An Efficient Miniature Condenser Microphone System *

By H. C. HARRISON and P. B. FLANDERS

It has been shown recently that microphones and contiguous amplifiers distort the sound field in which they are placed by reason of their size and the cavity external to the diaphragm of the microphone. For frequencies such that the size is large compared to the wave-length of perpendicularly incident sound, reflection causes the actuating pressure to be double that which would exist in the undisturbed field. If the direction of the incident sound be along the plane of the diaphragm, the increase of pressure due to reflection is not as great; but there may be a substantial reduction in effective pressure due to differences in phase across the diaphragm. In addition, cavity resonance produces an increase of pressure at frequencies usually within the working range of the microphone.

This paper describes a laboratory model of a Wente-type condenser microphone of high efficiency and an associated coupling amplifier which are of such small size that reflection and phase-difference effects are of negligible importance within the audible frequency range; while the cavity is so proportioned that its resonance effect is an aid rather than a detriment to uniformity of response in a constant sound field.

SEVERAL writers [1] have recently called attention to the fact that a microphone distorts the sound field in which it is placed by reason of its size and the cavity external to the diaphragm. The distortion due to size was first mentioned by I. B. Crandall and D. MacKenzie in 1922.[2] It is a function of the direction of the sound with respect to the diaphragm.[3] The distortion due to cavity resonance is substantially independent of direction and depends mainly on the relation between the dimensions of the cavity and the wave-length of sound.

If a microphone were to be designed so that it would respond uniformly to sound coming from any direction, it is apparent that first the size would have to be diminished to such an extent that reflection and phase-difference effects became negligible. Secondly, the cavity would either have to be eliminated entirely [4] or else be so proportioned that resonance occurred at frequencies above the resonance frequency of the diaphragm, where the response of the latter was diminishing. Such mutual compensation is possible in a small microphone and the effect is substantially independent of the direction of sound.

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[1] A. J. Aldridge in *P. O. E. E. Jour.*, Oct., 1928, pp. 223–225; S. Ballantine in *Phys. Rev.*, Dec., 1928, pp. 988–992; W. West in *I. E. E. Jour.*, 1929, pp. 1137–1142.

[2] *Phys. Rev.*, March, 1922.

[3] L. J. Sivian in *B. S. T. J.*, Jan., 1931. pp. 96–116.

[4] S. Ballantine in "Contributions from the Radio Frequency Laboratories," No. 18, April 15, 1930.

This paper will discuss the factors relating the dimensions of a condenser-type microphone system with the several types of field distortion, and will describe a miniature system designed to practically eliminate such distortions over a wide frequency range.

Diffraction of Sound Around an Obstacle

The shapes of condenser microphones alone or in association with amplifiers are so irregular that it is impossible to calculate their effect as diffractors of sound waves. It will suffice, however, to assume some regular shape approximating actuality, for which calculations can be made. The diffraction effects so obtained for the regular shape will be substantially the same as those caused by the actual irregular shape, provided their areas projected on the plane of the incident sound-waves be equal. Cavity resonances, of course, may be quite different in the two cases. But these can be treated as separate effects, and will be so considered in a later section of the paper. In this section, only those disturbances of the sound field, caused by the smooth envelope of the microphone alone or with its amplifier, will be considered.

The case of diffraction of plane sound waves around a spherical

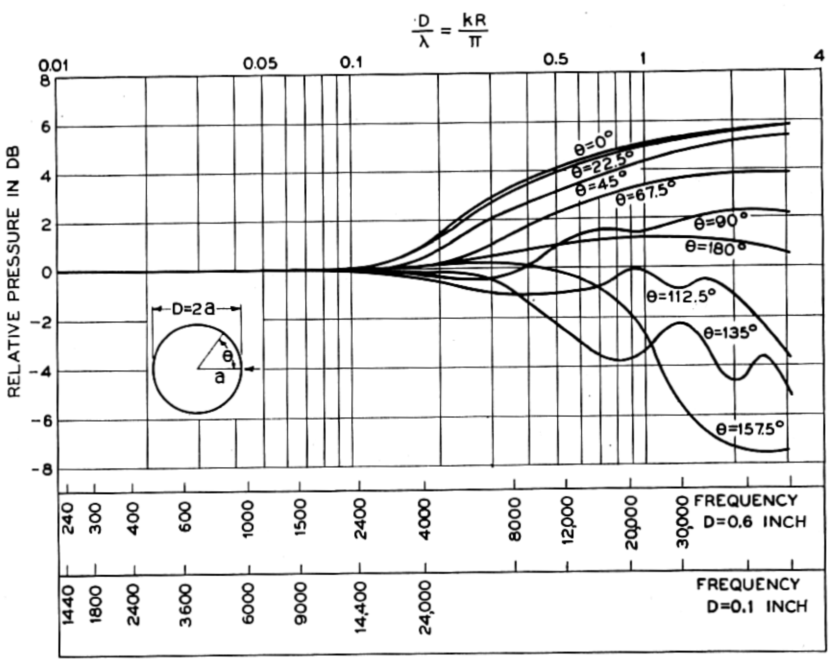

Fig. 1—Variation in pressure on rigid sphere due to diffraction of plane sound waves.

obstacle is amenable to mathematical treatment, and was considered theoretically by Raleigh. Quantitative consideration of the effect at a point on a sphere directly in line with the oncoming sound has been given by S. Ballantine.[1] Fig. 1 shows the effect for other polar angles around the sphere, as computed from Ballantine's equation. Of particular theoretical interest is the curve for a polar angle of 180°; that is, the point that should be most completely "shadowed" from the sound. Actually, no shadowing effect appears, the pressure remaining substantially equal to that of the undisturbed field. This case is analogous to that where diffraction of light causes a bright spot to appear in the center of the shadow of a circular disk. The area of this acoustic bright spot is small, as may be seen by the pronounced shadowing of a point only 22½° away. Because of its small area, it is impractical to make use of the effect in microphone design.

Effect of Phase-Shift in a Plane Sound Wave Traveling Along the Plane of the Diaphragm

In Appendix I is given an approximate calculation of the reduction in effective pressure on a circular diaphragm, due to the change in

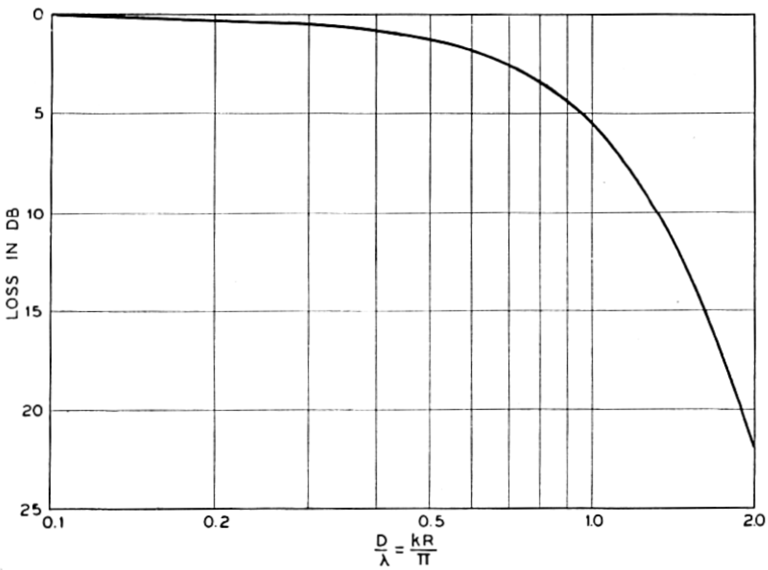

Fig. 2—Loss in effective pressure due to phase-shift in plane sound waves traveling across circular diaphragm.

phase of a progressive plane wave traveling across it. The effect is plotted in Fig. 2. As might be expected, the reduction becomes

[1] Loc. cit.

considerable when the diameter of the diaphragm exceeds the wave-length. Since in normal use, a large proportion of the sound actuating the microphone comes in a transverse direction, the distortion due to this phase-cancellation effect may often be more serious than the distortion due to diffraction.

Cavity Resonance

The effect of a cylindrical cavity on the pressure actuating a diaphragm is given by equation (5) in Appendix II and is shown graphically in Fig. 3. It is apparent that the larger the ratio of diameter

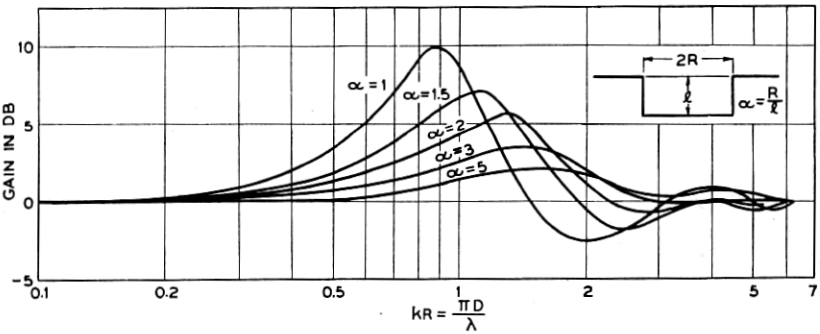

Fig. 3—Gain in effective pressure on circular diaphragm due to cavity resonance.

to wave-length, the smaller is the resonance effect; and that the greater the ratio of a given diameter to the depth of the cavity, the higher the frequency at which such resonance occurs. There is, of course, more than one resonance. However, for the higher resonances there is a greater ratio of diameter to wave-length with a consequent increase in damping; so that the resonance effect is less pronounced. Compared to the primary resonance, the secondary resonances are, as a rule, of negligible importance.

Acoustic and Electrical Considerations Affecting the Size of a Condenser Microphone

If diffraction effects for all angles of incidence are to be negligible in a frequency range extending, for example, to 15,000 c.p.s., it is apparent from Fig. 1 that the diameter of the microphone should not be greater than about a tenth of an inch. Assuming that all other dimensions and characteristics remain fixed, including the resonance frequency of the diaphragm and the ratio of dead to active capacity, it can be shown that as the diameter of a condenser microphone diaphragm is decreased, the ratio of generated voltage to actuating pressure remains constant. The diameter can not be decreased indefinitely, however, because of the limitations of amplifiers with which the condenser microphone must of necessity be closely associated. The resistor for feeding the polarizing voltage and the grid biasing resistor must be increased as the diameter of the diaphragm (and consequently the active capacity) is reduced, in order that, at low frequencies, the same proportion of generated voltage may get to the grid of the amplifier tube. They must not be made too large, however, for then the voltages due to thermal agitation [5] in the resistors will become comparable to the signal voltage. Similarly, the capacity of the input leads, vacuum tube and resistors will become comparable to the lowered capacity of the microphone, with a consequent reduction in signal voltage at the grid, over the whole frequency range. The actual limit in reducing microphone size can not be defined accurately; but it is definitely greater than one-tenth of an inch.

Further consideration of the diffraction problem, however, shows that such an extremely small size is not really necessary in order to practically eliminate sound-field distortion. When sound is picked up indoors at some distance from the source, the directly incident sound contributes much less to the microphone output than does the reflected sound arriving from other angles of incidence.[3] The greater part of the effective actuating pressure comes then at polar angles in the vicinity of 90°, where the diffraction effect is much less pronounced. If 90° be taken as an effective average angle, it is seen from Fig. 1 that the diameter of a microphone need only be reduced to about six-tenths of an inch in order to make this type of distortion negligibly small.

If sound is picked up out-of-doors, or indoors near the source, the directly incident waves predominate over the reflected waves. For this case it will suffice to place the microphone so that the sound arrives at a polar angle of 90°; and a six-tenths inch diameter is still sufficiently small.

Inspection of Fig. 2 shows that the phase-difference loss is about 1 db at 10,000 c.p.s. for this diameter; so that six-tenths of an inch can safely be chosen as an acceptable design value.

The Amplifier

Consideration has now been given to the problem of reducing the size of a microphone to such an extent that it would not appreciably disturb the sound-field. But all such labor is in vain if the size of

[5] J. B. Johnson, *Phys. Rev.*, July, 1928, pp. 97–109.
[3] Loc. cit.

the coupling amplifier be not correspondingly decreased, since, for efficient operation, the high impedance of the microphone necessitates a close spacial coupling between the two.

Use of a special miniature type vacuum tube affords the possibility of materially reducing the size of the coupling amplifier. It is but slightly greater in diameter than the microphone just described, the inter-electrode capacities are quite low, and the plate resistance is not too high. This tube, with the necessary coupling resistors and a small stoppage condenser are placed within a cylindrical metal tube of about 0.8 inch diameter, to one end of which is attached the condenser microphone. From the other end of the cylinder extends a shielded cable along the axis of which runs the plate lead from the vacuum tube. This cable is constructed so that the capacity of the lead to ground is small. Surrounding the lead are two filament supply conductors and a conductor for supplying polarizing voltage to the microphone. The impedance between these and ground being very small, their capacity to ground may be as large as desired. Of course, the longer the connecting cable, the lower must be the capacity of the plate lead per unit length. The second stage, to which the cable runs, may be large, and as distant from the miniature first stage as is consistent with these lead capacity requirements.

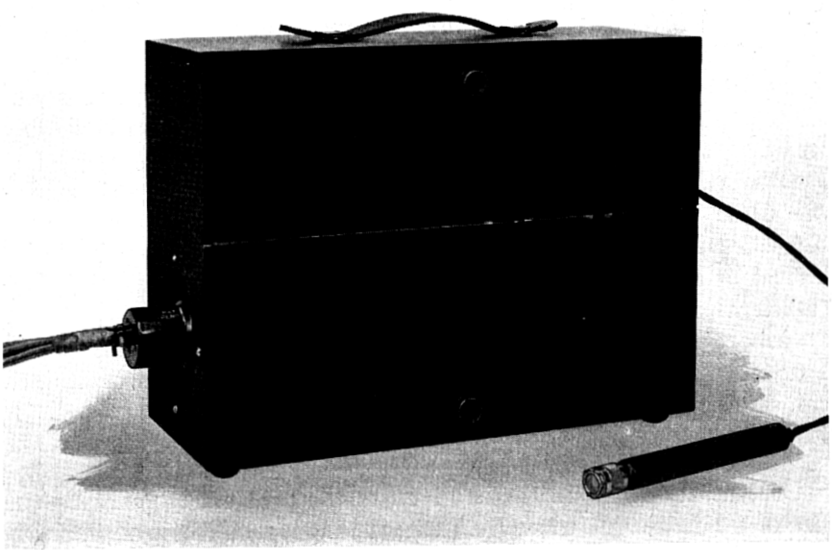

Fig. 4—View of miniature microphone and attached miniature coupling amplifier, together with second amplifier stage.

The miniature microphone and the miniature vacuum tube with necessary coupling resistors and a stoppage condenser are contained in the metal tube shown in the right foreground of Fig. 4. The dimensions of the container tube are about 7.5 inches long and 0.8 inch in diameter. The carrying case houses the second stage amplifier together with other accessories.

Conclusion

For the same frequency range, the efficiency of this miniature microphone as determined by a thermophone calibration is about 2.5 db greater than that of the 394W type, because of a lower proportion of dead to active capacity. In combination with a well designed amplifier, the efficiencies as determined by the voltages on the grid of the tube are about equal, most of the proportional contribution to dead capacity in the one case coming from the amplifier, and in the other case from the microphone.

In this miniature condenser microphone, the diaphragm is tuned higher than is the 394W, so that the efficiency in association with the amplifier is about 3 db lower than that of the 394W. The resonance of the external cavity gives a maximum lift in response of about 3 db. The microphone as a whole responds uniformly up to 10,000 c.p.s. The diffraction and phase-difference effects are negligible up to that frequency.

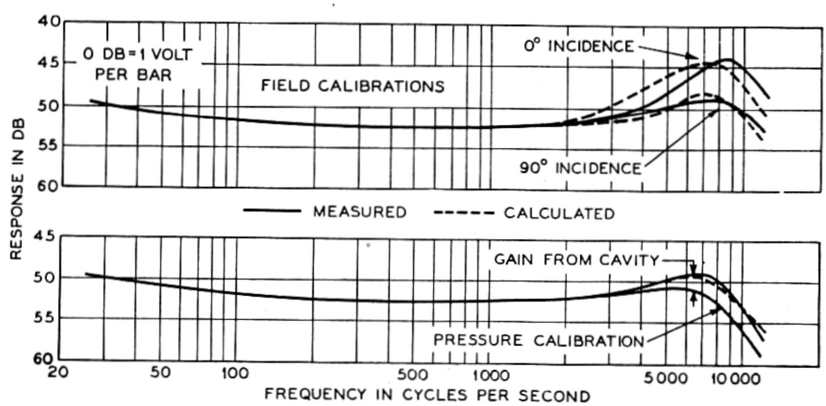

Fig. 5—Pressure and field calibrations of miniature condenser microphone, showing cavity effect.

Curves showing the constant pressure and constant field [3] calibrations of this microphone are given in Fig. 5.

The work on this miniature microphone system has so far been essentially of a research nature, and its use has been directed primarily

[3] Loc. cit.

to fundamental laboratory problems in the field of sound measurements. The necessary work toward commercialization has not been effected, in view of the high quality performance and certain practical advantages of available types of microphones.

APPENDIX I

For a stretched membrane, the equation expressing the statical deflection ξ as a function of the radius r, for a symmetrical distribution of pressure p, is [6]

$$p = -\frac{\tau}{r}\frac{d}{dr}\left(r\frac{d\xi}{dr}\right), \tag{1}$$

where τ is the tension coefficient. Two integrations give

$$\xi = \frac{1}{\tau}\int_r^R \left[\frac{1}{r}\int_0^r prdr\right] dr, \tag{2}$$

where R is the bounding radius. The central displacement is evidently

$$\xi_0 = \frac{1}{\tau}\int_0^R \left[\frac{1}{r}\int_0^r prdr\right] dr. \tag{3}$$

Now, considering the case of a progressive plane wave

$$p = P\cos(\omega t - kx)$$

$\left(\text{where } k = \dfrac{2\pi}{\text{wave-length}}\right)$ traveling across this membrane, an expression can be computed for the average pressure on the boundary of the circle of radius r. From Fig. 6 it is clear that

$$x = R - r\cos\theta$$

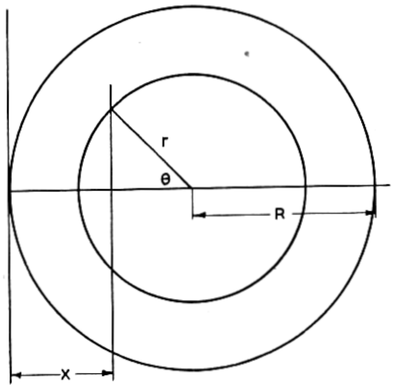

Fig. 6—

[6] See Lamb's "Dynamical Theory of Sound," § 54.

and hence that

$$\begin{aligned} p &= P \cos [(\omega t - kR) + kr \cos \theta] \\ &= P[\cos (\omega t - kR) \cos (kr \cos \theta) - \sin (\omega t - kR) \sin (kr \cos \theta)]. \end{aligned}$$

The average pressure is

$$\begin{aligned} p_{av} &= \frac{1}{\pi} \int_0^\pi p d\theta \\ &= \frac{P \cos (\omega t - kR)}{\pi} \int_0^\pi \cos (kr \cos \theta) d\theta \\ &\qquad - \frac{P \sin (\omega t - kR)}{\pi} \int_0^\pi \sin (kr \cos \theta) d\theta. \end{aligned}$$

Here the second integral is zero, while the first may be written

$$\begin{aligned} p_{av} &= \frac{2P}{\pi} \cos (\omega t - kR) \int_0^{\pi/2} \cos (kr \cos \theta) d\theta \\ &= \frac{2P}{\pi} \cos (\omega t - kR) \int_0^{\pi/2} \cos (kr \sin \theta) d\theta \end{aligned}$$

and is readily identified as a Bessel function.

(4) $$p_{av} = P \cos (\omega t - kR) J_0(kr).$$

Substitution of (4) in (3) gives an approximation to the total effect (on the central displacement) of these average pressures acting over the whole diaphragm.

(5) $$\xi_0 = \frac{P \cos (\omega t - kR)}{\tau} \int_0^R \left[\frac{1}{r} \int_0^r J_0(kr) r dr \right] dr.$$

Now

$$\int_0^r J_0(kr) r dr = \frac{r}{k} J_1(kr)$$

and

$$\int_0^R \frac{1}{k} J_1(kr) dr = \frac{1}{k^2} [1 - J_0(kR)]$$

so that

(6) $$\xi_0 = \frac{P \cos (\omega t - kR)}{k^2 \tau} [1 - J_0(kR)].$$

The displacement when R is small compared to the wave-length, i.e. $k = 0$ is

(7) $$\xi_0' = \frac{PR^2 \cos \omega t}{4\tau}.$$

The ratio of (6) to (7) in amplitude is

$$\left|\frac{\xi_0}{\xi_0'}\right| = \frac{4[1 - J_0(kR)]}{(kR)^2}, \tag{8}$$

which is plotted as db loss *vs.* kR in Fig. 2.

There are two approximations involved in this analysis, both involving equation (3). One is that for p (which should be constant for a given r), can be taken the average of the actual pressures around the circle of radius r. The other is that the shape of the static deflection curve represents the actual shape up to the highest frequencies of interest in (8).

APPENDIX II

Assuming (1) that the air particles, in the plane of the entrance to the cavity, all move in phase with equal velocities v_1 which are normal to that plane, and (2) that the impedance per unit area of the microphone diaphragm is large compared to ρc, where ρ is the density of air and c is the velocity of sound, the following three relations hold: From the theory of plane wave propagation in a tube,

$$p_2 = p_1 \cos kl - i\rho c v_1 \sin kl \tag{1}$$

where p_1 is the pressure in the plane of the entrance to the cavity of depth l and p_2 is the pressure at the diaphragm. Also, the input impedance per unit area of this closed cylindrical tube is

$$\frac{p_1}{v_1} = -i\rho c \cot kl. \tag{2}$$

Now p_1 is equal to the pressure P that would exist at the opening if the air particles were held stationary, diminished by the drop in pressure due to their motion and the consequent radiation from the opening. In symbols,

$$p_1 = P - \rho c(a + ib)v_1, \tag{3}$$

where $(a + ib)$ is the radiation impedance coefficient given by Raleigh [7] for the case of a circular piston in an infinite wall:

$$\begin{aligned} a &= 1 - \frac{J_1(2kR)}{kR}. \\ b &= \frac{8kR}{\pi}\sum_{n=1}^{n=\infty}(2n+1)\left(\frac{2^n\lfloor n}{\lfloor 2n+1}\right)^2(-4k^2R^2)^{n-1}. \end{aligned} \tag{4}$$

[7] "Theory of Sound," Vol. II, § 302.

Elimination of p_1 and v_1 from the first three equations gives

$$(5) \qquad \left|\frac{P}{p_2}\right| = \sqrt{(\cos kl - b \sin kl)^2 + a^2 \sin^2 kl}$$

as the expression for the change in acoustic pressure on a diaphragm, caused by the entrance cavity.[8] It is plotted as db gain in Fig. 3.

Similar calculations have been given by other writers.[3, 9]

[8] Numerical values of the functions a (kR) and $b(kR)$ are given in Crandall's "Theory of Vibrating Systems and Sound," Fig. 19, p. 172.
[3] Loc. cit.
[9] W. West, in *Jour. I. E. E.*, April, 1930.