An Artificial Stereophonic Effect Obtained from a Single Audio Signal*

MANFRED R. SCHROEDER
Bell Telephone Laboratories, Inc., Murray Hill, New Jersey

In 1954, H. Lauridsen reported an experiment which gave a remarkable stereophonic effect using a single input signal. The signal was fed to both ears once directly in phase, and a second time (delayed by 50 to 150 msec) in anti-phase. This experiment is recognized as resulting in two different intensity *vs* frequency responses in the paths to the two ears, namely, two interlaced comb filters. The presence of such different responses, rather than the time delay, is postulated, from the results of the experiments described here, as the essential prerequisite that stereophonic effects be obtained from a single input signal.

INTRODUCTION

In 1954, H. Lauridsen of the Danish National Broadcasting System discovered a remarkable stereophonic effect using a single audio signal. The subjective impression is that of sound coming from all directions resulting in a unique spatial illusion and an enhanced sensation of presence and immediacy for the listener.

In order to obtain this effect the signal is applied to both ears in phase and, in addition, a delayed (50-150 ms) version of the same signal is fed to both ears in anti-phase. This experimental condition can be described in terms of two amplitude responses and a differential phase response for the paths to the two ears. The amplitude responses are two complementary comb-filters. The differential phase response is a meander-type function jumping discontinuously between $-\pi/2$ and $+\pi/2$ at frequencies which are integer multiples of $1/2\tau$, where τ is the delay.

A number of experiments have been performed involving complementary comb-filters of different kinds and various types of differential all-pass filters in order to distinguish between the relative contributions of the intensity variations and phase variations, respectively.

The result of these experiments is that "wiggly" differential phase responses alone are not sufficient to give rise to the baffling spatial illusion first reported by Lauridsen. Rather, strong spectral intensity modulations, preferably of a complementary type, are required. These findings and the fact that the original experiment can be successfully duplicated with delays as short as 2.5 ms suggest that the delay is not the primary agent of this effect. Instead, the simple fact that some frequencies enter the head through one ear while others prefer the other ear as their path is offered as an explanation for the psychoacoustic illusion of "sitting in the middle of the orchestra" (if orchestral music is played).

Background

The "pseudo-stereophonic" effect was obtained by H. Lauridsen[1] in a manner sketched in Fig. 1. By pseudo-stereophonic we designate a situation in which a spatial subjective impression is created by applying to the two ears two different versions of a single audio signal. The spatial effect created in this manner can never be a simple and reversible mapping of the real space from which the signal originated into the subjective space. For true stereophony one needs at least two *independent* signals.

Figure 1 shows Lauridsen's setup. The signal from a single microphone is applied to one loudspeaker directly and to another one, at right angles with the first one, delayed by 50 to 150 ms. If the observer P is located on the center line the interferences at his two ears will be of opposite sign. For certain frequencies the contributions from the two loudspeakers will add at one ear and subtract at the other ear, while for a different frequency nearby, depending upon the delay, the effect is reversed. With no interference from echoes, and with equal amplitudes at P of the "point source" speaker $f(t-\tau)$, and the "dipole source" speaker $f(t)$, the signals at the two ears of P will be $f(t-\tau) + f(t)$ and $f(t-\tau) - f(t)$, respectively.

Figure 2 illustrates another of Lauridsen's experiments where the adding and subtracting is done electrically, not in the air as in Fig. 1. The complex frequency responses in

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[1] H. Lauridsen, "Nogle forsøg med forskellige former rum akustik gengivelse," *Ingeniøren, No. 47,* 906 (1954).

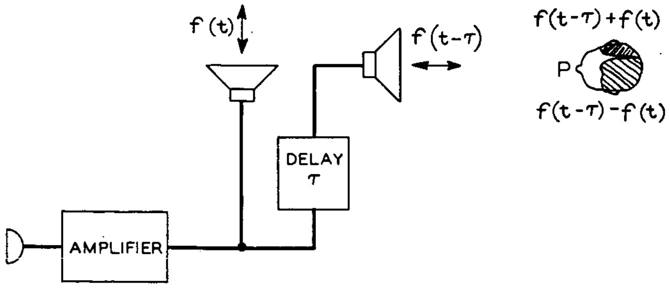

FIG. 1. Lauridsen's binaural experiment with two loudspeakers at right angles to each other. (Actually, Lauridsen delayed the signal to the left speaker.)

the paths to the two ears are independent of the geometric and room-acoustical restrictions of the setup sketched in Fig. 1,

$$S_1(\omega) = \exp[-i\omega\tau] + 1 = 2\cos(\omega\tau/2)\exp[-i\omega\tau/2], \quad (1)$$

$$S_2(\omega) = \exp[-i\omega\tau] - 1 = -2i\sin(\omega\tau/2)\exp[-i\omega\tau/2]. \quad (2)$$

These two relations can be rewritten in terms of positive amplitude responses and phase responses (for positive frequencies)

$$S_1(\omega) = 2\,|\cos(\omega\tau/2)|\ \exp\left[-\tfrac{1}{2}i\left(\omega\tau + 2\pi\sum_{n=0}^{\infty}\sigma(\omega\tau-\pi-2n\pi)\right)\right], \quad (3)$$

$$S_2(\omega) = 2\,|\sin(\omega\tau/2)|\ \exp\left[-\tfrac{1}{2}i\left(\omega\tau - \pi + 2\pi\sum_{n=0}^{\infty}\sigma(\omega\tau-2n\pi)\right)\right]. \quad (4)$$

Here $\sigma(x) = 0$ for $x < 0$ and $\sigma(x) = 1$ for $x \geq 0$.

We have thus two sinusoidal intensity responses,

$$|S_1(\omega)|^2 = 4\cos^2(\omega\tau/2) \quad (5)$$

$$|S_2(\omega)|^2 = 4\sin^2(\omega\tau/2) \quad (6)$$

with

$$|S_1(\omega)|^2 + |S_2(\omega)|^2 = 4. \quad (7)$$

That is, the sum of the intensities at the two ears is constant and independent of frequency. The two complementary intensity responses are plotted in Fig. 3.

In addition to the frequency responses we have two different phase responses.

$$\Phi_1(\omega) = -\omega\tau/2 - \pi\sum_{n=0}^{\infty}\sigma(\omega\tau - 2n\pi - \pi), \quad (8)$$

$$\Phi_2(\omega) = -\omega\tau/2 + \pi/2 - \pi\sum_{n=0}^{\infty}\sigma(\omega\tau - 2n\pi). \quad (9)$$

In this report we will be little concerned with absolute phase. The phase *difference* between the two ears is the important quantity. From (8) and (9) we obtain

$$\Delta\Phi(\omega) = \Phi_1 - \Phi_2 = -\pi/2 + \pi\sum_{n=0}^{\infty}\left[\sigma(\omega\tau - 2n\pi) - \sigma(\omega\tau - 2n\pi - \pi)\right]$$

or

$$\Delta\Phi(\omega) = -\pi/2 + \pi\,\sigma(\sin\omega\tau). \quad (10)$$

This differential phase response is plotted in Fig. 4.

We have thus two distinct effects:

(1) Two sinusoidally varying intensity *vs.* frequency responses.

(2) A meander-type differential phase response.

Which of these two effects is more important in obtaining a pseudo-stereophonic effect? A number of experiments are described which were designed to differentiate between these two influences.

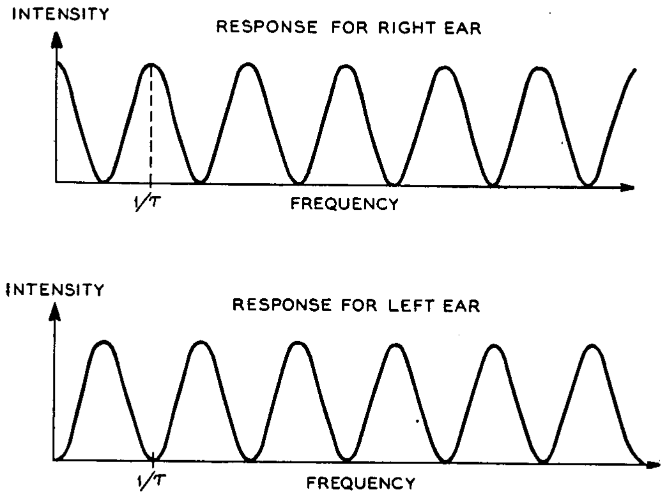

FIG. 3. Two complementary comb filters obtained by means of a delay line.

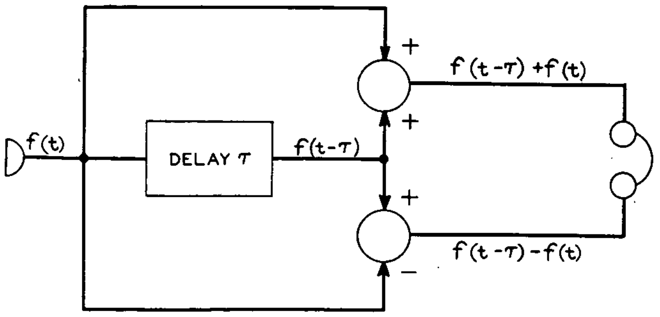

FIG. 2. Lauridsen's binaural experiment with earphones.

Comb-Filter Experiments

There are ways different from the one used by Lauridsen to "split" the frequency domain between the two ears in comb-filter fashion. In Fig. 5 for example, we have a bank of contiguous band-pass filters such as is used in sound analyzing equipment. If we connect all odd-numbered filters together and feed the sum to one ear and the outputs of all even-numbered filters to the other ear, we have again two complementary comb-filters with responses similar to the ones shown in Fig. 3. An experiment with this arrangement was performed using 16 filters, each being about 200

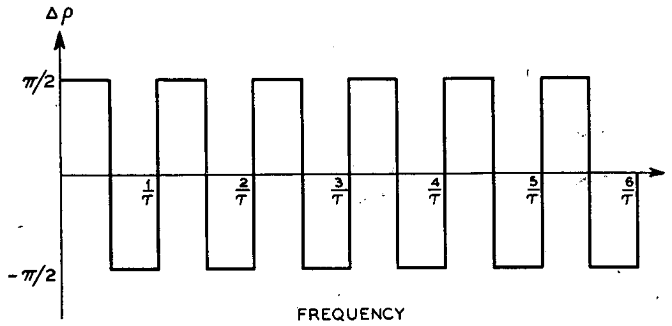

FIG. 4. Differential phase characteristic obtained by means of a delay line.

cps wide. As one would expect from the close analogy with the original setup of Fig. 2, the pseudostereophonic effect is just as striking as in Lauridsen's experiment. Of course, even the differential phase responses are similar. Only the phase variations at the crossover frequencies may be greater than π depending on the complexity of the filters used.

However, there is one important difference: a filter width of 200 cps corresponds to a delay of only 2.5 ms in the circuit of Fig. 2. In contrast, the delays used by Lauridsen were between 50 and 150 ms. Here we obtain the same result with an equivalent delay of 1/10 or less. This observation suggests that the comb-filter-type frequency splitting between the two ears is the major cause of the strange effect observed first by Lauridsen. The fact that certain frequencies enter the auditory senses predominantly through one ear and other frequencies predominantly through the other ear seems a seductively simple explanation. It would also explain why the effect is so strong at very low and very high frequencies for which an explanation in terms of delay is impossible.[2]

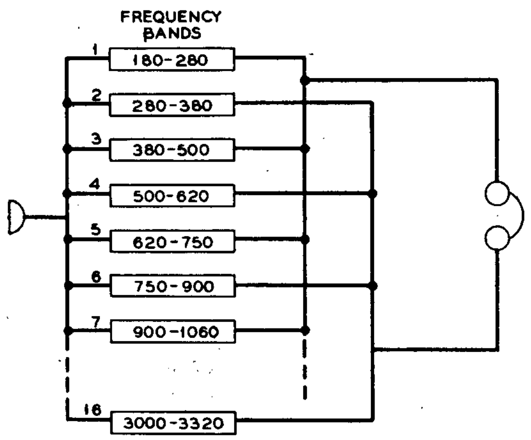

FIG. 5. Two complementary comb filters obtained by splitting a bank of contiguous band-pass filters.

[2] G. R. Schodder, "Vortaeuschungen eines akustischen Raumeindrucks," Akust. Beihefte, *Acustica*, **6**, 482 (1956). See also R. L. Hanson and W. E. Kock, "Interesting Effect Produced by Two Loudspeakers Under Free Space Conditions," *J. Acoust Soc. Am.*, **29**, 145 (1957).

Experiments with Phase-Linear Comb-Filters and All-Pass Filters

In order to shed more light on the possible causes of the pseudo-stereophonic effect, a number of experiments involving *phase-linear* comb-filters and all-pass filters were conducted. The idea was to separate the amplitude effect shown in Fig. 3 from the phase effect shown in Fig. 4 and to assess their relative contributions. The result of these experiments is that the intensity variations are more important than the phase variations. All experiments with all-pass filters gave only weak spatial illusions compared to the strong effect obtained with either Lauridsen's setup or other complementary comb-filters. In contrast, using a pair of phase-linear comb-filters described below resulted in a strong spatial effect even though the delay is the same for both ears.

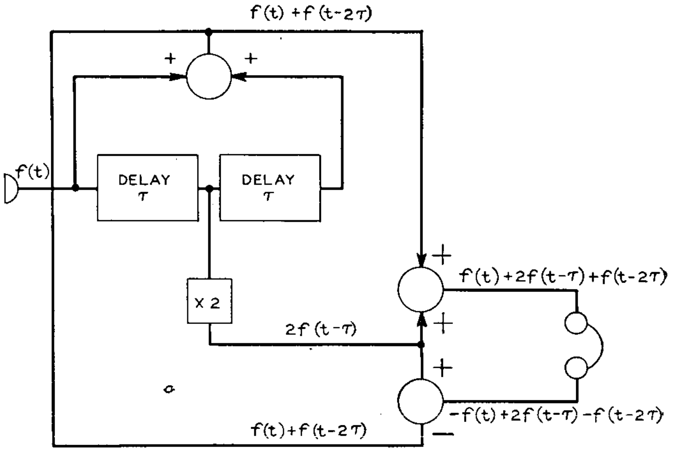

FIG. 6. A pair of phase-linear comb filters.

Figure 6 shows the circuit used to realize a pair of phase-linear comb-filters. The complex frequency responses are

$$1+2\exp[-i\omega\tau]+\exp[-2i\omega\tau]=4\cos^2(\omega\tau/2)\cdot\exp[-i\omega\tau], \tag{11}$$

$$-1+2\exp[-i\omega\tau]-\exp[-2i\omega\tau]=4\sin^2(\omega\tau/2)\cdot\exp[-i\omega\tau]. \tag{12}$$

Since both $\cos^2(\omega\tau/2)$ and $\sin^2(\omega\tau/2)$ are nowhere negative the phase angles are in both cases $-\omega\tau$ radians. Thus there is no phase difference between the signals at the two ears. But the amplitude responses are similar to those in the original experiment. In fact, they are identical to the intensity responses shown in Fig. 3.

As expected the effect was as pronounced, if not more so, as in Lauridsen's case. The reason why the effect could be stronger may be found in the fact that the amplitude responses have less overlap than in the original experiment.[3]

[3] A possible measure of overlap of two filters is the following ratio

$$R=\frac{\int|S_1(\omega)|\cdot|S_2(\omega)|\,d\omega}{\left[\int|S_1(\omega)|^2d\omega\cdot\int|S_2(\omega)|^2d\omega\right]^{1/2}}.$$

In the original experiment $R=0.636$. Here $R=0.333$, indicating less overlap of the two frequency responses.

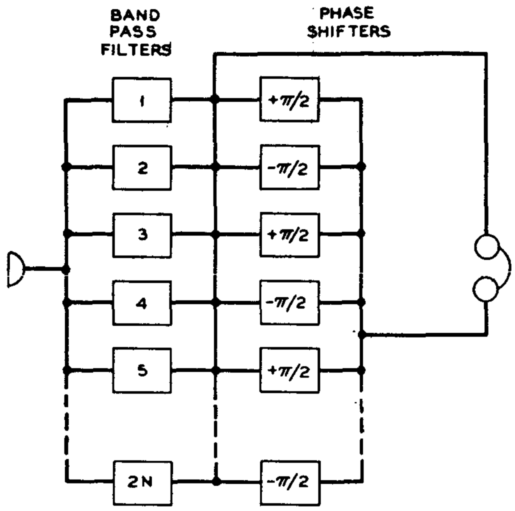

FIG. 7. Differential phase $\Delta\rho = \pm\,\pi/2$.

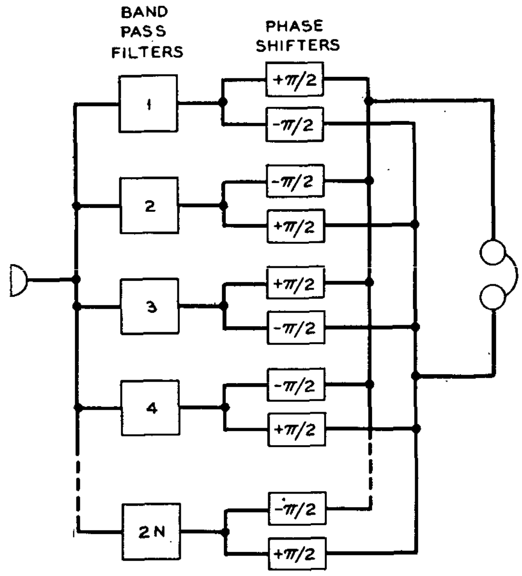

FIG. 9. Differential phase $\Delta\rho = \pm\,\pi$.

While the experiments with a pair of phase-linear comb-filters prove that a spatial illusion can be obtained without a phase difference of the signals at the two ears, the question remains unanswered whether different phases in the absence of spectral intensity modulations are capable of producing the spatial illusion. To this end, a number of experiments with all-pass filters have been performed. Figure 7 shows the circuit used to duplicate the differential phase characteristic plotted in Fig. 4 without appreciable intensity fluctuations. It consists of a bank of comb-filters and simple *R-C* circuits as phase shifters. The differential phase at the outputs is $\pm\,\pi/2$. Figure 8 shows a similar circuit with differential phase $\pm\,\pi$. The arrangements shown in Fig. 9 and Fig. 10 vary in their input-output phase relations but have the same differential phase at their outputs. Experiments with any of the arrangements shown in Figs. 7-10 give rather similar effects. While they differ from a diotic presentation of a single signal, they do not result in a strong spatial effect. In fact, the perception is quite comparable to that obtained from an inversion of one of two identical signals. The simple circuit for this condition is pictured in Fig. 11a. It should be noted that this connection results in a constant differential phase in contrast to the oscillatory phase characteristics of the previous circuits. Another filter having a constant differential phase at its outputs and giving similarly weak results is sketched in Fig. 11b. It is the well known $\pi/2$ all-pass filter.

For completeness another simple phase filter should be mentioned; a delay in the path to one ear shown in Fig. 11c. While this is another case of an all-pass filter, it lacks the symmetry of the previously described arrangements. One ear receives the signal earlier than the other. If this time difference is great enough, it is noticeable and gives the impression of the sound coming from one side, or, for even greater delays, the signal and "echo" are heard separately.

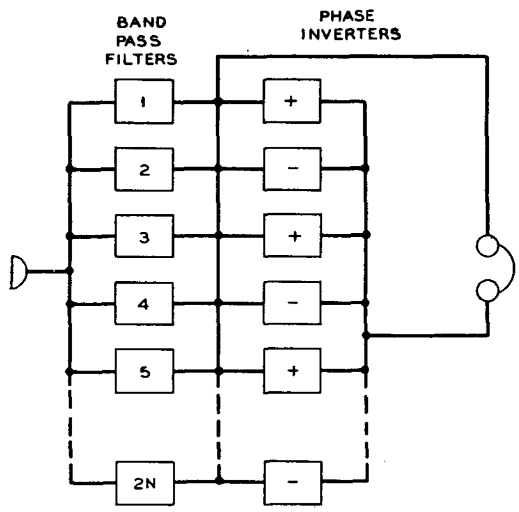

FIG. 8. Differential phase $\Delta\rho = \pm\,\pi$.

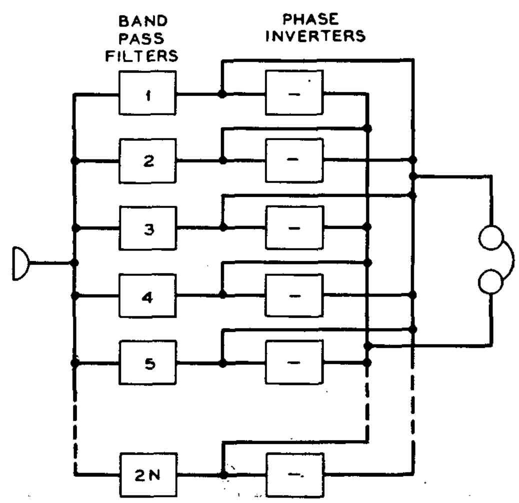

FIG. 10. Differential phase $\Delta\rho = \pm\,\pi$.

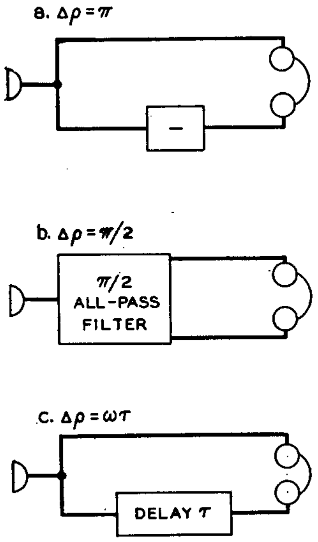

FIG. 11. Three all-pass filters with various differential phase characteristics.

However, no real three-dimensional impression is conveyed.

As a curiosity it may be mentioned that a loudspeaker and two microphones in a reverberant room can be used to realize a filter with two different outputs. This situation is depicted in Fig. 12. If the distances between the two microphones and the microphones and the loudspeaker are large enough, the two outputs will be uncorrelated. Listening over a pair of earphones connected to the outputs of this "mechanical" filter results in the familiar spatial illusion.

Conclusions

Lauridsen's binaural experiment was duplicated using a bank of contiguous band-pass filters. While it is not surprising that comb-filtering realized by band-pass filters should give the same effect as comb-filtering realized by the use of a delay line, because of the similar amplitude and phase characteristics in both cases, a significant finding results from the experiments described here: for the delays used by Lauridsen (around 100 ms) the bandwidth of an individual "tooth" in the comb-filters is approximately 5 cps. The band-widths used here are around 200 cps corresponding to an equivalent delay of 2.5 ms. This result makes an explanation of the pseudostereophonic effect by analogy to room-acoustic delays (between direct sound and echoes) look farfetched. Rather, the simple fact that some frequencies enter the auditory center through one ear while other frequencies travel by way of the other ear may well be the real cause of the extraordinary effect discovered by Lauridsen.

A variety of experiments with all-pass filters are interpreted as supporting this view. In these cases there are no significant intensity differences between the two ears. In one experiment (Fig. 4) the differential phase response is very nearly identical to the one obtained in the original experiment with earphones. But the strong pseudo-stereophonic effect is missing in all experiments not involving strong spectral intensity modulations. This establishes different amplitude responses as a necessary condition for the binaural effect reported by Lauridsen.

A pair of comb-filters was constructed that have identical linear phase responses. The successful experiments with this filter pair eliminate inter-aural phase differences as a necessary condition for auditory spatial illusions.

The technical assistance of Mr. H. W. Hines in this study is gratefully acknowledged.

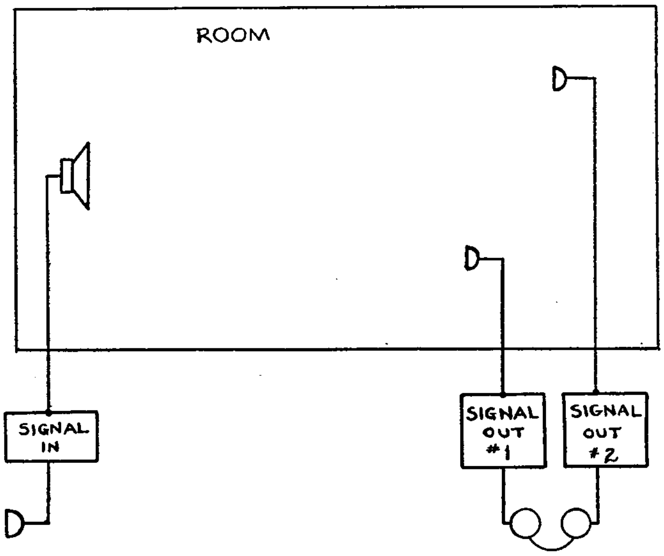

FIG. 12. Reverberant room used as a "mechanical" filter with one input and two outputs.

Discussion

Q. (Paul Conklin, Baldwin Piano Co.): The fact that in the original experiment, as you have it set up here, the second speaker is unbaffled suggests that low frequency response is not essential in order to produce this effect. I was wondering if you have made any controlled experiments with comb-filters by limiting the frequency response to the upper frequency region to see to what extent frequency response affects this effect.

A. Ideally, of course, the two frequency responses apart from the comb-filter effect should be the same. In this particular experiment the intensity you get from this upper speaker and the intensity that you get from the lower should be the same. This is true only for a limited range in this room; the frequency characteristics are also different and coincide only in a limited range, say from 200 or 300 cps to several kc. Even that may be an optimistic statement. Here in this loudspeaker demonstration, you don't have the clearcut relations which you have in an earphone demonstration.

Q. If, in the earphone demonstration, you were to deliberately restrict the frequency range over which these amplitude fluctuations occur, what effect would this have on the pseudo-stereophonic impressions? Could you restrict the effect to high frequencies alone, say, above 2 or 3 kc?

A. No. The point in this effect is that you have two comb-filters over the whole frequency range which you actually want to present. You can limit your signal at the high and the low end, but you get a poorer signal, not as "hi-fi." Actually the signal we have on the earphones, and also on the speakers, is limited to around 4 kc, because the delay lines we used worked only up to 4 kc. If you make the band even narrower, the signal sounds poorer, but you have the effect still.

Q. I just wanted to make a comment. I was very surprised to observe the apparent bass response of the little unbaffled speaker; surprised because it should be very inefficient.

THE AUTHOR

A Westphalian by birth, Dr. Schroeder was educated in Germany. He received the degree of "Diplom-Physiker" from the University of Goettingen and also its doctorate in physics. During his stay in Goettingen, Dr. Schroeder was active in solid state physics, microwaves, and acoustics. He published a number of papers resulting from his research in these fields, including several on the applications of microwave-cavity techniques to the solution of problems in room acoustics.

Dr. Schroeder's experience in industry includes association with the Telefunken Microwave Tube Division in 1944, and work with Grundig Electronics Laboratory in 1952. He joined Bell Telephone Laboratories in 1954 and since that time he has been engaged mainly in research and development work in the field of speech communication.