

Theater Loudspeaker System Incorporating an Acoustic-Lens Radiator

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This paper describes a two-way loudspeaker system having an extended frequency range and exceptionally uniform distribution. These characteristics, which effectively meet the requirements for the presentation of stereophonic sound in motion-picture theaters, are obtained by the use of an acoustic lens. Spherical and elliptical lens elements accommodate the distribution pattern to variously shaped auditoria. Design features of the low-frequency horn provide a clean response which is essentially free from resonance.

THEATER loudspeaker systems have been steadily improved through the past years so that, for single-channel operation, the audience receives an impression that it is listening to a reasonable likeness of the original sound. This has been pointed out in a paper previously presented before the Society.¹ This steady improvement in performance has been achieved largely by technical advancements in the design of driver units and in the case of the low-frequency speaker by the replacement of folded horns with short, front-loaded horns.

The advent of stereophonic and pseudostereophonic presentation in the theater has introduced new requirements which call for a re-examination of loudspeaker performance.² In stereophonic presentation, exceptionally uniform distribution of high frequencies is particularly desirable in order to obtain a realistic auditory perspective. If loudspeakers have a high-frequency distribution characteristic which varies materially with frequency or if there are sizable level changes over the angle of distribution, the localization of the apparent source of sound will appear to be different from various points in an auditorium.

Since fidelity in stereophonic localization is almost entirely attributable to the upper register of the frequency spectrum, the major problem is the design of satisfactory high-frequency sound-dispersing mechanisms. In approaching this problem, it was arbitrarily decided that two types of units, one having 50° and the other 80° horizontal distribution, would be provided. Using two of either of these units provides 100° or 160°, respectively, of horizontal coverage. The vertical coverage in all cases was set at approximately 50°.

The high-frequency driver unit is of the permanent-magnet type and provides approximately 21,000 gauss at the voice coil. The diaphragm is approximately

4 in. in diameter and is of 0.003-in. thick aluminum. A typical power-output curve of the driver unit is shown in Fig. 1. This curve was made by measuring the sound pressure at the sending end of a tube which was filled with a long, tapered, sound-absorbent wedge and which was driven by the high-frequency unit. The sound-measuring device was a 640AA microphone. The results of this test are believed to be accurate to approximately 9 kc.

For uniform distribution over the required angles of auditorium coverage, the principle of the acoustic lens has been employed. This involves the use of a type of structure which refracts and diverges sound waves and is similar in function to certain electromagnetic-wave lenses in that it consists of arrays of obstacles which are small compared to the wavelengths involved. These obstacles create an effect which is equivalent to increasing the effective density of the air which results in a reduced propagation velocity of sound waves passing through the array. This reduced velocity is synonymous with refractive power, effecting a refractive index higher than unity. The theory of this type of lens is ably set forth in a paper by Winston E. Kock and F. K. Harvey of the Bell Telephone Laboratories.³

Several types of acoustic lenses have been described³ and of these, two are used—a perforated-disk type having an index of refraction of about 1.2 which provides a horizontal-distribution angle of 50° and a slant-plate type having an

index of refraction of about 1.5 which is easily capable of providing a horizontal-distribution angle of 80°. By using two of either type of lens, the horizontal coverage is increased to 100° or 160°, respectively. In all cases the vertical-distribution angle has been set at approximately 50°.

It may be well to discuss briefly the principle of operation of the two types of lenses currently being used. The first depends upon increasing the effective density of the sound-transmitting medium within the boundaries of the lens. Refraction occurs in media consisting of arrays of individual discrete particles, providing that the particles and distances between them are small compared to the wavelength of the wave propagation under consideration. In other words, if an array of small, rigid particles, having infinite mass for our acoustical consideration, is set up in space, the combination of rigid particles immersed in air results in a new medium having an index of refraction which is greater than unity. Since the velocity of propagation of sound is inversely proportional to the square root of the density of the medium, it will be less through an obstacle array than in free air. Depending on the profile or shape of the obstacle array, the sound waves can be focused or diverged as desired. This obstacle-array type of lens is limited for practical reasons to an index of refraction of about 1.2. A series of perforated metal plates, properly shaped and spaced, can provide similar lens effects and is suitable for loudspeaker applications where the required angle of distribution is not excessive.

Another method of slowing down a progressive wave is to guide it through a conduit or the equivalent, which provides a longer path than that which the unguided wave would normally take. Thus, if a series of parallel plates of varying length are tilted at an angle to the direction of propagation, a delay will

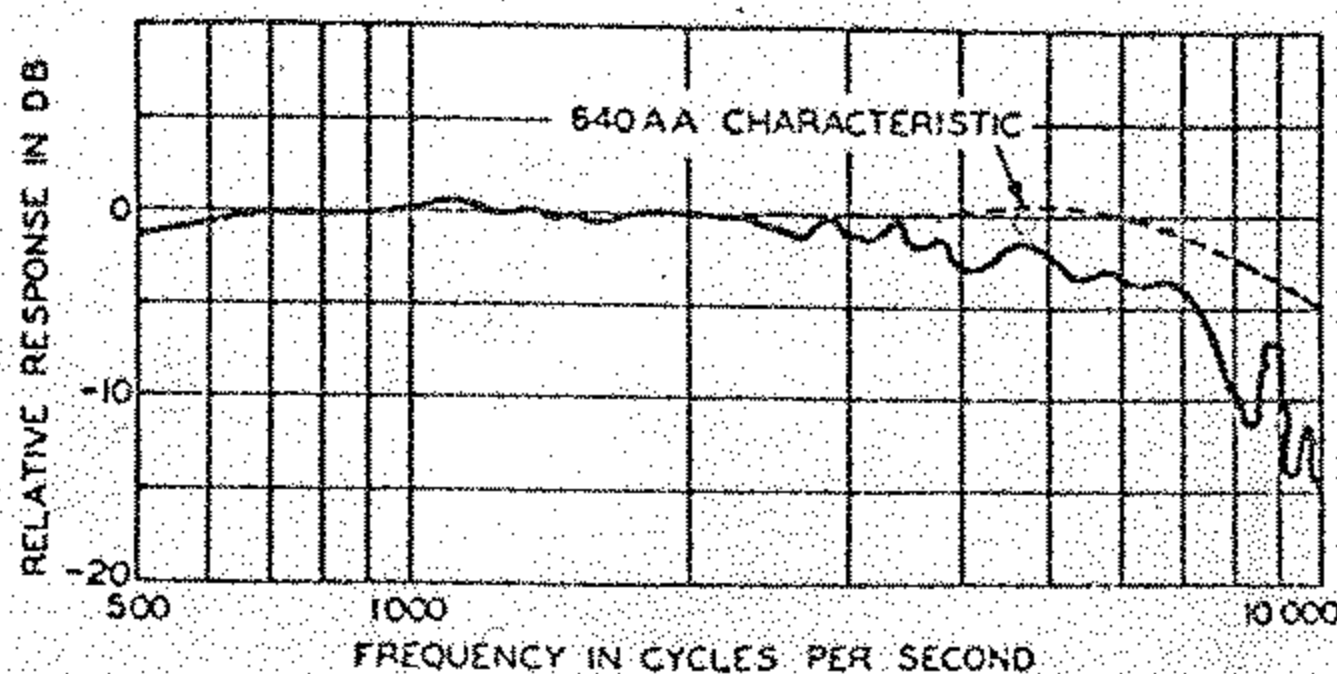


Fig. 1. Power-output curve for T530A loudspeaker.

Presented on May 5, 1954, at the Society's Convention at Washington, D.C., by John G. Frayne (who read the paper), Westrex Corp., 6601 Romaine St., Hollywood 38, and B. N. Locanthi, Consultant, 2552 Boulder Rd., Altadena, Calif. (This paper was received on June 4, 1954.)

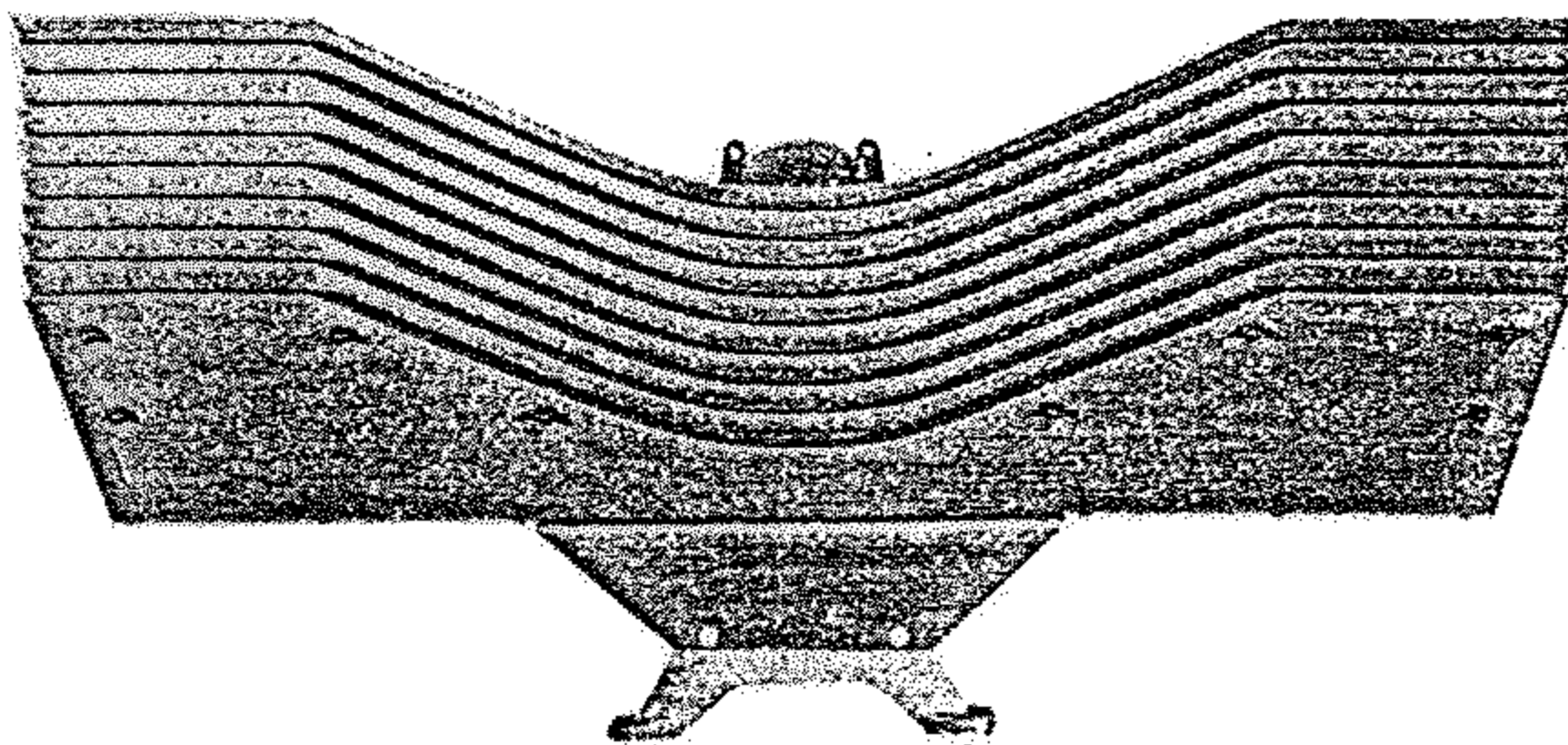


Fig. 2. Front view of T551A acoustic lens assembly.

be produced since the waves will be forced to traverse the longer inclined path. It is then a question of shaping the plates to obtain the desired type of lens action. The effective index of refraction, n , can be shown to be equal to the reciprocal of the cosine of the angle between the slanted plates and the direction of the oncoming wave. In such path-length devices, n remains constant with frequency to a point where the plate spacing approaches a half-wavelength, and an index of refraction up to 1.5 is readily achieved.

Figure 2 shows such a lens designed to give 80° of coverage horizontally and 50° of coverage in the vertical direction. To obtain this type of coverage calls for a bicylindrical lens which is obtained by shaping the individual plates in accordance with the following:

The final surfaces of the refracting lens are determined empirically; however, the first approximation involves the following calculation of an aplanatic surface which will convert a plane wave to a spherical wave:

Referring to Fig. 3, let F represent the point on the axis of the lens from which all refracted rays will appear to be radiated. The distance from the curved surface on the axis to the apparent focal point is represented by f , and t is the thickness of the lens at the narrowest point.

Since S_1 is plane and normal to the

incident plane wave, the incident rays are undeflected after entering the first surface.

In order for an incident ray entering the lens at some arbitrary distance, h , from the axis of the lens to appear to have come from F after leaving surface S_2 , the time required to travel from F to a should equal the time required for an axial ray to travel from F to b . That is:

$$\frac{f-t}{v_0} + \frac{nt}{v_0} + \frac{\sqrt{(f+x)^2 + h^2} - f}{v_0} = \frac{n(t+x)}{v_0} + \frac{f-t}{v_0}$$

which simplifies to

$$(n^2 - 1)x^2 + 2fx(n - 1) - h^2 = 0$$

which is a hyperbolic surface.

These calculations produce an idealized acoustic lens, the plates of which must be modified in shape empirically to produce the desired overall results. Experience has further shown that closing the sides of the plates introduces sizable irregularities in the frequency response. On the other hand, with the sides open, the plates must be extended horizontally for a minimum of some 5 or 6 in. beyond the curved edges of the plates to obtain a smooth frequency response with uniform angular distribution.

The driver unit is coupled to a short elliptical horn terminated in a bicylindrical slant-plate lens. Figure 4 shows the results of tests made under open-air conditions at 10 kc on the horizontal axis with and without a cylindrical lens. This gives a fairly good idea of the refracting power of the lens.

Figure 5 shows the horizontal distribution of an 80° horn assembly at four frequencies as measured under open-air conditions. Similar measurements of the vertical distribution are shown in Fig. 6. The horizontal distribution of the same unit as measured on a studio sound stage is shown in Fig. 7. Warble tones were used in this case and the curves shown are of the average response. The sound-stage measurements and the equivalent open-air measurements will be found to be in close agreement.

By way of comparison, Figs. 8 and 9

show the horizontal and vertical distribution of a typical 2 × 5 multicellular theater-type horn, measured under open-air conditions. The rather sizable lobes in the distribution characteristic are apparently typical of this type of loudspeaker and are particularly undesirable for stereophonic reproduction.

The 50° acoustic lens employs the principle of the obstacle array in the form of perforated plates. Since the horizontal and vertical distribution angles are the same in this case, a horn having a circular cross section is used. Figure 10 shows this type of lens. The driver unit is the same as that used with the 80° unit. The distribution curves obtained with this unit are substantially similar to those obtained with the 80° lens except for the smaller angle of horizontal coverage. Here again, as in the case of the slant-plate lens, closing the sides of the perforated plates introduces a rise at the upper end of the frequency response as well as a too rapid falling off of the angular distribution with increase of angle from the axis of the lens. These undesirable factors have been corrected by introducing rectangular openings in the side walls of the casting in which the perforated plates are mounted.

The very low frequencies of the audible spectrum contribute essentially nothing to stereophonic localization. The design problems pertaining to low-frequency horns are therefore the same as those for single-channel reproduction; namely, the design of the driver units and the coupling between these units and their horn.

For the systems under discussion, two low-frequency horn systems have been developed, one equipped with two driver units and one with four driver units. These consist essentially of short front-loaded horns having efficiencies of approximately 25%. In order to avoid high-frequency attenuation due to an air volume between the driver diaphragm and the horn throat, the ratio of the diaphragm area to the horn-throat area has been kept at 1:1. In order to minimize distortion at low frequencies, the voice coils of the drivers overhang the pole pieces by about 20%. A theoretical response curve for a four-driver, low-frequency horn assembly is shown in Fig. 11.

The dividing network which couples the low-frequency and high-frequency horn assemblies to the amplifier output has a crossover at 500 cycles with a 12-db/octave attenuation on both sides of this point. The network input and output impedances are 16 ohms. In the 50-w horn system one network serves to couple one high-frequency and two low-frequency drivers. In the 100-w horn system, two networks are employed to couple two high-frequency and four low-frequency drivers.

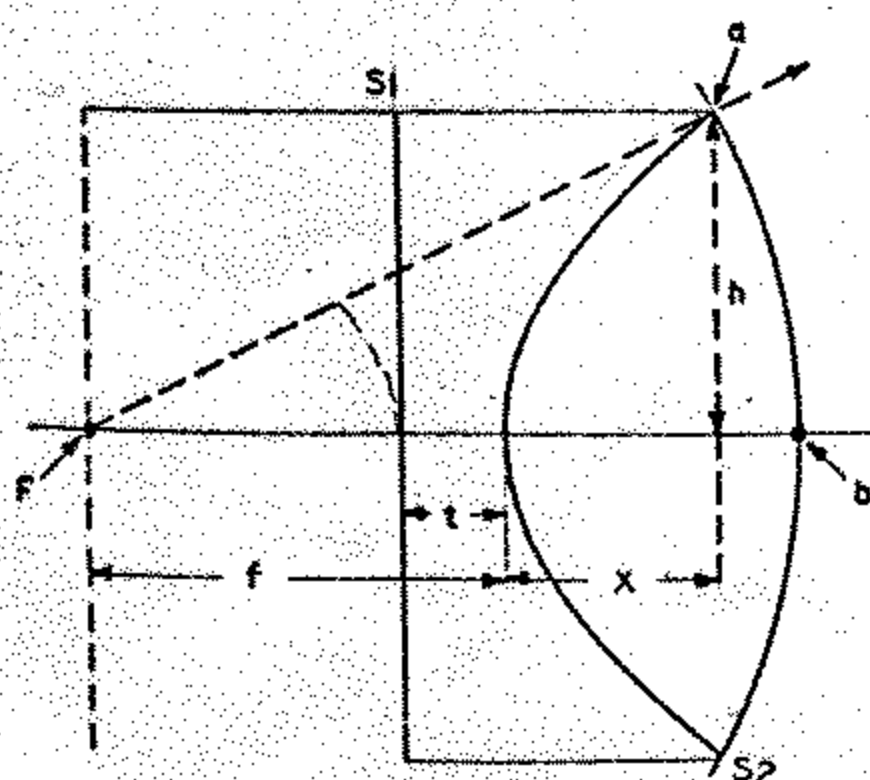


Fig. 3. Ray diagram. Medium of index n between surfaces S_1 and S_2 . Index of refraction unity outside S_1 and S_2 .

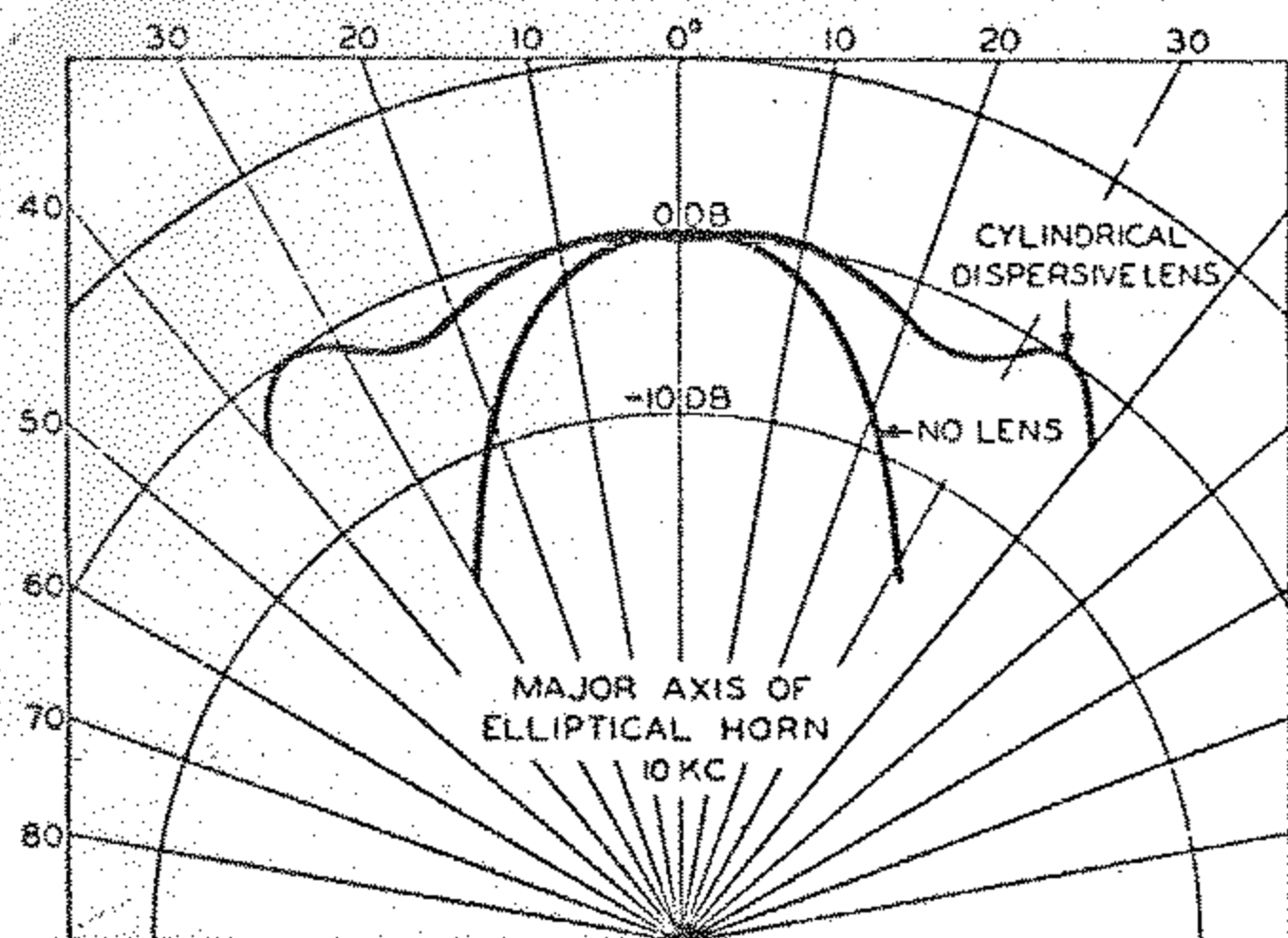


Fig. 4. Effect of acoustic lens on horizontal distribution.

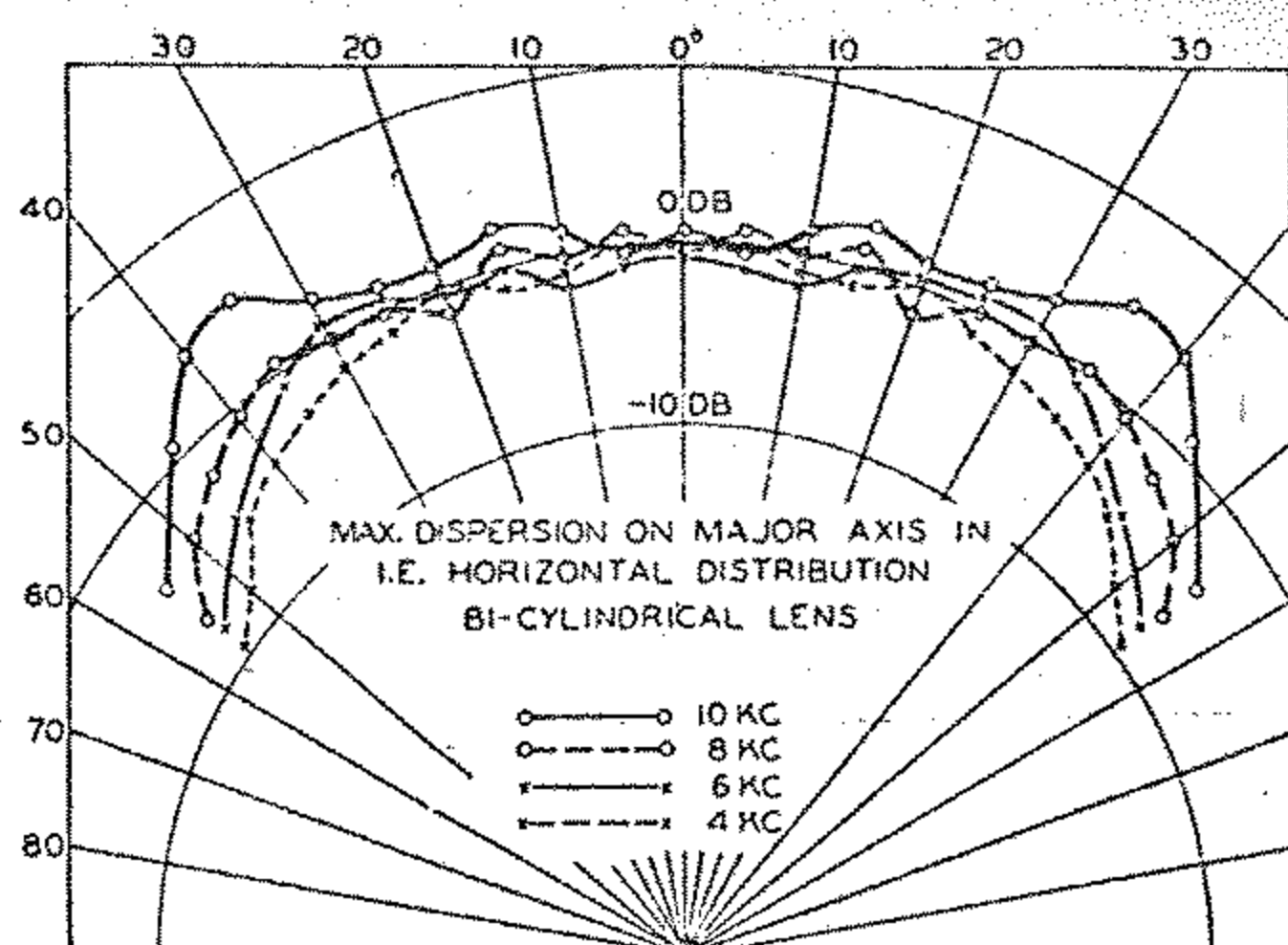


Fig. 5. Horizontal distribution of slant-plate acoustic lens assembly — open-air measuring conditions.

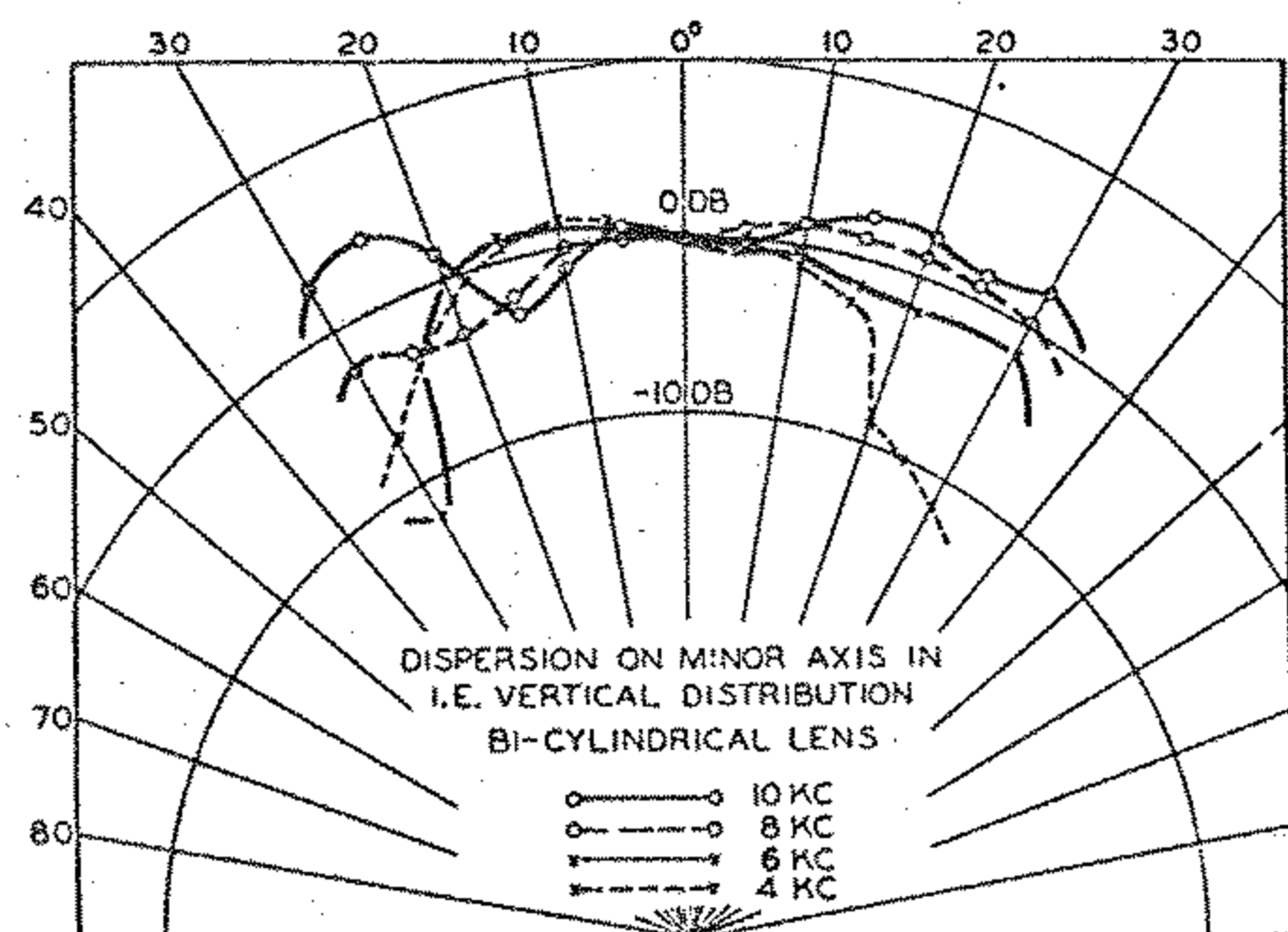


Fig. 6. Vertical distribution of slant-plate acoustic lens assembly — open-air measuring conditions.

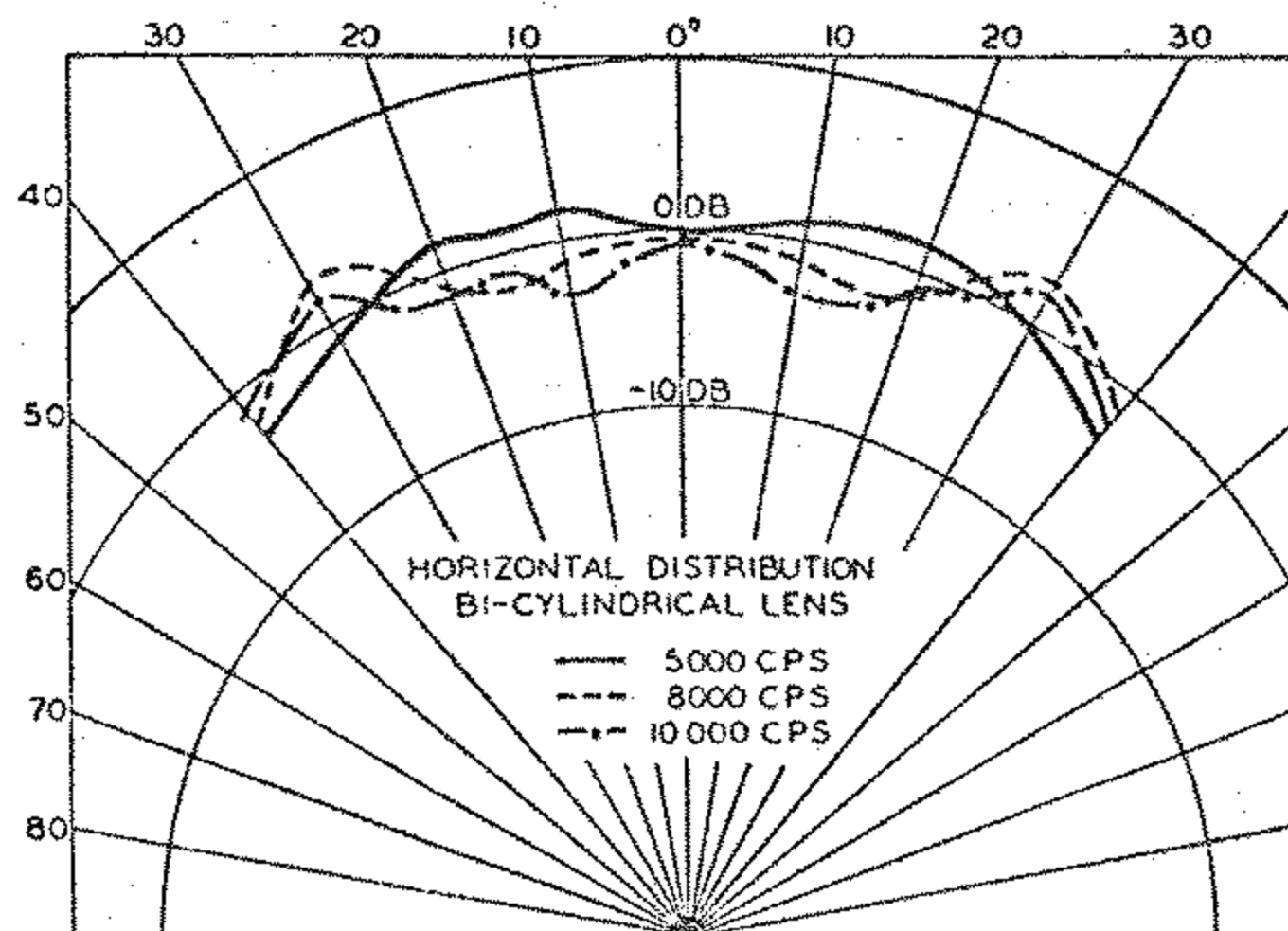


Fig. 7. Horizontal distribution of slant-plate acoustic lens assembly — measured on sound stage.

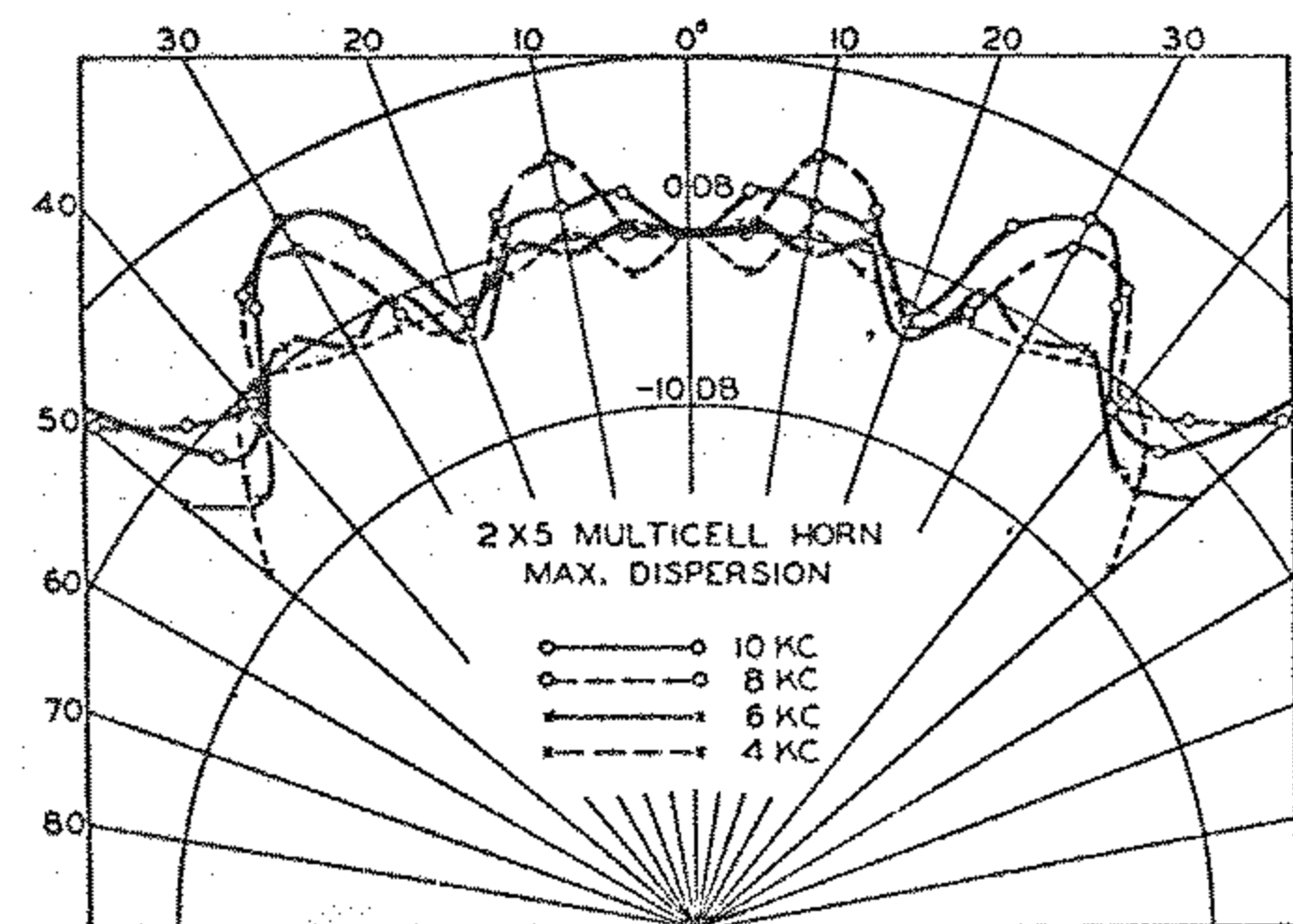


Fig. 8. Horizontal response of typical 2 X 5 multicell theater horn — open-air measuring conditions.

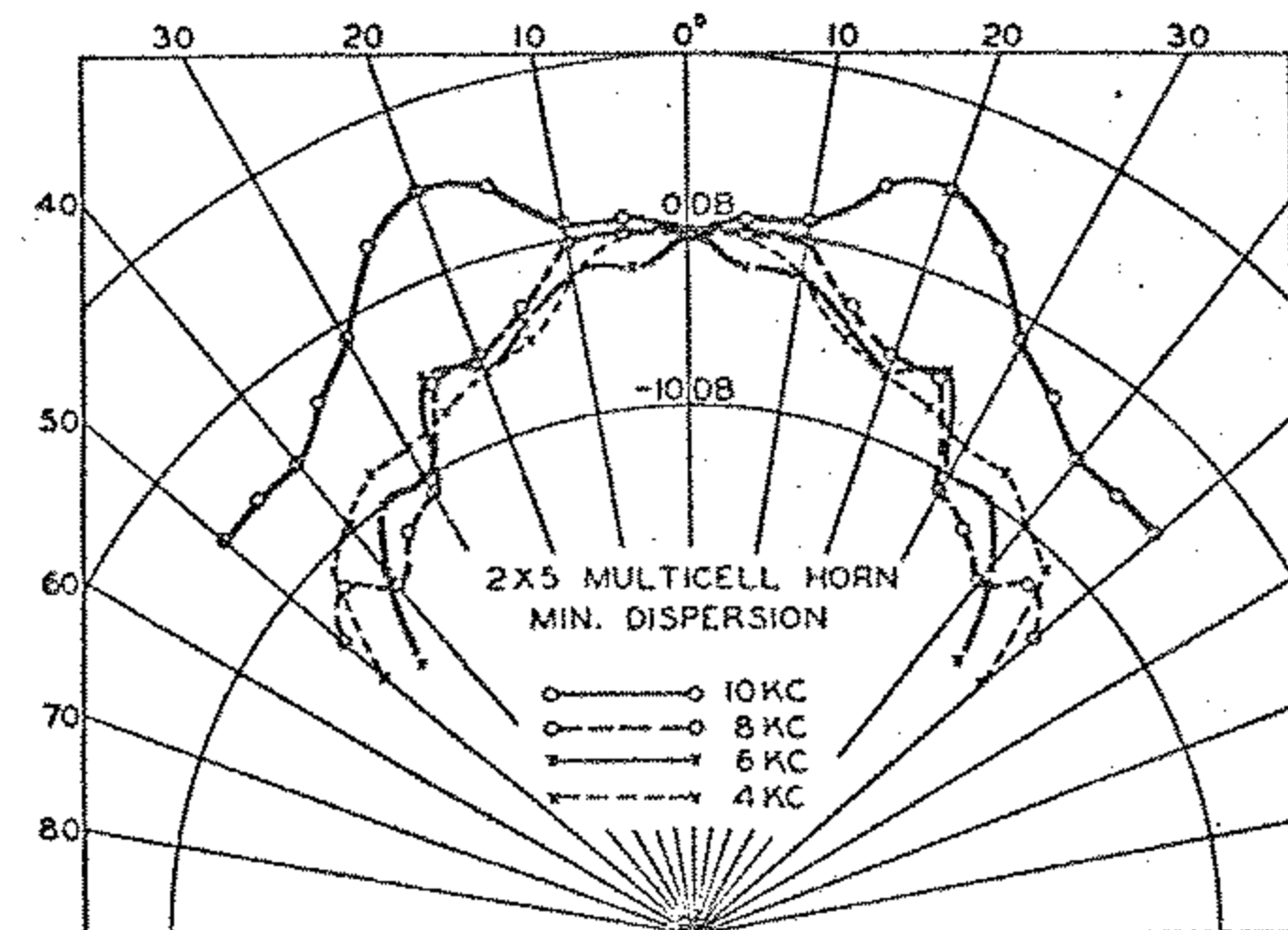


Fig. 9. Vertical response of typical 2 X 5 multicell theater horn — open-air measuring conditions.

A view of a 100-w loudspeaker system consisting of a low-frequency horn equipped with four driver units and two 80° acoustic lens assemblies is shown in Fig. 12. The response characteristic of a 50-w loudspeaker system, using two low-frequency driver units and one 80° acoustic lens system, is shown in Fig. 13. This curve represents a smoothed average

of warble-tone measurements taken on the horn axis on a studio sound stage. Corrections have been applied for the characteristic of the measuring microphone and the scale is substantially similar to that used on the charts of the usual types of sound-measuring equipment.

Listening tests using program material

have been very gratifying. No low-frequency resonances were observed and the high-frequency tones were exceptionally clean. The horizontal distribution was observed to be in conformance with the curves previously shown. When compared with a conventional theater loudspeaker system under A-B test conditions, the new system brought the

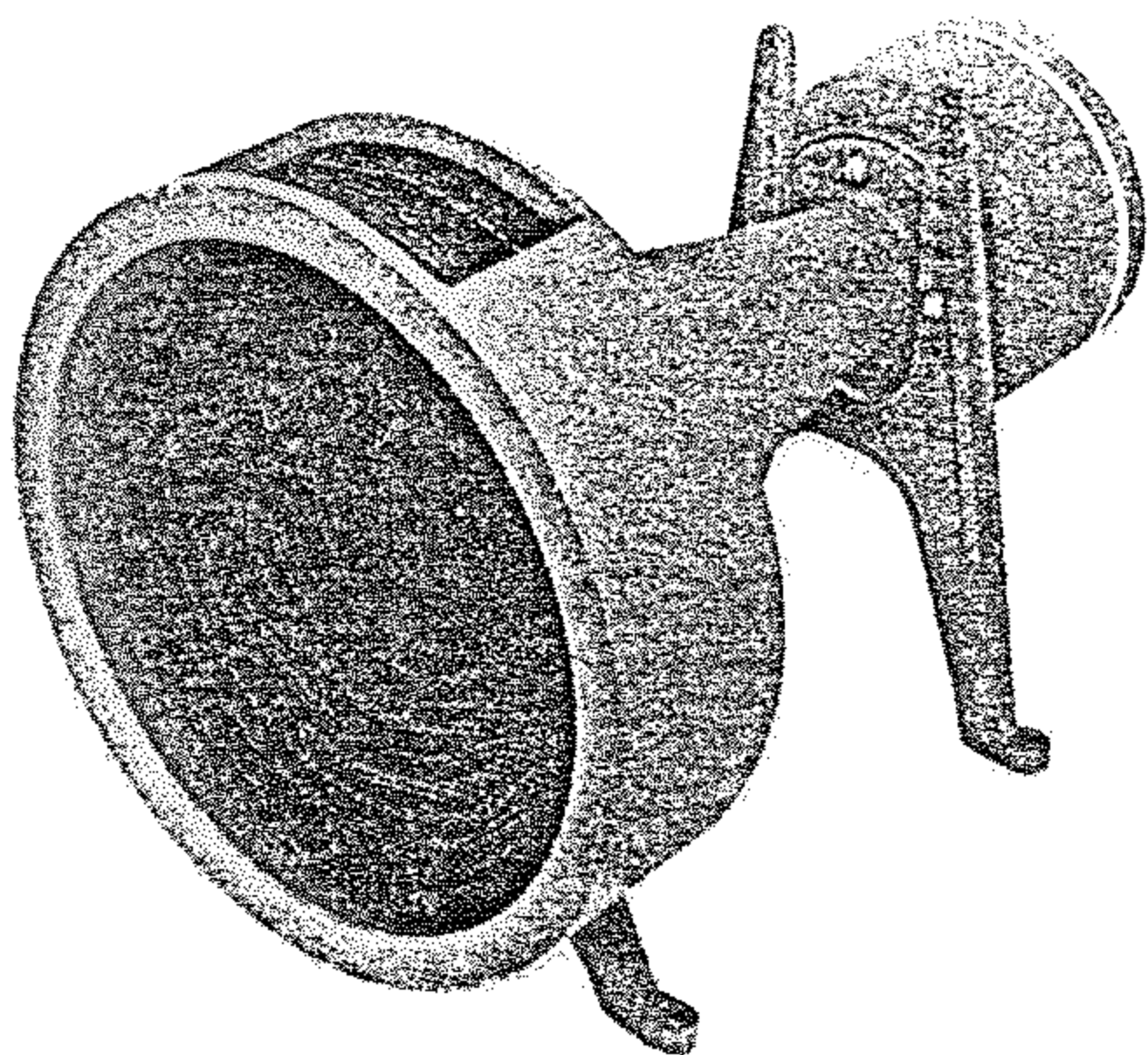


Fig. 10. Front view of T550A acoustic lens assembly.

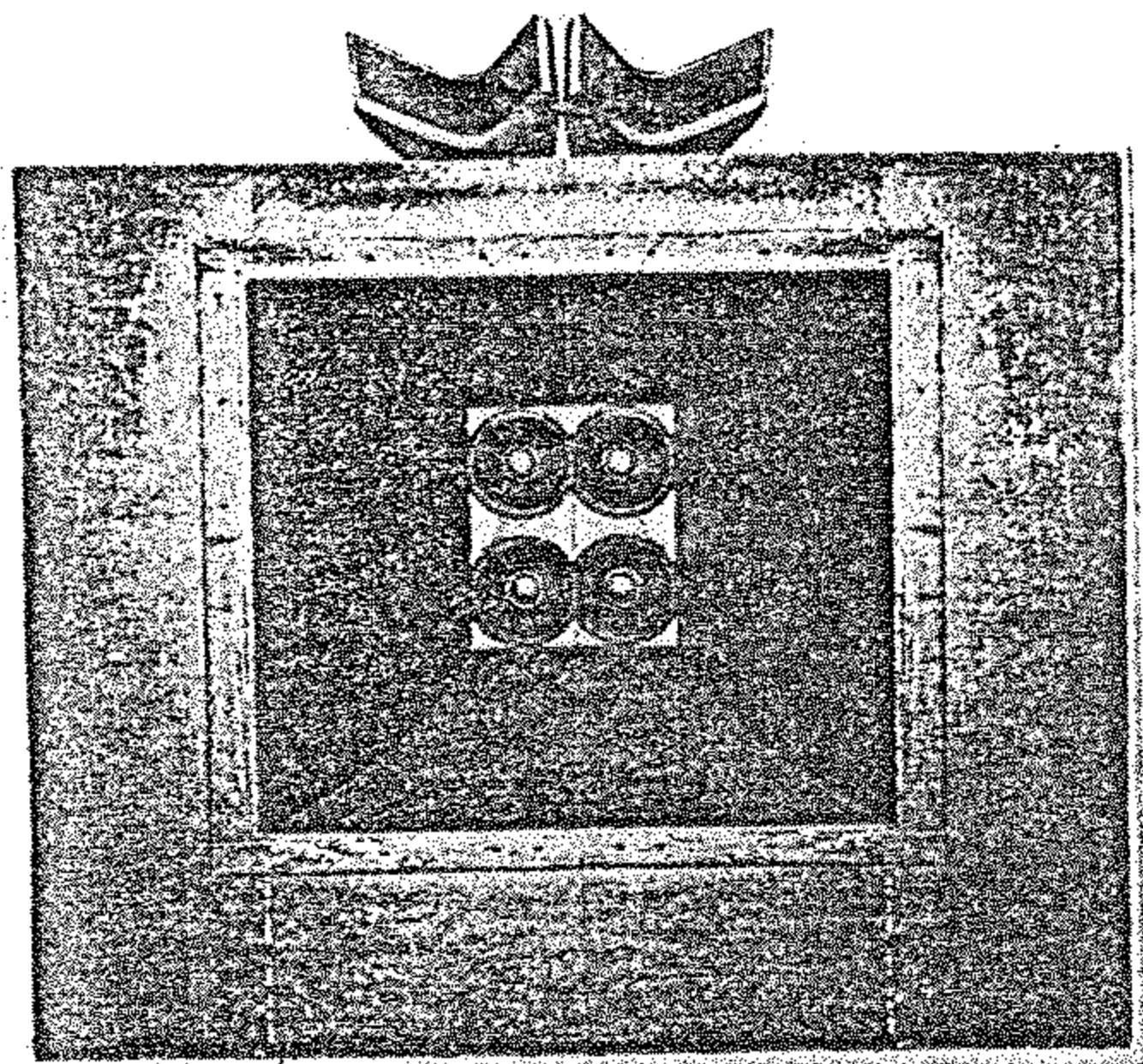


Fig. 12. View of T502B loudspeaker system.

Fig. 11. Theoretical response of four-driver low-frequency horn assembly.

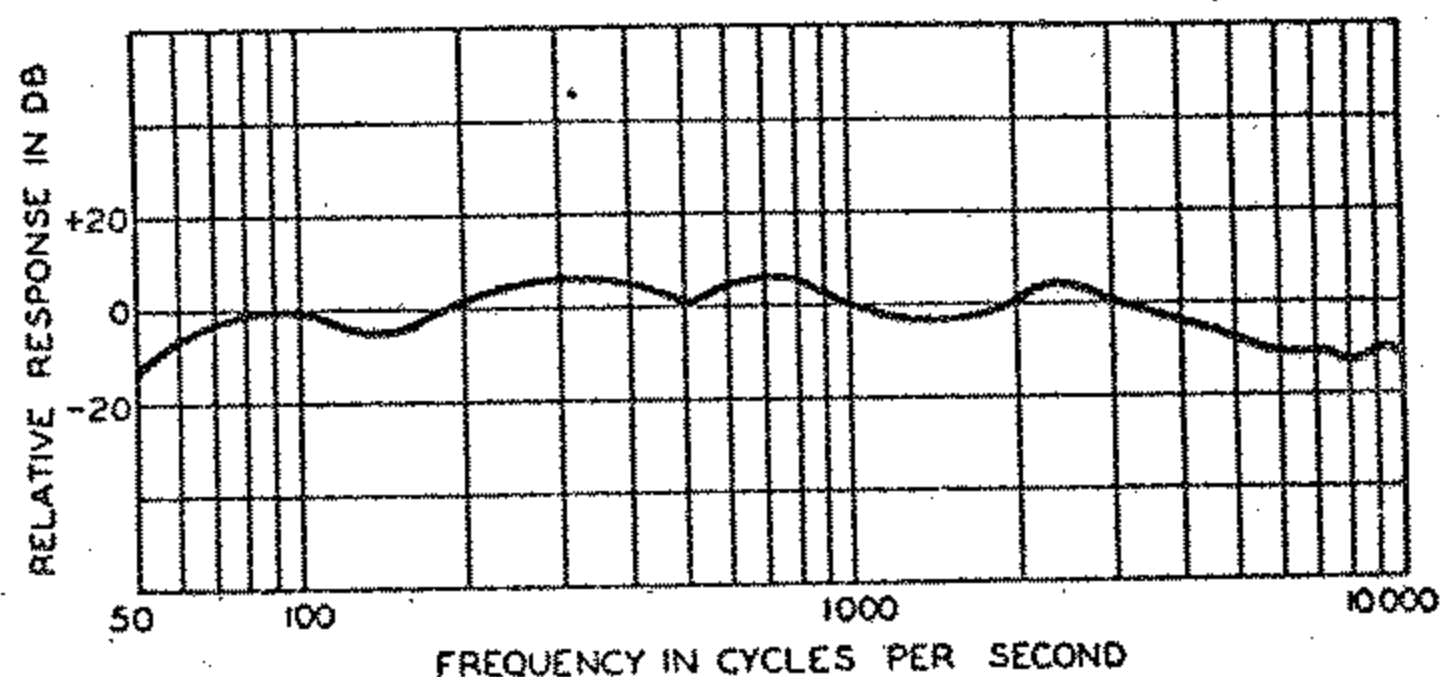
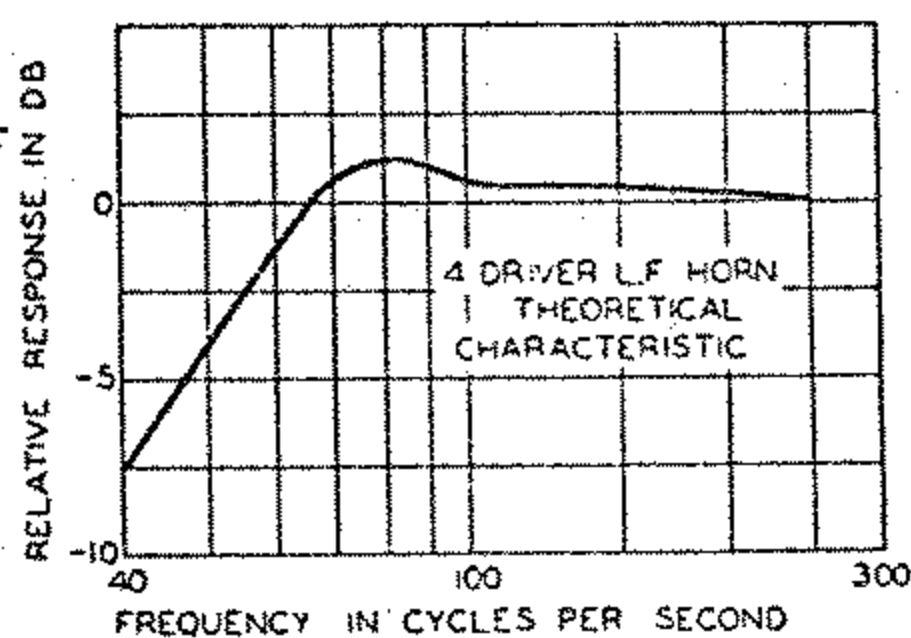


Fig. 13. Response characteristic of 50-w system — smoothed average warble-tone measurements.

apparent source of sound considerably closer to the audience, thus indicating a desirable presence factor.

References

1. J. K. Hilliard, "Theater loudspeaker design, performance and measurement," *Jour. SMPE*, 52: 629-640, June 1949.
2. William B. Snow, "Basic principles of stereophonic sound," *Jour. SMPTE*, 61: 567-589, Nov. 1953.
3. Winston E. Kock and F. K. Harvey, "Refracting sound waves," *J. Acoust. Soc. Am.*, 21: 471-481, Sept. 1949.

Discussion

John Hilliard (Altec Lansing Corp., Calif.): In one of the slides you showed a round, diffusing-type horn system. How does that compare with the one of the rectangular type?

Dr. Frayne: The curves are quite similar over their respective design angle of distribution. I'm sorry we don't have a curve on it here. It was designed for 50° distribution. At 25° off the axis the response was falling off.

Mr. Hilliard: By coincidence, I happened to measure two or three of them and found that whenever you take the lens properties out of it, the directional properties increase, that is the frequency response was extended and the drop-off with azimuth was less than it was with the lens assembly on it.

Dr. Frayne: That's not in accordance with measurements shown in Fig. 4.

Mr. Hilliard: This was a general statement that in all cases when the diffuser element was taken off the properties of the two units measured were improved and these were measured in an anechoic chamber with the 640AA microphone as the standard.

Dr. Frayne: I wouldn't want to dispute your word, but I don't think it agrees with our findings.

M. A. Kerr (Bureau of Ships): You said in the beginning of your paper that the spread of sound at the high frequencies was necessary for the spatial illusion and this work that you're showing begins at the high-frequency end and works downward. That would assume that there is a crossover point where the spatial illusion effect is no longer necessary, because I don't see any similar spread in your low-frequency units. Is there any critical frequency point or general area where it is no longer necessary to properly spread the low frequencies?

Dr. Frayne: According to Snow² very poor localization is obtained below 1000 cycles.

John Volkmann (Radio Corp. of America, Camden, N.J.): Your paper did not show any directional characteristics for the low-frequency speaker?

Dr. Frayne: No.

Mr. Volkmann: Does it match the directional pattern of the high-frequency speakers? In particular, how does the directional pattern of the combined systems act in the crossover frequency range?

Dr. Frayne: The 50-cycle distribution is very uniform. The 500-cycle distribution of the low-frequency speaker measures essentially the same as that obtained from the lens. I would say that the performance of the low-frequency system is quite comparable to any 50- or 100-w system today in theaters. The thing we're trying to emphasize here is the lens of the high-frequency units.

Mr. Volkmann: I'd like to point out that there is a fundamental difference in the design of the low-frequency horn relative to the high-frequency horn, namely, if I judge the design correctly, the low-frequency horn is designed on a basis of a plane-wave progression in the horn.

Dr. Frayne: That's right.

Mr. Volkmann: In a straight-axis exponential horn design the plane wave radiation would tend to give a sharpening of the directional pattern with an increase in frequency, whereas the high-frequency horn design, being based on the lens principle, the radiation would tend to give a spherical distribution of the sound within its angular range and there would be, in the crossover region, then, a disparity between the two types of directional patterns.

Dr. Frayne: Well, I've seen curves on both the 50-w and 100-w systems covering the angles we mention here. There were no signs of such disparity.

Mr. Volkmann: My second question is whether or not you really desire a spherical distribution pattern in the vertical angle, where, for example, in an auditorium you want the same level in the front rows of seats as in the back rows? Except where the loudspeakers are up high enough, is it not more desirable to have a sharp directional pattern in the vertical plane in order to balance the level from front to back more uniformly?

I would like to make another point. The low-frequency horn has a very similar likeness to one of the models (straight axis) that RCA tested in connection with the experiments that were conducted by Douglas Shearer back in 1935 or 1936.

Dr. Frayne: I believe the model you were referring to was a folded-type horn while the present unit is a short front-loaded horn.

Richard H. Ranger (Rangertone, Inc.): Isn't your premise that the intensity is the most important factor in initial stereophonic work, directly limited to frequencies from 1000 cycles up, because the human head itself serves as a cross-over point where below 1,000-cycles phase is predominant, and above 1,000-cycles intensity is the dominant factor for spatial emphasis.

Dr. Frayne: Somewhere in that neighborhood.