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Direct Radiator Loudspeaker Enclosures

HARRY F. OLSON*

A comprehensive analysis of the effect of cabinet configuration on the sound distribution pattern and overall response-frequency characteristics of loudspeakers.

THE PRINCIPAL FACTORS which influence the performance of a direct-radiator loudspeaker are the mechanism itself, the acoustical impedance presented to the back of the mechanism by the enclosure, and the outside configuration of the enclosure. The major portion of the work involving cabinet research, development, and manufacture has been directed towards the acoustical impedance presented to the back of the loudspeaker mechanism by the enclosure. The volume of the cabinet and the internal damping means play the most important role in determining the acoustical impedance presented to the back of the loudspeaker. In other words, most of the considerations concerning the design of cabinets for direct-radiator loudspeakers have involved the volume or overall dimensions of the cabinet which—together with the mechanism—determines the low-frequency performance. The third factor, namely, the exterior configuration of the cabinet, influences the response of the loudspeaker system due to diffraction effects produced by the various surface contours of the cabinet. The diffraction effects are usually overlooked and the anomalies in response are unjustly attributed to the loudspeaker mechanism. Therefore, in order to point up the effects of diffraction, it appeared desirable to obtain the performance of a direct-radiator loudspeaker mechanism in such fundamental shapes as the sphere, hemisphere, cylinder, cube, rectangular parallelepiped, cone, double cone, pyramid, and double pyramid. It is the purpose of this paper to present the results of the diffraction studies made upon these fundamental shapes. The response-frequency characteristics of a direct-radiator loudspeaker mechanism mounted in these different housings yield fundamental information regarding the effect of the outside configuration of the cabinet upon the performance of this combination. From this study it is possible to evolve a cabinet shape which has the least effect in modifying the fundamental performance of a direct-radiator loudspeaker mechanism.

**RCA Laboratories, Princeton, New Jersey*

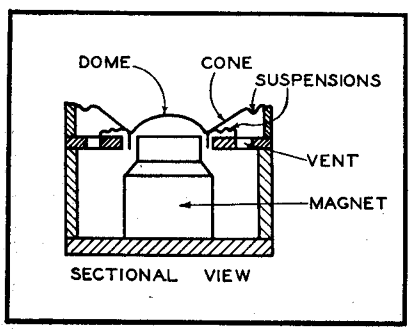


Fig. 1. Sectional view of the loudspeaker mechanism.

Characteristics of the Sound Source

In the experimental determination of the performance of direct-radiator loudspeaker mechanisms in various shaped enclosures, some consideration must be given to the radiating system. These considerations include the directional characteristics of the sound source and the sound power output characteristics of the sound source as a function of the frequency.

In order to obtain the true diffraction effects which are produced by the different enclosures, the radiation emitted by the sound source must be independent of the direction. Since the diaphragm of the direct-radiator loudspeaker mechanism used in these tests is relatively very small, it can be assumed that it is a piston source. The directional characteristics of a piston source are given by

$$R_a = \frac{2J_1\left(\frac{2\pi R}{\lambda}\sin\alpha\right)}{\frac{2\pi R}{\lambda}\sin\alpha} \qquad (1)$$

where R_a = ratio of the pressure for an angle α to the pressure for an angle $\alpha = 0$,

J_1 = Bessel function of the first order,
R = radius of the piston, in centimeters,
α = angle between the axis of the piston and the line joining the point of observation and the center of the piston, and
λ = wavelength, in centimeters.

The upper frequency limit for this investigation will be placed at 4000 cps. The reason for selecting this limit is that the enclosures which will be used are relatively large. For example, the linear dimensions are eight to ten wavelengths at 4000 cps. It will be stipulated that the radiation from the cone of the loudspeaker mechanism at this frequency shall be down not more than 1.0 db for $\alpha = 90$ deg. as compared to $\alpha = 0$ deg. This insures a reasonably nondirectional sound source even at the upper end of the frequency range, that is, at 4000 cps. Of course, at lower frequencies the response discrepancy with respect to angle is much less. To satisfy the above requirements, the diameter of the diaphragm or cone must be ⅞ in. Accordingly a small direct-radiator loudspeaker mechanism employing a cone ⅞ in. in diameter was designed, built, and tested. A sectional view of the loudspeaker mechanism is shown in *Fig.* 1. Measurements indicated that the directional performance agreed with that predicted by equation *(1)*.

The next consideration is the sound

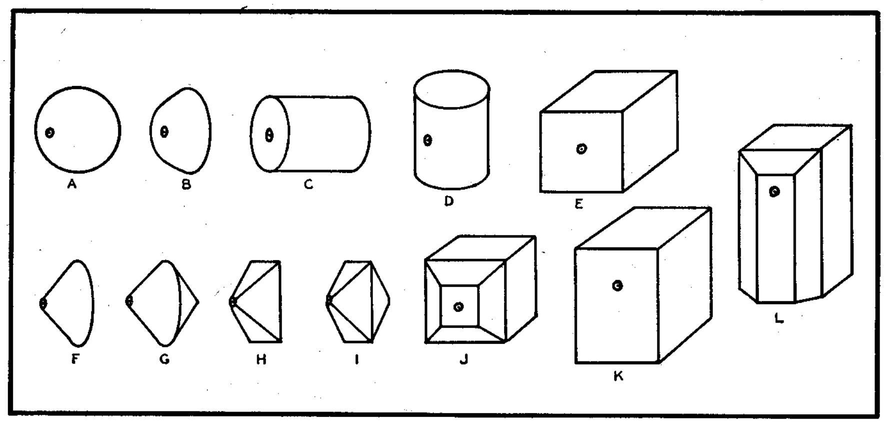


Fig. 2. Direct-radiator loudspeaker mechanism enclosures. The small circle with the dot in the center represents the speaker unit.

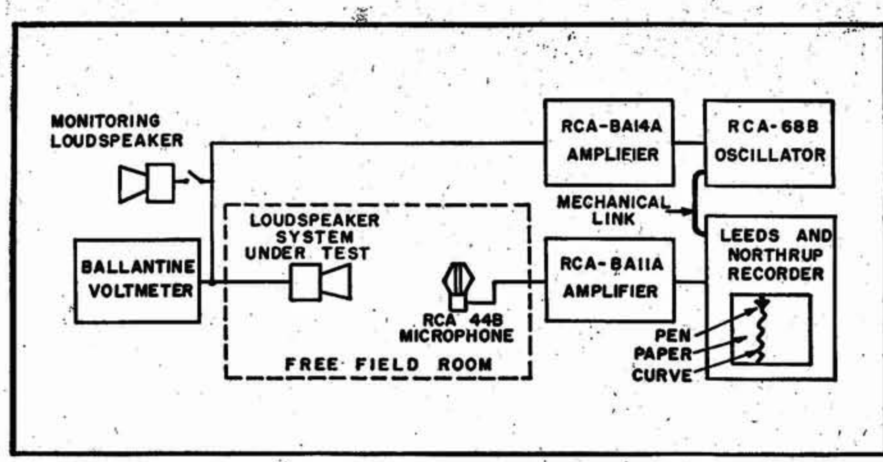


Fig. 3. Schematic diagram of the apparatus for obtaining the response-frequency characteristics of loudspeakers.

power output calibration of the sound source. The sound power output of a piston sound source radiating into 4π solid angles and operating in the frequency region in which the diameter of the piston is less than one-quarter wavelength[1] is given by

$$P_T = \frac{\rho\omega^2}{4\pi c} S^2 \dot{x}^2 = \frac{\rho\omega^2}{4\pi c} \dot{X}^2 \qquad (2)$$

where ρ = density of air, in gms./cu. cm.,
c = velocity of sound, in cm./sec.,
$\omega = 2\pi f$,
f = frequency, in cps,
S = area of the diaphragm, in sq. cm.,
$\dot{x}$ = r.m.s. velocity of the diaphragm, in cm./sec., and
$\dot{X}$ = r.m.s. volume current produced by the mechanism, in cu. cm./sec.

Equation *(2)* shows that the sound power output P_T of the sound source will be independent of the frequency f, if the velocity $\dot{x}$, of the piston is inversely proportional to the frequency. The characteristics depicted in this paper have been reduced to a sound source of this type, namely, that when it radiates into 4π solid angles the sound power output will be independent of the frequency. Since the directivity pattern of the sound source is independent of the frequency, the sound pressure, under these conditions, will also be independent of the frequency.

It may be mentioned in passing that, in the case of a direct-radiator loudspeaker mechanism operating in the frequency range below the ultimate acoustical radiation resistance, the velocity of the cone must be inversely proportional to the frequency in order to obtain constant sound power output, because the acoustical radiation resistance is proportional to the square of the frequency. In order to obtain this type of motion, the system must be mass controlled, which is the natural state of affairs in the direct-radiator type of loudspeaker mechanism above the fundamental resonant frequency of the system. In other words, the performance characteristics depicted in this paper are, for all practical purposes, the characteristics which will be obtained if conventional direct-radiator loudspeaker mechanisms are used in these enclosures.

[1] If the upper frequency limit is placed at 4000 cps, the diameter of the ⅞-in. cone will be less than one-quarter wavelength in the frequency range below 4000 cps.

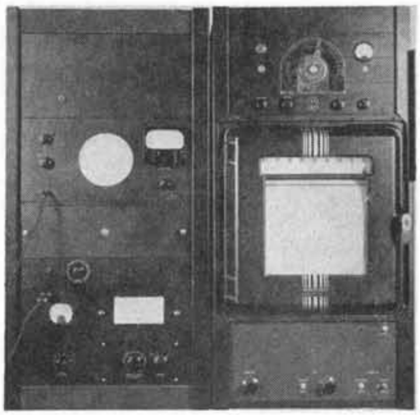


Fig. 4. Equipment set-up for obtaining the response-frequency characteristics of loudspeakers.

Enclosures

The enclosures used in these experiments are depicted in *Fig. 2*. The sheet metal sphere shown at (A) is 2 ft. in diameter. The loudspeaker mechanism is mounted with the cone approximately flush with the surface. The sheet metal hemisphere shown at (B) is 2 ft. in diameter with the back closed by a flat board of hard wood. The loudspeaker mechanism is mounted upon the zenith of the hemisphere with the cone of the loudspeaker mechanism approximately flush with the surface. The sheet metal cylinder shown at (C) is 2 ft. in diameter and 2 ft. in length. The ends of the cylinder were closed by plywood boards of hard wood. The loudspeaker mechanism is mounted in the center of one end with the cone of the loudspeaker mechanism mounted flush with the surface. The cylinder shown at (D) is of the same size as that of (C). In (D) the cone of the loudspeaker mechanism is mounted approximately flush upon the cylindrical surface midway between the ends. The sides of the wood cube shown at (E) are 2 ft in length. The loudspeaker mechanism is mounted in the center of one face with the cone flush with the surface. The base of the sheet metal cone shown at (F) is 2 ft. in diameter. The height of the cone is 1 ft. The base of the cone is closed by

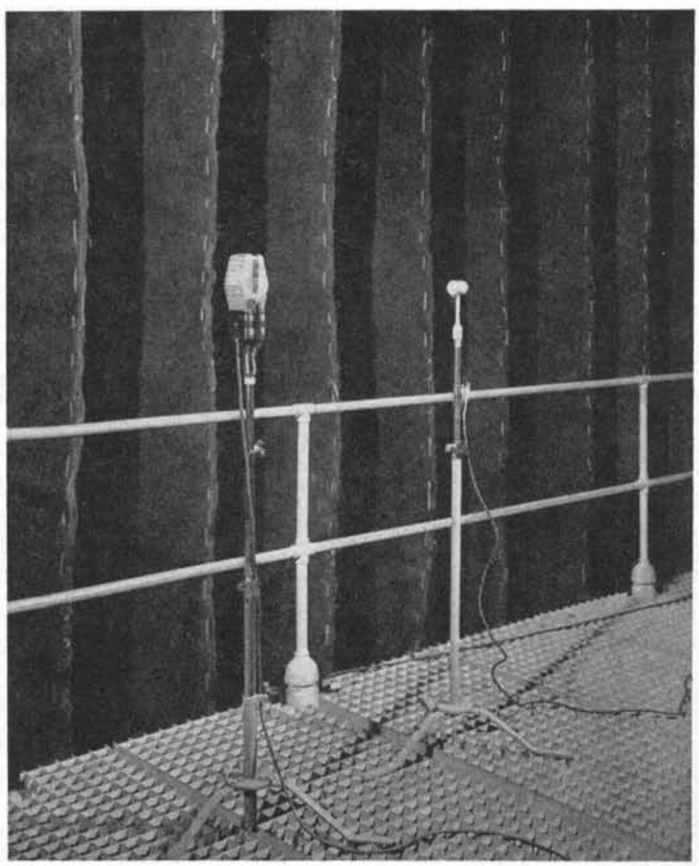


Fig. 5. Microphone and small direct-radiator loudspeaker mechanism of Fig. 1 under test in the free-field room.

a board of hard wood. The loudspeaker mechanism is mounted in the apex of the cone. The cone was truncated to accommodate the small loudspeaker mechanism. The double cone of (G) consists of two cones, each of the same size as that of the single cone of (F), with the bases placed edge to edge. The loudspeaker mechanism is mounted in the apex of one of the cones. The length of the edges of the square base of the wood pyramid shown at (H) is 2 ft. The height of the pyramid is 1 ft. The base of the pyramid is closed by a board of hard wood. The loudspeaker mechanism is mounted in the apex of the pyramid. The pyramid was truncated to accommodate the small loudspeaker mechanism. The double pyramid of (I) consists of two pyramids, each of the same size as that of the single pyramid of (H), with the bases placed edge to edge. The loudspeaker mechanism is mounted in the apex of one of the pyramids. The truncated pyramid of (J) is mounted upon a rectangular parallelepiped. The length of the edges of the truncated surface is 1 ft. The height of the truncated pyramid is 6 in. The lengths of the edges of the rectangular parallelepiped are 1 ft. and 2 ft. The loudspeaker mechanism is mounted in the center of the truncated surface. The lengths of the edges of the rectangular parallelepiped of (K) are 2 ft. and 3 ft. The loudspeaker mechanism is mounted midway between two long edges and 1 ft. from one short edge. At (L) a rectangular truncated pyramid is mounted upon a rectangular parallelepiped. The lengths of the edges of the rectangular parallelepiped are 1, 2, and 3 ft. The lengths of the edges of the truncated surface are 1 ft. and 2½ ft. The height of the truncated pyramid is 6 in. One surface of the pyramid and one surface of the parallelepiped lie in the same plane.

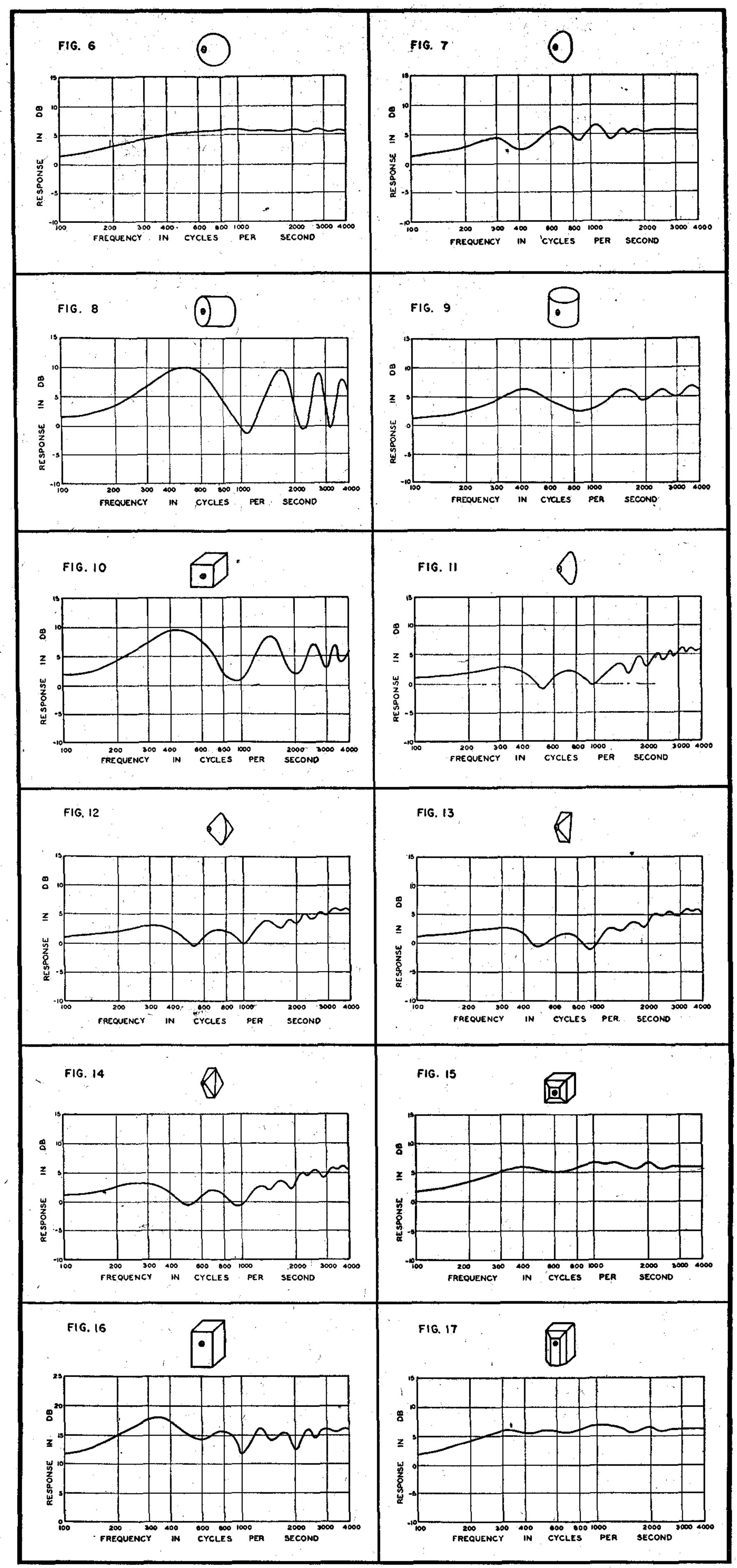
Measurement Apparatus and Techniques

The small loudspeaker mechanism of *Fig.* 1 was mounted in the enclosures shown in *Fig.* 2. In obtaining true diffraction effects it is important that reflection effects produced by room in which the response-frequency characteristic is obtained be reduced to a negligible minimum. Therefore, all the response-frequency characteristics depicted in this paper were obtained in the free field room[2, 3] of the Acoustical Laboratory of the RCA Laboratories. A schematic diagram of the apparatus used for obtaining the response-frequency characteristics, along with detailed designations of the components are shown in *Fig.* 3. The complete recording system—including the RCA-44B velocity microphone, BA1A amplifier, and Leeds and Northrup Speedomax recorder—was calibrated by the free

[*Continued on page 59*]

[2] H. F. Olson, *J. Acous. Soc. Am.*, Vol. 15, No. 2, p. 96, 1943.

[3] Olson, *Elements of Acoustical Engineering*, D. Van Nostrand Company, New York, 2nd Edition, 1947, p. 359.



Figs. 6 to 17. Response-frequency characteristic of a small direct-radiator loudspeaker mechanism mounted in the enclosures of Fig. 2.

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field reciprocity method.[4, 5] A sinusoidal input was applied to the loudspeaker system under test by means of the combination RCA-68B beat-frequency oscillator and a BA-14A amplifier. The voltage applied to the loudspeaker system was measured by means of a Ballantine voltmeter. The measuring apparatus is shown in *Fig.* 4, and the microphone and the small loudspeaker mechanism of *Fig.* 1 under test in the free field sound room are shown in *Fig.* 5. The response-frequency characteristics illustrated and described in the sections which follow were obtained by means of the apparatus and arrangements described above.

Sphere

The first consideration will be the combination of the direct-radiator loudspeaker mechanism of *Fig.* 1 and the spherical enclosure as shown at (A) in *Fig.* 2. The axial response-frequency characteristic thus obtained was corrected so that the volume current produced by the mechanism was inversely proportional to the frequency, as previously described. The response-frequency characteristic[6, 7] of the combination of a small direct-radiator sound source in which the volume current is inversely proportional to the frequency and a large spherical enclosure is shown in *Fig.* 6. It will be seen that the response is uniform and free of peaks and dips. This is due to the fact that there are no sharp edges or discontinuities to set up diffracted waves of a definite phase pattern relation with respect to the primary sound emitted by the loudspeaker. The diffracted waves are uniformly distributed as to phase and amplitude. Therefore, the transition from radiation by the loudspeaker mechanism into 4π solid angles to radiation into 2π solid angles takes place uniformly with respect to the frequency. It will be noted that the sound pressure increases uniformly in this transition frequency. The ultimate pressure is 6 db higher than the sound pressure where the dimension of the sphere is a small fraction of the wavelength.

Hemisphere

The axial response-frequency characteristic of the loudspeaker mechanism of *Fig.* 1 mounted in the hemispherical enclosure of (B), *Fig.* 2, is shown in *Fig.* 7. The sharp discontinuity at the boundary of the spherical and plane surfaces produces a strongly diffracted wave. There is a phase difference between the primary and diffracted waves which results in peaks and dips in the response-frequency characteristic corresponding to in and out of phase relationships between the primary and diffracted sound. A physical explanation of the phenomena is as follows: The sound flows out in all possible directions from the sound source. The sound which follows the contour of the spherical surface encounters a sudden change in acoustical impedance at the intersection of the plane and spherical surface. A reflected wave is sent out at this point in all possible directions. The distance from the diaphragm of the loudspeaker mechanism to the circular diffracting edge is $\pi/2$ feet. The distance between the plane of the diaphragm and the plane containing circular diffracting edge is 1 ft. Therefore, the difference in path between the primary and the diffracted wave at the observation or measurement point on the axis is $(\pi/2+1)$ ft. The sound wave which follows the contour of the spherical surface encounters a decrease in acoustical impedance at the boundary of the spherical and plane surfaces, and the diffracted or reflected wave suffers a phase change of 180 deg. Therefore, when the distance $(\pi/2+1)$ ft. corresponds to odd multiples of one-half wavelength, there will be maxima of response because the primary and diffracted waves are in phase. The maxima will occur at 215, 645, 1075, etc. cps. It will be seen that this agrees with experimental results. When the distance $(\pi/2+1)$ ft. corresponds to multiples of the wavelength, there will be minima in the response because the primary and diffracted waves are out of phase. The minima will occur at 430, 860, 1290, etc. cps. It will be seen that this agrees with the experimental results.

Cylinder

The axial response-frequency characteristic[8] of the loudspeaker mechanism of *Fig.* 1 mounted in the center of one end of the cylinder of (C), *Fig.* 2 is shown in *Fig.* 8. The sharp boundary at the intersection of the plane and cylindrical surface introduces a strongly diffracted wave. The distance from the mechanism to the circular boundary is 1 ft. Therefore, since the diaphragm and the edge lie in the same plane, the path difference between primary and diffracted wave is 1 ft. Following the explanation of the preceding section, there should be maxima of response at 550, 1650, 2750, 3850, etc. cps, and there should be minima of response at 1100, 2200, 3300, etc. cps. It will be seen that there is remarkable agreement with the experimental results of *Fig.* 8. It is also interesting to note that the variations in response are very great, being of the order of 10 db.

The axial response-frequency characteristic of the loudspeaker mechanism of *Fig.* 1 mounted in the cylindrical surface of the cylinder of (D), *Fig.* 2, is shown in *Fig.* 9. Again the sharp boundary between the cylindrical and the plane surfaces produces a diffracted wave. However, the path difference between the primary and diffracted wave is not confined to a single discrete distance. Therefore, the maxima and minima of response are not as pronounced as in the case of (C), as shown in *Fig.* 8. From the response frequency characteristic of *Fig.* 9, it would appear that the effective distance between the primary and diffracted wave is about 1.17 ft. As would be expected, this means that the forward portion of the diffracting edge plays the predominant part.

Cube

The axial response-frequency characteristic[9] of the loudspeaker mechanism of *Fig.* 1 mounted in the center of one of the faces of the cube (E), of *Fig.* 2, is shown in *Fig.* 10. The sharp boundary at the edges of the cube produces a strongly diffracted wave. The average path between the mechanism and the

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[4] H. F. Olson, *RCA Review,* Vol. 6, No. 1, p. 36, 1941.

[5] Olson, *Elements of Acoustical Engineering,* D. Van Nostrand Company, New York, 2nd Edition, 1947, p. 345.

[6] The response-frequency characteristics depicted in this paper were obtained on enclosures having the dimensions given. The response-frequency characteristics for enclosures of other dimensions can be obtained by multiplying the ratio of the linear dimensions of the enclosure given in this paper to the linear dimensions of the new enclosure by the frequency of the response-frequency characteristic given in this paper. For example: if the linear dimensions of the new enclosures are two times those of the enclosures described, the frequency scales of *Figs.* 6 to 17 inclusive should be multiplied by one-half.

[7] The theoretical and experimental sound pressures on a sphere as a function of the frequency for an impinging plane wave of constant intensity have been investigated by G. W. Stewart, *Phys. Rev.,* Vol. 33, No. 6, p. 467. 1911, S. Ballantine, *Phys. Rev.,* Vol. 32, No. 6, p. 988, 1928 and Muller, Black and Dunn, *J. Acous. Soc. Am.,* Vol. 10, No. 1, p. 6, 1938. The results reported by these investigators agree with those depicted in *Fig.* 6. This is to be expected from the reciprocity theorem which states that under appropriate conditions the source and observation points may be interchanged without altering the response frequency characteristics of the system. See Olson, *Elements of Acoustical Engineering,* D. Van Nostrand Company, New York, N. Y., 1947, p. 21.

[8] The theoretical and experimental sound pressures on the center of the face of a cylinder as a function of the frequency have been investigated by Muller, Black and Dunn, *J. Acous. Soc. Am.,* Vol. 10, No. 1, p. 6, 1938. The results reported by these investigators agree with those depicted in *Fig.* 8. This is to be expected from a consideration of the reciprocity theorem. See footnote 7.

[9] The theoretical and experimental sound pressures on the center of a face of a cube as a function of the frequency have been investigated by Muller, Black and Dunn, *J. Acous. Soc. Am.,* Vol. 10, No. 1, p. 6, 1938. The results reported by these investigators agree with those depicted in *Fig.* 10. This is to be expected from a consideration of the reciprocity theorem. See footnote 7.

edges is about 1.2 ft. Therefore, since the diaphragm and the edges lie in the same plane, the path difference between the primary and diffracted waves is 1.2 ft. Following the explanations of the preceding sections, there should be maxima of response at 460, 1380, 2300, 3200, etc. cps, and there should be minima of response at 920, 1840, 2760, etc. cps. There is reasonably good agreement with the experimental results of *Fig.* 10.

Cone

The axial response of the loudspeaker mechanism of *Fig.* 1 mounted in the apex of the cone, (F) of *Fig.* 2, is shown in *Fig.* 11. The sharp boundary at the base of the cone produces a diffracted wave. The distance from the mechanism to this edge is 1.3 ft. The distance between the plane of the diaphragm of the mechanism and the plane of the base is 0.95 ft. Therefore, the difference in path between the primary and diffracted waves is 2.25 ft. Following the explanations of the preceding sections, there should be maxima of response at 250, 750, 1250, etc. cps. and there should be minima of response at 500, 1000, 1500, 2000, etc. cps. There is very good agreement with the experimental results of *Fig.* 11. Another interesting fact is that the average magnitude of the response does not increase as rapidly with frequency as in the case of the examples in the preceding sections. This is due to the fact that the free space subtended by the loudspeaker mechanism is 2.6 steradians as compared to 2π steradians for most of the other systems considered in the preceding sections. Therefore, the ultimate sound pressure occurs at a higher frequency than in the case of enclosures in which the loudspeaker subtends 2π steradians.

The axial response of the loudspeaker mechanism of *Fig.* 1 mounted in the apex of the double cone, (G) of *Fig.* 2, is shown in *Fig.* 13. The sharp boundary at the bases of the cones produces a diffracted wave. The phase differences between the primary and diffracted waves are the same as those of the single cone. The performances of the single and double cone are about the same, as will be seen by comparing *Figs.* 11 and 12.

Pyramid

The axial response of the loudspeaker mechanism of *Fig.* 1 mounted in the apex of the pyramid, (A) of *Fig.* 2, is shown in *Fig.* 13. The sharp boundary at the base produces a diffracted wave. The average distance from the mechanism to this edge is 1.6 ft. The distance between the plane of the diaphragm of the mechanism and the plane of the base is 0.95 ft. Therefore, the difference in path between the primary and diffracted waves is 2.55 ft. Following the explanations of the preceding sections, there should be maxima of response at 220, 660, 1100, etc. cps, and minima at 440, 880, 1320, etc. cps. There is very good agreement with the experimental results of *Fig.* 13. The shape of the response-frequency characteristics is similar to that of the cone of a preceding section. As in the case of the cone, the ultimate response occurs at a relatively high frequency.

The axial response of the loudspeaker mechanism of *Fig.* 1 mounted in the apex of the double pyramid, (I) of *Fig.* 2, is shown in *Fig.* 14. The sharp boundary at the base of the pyramid produces a diffracted wave. The phase differences between the primary and diffracted waves are the same as those of the single cone. The performance of the single and double cone are about the same, as will be seen by comparing *Figs.* 13 and 14.

Truncated Pyramid and Rectangular Parallelepiped Combination

From the preceding examples, it will be seen that wide variations in the response-frequency characteristics occur when there is a sharp boundary or edge upon the surface of the enclosure which produces a strongly diffracted wave. The diffracted wave is further accentuated when all paths from the mechanism to the boundaries or edges are the same. The truncated pyramid and rectangular parallelepiped combination shown at (J) in *Fig.* 2 is designed with the object of reducing sharp boundaries on the front portion of the enclosure. Furthermore, the distances from the mechanism and the edges are not all the same. The response frequency characteristic of the loudspeaker mechanism of *Fig.* 1 mounted in the enclosure (J) is shown in *Fig.* 15. It will be seen that the response is quite uniform and free of large maxima and minima. This bears out the idea that the reduction of sharp boundaries on the surface of the enclosure and the elimination of equal path lengths from these boundaries to the mechanism will yield smoother response frequency characteristics.

Rectangular Parallelepiped

The rectangular parallelepiped in all its possible variations in dimensions is the most common direct-radiator loudspeaker enclosure. One of the obvious reasons for this state of affairs is that this shape is the simplest to fabricate. This is unfortunate, because the rectangular parallelepiped produces diffraction effects which adversely modify the response-frequency characteristic of a direct-radiator loudspeaker mechanism. The response-frequency curve of *Fig.* 16 was obtained with the loudspeaker mechanism of *Fig.* 1 mounted in the rectangular parallelepiped of (K), *Fig.* 2. The pronounced minima in the response at 1000 and 2000 cps are due to shorter distances from the mechanism to the upper and side edges. The minimum in response at 500 cps is due to the longer distance from the mechanism to the lower edge. The variations in response, due to diffraction effects by the cabinet, are of the order of 6 to 7 db. The response frequency characteristic of *Fig.* 16 is typical of the response obtained with this type of enclosure. Therefore, this cabinet shape is unsuitable for housing a direct-radiator loudspeaker mechanism, because of the wide variations in response produced by diffraction from the sharp edges of this cabinet.

Rectangular Truncated Pyramid and Parallelepiped Combination

From the data given the preceding sections is is possible to devise many cabinet shapes which will reduce the effects of diffractions in modifying the response frequency characteristics of the loudspeaker mechanism.

An example of the application of the principles outlined in this paper is shown at (L) in *Fig.* 2. In this cabinet the diffraction effects have been ameliorated by the reduction of abrupt angular discontinuities on the surface of the cabinet and the elimination of equal paths from these discontinuities to the mechanism. At the same time a practical exterior configuration has been retained which is not undesirable from an esthetic standpoint. The response-frequency characteristic of the loudspeaker mechanism of *Fig.* 1 mounted in the enclosure (L) is shown in *Fig.* 17. It will be seen that the response-frequency characteristic is quite smooth.

Conclusions

The response-frequency characteristics, which depict the performance of a direct-radiator loudspeaker mechanism in various enclosures of fundamental shapes, show that the outside configuration plays an important part in determining the response as a function of frequency. For example, in some of the enclosures the variation in response produced by diffraction exceeds 10 db.

All of the response-frequency characteristics depicted in this paper were taken on the axis of the loudspeaker mechanism and enclosure combination. In this connection, it should be mentioned that the variations in response are mitigated for locations off the axis. The reason for using the axial response is that the reference response-frequency characteristic of a direct-radiator loudspeaker is always taken on or near the axis. Practically all serious listening to direct-radiator loudspeakers is carried out on or near the axis.

The response of a loudspeaker in an enclosure will be modified by the directivity pattern of the mechanism, because the diffraction effects are influenced by the direction of flow of sound energy from the diaphragm. However, the performance in the frequency range in which the dimensions of the cone are less than a wavelength will not be markedly different.

The experiments described in this paper show that the deleterious effects of diffraction can be reduced by eliminating all sharp boundaries on the front portion of the enclosure upon which the mechanism is mounted, so that the amplitude of the diffracted waves will be reduced in amplitude and by making the distances from the mechanism to the diffracting edges varied so that there will be a random phase relationship between the primary and diffracted sound waves.