A Non-Directional Microphone

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A moving coil microphone is described which responds uniformly over a wide frequency range to sound arriving from any direction. A study of diffraction, the main factor causing directivity of microphones of the pressure type, leads to the conclusion that a small spherical shape is the most desirable for a non-directional microphone. But even fulfilling this requirement in the design of the housing leaves a large directional effect. Hence an acoustic screen has been developed which diminishes diffraction to an extent necessary to make the change in response due to angle of sound incidence imperceptible to the ear. The non-directional microphone is of simple and rugged construction. Adequate precautions have been taken to prevent atmospheric changes from affecting the stability. The small size and unusual shape of the microphone contribute much to its attractive appearance.

IN many situations—such as when a microphone is used as a pick-up for large orchestras or choruses, or in sound picture studios—the sound reaching the microphone directly may be only a small part of the total. Most of the sound arrives at the microphone from directions other than normal to the plane of the diaphragm. If the microphone response differs in these various directions, the output will not truly represent the sound at the point of pick-up—and this is, of course, a form of distortion. This distortion was minimized in the Western Electric 618–A type moving coil microphone [1] by selecting the constants of the instrument so that the field response would be as uniform as possible for sound of random incidence. Still there remained a considerable change of response with the angle of sound incidence and with frequency as is shown in Fig. 2. In the non-directional microphone this variation (Fig. 3) has been greatly reduced so that it is imperceptible to the ear. Moreover, the new microphone is designed to be mounted so that its diaphragm is horizontal.* In this position the instrument is symmetrical with respect to a vertical axis through the center of the diaphragm. If a sound source is placed at some arbitrary location we may rotate the microphone around this vertical axis without changing its response. Hence the instrument is entirely non-directional with respect to the vertical axis. If the microphone is rotated around an axis in the plane of and through the center of the diaphragm a very slight residual directional effect remains and it is this one which has been plotted.

* Since the non-directional microphone is generally mounted with its diaphragm in a horizontal plane the angles of incidence have been labeled 0°, ± 30°, ± 60°, ± 90° retaining 0° as the angle of incidence for sound waves moving in the horizontal plane.

The directivity of pressure type microphones is caused by two factors: (*a*) the variation of the diffraction effect with frequency and with the angle of incidence of the sound wave, and (*b*) the decrease in pressure due to phase shift which occurs when the direction of the progressive

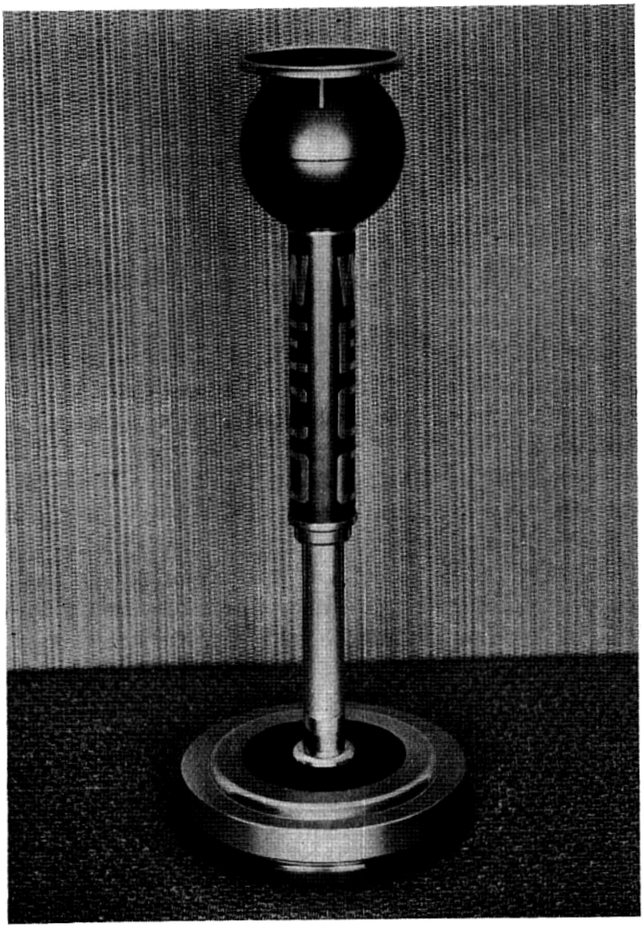

Fig. 1—630-A type moving coil microphone with deskstand.

sound wave has a component parallel to the plane of the diaphragm. Each is also a function of the dimensions of the microphone relative to the wave length of the sound, and in the instruments of the size discussed in this paper the effects become large only at frequencies above 1000 cycles. Directivity might be avoided, therefore, if the microphone could be made small enough; but calculation shows that to make the effect negligible at 10,000 cycles the instrument would have to be approximately one-half inch in diameter. While a microphone of this size could be built, it is doubtful whether an output level could be obtained which would be adequate for public address, broadcasting, and sound picture use.

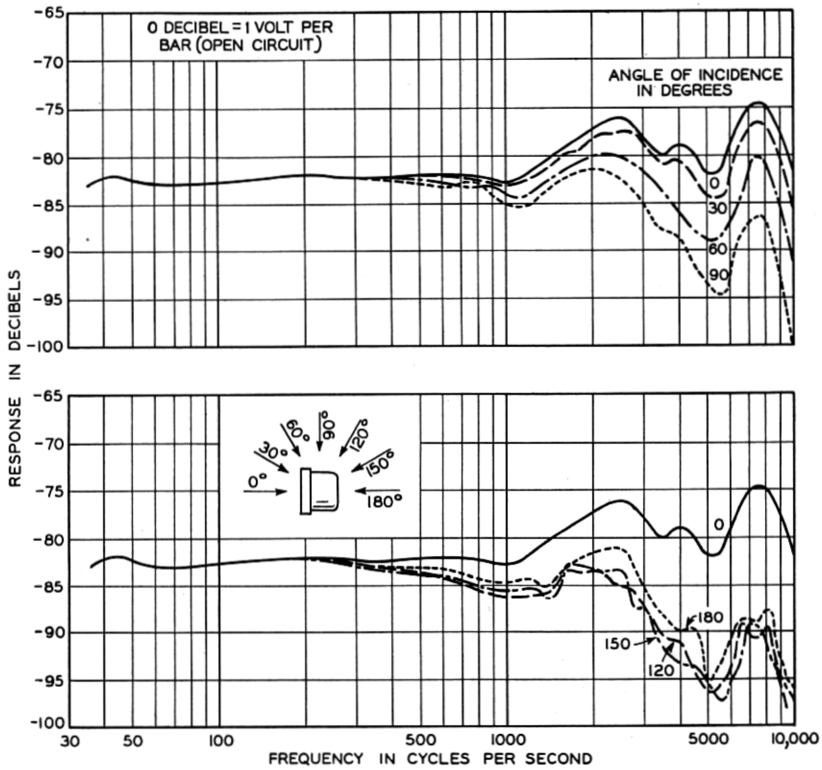

Fig. 2—Field response of the 618-A microphone showing the effect of angle of sound incidence.

Diffraction plays by far the predominant role up to a frequency where the wave-length is comparable to the diameter of the diaphragm, and the effect of phase shift may be neglected. It is principally diffraction which causes the field response of a microphone to differ from the pressure response, and because of the variation of the effect with angle of sound incidence it is impossible to correct for it by adjusting the pressure response. The only alternative is to attack the diffraction problem directly.

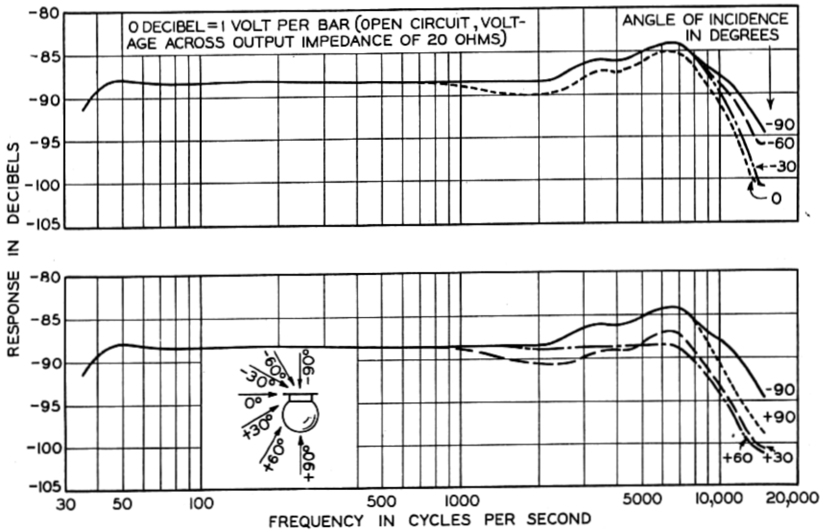

Fig. 3—Field response of a laboratory model of the new 630-A non-directional microphone for several angles of sound incidence.

Diffraction of Sound Around the Microphone

The effect of the shape of the microphone on the directional response has been brought out by study of the diffraction effect of different geometrical objects of equal diameter. The diffraction of a sphere was first treated by Rayleigh [2] and evaluated for a point on the sphere for normal incidence by S. Ballantine,[3] and for other angles of incidence by H. C. Harrison and P. B. Flanders.[4] The effect for a circular plate has been given by L. J. Sivian and H. T. O'Neil.[5] Figure 4 shows the calculated diffraction effect of the cylinder, cube, and sphere * as a function of frequency and angle of incidence in terms of the ratio of the disturbed to the undisturbed sound pressure at a point located centrally in the surface of the object. The abscissae are given as the ratio of the diameter of the object to the wave-length of sound, but the table at the bottom indicates the corresponding frequencies for diameters of 1 inch, 2 inch and 4 inch. If a microphone were built having any one of these shapes, and its diaphragm were made very small and located at the point for which the curves were computed, its response would be increased or decreased approximately in correspondence with these curves as the angle of incidence is changed from + 90° to − 90°. It will be noticed that both cylinder and cube show a marked directional

* The calculated values for the diffraction of the circular plate and cube have been taken from an unpublished work of G. G. Muller of the Bell Telephone Laboratories.

effect, made more serious by the wavy character of the response, while the variation in response for the sphere is much less and the waviness has practically disappeared.

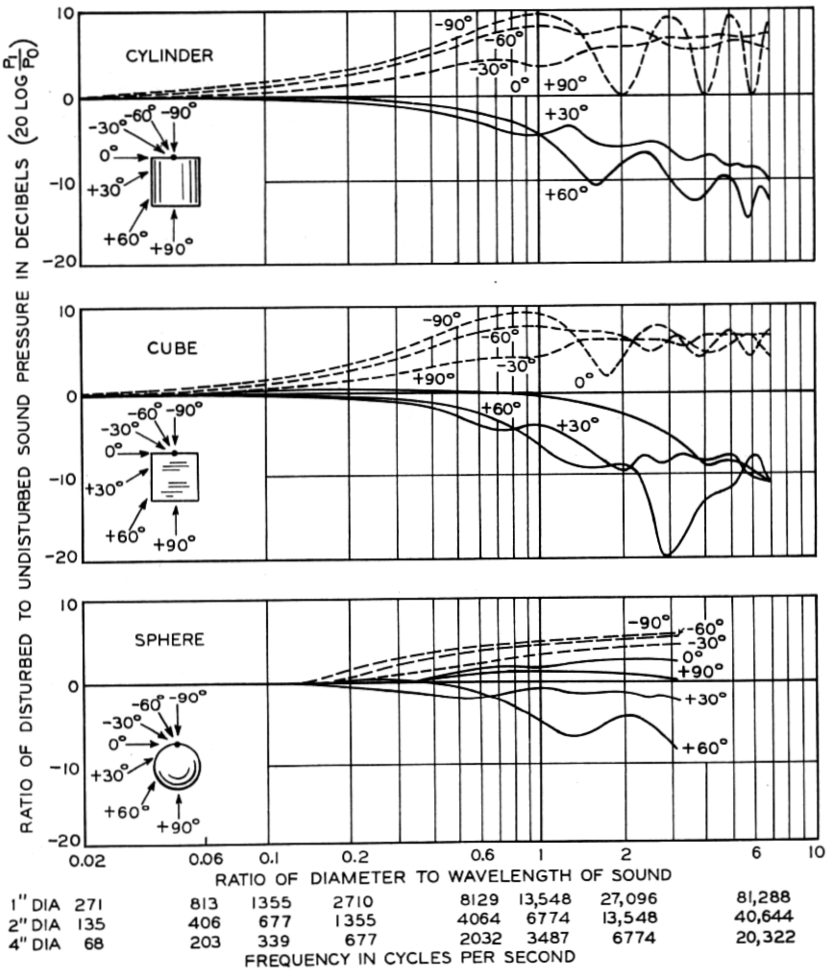

Fig. 4—Calculated diffraction effect at the center of the end form of a cylinder, cube, and sphere for sounds coming from different directions.

It appears then that a very small sphere would be the most desirable shape, but it was found impracticable to reduce the microphone housing below a 2½ inch sphere and to reduce the diaphragm diameter below 1 inch. The field response of the resultant microphone without the acoustic screen for various angles of sound incidence is shown in Fig. 5.

The directional effect, while diminished somewhat compared with that of the 618–A type (Fig. 2), is still not negligible. It was possible, however, to achieve a fairly uniform response with respect to frequency for sound of 0° incidence, that is, sound arriving in the plane of the diaphragm. Since in most instances the direct energy arrives in the horizontal plane, uniform, non-directional response for this important plane may be secured by mounting the microphone with the diaphragm in a horizontal position. Still there is a tendency for the response to be

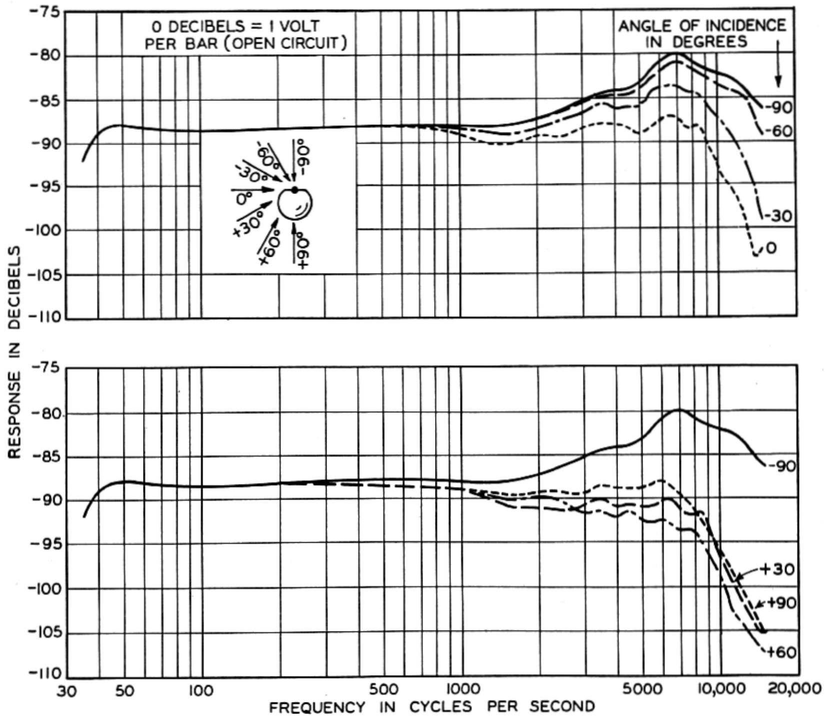

Fig. 5—Field response of a laboratory model of the 630-A non-directional microphone without screen.

too high for high-frequency sounds coming down from above, that is, directly toward the diaphragm, and too low for similar frequencies coming from angles very much below the horizontal.

To determine to what extent diffraction contributes to this residual directivity in the vertical plane let us consider the diffraction of a geometrical shape resembling that of the microphone, namely, a two and one-half inch sphere with a flat face one and one-eighth inches in diameter. We may approximate the diffraction effect for this shape by combining the known effects for a sphere and flat plate shown in Fig. 6.* Although the sphere is twice the diameter of the circular plate, it is seen that it has the larger effect only at the lower frequencies. The arrows indicate the probable effect to be taken for that of the flat-faced sphere. Although this result applies strictly only at a point at the center, measurements [5] have shown that up to 15,000 cycles for a one and one-

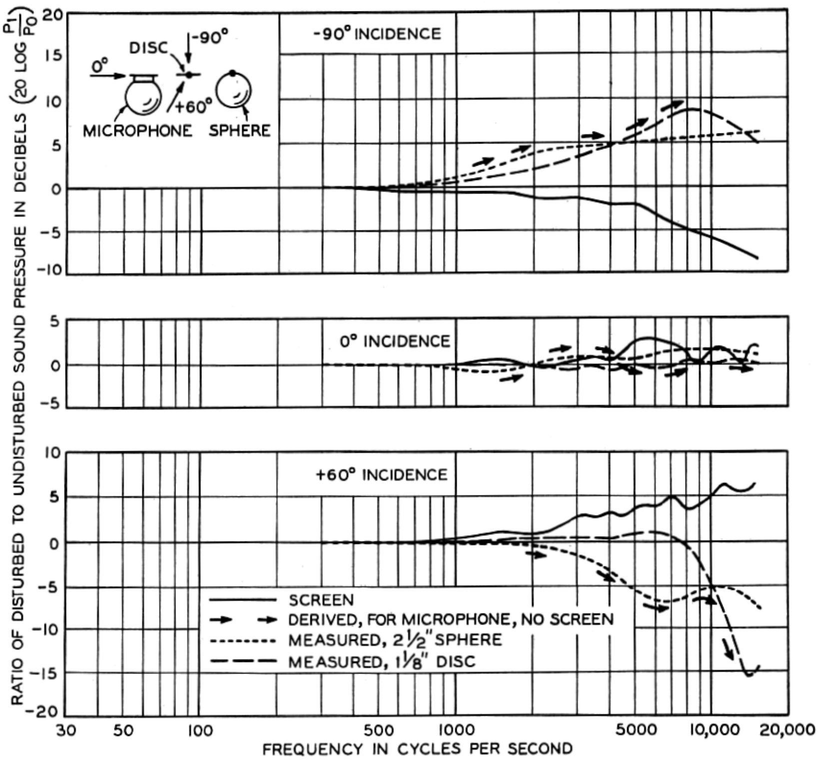

Fig. 6—Measured diffraction effect of a 2½″ sphere, 1⅛″ circular plate, and acoustic screen and derivation of diffraction effect of 630-A microphone without screen.

eighth inch circular disc there is little variation over an area comparable to the effective area of the microphone diaphragm. Hence, the diffraction effect derived in this manner is added to the computed contour pressure response (see Appendix A) to obtain the theoretical field

* The effect at + 60° incidence has been shown as more significant since the diffraction for + 90° is small. The latter effect corresponds to the optical bright spot at the center of the disc on the side away from the light source. This effect occurs over such a small area for angles very close to + 90° that it is of no practical use in this case. However, this does account for the + 90° response of microphones often being higher than the + 60° or + 30° response.

response shown in Fig. 7 where it is compared with the experimental response. The largest deviation between theoretical and experimental values is in the zero degree response at frequencies from 10,000 to 15,000 cycles. This difference is attributable to the factor mentioned earlier, namely, the decrease in effective pressure due to the phase shift of a plane sound wave traveling across the face of the diaphragm. It is of the same order of magnitude as that calculated by H. C. Harrison and P. B. Flanders [4] for a stretched circular membrane. It is concluded, therefore, that the diffraction effect indicated by arrows in Fig. 6 is representative of that of the actual microphone.

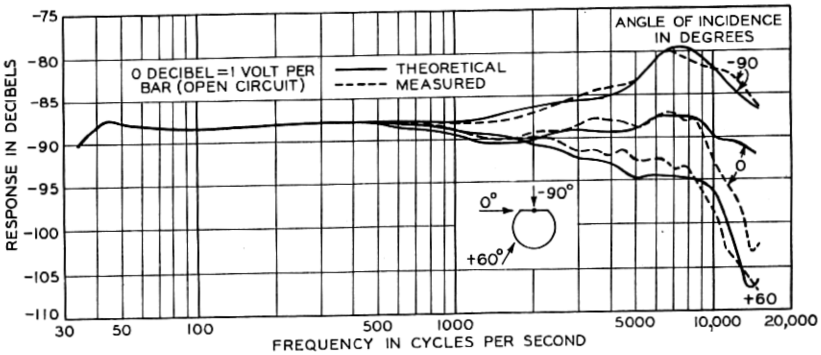

Fig. 7—Comparison of theoretical and experimental field response of a laboratory model of the No. 630-A non-directional microphone without screen.

Effect of Acoustic Screen

From the quantitative considerations of the diffraction of the spherical moving coil microphone without screen it becomes clear that if the microphone is to be made non-directional in the vertical plane also, an element must be introduced which compensates for the increase and decrease in field response due to diffraction.

The screen which was developed for this purpose is a disc 2½ inches in diameter and made of material having a very high resistance-to-mass ratio. This disc is supported approximately 1/8 inch in front of the microphone grid. The diffraction effect of this screen has been measured in terms of the effect on the face of the microphone. Figure 6 gives the effects for sound of 0°, − 90°, and + 60° incidence and compares them with those of the microphone without the screen. From these data it may be seen that the acoustic screen compensates for the microphone diffraction effect, for (1) it has least effect for sound of 0° incidence; (2) it causes a decrease in the − 90° field response; and (3) it causes an increase in the + 60° response.

The variables in a screen of this type are its diameter, impedance, and distance from the microphone grid. It is a combination diffraction and impedance screen; for part of the sound is attenuated by passing directly through the screen while the rest is diffracted. The proportion between the two is a function of the impedance of the screen and of the ratio of its diameter to the wave-length of the sound. At lower frequencies most of the sound coming from the top is bent around the screen while at higher frequencies more of it travels directly through and becomes attenuated. For sound coming from the side, the screen has little effect. When sound comes from the bottom some of it is reflected onto the face of the microphone. The acoustic screen thus makes the instrument non-directional in its response characteristics.

General Design

Besides these changes designed primarily to reduce the directional effects, extensive changes were made in the internal construction and arrangement of the microphone to make the response more uniform and to extend the frequency range. The general construction is shown in Fig. 8. The desirability of making the diaphragm as small as possible

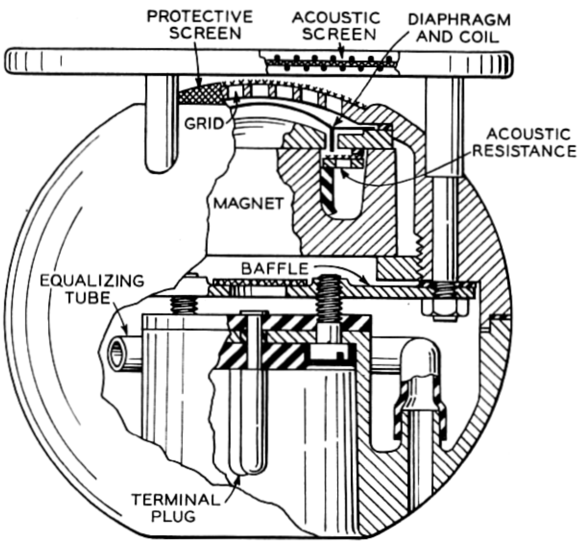

Fig. 8—Simplified cross-sectional view of the non-directional microphone.

has been pointed out in the discussion of microphone diffraction. However, decreasing the size rapidly reduces the sensitivity which is proportional to the area of the diaphragm and the flux density of the magnetic field around the coil. In order to obtain in this instrument a signal-to-noise ratio sufficiently high for all practical purposes, it was not considered advisable to use a diaphragm smaller than 1 inch in diameter. The loss in sensitivity resulting from this choice was partly offset by making the diaphragm light in weight and of very low stiffness. It is also very important that this diaphragm vibrate as a simple piston throughout the entire range; but to obtain this action over a wide range of frequencies has proved in the past to be a very difficult problem. For this new microphone, a diaphragm was developed which has a rigid spherical center and a tangentially corrugated annulus and which has in addition a high area to stiffness ratio. No evidence of vibrating in other modes is shown by this structure below 15,000 cycles. The diaphragm is cemented to a raised annulus on the outer pole-piece. The outer and inner pole pieces are of soft iron and are welded directly to the magnet which is made of high grade magnet steel. The diaphragm is damped by an acoustic resistance which is supported below the coil by a brass ring. This ring is held in place with rubber gaskets.

The size and shape of the housing were selected with particular reference to the requirements that had to be met. The size is such that the housing fits closely over the diaphragm and thus produces little more diffractive effect than would the diaphragm itself, and the spherical form allows sufficient amount of air space behind the diaphragm, which is essential to minimize the impedance to vibration. To prevent resonance within the case an acoustic resistance baffle is provided to divide the space into two parts. A tube with its outlet at the back of the housing serves the double purpose of equalizing the inside and atmospheric pressures and of increasing the response of the instrument at low frequencies.

In the non-directional microphone the resonance in the cavity in front of the diaphragm is controlled by the design of the protective grid. Instead of being the source of an undesirable distortion, the grid and cavity have become a valuable aid in improving the response of the instrument at frequencies from 8,000 to 15,000 cycles. This grid also incorporates a screen which prevents dust and magnetic particles from collecting on the diaphragm.

Method of Measuring Field Response

The method of making the frequency-response measurements is similar in general details to the method outlined in a paper by W. C. Jones and L. W. Giles[1]. Figure 9 shows the arrangement of the room and testing apparatus. A very small, specially developed, condenser microphone was used in determining the sound field pressure. The determination of the field calibration of this reference microphone presented an interesting problem and an original solution is described in Appendix B.

At low frequencies where the wave-length of sound is very large compared to the dimensions of the microphone, the coupler shown in Figure 9 is used. At the higher frequencies a steady state sound field is set up in the damped test room and the pressure at a given point is measured by means of the small reference condenser microphone; then

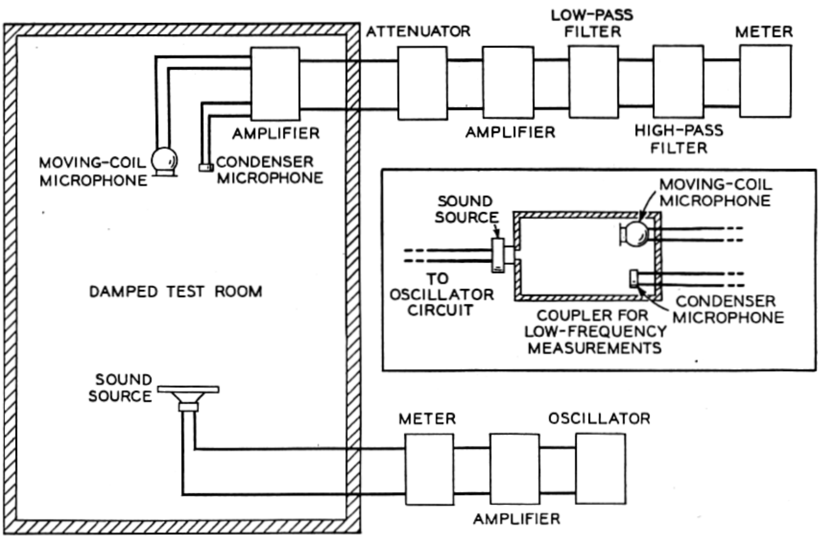

Fig. 9—Response measuring circuit.

the instrument to be tested is substituted at this point and its generated voltage recorded. The response is obtained in terms of decibels below a reference level of one volt per bar of undisturbed sound pressure.

In conclusion we wish to acknowledge our indebtedness to Mr. L. W. Giles and Mr. R. C. Miner of the Bell Telephone Laboratories who have aided us greatly in this work.

APPENDIX A

Theory

Since in most papers on moving coil microphones an equivalent circuit of this instrument is given without deriving it, it does not seem superfluous to indicate here the method of obtaining such a circuit and the calculation of its constants.

In deriving the theory of this instrument it is convenient to speak of the contour pressure response of a microphone.* We shall define the contour pressure response at a certain frequency as the generated open-circuit voltage per bar of uniform pressure over the face of the microphone. On the other hand the field response at a certain frequency is defined as the generated open-circuit voltage per bar of pressure of the undisturbed sound field. The difference between the contour pressure response and the normal incidence field response is caused by diffraction around the microphone, as explained earlier in this paper. We may approximate the normal incidence field response by adding to the contour pressure response the diffraction of the corresponding sphere and circular plate. In the considerations that follow the influence of the screen on the response will be omitted.

To obtain this contour pressure response we assume, then, a uniform pressure over the microphone face. We further require that no wave propagation shall occur within the microphone. Let a small alternating pressure be applied and consider the motion of the system when the pressure is positive. Then the air in the grid holes moves as a whole and imparts an excess pressure to the grid chamber and to the diaphragm. The central portion of the latter moves as a rigid piston. The air volume underneath the diaphragm is compressed, and some air is forced through the coil slot into a very small chamber just in front of the damping ring. We shall assume again that the air in the coil slot moves as a whole. From here the air flows through the acoustic resistance into the larger case chamber. The outside pressure instead of acting upon the diaphragm in the described manner may enter the case through the equalizing tube. On its travel through the tube it is attenuated and its phase is changed. At low frequencies this property of the tube is used to increase the response of the instrument. In the theory that follows, the tube circuit is omitted at first, but its position in the general arrangement will be shown later.

Let us use the following notation for the elements of the vibrating structure:

r_{-1} = equivalent mechanical resistance of all holes in grid,

m_{-1} = equivalent mass of all holes in grid,

n = number of holes in grid,

A_{-1} = area of all holes in grid,

* The term contour pressure response is useful when the microphone has acoustic circuits in front of its diaphragm. Pressure response is a term which has been reserved specifically for the condition where uniform pressure is applied directly to the diaphragm. (See the report of a subcommittee on fundamental sound measurements on the calibration of microphones in the journal of the *Acoustical Society of America*, Vol. 7, April, 1936, p. 301.)

A_0 = effective area of diaphragm,
m_0 = effective mass of diaphragm,
r_0 = mechanical resistance of diaphragm,
S_0 = stiffness of diaphragm,
V_1 = volume of air under diaphragm,
m_2 = equivalent mass in coil slot,
r_2 = equivalent mechanical resistance in coil slot,
A_2 = total area of coil slots,
V_s = volume of air chamber in front of resistance ring,
m_4 = equivalent mass of air in acoustic resistance silk,
r_4 = mechanical resistance to air flow in silk,
A_4 = total area of holes in silk,
V_5 = volume of case,
r_T = equivalent mechanical resistance of tube,
m_T = equivalent mass of air in tube,
A_T = area of tube,
$\dot{x}_{-1,\,0,\,2,\,4}$ = linear velocities,
$x_{-1,\,0,\,2,\,4}$ = linear displacements,
P_0 = atmospheric pressure,
λ = ratio of specific heats for a gas,
$\frac{\text{Force}}{\text{Velocity}}$ = mechanical impedance (Force and Velocity are both complex quantities),
$\frac{\text{Force}}{\text{Displacement}}$ = stiffness coefficient.

The Lagrangian equations for a system with four independent coordinates can be written in the form:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{x}_n}\right) + \frac{\partial F}{\partial \dot{x}_n} + \frac{\partial V}{\partial x_n} = e_n(t) \qquad (n = -1, 0, 2, 4), \tag{1}$$

in which T is the kinetic energy, F is Rayleigh's dissipation function, V is the potential energy, and $e_n(t)$ is a periodic force. The kinetic energy of the system is

$$T = \tfrac{1}{2}m_{-1}\dot{x}_{-1}^2 + \tfrac{1}{2}m_0\dot{x}_0^2 + \tfrac{1}{2}m_2\dot{x}_2^2 + \tfrac{1}{2}m_4\dot{x}_4^2. \tag{2}$$

Rayleigh's dissipation function becomes

$$\mathrm{F} = \tfrac{1}{2}r_{-1}\dot{x}_{-1}^2 + \tfrac{1}{2}r_0\dot{x}_0^2 + \tfrac{1}{2}r_2\dot{x}_2^2 + \tfrac{1}{2}r_4\dot{x}_4^2, \tag{3}$$

and the potential energy takes the form

$$V = \frac{1}{2}\frac{\lambda P_0}{V_{-1}}(A_{-1}x_{-1} - A_0x_0)^2 + \frac{1}{2}S_0x_0^2 + \frac{1}{2}\frac{\lambda P_0}{V_1}(A_0x_0 - A_2x_2)^2 + \frac{1}{2}\frac{\lambda P_0}{V_3}(A_2x_2 - A_4x_4)^2 + \frac{1}{2}\frac{\lambda P_0}{V_5}(A_4x_4)^2. \quad (4)$$

Let

$$a_{-1} = \frac{\lambda P_0}{V_{-1}},$$

$$a_1 = \frac{\lambda P_0}{V_1}, \text{ etc.}$$

Differentiating the above expressions, substituting into (1), writing $\ddot{x} = j\omega\dot{x}$, $x = \frac{\dot{x}}{j\omega}$, and noting that $e_2 = e_3 = e_4 = 0$, we have

$$\left(j\omega m_{-1} + r_{-1} + \frac{a_{-1}A_{-1}^2}{j\omega}\right)\dot{x}_{-1} + \left(\frac{-a_{-1}A_{-1}A_0}{j\omega}\right)\dot{x}_0 = e_1,$$

$$-\frac{a_{-1}A_0A_{-1}}{j\omega}\dot{x}_{-1} + \left(j\omega m_0 + r_0 + \frac{a_{-1}A_0^2 + S_0 + a_1A_0^2}{j\omega}\right)\dot{x}_0 - \frac{a_1A_0A_2}{j\omega}\dot{x}_2 = 0,$$

$$-\frac{a_1A_2A_0}{j\omega}\dot{x}_0 + \left(j\omega m_2 + r_2 + \frac{a_1A_2^2 + a_3A_2^2}{j\omega}\right)\dot{x}_2 - \frac{a_3A_2A_4}{j\omega}\dot{x}_4 = 0,$$

$$-\frac{a_3A_4A_2}{j\omega}\dot{x}_2 + \left(j\omega m_4 + r_4 + \frac{a_3A_4^2 + a_5A_4^2}{j\omega}\right)\dot{x}_4 = 0.$$

If we were to draw the equivalent circuit from these equations we would find that negative stiffnesses are introduced by the different areas through which the air has to flow. In the shunt arms, however, only positive stiffnesses appear. In order to eliminate the negative stiffnesses it is customary to group the shunt stiffness with a negative stiffness and another positive stiffness into a T structure. It is simple to show that this T structure is equivalent to an ideal auto-transformer shunted by a positive stiffness. The turn ratio of the transformer is given by the ratio of two areas. Of course, we may write for the impedance looking into the high side of the auto-transformer

$$Z_H = \left(\frac{A_n}{A_m}\right)^2 Z_L,$$

where

Z_L = impedance in the low side of auto-transformer,

$A_{n,\,m}$ = areas where $A_n > A_m$.

If a voltage is in series with Z_L it must be multiplied by the ratio of A_n/A_m. If these transformations are carried out we obtain the following equations.

$$\left[j\omega m_{-1}\left(\frac{A_0}{A_{-1}}\right)^2 + r_{-1}\left(\frac{A_0}{A_{-1}}\right)^2 + \frac{a_{-1}A_0{}^2}{j\omega}\right]\dot{x}_{-1} - \frac{a_{-1}A_0{}^2}{j\omega}\dot{x}_0 = e_1\frac{A_0}{A_{-1}},$$

$$-\frac{a_{-1}A_0{}^2}{j\omega}\dot{x}_{-1} + \left[\frac{(a_{-1}+a_1)A_0{}^2 + S_0}{j\omega} + j\omega m_0 + r_0\right]\dot{x}_0 - \frac{a_1A_0{}^2}{j\omega}\dot{x}_2 = 0,$$

$$-\frac{a_1A_0{}^2}{j\omega}\dot{x}_0 + \left[\frac{(a_1+a_3)A_0{}^2}{j\omega} + j\omega m_2\left(\frac{A_0}{A_2}\right)^2 + r_2\left(\frac{A_0}{A_2}\right)^2\right]\dot{x}_2 - \frac{a_3A_0{}^2}{j\omega}\dot{x}_4 = 0,$$

$$-\frac{a_3A_0{}^2}{j\omega}\dot{x}_2 + \left[\frac{(a_3+a_5)A_0{}^2}{j\omega} + j\omega m_4\left(\frac{A_0}{A_4}\right)^2 + r_4\left(\frac{A_0}{A_4}\right)^2\right]\dot{x}_4 = 0.$$

These equations can be translated into an equivalent circuit in which the effect of the equalizing tube may be inserted as a shunt enabling the impressed force to enter the case and to reach the diaphragm after passing through numerous circuit elements.

The voltage generated in the coil due to its motion in an air gap of a permanent magnet is proportional to $\dot{x}_0$ the velocity of the coil. Hence the expression should be solved for the expression $\dfrac{e_1}{\dot{x}_0}\dfrac{(A_0)}{(A_{-1})} = Z$. If l is the length of the wire in the coil, B the flux density in the gap, then the voltage generated in the coil is

$$V = Bl\dot{x}_0$$
$$= \frac{Ble_1}{Z}\frac{(A_0)}{(A_{-1})},$$

and since $e_1 = pA_{-1}$ where p is the pressure we have finally

$$\frac{V}{p} = \frac{BlA_0}{Z}\cdot 10^{-8} \text{ volts per bar.}$$

The response in db is equal to

$$\eta = 20\log_{10}\frac{BlA_0}{Z}\cdot 10^{-8}. \tag{5}$$

This quantity when plotted against frequency constitutes the contour pressure calibration. The normal incidence field calibration is found by always adding at any frequency the larger ordinate of the curves representing the diffraction of a sphere and of a flat plate. For convenience these effects shown already in Fig. 6 are given again in Fig. 10 which also compares the theoretical with the experimental response. We observe that the theoretical field calibration is in good agreement with the experimental response.

The meaning of most constants used in evaluating (5) is evident. Some are easily calculated, while others have to be found by measurement. The resistance of the silk is found by allowing air of a certain

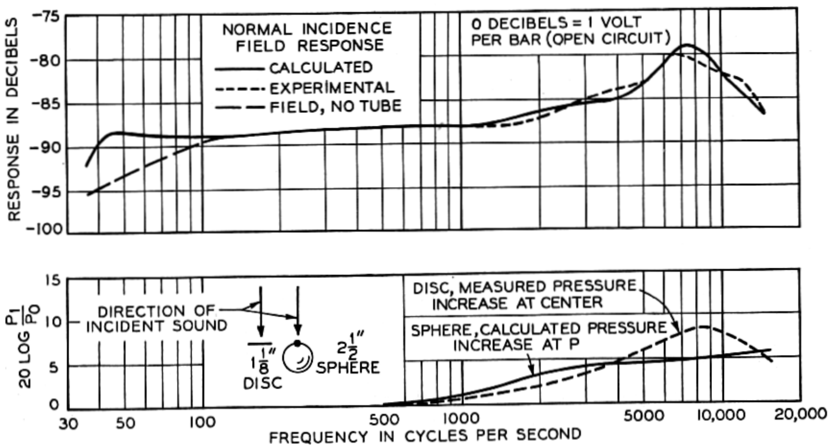

Fig. 10—Field response of 630-A microphone without screen for sound incident normally to diaphragm.

volume velocity to flow through it and by measuring at the same time the pressure drop across the resistance.[1] The mass of the silk is found by impedance measurements.[6] To find the equivalent mass of the coil slot is somewhat difficult since it consists of the mass of the slot plus a certain mass under the dome and under the outer annulus. If the separations between diaphragm and magnet structure are large the problem becomes much simpler since only the mass in the coil slot needs to be considered. The velocity in the slot varies along its width and for any point is given by

$$V = \frac{1}{\mu}\frac{\partial p}{\partial x}\frac{Z(Z - h)}{2}, \tag{6}$$

where Z is the distance from the side wall of the slot to the point in question, h is the width of the slot, $\frac{\partial p}{\partial x}$ is the pressure gradient and μ is the coefficient of viscosity of air.[7] If m is the mass per unit volume, the kinetic energy for a unit length of the slot and for a unit length along the circumference is

$$\text{K.E.} = \frac{1}{2}\int_0^h \frac{m}{\mu^2}\left[\frac{\partial p}{\partial x}\right]^2 \frac{Z^2(Z-h)^2}{4}\,dZ. \tag{7}$$

The same kinetic energy expressed in terms of the average linear velocity and the effective mass of the whole width is

$$\text{K.E.} = \frac{1}{2}m_e\frac{1}{\mu^2}\left[\frac{h}{12}\right]^2\left[\frac{\partial p}{\partial x}\right]^2. \tag{8}$$

Comparing the integrated expression of (7) with (8) we find that the ratio of the effective mass to the physical mass in the slot is $\frac{6}{5}$, that is

$m_2 = \frac{6}{5}$ mass of two slots.

Knowing the average linear velocity in the slot it is quite simple to calculate the mechanical resistance as

$$r_2 = \frac{24\,\mu\, l\pi D}{h}.$$

If the diameter of the coil is large compared to the air passages then D can be taken to be the diameter of the coil.

The constants r_0 and s_0 can be found from the location and magnitude of the resonant peak when the diaphragm is not damped by any external resistance. In making such measurements it was found that r_0 was a function of frequency. It is sufficient, however, to choose an average value because r_0 is usually small as compared to the resistance of the damping ring. m_0 is again calculated from a consideration of the kinetic energy. If the diaphragm behaves like a simple piston the dome-shaped center portion will have the same velocity at all points. For the annulus we may assume parabolic deflection. The inner region plus the effective mass of the outer annulus make up m_0.

When we consider the grid we again make the assumption that the air in the holes moves like a slug, and that the frictional losses due to the walls can be neglected. Even the impedance due to the effective mass of the slug itself is less important than its radiation impedance. Since the latter is a function of frequency it is necessary to change r_{-1} and m_{-1} for each frequency which is being considered. An account of a similar problem can be found in I. B. Crandall's "Theory of Vibrating System and Sound" and therefore will not be considered here.[8]

In order to evaluate the constants of the narrow tube used to increase the low-end response we must investigate the discriminant kr. If $|kr|$ lies between the limits $+ 1$ and $+ 10$ then the mechanical impedance for a tube of length l and area A_T is given by

$$Z = -\frac{\mu k^2 A_T l}{\left[1 - \frac{2}{kr}\frac{J_1(kr)}{J_0(kr)}\right]},^*$$

where $k = \sqrt{\frac{-\omega\rho i}{\mu}}$, $n = \sqrt{\frac{\omega\rho}{\mu}}$, r the radius of tube and ρ is the density of air. $J_1(kr)$ and $J_0(kr)$ are Bessel's functions of first and zero order respectively with complex argument. Substituting for the values of k and expressing J_0 and J_1 in terms of ber and bei functions we have [9]

$$Z = \frac{i\rho\omega A_T l}{\left[1 - \frac{2}{nr} \times \frac{\text{ber}' \, nr + i \, \text{bei}' \, nr}{-\text{bei} \, nr + i \, \text{ber} \, nr}\right]}.$$

If values of this impedance are plotted it will be found that the resistance and mass components vary again with frequency. It is therefore necessary to use a new value for r_T and m_T for each frequency when the response of the network is calculated.

APPENDIX B

The "pressure calibration" of the miniature condenser microphone is measured on the thermophone, but the field calibration must also be determined very carefully. The field correction to be applied to this thermophone calibration is made up of two factors, (1) the diffraction effect of the microphone and (2) the resonance of the small cavity in front of the diaphragm. The latter has been calculated carefully and checked experimentally (Fig. 11).

The condenser microphone itself was used to determine its own diffraction effect. This is possible because of the verified theoretical law giving the diffraction effect to be a function of the product of the diameter and frequency. For example, the diffraction effect that occurs at 2,000 cycles for a 6-inch disc will occur for a 1-inch disc at 12,000 cycles. Since the diffraction effect of the small condenser microphone is essentially that of a cylinder of the same diameter, it was only necessary to measure the effect of a large cylinder in a frequency

* Reference 8, p. 237.

range where the disturbance caused by the test microphone is negligible. This was accomplished by setting the microphone flush into the face of the obstacle when obtaining the disturbed sound pressure. Then by the simple law given, this diffraction effect was applied to the microphone itself and is shown in Fig. 11. The resultant normal incidence field calibration for the small condenser microphone is shown in the same figure.

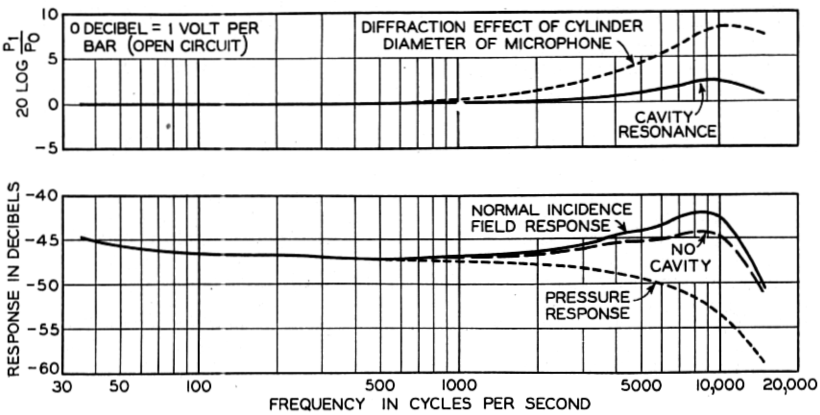

Fig. 11—Response and diffraction of miniature condenser microphone.

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