Controlling Sound-Image Localization in Stereophonic Reproduction*

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In conventional two-channel stereophonic reproduction the sound image appears only between the left and right loudspeakers. A new localization theory, derived from a model of hearing, governs a reproducing system that extends the sound-image area beyond the loudspeakers. The basic theory of this new technology and its applications in stereophonic systems are described.

0 INTRODUCTION

In conventional stereophonic reproduction the sound images are localized between the two loudspeakers. The image can appear elsewhere if special circuits are used in stereophonic reproduction of binaural sources [1], and image localization is possible if the head-related acoustic transfer functions of the listener are simulated by computers. [2]. Not much has been reported on the technology to localize the image of an optional source at any desired position relative to the listener.

By observing natural listening conditions, we have discovered the role of two significant acoustic transfer functions. Using these functions, we have realized the technology to place the sound image at any position with a two-loudspeaker stereophonic system [4]–[6] and have demonstrated extremely effective reproduction.

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1 THEORY OF IMAGE-LOCALIZATION CONTROL FOR TWO-LOUDSPEAKER REPRODUCTION

1.1 Natural Acoustic Information at Both Ears

The signals at both ears of a listener in a free sound field are characterized by acoustic transfer functions. These functions depend on the distance from the source and are illustrated in Fig. 1 as $H_{\phi 1}$ and $H_{\phi 2}$. Shown in diagrammatic form as Fig. 2(a), the same functions can be transformed to Fig. 2(b), where $H_{\phi 2}/H_{\phi 1}$ represents the sound-pressure ratio between right and left ears. If these two generalized functions can be simulated, it

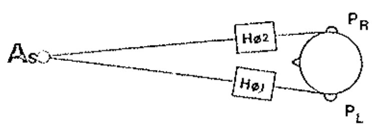

Fig. 1. Head-related acoustic transfer functions.

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should be possible to produce a sound image at any arbitrarily selected location.

1.2 Theory of Image-Localization Control in Two-Loudspeaker Reproduction

1.2.1 *Concept*

In two-loudspeaker reproduction sound-image localization can be controlled if we insert in the signal channels to the loudspeakers two networks, one of which produces a ratio of signals between channels while the other produces a signal common to both channels. The networks thus represent the two acoustic transfer functions which work to produce the sound-pressure ratio between both ears and the sound pressure common to both ears. We shall call the first network ratio circuit H and the second, common circuit G.

1.2.2 *Derivation of Ratio Circuit H*

The acoustic transfer functions between each loudspeaker and both ears are shown in Fig. 3(a). In the ideal arrangement the listener is located centrally between the two loudspeakers, and because of symmetry, transfer function $H_{21} = H_{12}$ and $H_{22} = H_{11}$, as shown in Fig. 3(b).

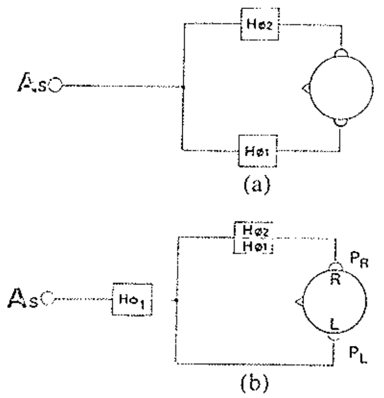


Fig. 2. Block diagram of acoustic transmission. (a) Original. (b) Transformed.

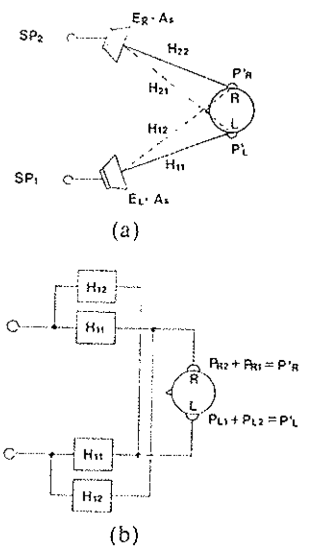


Fig. 3. (a) Acoustic transfer functions in stereophonic listening. (b) Acoustic transmission in ideal streophonic listening.

In Fig. 4 the sound pressures produced at the left and right ears are P_L' and P_R', and the voltages applied to the loudspeakers as the outputs of black boxes G and H are $E_L \cdot A_S$ and $E_R \cdot A_S$.

The influence of circuit G can be neglected when considering the sound-pressure ratio, and thus function H is equal to E_R/E_L.

Assuming the loudspeakers to be uniform in response, the following equations can be obtained for the sound-pressure ratio:

$$\frac{P_R}{P_L} = \frac{H_{\phi 2}}{H_{\phi 1}} = A \tag{1}$$

$$\frac{P_{R1}}{P_{L1}} = \frac{H_{12}}{H_{11}} = B \tag{2}$$

$$\frac{E_R}{E_L} = H \; . \tag{3}$$

Similarly, from Fig. 4,

$$\frac{P_R'}{P_L'} = \frac{H_{11} \cdot E_R + H_{12} \cdot E_L}{H_{11} \cdot E_L + H_{12} \cdot E_R}$$

$$= \frac{H_{12}}{H_{11}} \left\{ \frac{1 + (E_R/E_L)\,(H_{11}/H_{12})}{1 + (E_R/E_L)\,(H_{12}/H_{11})} \right\}$$

$$= B \left\{ \frac{1 + (H/B)}{1 + H \cdot B} \right\} \; . \tag{4}$$

If P_R/R_L and P_R'/P_L' are equal, then

$$H = \frac{E_R}{E_L} = \frac{A - B}{1 - A \cdot B}$$

$$= \frac{H_{11} \cdot H_{\phi 2} - H_{12} \cdot H_{\phi 1}}{H_{11} \cdot H_{\phi 1} - H_{12} \cdot H_{\phi 2}} \; . \tag{5}$$

1.2.3 *Derivation of Common Circuit G*

As loudspeaker SP_1 has only G in its channel, the sound pressure produced at the left ear in response to input signal A_S is

$$P_L' = (H_{11} \cdot E_L + H_{12} \cdot E_R)\, A_S \tag{6}$$

$$= H_{11} \cdot E_L \left\{ 1 + \left(\frac{H_{12}}{H_{11}}\right) \left(\frac{E_R}{E_L}\right) \right\} A_S \; . \tag{7}$$

The sound pressure P_L produced acoustically would

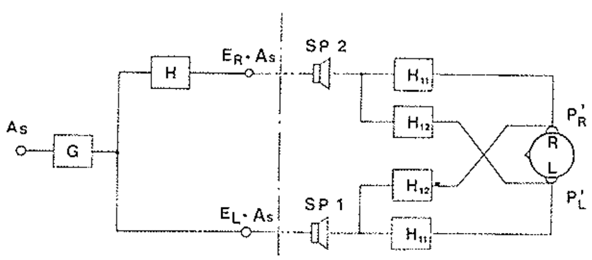


Fig. 4. Stereophonic system using sound-image localization theory.

be

$$P_L = H_{\phi 1} \cdot A_S \,. \tag{8}$$

We can obtain the input voltage $E_L \cdot A_S$ required at SP_1 to make P_L and P_L' equal by setting Eq. (7) equal to Eq. (8):

$$H_{\phi 1} \cdot A_S = H_{11} \cdot E_L \left\{ 1 + \left(\frac{H_{12}}{H_{11}}\right) \left(\frac{E_R}{E_L}\right) \right\} A_S$$

which can be rearranged to obtain

$$G = E_L = \left(\frac{H_{\phi 1}}{H_{11}}\right) \left\{ \frac{1}{1 + (H_{12}/H_{11})\,(E_R/E_L)} \right\}$$

$$= \left(\frac{H_{\phi 1}}{H_{11}}\right) \left[\frac{1}{1 + \left(\frac{H_{12}}{H_{11}}\right) \left(\frac{H_{\phi 2}}{H_{\phi 1}}\right) \frac{\{1 - (H_{12}/H_{11})\,(H_{\phi 1}/H_{\phi 2})\}}{\{1 - (H_{12}/H_{11})\,(H_{\phi 2}/H_{\phi 1})\}}} \right]$$

$$= \left\{ 1 + \sum_{n=1}^{\infty} \left(\frac{H_{12}}{H_{11}}\right)^{2n} \right\} \left\{ 1 - \left(\frac{H_{12}}{H_{11}}\right) \left(\frac{H_{\phi 2}}{H_{\phi 1}}\right) \right\} \left(\frac{H_{\phi 1}}{H_{11}}\right) . \tag{9}$$

A sample calculation of the first and second terms of Eq. (9) using the data by Mertens [7] is shown in Fig. 5. The characteristics of these terms are relatively flat when the loudspeakers are arranged at positions of ±30° to the listener and the localization of the sound image is set in the direction of (backward) 120°. Interaural differences in frequency response are important cues for localization, but the G circuit produces a sound pressure common to both ears. Thus the flat response of this circuit is not so important for sound localization. It follows that the influence of the first and second terms can be neglected in practice and Eq. (9) simplified to

$$E_L \approx \frac{H_{\phi 1}}{H_{11}} \,. \tag{10}$$

Two examples of this transfer function are shown in Fig. 6.

Using Eqs. (5) and (10), the circuit in Fig. 4 can be shown as Fig. 7. An electronic circuit can now be modeled which is capable of placing sound images at any desired position.

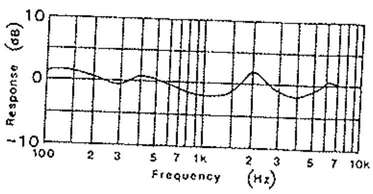


Fig. 5. Frequency response of terms 1 and 2 of Eq.(9) when direction of loudspeaker $\theta = 30°$ and direction of sound image $\phi = 120°$.

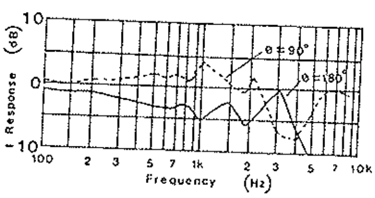


Fig. 6. Frequency response of $H_{\phi 1}/H_{11}$, where ϕ is direction of the sound image to be localized.

2 APPLICATION OF IMAGE-CONTROLLING CIRCUITS

2.1 Conventional Types of Stereophonic Reproduction

In conventional reproduction the "stage width" is only as broad as the distance between the two loudspeakers.

In this application the left and right signals are first passed through the image-control circuit block so as to be localized outside the loudspeakers, and are then mixed with the original signals and reproduced by two loudspeakers in front of the listener. The method is shown in Fig. 8(a). Differential signal components $(L - \alpha R)$ and $(R - \beta L)$ are extracted from the input signal by the reflective-sound signal processor (R.S.P.) and are then passed through the G and H circuits.

Fig. 8(b) illustrates the extent to which sound images can be reproduced. Depending on the characteristics of the program source, the indirect signal has a complicated amplitude and phase relationship with the direct signal. In consequence, the sound image is extended beyond the confines of the two loudspeakers in front, and images at the sides and back can be detected clearly.

2.2 Application to Four-Channel Two-Loudspeaker Reproduction

In conventional four-channel systems two loudspeakers are added behind the listeners, and four independent signals are reproduced. When image control is applied, signals originally intended for the rear loudspeakers are processed by the image-controlling circuitry. The positions of the loudspeakers (the angles to the

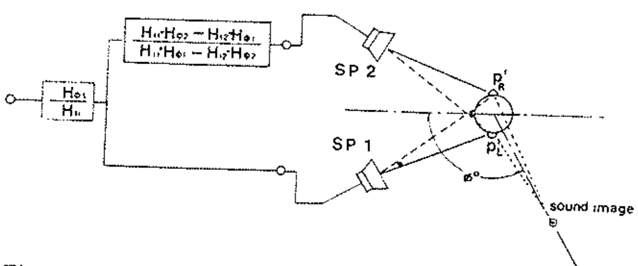


Fig. 7. Image-localization control circuit for two-loudspeaker reproduction.

listener) are chosen, and then the values for the *G* and *H* circuits are calculated.

The block diagram becomes as shown in Fig. 9(a). As the acoustic transfer functions of the rear channels differ from those of the front signals, the listener experiences the same sound field as if the four signals were sent to independent loudspeakers. The effect is shown in Fig. 9(b).

In the audio market several four-channel systems are available. However, only a discrete four-channel source with totally independent signal-transmission paths and uniform phase characteristics are satisfactory. A 4–2–4 or matrix input is incompatible and will not allow proper image localization because of the inherent inability of such systems to decode back to the characteristics of the original source.

2.3 Application to Quadraphonic Reproduction (Four Input Channels, Four Loudspeakers)

Conventional quadraphonic reproduction has a more extensive sound field than conventional stereophonic reproduction, but the reproduction of left and right side images is poor and has been regarded as difficult to achieve.

The image-control method described in Section 2.1 is also applicable where four discrete channels and four loudspeakers are used. In the system we have developed, quadrastereophony is regarded as a pair of two-channel stereophonic systems, one for the front and one for the rear, with the indirect components for side localization extracted from the respective two-channel signals for each stereo system. After signal processing for side localization, the component signals are mixed with the originals for reproduction.

The block diagram of this system is shown in Fig. 10(a). The characteristics of the *G* and *H* circuits applied in this system are somewhat different for the two front channels as compared with the characteristics for the rear. The sound field obtained by this method is shown in Fig. 10(b). The ability of this system to extend the sound stage beyond the physical location of the loudspeakers has the effect of producing excellent side images. When it is compared with a conventional four-channel four-loudspeaker system, this system is found particularly effective in bringing the sound out of the four corners and spreading it uniformly around a 360° circle while maintaining the integrity of the source positions.

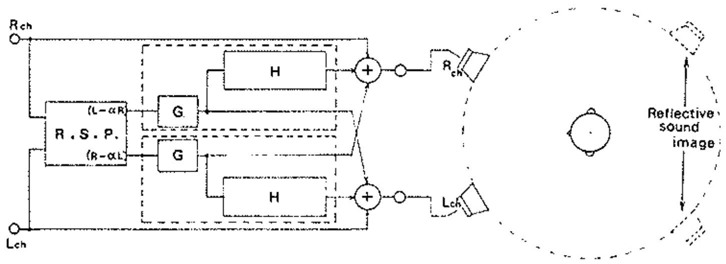
3 DISCUSSION

To verify the image-control theory mentioned above, tests were made in an anechoic room:

1) Subjects (eight men) were clearly able to localize the sound images in all directions except for the rear center.

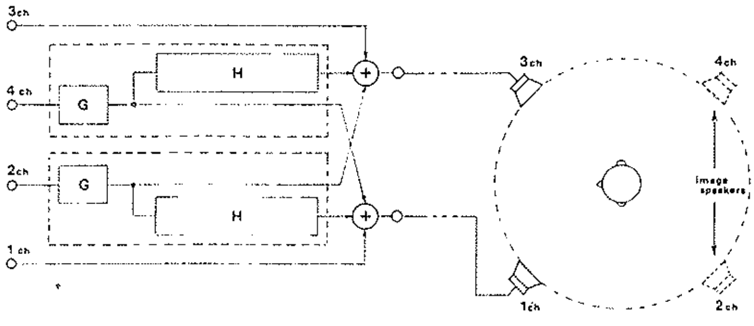
2) The *G* circuit seems important in positioning the images either in front of or behind the listener.

The image-control system may have about the same limitations in a listening room as has conventional stereophony, because the reflected sound tends to mask the direct sound. We found that sound images can be localized without difficulty in a room where the reverberation time is 0.3 second. Furthermore, the lateral allowable deviation of the listening position is about 30



(a) (b)

Fig. 8. Application to conventional stereophonic reproduction (two input channels, two loudspeakers). (a) Block diagram. (b) Sound image.



(a) (b)

Fig. 9. Application to four-channel, two-loudspeaker reproduction (four input channels, two loudspeakers). (a) Block diagram. (b) Sound image.

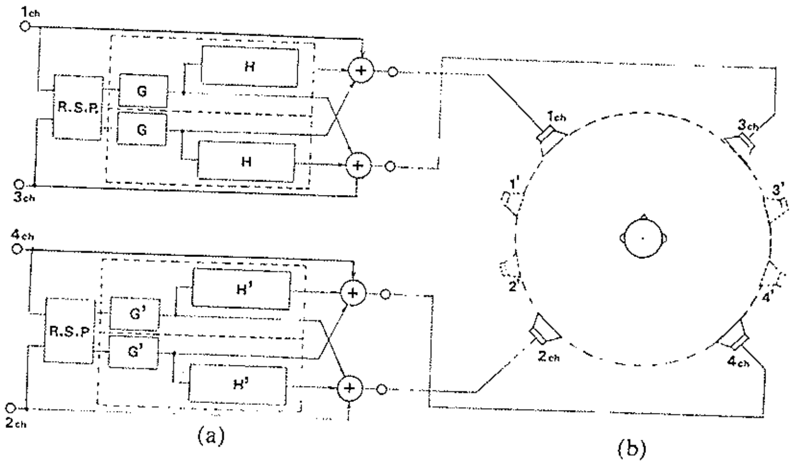


Fig. 10. Application to quadraphonic reproduction (four input channels, four loudspeakers). (a) Block diagram. (b) Sound image.

cm in the case where accurate simulation circuitry was used and average values of the head-related acoustic transfer functions were chosen.

4 CONCLUSION

1) The sound-image localization of a source in the field governed by direct sound is determined by two factors:

a) the acoustic transfer function common to both ears

b) the acoustic transfer function which represents the sound-pressure ratio between the ears.

2) A two-loudspeaker stereophonic system can, by virtue of conclusion 1), produce sound-image localization in all directions around the listener.

3) By applying this theory to conventional and four-channel stereophony, sound-image localization is greatly improved, especially in width, depth, and side directions. The technology will be very useful in the future for freely manipulating the sound image.

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Mr. Sakamoto's biography was published in the October issue.