correct space perspective to be obtained with binaural

earphones when listening to a stereophonic program. One of the networks is designed to work from low impedance sources and feed into high impedance earphones. A second network, which is a dual of the first, is more suited to high impedance sources and low impedance earphones. It is hypothesized that similar networks might be usable for listening to a binaural program over a stereophonic loudspeaker system.

ACKNOWLEDGMENTS

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THE AUTHOR



Mr. Bauer graduated from Pratt Institute in 1932 and received the degree of electrical engineer at the University of Cincinnati in 1937. He joined Shure Brothers, Inc., manufacturers of electroacoustical devices in Chicago as a co-op student in 1936, became chief engineer in 1940, and vice president in 1950.

In 1957, Mr. Bauer joined the CBS Laboratories, and was appointed a vice president in 1958. He has charge of the audio, acoustics, and magnetics research in the laboratories.

Mr. Bauer is responsible for the development of a great many electroacoustical devices such as microphones, phonograph pickups, and tape recording heads. He has over 30 patented inventions in his name in the fields of audio, acoustics, and magnetic recording and has also published many papers covering a wide range of subjects in these fields.

He is a Fellow of the Institute of Radio Engineers, the Acoustical Society of America, and the Audio Engineering Society. He is also associate editor of the *Journal of the Acoustical Society of America* and in 1955 as co-founder and past national chairman and present secretary of the IRE Professional Group on Audio he was recipient of the group's Achievement Award. Mr. Bauer is a member and recipient of the Recognition Award of the Eta Kappa Nu and a member of the Tau Beta Pi and Sigma Xi.