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USE OF PRESSURE GRADIENT MICROPHONES FOR ACOUSTICAL MEASUREMENTS

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Abstract

The operation of the pressure gradient microphone is compared with that of the pressure microphone It is shown that the pressure gradient microphone may be used to measure particle velocity in a sound wave. The advantages of the pressure gradient microphone in making loudspeaker measurements, particularly outdoors, are pointed out and experimental data are given for some arrangements which were tried out. The characteristics of the distribution of particle velocity in a complex sound field are studied theoretically and experimentally with a ribbon microphone. A method is described for measuring the energy density in a sound field and some measurements which were taken in complex sound fields in rooms are discussed. It is shown that a combination of three pressure gradient or velocity microphones with a pressure microphone, placed adjacent to each other, may be equivalent in eliminating interference patterns to four pressure microphones placed at distances large compared to the wave-length and with random distribution. A microphone for measuring energy flow in a sound field is described.

Introduction

Until very recently the condenser microphone has been the most commonly used microphone for acoustical measurements. It has been generally selected because of its comparatively flat frequency response, freedom from disturbing sounds when in good operation, and constancy of calibration. It has been realized, however, that the condenser microphone possesses characteristics which introduce errors when it is used for certain acoustical measurements. In the first place, being a pressure actuated device, it is sensitive to sound coming from all directions and cannot discriminate against any undesirable component at the lower frequencies where its size is small compared to the wave-length. Secondly, the construction of the condenser microphone is such that distortion is introduced in the sound field in which it is being used at frequencies above 4000 cycles. The distortion is introduced both by the fact that at the higher frequencies, the diaphragm acts as an infinite wall, causing the effective pressure at its surface to be doubled; and also, the air cavity which exists in front of the diaphragm introduces resonance, causing the sensitivity of the microphone (to sound travelling at normal incidence to the diaphragm) to be increased by over 100 percent for even small microphones which have been particularly constructed for measurement work.

A type of ribbon microphone has been described by Olson[1] which eliminates many of the disadvantages of the condenser microphone, and

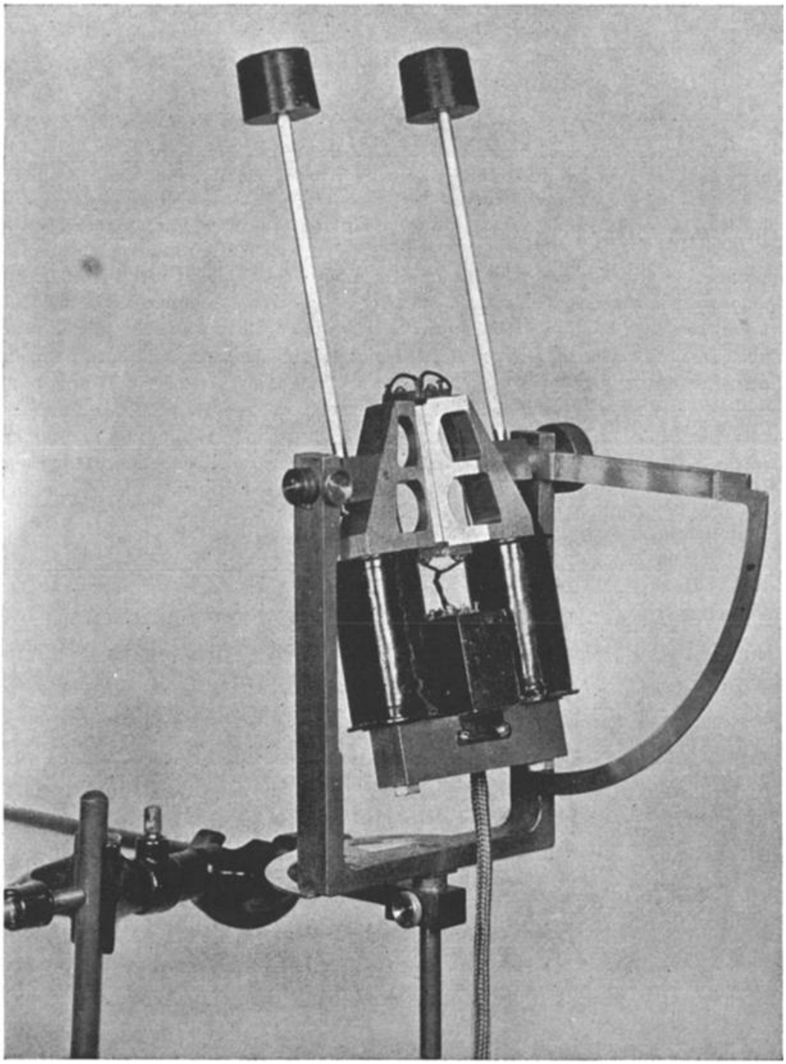

FIG. 1.

which, because of its directional characteristics and means of operation, may be used alone and in conjunction with a pressure operated micro-

[1] Olson, *Mass Controlled Electrodynamic Microphones, The Ribbon Microphone,* J. Acous. Soc. Am. **III,** 56 (1931); *The Ribbon Microphone,* J. Soc. Mot. Pic. Eng. **XVI,** 695 (1931).

phone for many measurements which cannot be made with the condenser microphone or which are made with difficulty.

The condenser microphone is actuated by the difference between sound wave pressure and atmospheric pressure. It has been shown by Olson[1] that the ventilated ribbon microphone is actuated by the difference between sound wave pressure on the front and rear sides. When the wave-length is long compared to the path from front to rear this difference in pressure is proportional to the space variation in alternating pressure or pressure gradient at the point where the microphone is located.

The ribbon microphone that was developed by the RCA Victor Company for acoustical measurements is shown in Fig. 1. The open structure in the vicinity of the ribbon is sufficient to prevent the microphone from reacting on the sound field in a way to introduce frequency distortion at the ribbon. This was determined experimentally by calibrating the unit with a Rayleigh disk, and showed a very smooth response (variations less than 1 db), flat up to 1500 cycles and then a gradual drop amounting to 6 db at 15,000 cycles. This type of frequency characteristic is very easily compensated for in the associated amplifier.

The microphone as shown in Fig. 1 is mounted on a fixture which permits rotation of the unit about a vertical and horizontal axis. A transformer is mounted on the magnetic structure which steps up the ribbon impedance to 500 ohms, permitting the use of long leads to the amplifier.

PRESSURE GRADIENT MICROPHONE MEASURES PARTICLE VELOCITY IN SOUND FIELD

It is of interest to note that the pressure gradient microphone measures particle velocity in a sound field. When steady state conditions are reached in a sound field, the following relations will hold, by using the symbols: p = sound pressure; ρ_0 = density of the medium; ϕ = velocity potential; $\nabla = \partial/\partial x + \partial/\partial y + \partial/\partial z$; u = particle velocity; ∇p = Pressure gradient;

$$\phi = F(x, y, z) \cos \left[\omega t + f(x, y, z)\right] \tag{1}$$

$$d\phi/dt = -\omega F(x, y, z) \cos \left[(\omega t - \pi/2) + f(x, y, z)\right] \tag{2}$$

since

$$p = -\rho_0 d\phi/dt \tag{3}$$

$$u = \nabla\phi \tag{4}$$

$$\nabla p = -\rho_0 \nabla d\phi/dt. \tag{5}$$

We can substitute (1) and (2) in (4) and (5) getting

$$u = \nabla F(x, y, z) \cos [\omega t + f(x, y, z)] \quad (6)$$

$$\nabla p = \rho_0 \omega \nabla F(x, y, z) \cos [(\omega t - \pi/2) + f(x, y, z)] \quad (7)$$

showing that with the exception of a phase shift of $\pi/2$, the space distribution of pressure gradient is the same as that of particle velocity.

Loudspeaker Measurements

Possibly one of the most practical applications of a microphone as a means for measuring sound intensity has been in the determination of frequency-response characteristics of loudspeakers. The disadvantage of using a condenser microphone has already been mentioned; *viz.*, fre-

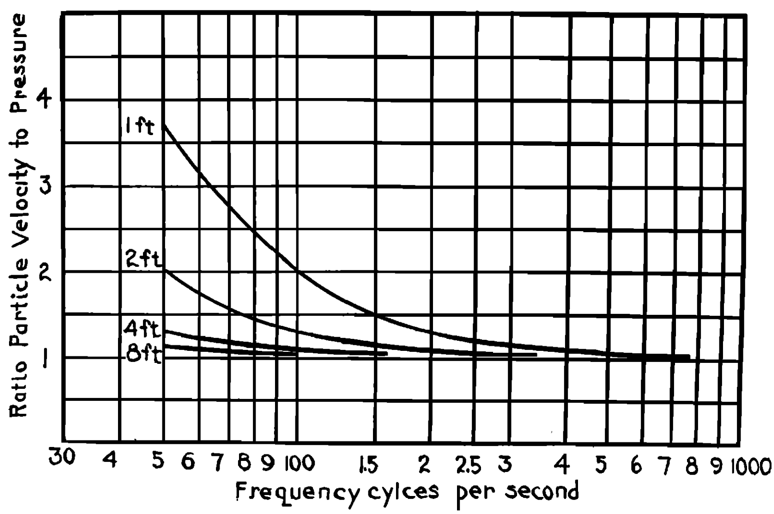

FIG. 2. *Showing accentuation of the low-frequency response in a ribbon microphone at various distances from a point source of sound.*

quency distortion at the high frequencies and no discrimination against undesirable reflected sound. The ribbon microphone, although free from the above disadvantages, possesses another possible type of frequency distortion which must be guarded against. At low frequencies there is a tendency to give false readings when used too close to the source of sound.

Assuming a spherical wave diverging from a source, calculation shows that a measurement of pressure gradient or velocity gives a value which is too high in the ratio $(1+c^2/\omega^2r^2)^{1/2}$ where $\omega = 2\pi \times$frequency, r is the distance from the source, and c the velocity of propagation of sound in the medium. Fig. 2 shows the error introduced as a function of frequency at various distances from a point source of sound. This difficulty can be easily overcome by choosing a distance which will not introduce error at the lowest frequency concerned. If the distance is somewhat too short, so that a small error is introduced, the formula given above may be used to obtain an approximate correction.

The ribbon microphone is very adaptable for loudspeaker measurements out of doors. This results from the particular directional characteristic of the ribbon microphone, or in fact of any pressure gradient microphone. As has been shown theoretically and experimentally by

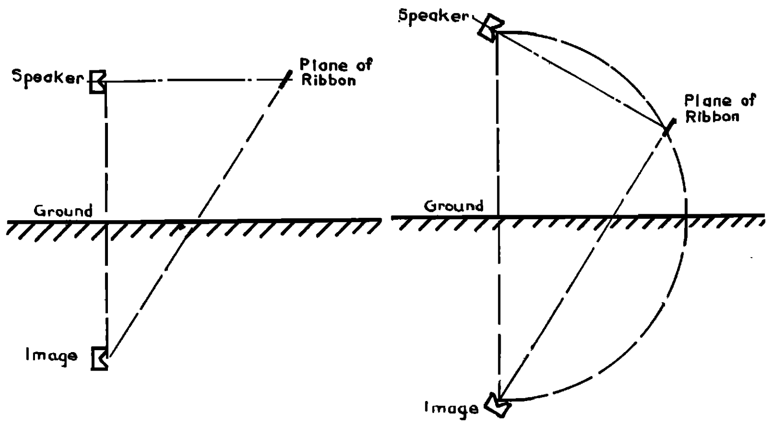

FIG. 3. *Showing two methods for arranging loudspeaker and ribbon microphone so that ground reflections will not be introduced in the data.*

Olson[1] the directional characteristic at all frequencies is very nearly that shown in Fig. 15. Reference to the figure shows that there is a plane of zero response corresponding to the plane of the ribbon while the response in all other directions is proportional to the cosine of the angle made between the direction and the perpendicular to that plane.

Usually the only reflection which is of any consequence when making loudspeaker measurements out of doors is that from the ground, and this can be prevented from affecting the microphone reading by arranging the units as shown in Fig. 3, with the plane of zero response of the ribbon in the direction of the reflected wave. The completeness with which the ground reflections are ruled out is indicated in Fig. 4. The solid curve was taken with a condenser microphone placed 10 ft. from a loudspeaker, both speaker and microphone being 6½ ft. above the ground. The dotted curve was taken by using a ribbon microphone instead of the condenser, with the axis tipped to eliminate the ground reflections.

An interesting group of curves is shown in Fig. 5 which indicate, quantitatively, the extent to which ground reflection errors are neutralized by using a ribbon microphone. Curve (a) shows the theoretical deviation in sound pressure due to perfect ground reflections at a point 10 ft. from a sound source which is $6\frac{1}{2}$ ft. from the ground. A spherical distribution of sound is assumed at the source and 100 percent reflection

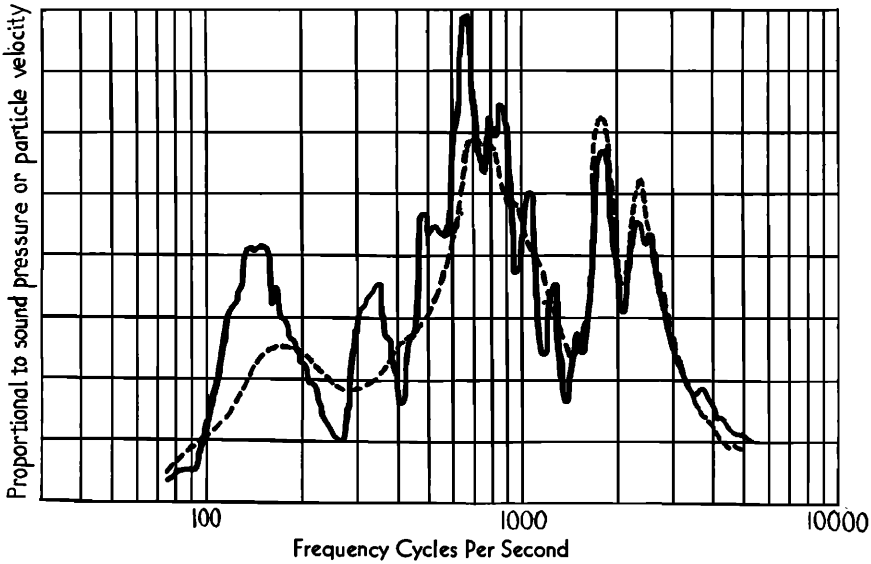

FIG. 4. *Showing elimination of ground reflection peaks by use of ribbon microphone. - - - - -, curve taken with ribbon microphone (plane of ribbon in line with speaker image). ———, curve taken with condenser microphone (corrected for pressure doubling and cavity resonance). Speaker and microphones 6½ feet above ground. Distance between microphones and speaker 10 feet.*

from the ground. The actual error introduced in a loudspeaker response curve taken with a condenser microphone is shown in curve (b). The deviation from the theoretical case at the high frequencies is normal since the sound distribution at these frequencies becomes more directional, resulting in a smaller component reaching the ground for reflection. Curve (c) shows the error introduced when a ribbon microphone was substituted for the condenser. The plane of the ribbon was vertical and the error introduced is less than in the condenser microphone, due to the fact that the reflected component striking the ribbon is effective only as the cosine of the angle which it makes with the normal to the ribbon. Curve (d) shows the error completely removed by tilting the plane of the ribbon so that the reflected component arrives in a direction parallel with the plane of the ribbon.

When we take loudspeaker measurements indoors in a fairly "dead" room, the first reflections are usually the most serious. Generally, the room is fairly large so that the loudspeaker and microphone are at a large distance from the walls. In this case, the most serious reflection

(a) Theoretical deviation in sound pressure at the microphone caused by ground reflection. Point source of sound and 100% reflection from ground assumed.

(b) Actual error introduced in a loudspeaker frequency characteristic due to ground reflection, by using a condenser microphone.

(c) Actual error introduced by using a ribbon microphone with the plane of the ribbon vertical.

(d) Actual error introduced by using a ribbon microphone with the plane of the ribbon in line with speaker image.

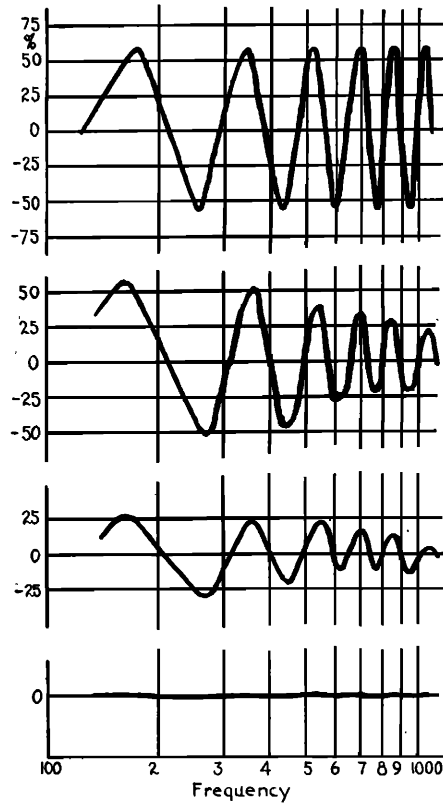

FIG. 5. *Showing the amount of error introduced in a loudspeaker frequency-response characteristic by using different methods of measurement. Distance of speaker and microphone from ground 6½ feet. Distance from speaker to microphone 10 feet.*

is that from the floor and the microphone can be placed to discriminate against this component. In special cases, where the loudspeaker and microphone can always be placed in the same predetermined position, it is possible to design the room with sloping walls and ceiling, such that all the more important reflections will lie in the plane of the ribbon, resulting in only the direct sound actuating the microphone.

It can be concluded that the superiority of the pressure gradient type of microphone for loudspeaker measurements lies, firstly, in the fact that no distortion is introduced by the microphone at the high frequencies, and, secondly, that the microphone can be arranged to discriminate against undesirable reflections.

MEASUREMENT OF SOUND FIELD IN A ROOM

In rooms where diffuse sound field conditions do not exist, it is often of interest to determine the amount of energy which is transmitted in different directions across the room. The use that can be made of the pressure gradient microphone to do this is illustrated by Figs. 6 and 7,

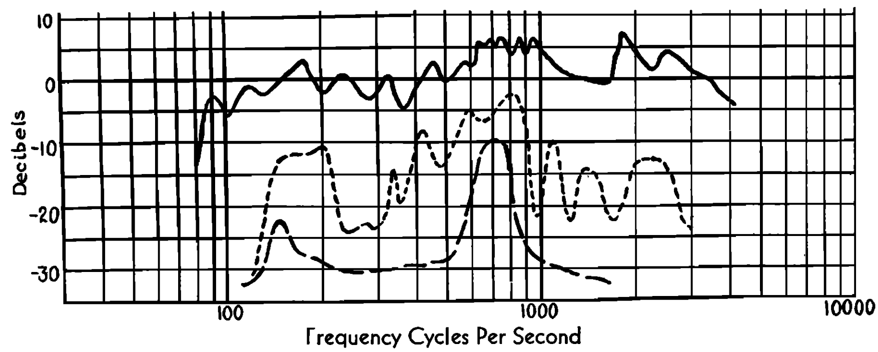

FIG. 6. *Application of ribbon microphone to indicate the amount of sound reflected from various wall surfaces in a fairly "dead" room.* ———, *plane of ribbon normal to loudspeaker axis.* - - - -, *plane of ribbon in loudspeaker axis and parallel to floor (distance between floor and ceiling unequal).* — — —, *plane of ribbon in loudspeaker axis and parallel to floor (distance between floor and ceiling equal). Room 20 feet square×10 feet high. All surfaces 4 inch mineral wool.*

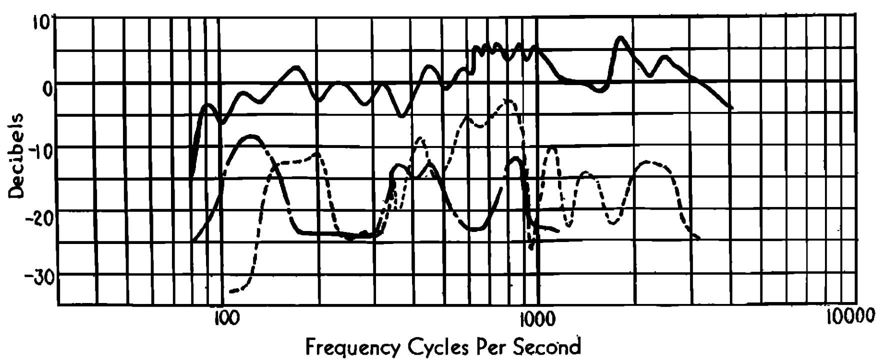

FIG. 7. *Application of ribbon microphone to indicate the amount of sound reflected from various wall surfaces in a fairly "dead" room.* ———, *plane of ribbon normal to loudspeaker axis.* —·—·—, *plane of ribbon in loudspeaker axis and parallel to side wall.* - - - - -, *plane of ribbon in loudspeaker axis and parallel to floor (distance between floor and ceiling unequal). Room 20 feet square×10 feet high. All surfaces 4 inch mineral wool.*

which show the sound being transmitted along various axes of a fairly dead room. In a "live" room, the variations of sound transmission along various axes would naturally not have been as noticeable as indicated above. The method of measurement used for Figs. 6 and 7 may be applied to the study of sound reflections from various types of walls.

MEASUREMENT OF PARTICLE VELOCITY IN A SOUND FIELD

As shown above (Eqs. (1) to (7)) the pressure gradient microphone will measure the particle velocity in a sound wave. The instantaneous value of the particle velocity is a simple vector quantity, which can be projected on any axis, obeys the cosine law and can be added vectorially, $v_\theta = v \cos\theta$, where θ is the angle between any direction and the direction in which the particle is moving, v is the instantaneous particle speed and v_θ is the projection of this instantaneous speed in the direction θ. The assumption should not be made on the basis that the velocity measured by the microphone, which depending on the type of electrical detector which is used, is either mean, square, average or maximum value, is also a vector of this type. Because of the probability of time phase differences, care must always be taken in determining the particle velocity due to a number of waves in a specified direction to add instantaneous values vectorially and not the maximum, mean square or average values given by the indicating instrument.

In plane or spherical progressive sound waves the value measured by the microphone can be taken as a simple vector quantity and may be predicted in any direction by the cosine law since $v_\theta = V \cos\theta \cos\omega t$ and $(v_\theta)_{\max} = V \cos\theta$.

A simple illustration to show that the measured velocity is not a simple vector quantity in a sound field in which interference takes place is obtained by studying the conditions when two equal plane wave trains travelling at right angles in the same plane intersect. Points in the region of intersection may be found in which the time phases of the two wave trains differ by $\pi/2$. If the instantaneous velocity in the one train is $v_1 = V \cos\theta \cos\omega t$, that in the other is $v_2 = V \sin\theta \sin\omega t$, where v_1 and v_2 are the components of the instantaneous velocity in the direction θ. The sum in direction θ is

$$v_\theta = V(\sin\theta \sin\omega t + \cos\theta \cos\omega t); \; v_\theta = V \cos(\theta + \omega t)$$

showing that the maximum, average or mean square values of the velocity are independent of the direction and the microphone should therefore give a reading on the electrical indicating instrument independent of direction in the plane of the two waves.

The particle velocity at these particular points in space is of the same nature as the field due to the electric or magnetic vectors in a circularly polarized light wave or like the rotating field in certain types of electrical generating or motor machinery. By choosing the magnitudes, directions and phase relations of the interfering waves properly, any form of rotation corresponding to elliptically polarized light may be obtained.

A ribbon microphone was mounted on a double swivel arrangement so that its plane could be rotated into any position. The readings taken in a plane progressive wave have corresponded to those to be expected for the vector projection on a perpendicular to the plane of the ribbon while those taken in a standing wave system show the elliptical and, in very special cases, circular rotating vector to be expected from the analysis.

In order to obtain the absolute value of particle velocity at a point, it is necessary to measure three right angle components and then add them vectorially. This may be accomplished by having three ribbon microphones mutually perpendicular with the distances between them small compared to the wave-length of the sound being measured. The outputs from each microphone must be squared and added, the result being the square of the particle velocity which is proportional to the kinetic energy in the sound field at the point. An alternative method is to make three independent readings at the same point with the microphone facing along right angle axes. This latter method was adopted in our measurements as it was considered the more expedient at the time.

In order to obtain a check on the operation of the ribbon microphone, readings were taken of the components along different sets of right-angle axes in the same plane in order to see if the vector sum for any pair of axes would be the same. Some typical data are shown in Table I,

TABLE I. *Showing the agreement of particle velocity at a point by measuring different sets of right-angle components in the same plane.*

Frequency	0°	90°		30°	120°		45°	135°		75°	165°	
150~	99	18	[117]	55	61	[116]	32	84	[116]	10	109	[119]
400~	170	10	[180]	124	57	[181]	83	103	[186]	16	166	[182]

the data given being proportional to the square of the particle velocity. The bracketed figures are the sum of the squares of the component velocities measured along the axes indicated on the chart and the agreement is well within the probable error of the measurements.

ENERGY DENSITY MEASUREMENTS

The energy density in a sound field is both kinetic and potential, and in a field in which standing waves are present may at some points be entirely potential and at others entirely kinetic, or consist of any combination of the two. The potential energy is proportional to the square of the pressure, while the kinetic energy is determined by the square of the air particle velocity. One method of measuring the energy density directly is to have one microphone which will measure the potential

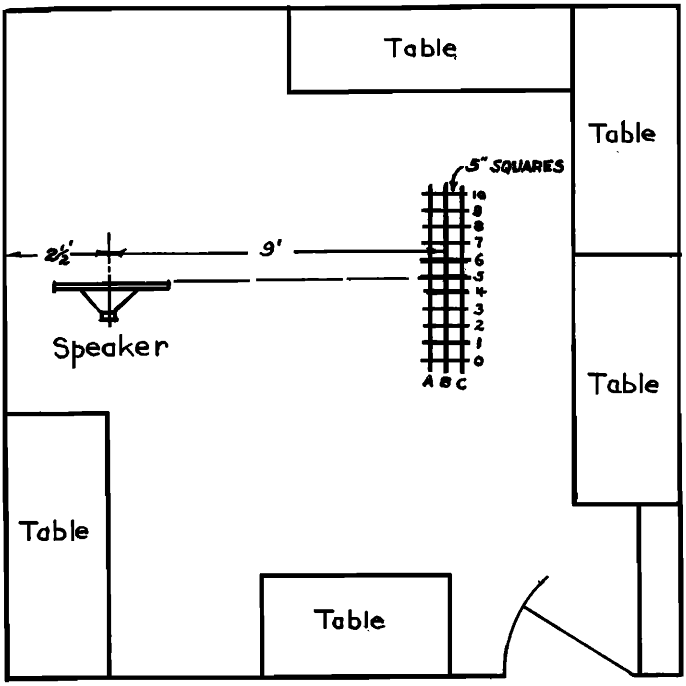

FIG. 8. *Showing arrangement for energy measurements at a set of points within a closed room. Room 16×16×16 feet. Celotex on walls and ceiling.*

energy and another which will measure the kinetic energy. It is well known that the condenser microphone measures the pressure in the sound wave, and, when small compared to the wave-length, exerts negligible influence on the sound field. It, or some other similar microphone, may therefore be used to measure potential energy. It was shown above how the ribbon microphone was used to measure particle velocity in a sound field; therefore, with the aid of both types of microphones the energy density at any point can be measured.

An experimental investigation of the distribution of energy density within a closed room, in which a constant sound signal was maintained, was conducted in order to learn how the variations of total energy from point to point compared with the variations in either the potential or kinetic energy. The investigation was conducted in a room approximating a 16 ft. cube which had a hard wood floor and ½ inch celotex on the walls and ceiling. Several tables lined the walls of the room, and the acoustical characteristic of the room was about equal to that of an average living room.

For the first stage in the investigation, a set of points were surveyed, as shown on Fig. 8. The speaker and microphones were placed 3 ft. from

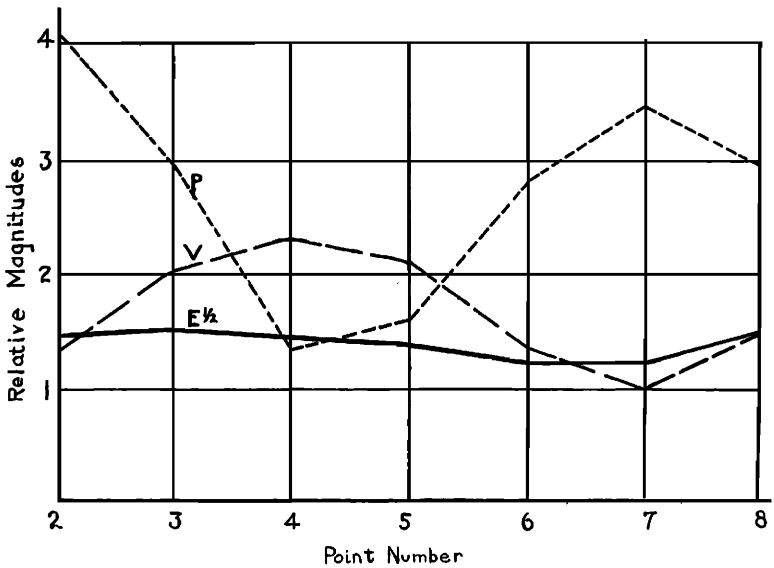

FIG. 9. *Showing variations in P, V and $E^{1/2}$ along row A of the points shown in Fig. 8 Frequency=290 cycles.*

the floor. The variation of the pressure, particle velocity and square root of energy along the points of row *A* of Fig. 8 is shown in Fig. 9. In Fig. 10 is shown another set of points that were surveyed. Figs. 11 to 14 show the variations in pressure, particle velocity, and square root of energy along the points on arcs *B* and *G* with two different sound sources; *viz.*, a 6 inch cone radiating from one side and then a 12 inch cone mounted in a 3 ft. square baffle. The curves on Figs. 11 to 14 are typical of all the arcs. As was to be expected, as the distance from the speaker increased the variations from point to point along the arcs became more violent because of the direct radiation from the cone being less effective at the greater distance.

In order to have a somewhat more quantitative measure of the variations in these quantities, the data covering the points on Fig. 10 were taken and analyzed by finding the average deviation from the mean along each arc. This was done for each velocity component, total velocity, pressure and energy. In addition to the points shown on Fig. 10, several observations were made keeping the speaker and microphone always 10 ft. apart in the room and moving them both around at ran-

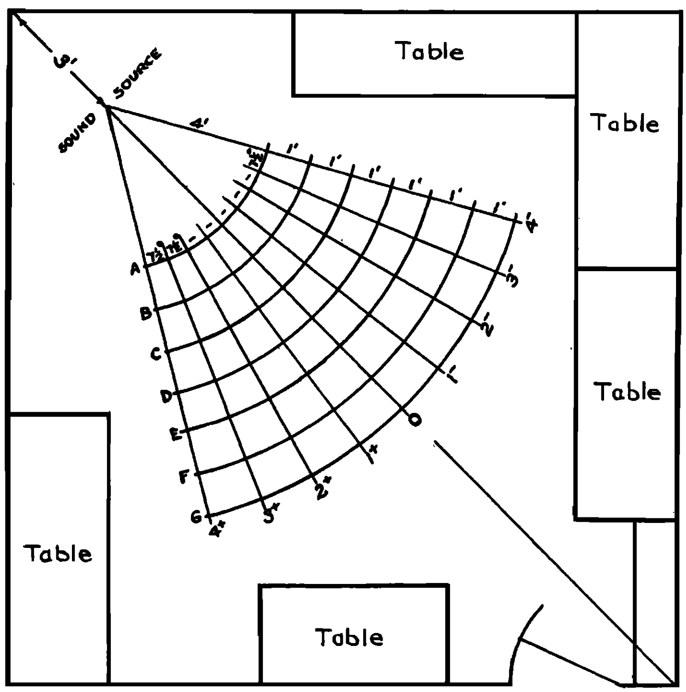

FIG. 10. *Showing arrangement for energy measurements at a set of points within a closed room. Room 16×16×16 feet. Celotex on walls and ceiling.*

dom positions within the room. The data on these points were also averaged, and in Table II is summaried the average deviations from the mean for all the above cases.

From Table II, it can be seen that, in general, the deviations in the pressure and two of the three velocity components have the same order of magnitude. The velocity component in which the ribbon has its plane normal to the speaker axis does not vary as much, which is to be expected since the ribbon will favor the direct sound from the loudspeaker because of its directional characteristic. A considerable reduction in the variations from point to point can be seen in the case of total particle velocity measurements (column 5). Total energy distribution is still more constant, as seen in column 6.

TABLE II. *Showing average deviations from the mean for different components of sound energy measurements within a closed room in which a constant sound source is maintained.*

	% P or $(PE)^{1/2}$	% V_1 Plane of ribbon in LS axis	% V_2 Plane of ribbon parallel to floor	% V_3 Plane of ribbon normal to LS axis	% V_0 or $(KE)^{1/2}$	% $E^{1/2}$
12″ cone on 3′×3′ baffle	38	36	31	26	17	15
6″ cone in box	28	36	28	27	16	11
Loudspeaker and microphone 10′ apart and moved about	51	51	49	33	22	21

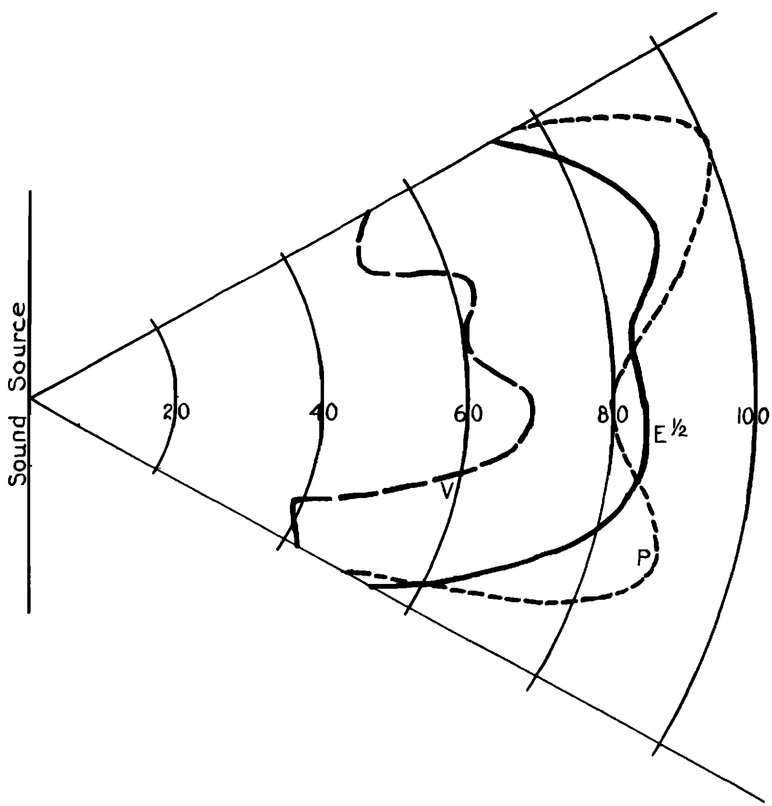

FIG. 11. *Showing P, V and $E^{1/2}$ along arc B 5 feet from speaker, 6 inch cone radiating from one side. f=290~.*

It will be noted that the $(KE)^{1/2}$ shows considerably less deviation than the $(PE)^{1/2}$, due to the fact that the $(KE)^{1/2}$ is made up of three independent velocity components. The improvement in the $E^{1/2}$ over the $(KE)^{1/2}$ is about what would be expected from the addition of an extra microphone and does not show the improvement which might be hoped for from some expected correlation between maxima of KE and

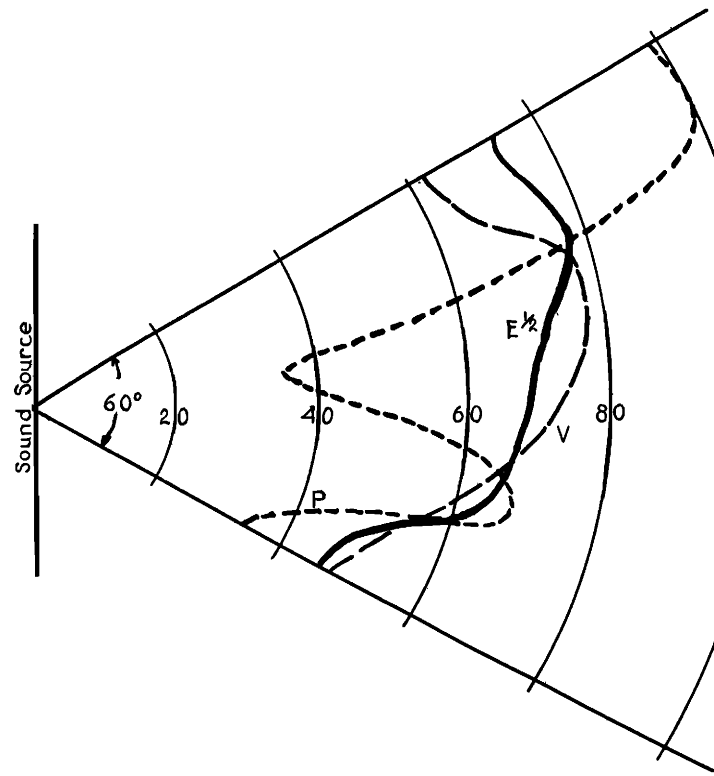

FIG. 12. *Showing P, V, and $E^{1/2}$ along arc B 5 feet from speaker. 12 inch cone in 3×3 feet baffle. f=290~.*

minima of PE or *vice versa*. Practically, the use of three pressure gradient microphones with their axes mutually perpendicular plus a pressure microphone obtains the effect of averaging the readings of four pressure microphones placed at random distances from each other and several wave-lengths apart, so that there is a random correlation between the readings of the microphone. The saving in space and simplicity of mounting obtained by using the pressure gradient microphone is a real advantage.

In making measurements of the kind described with four separate microphones, they must of course be used with separate amplifiers so that the outputs are not added until after they are detected. As a practical matter, the four microphones can feed into amplifiers, each one of which is terminated by a thermocouple, the outputs of all the thermocouples being in series so as to give a single output deflection on the meter which is porportional to the energy.

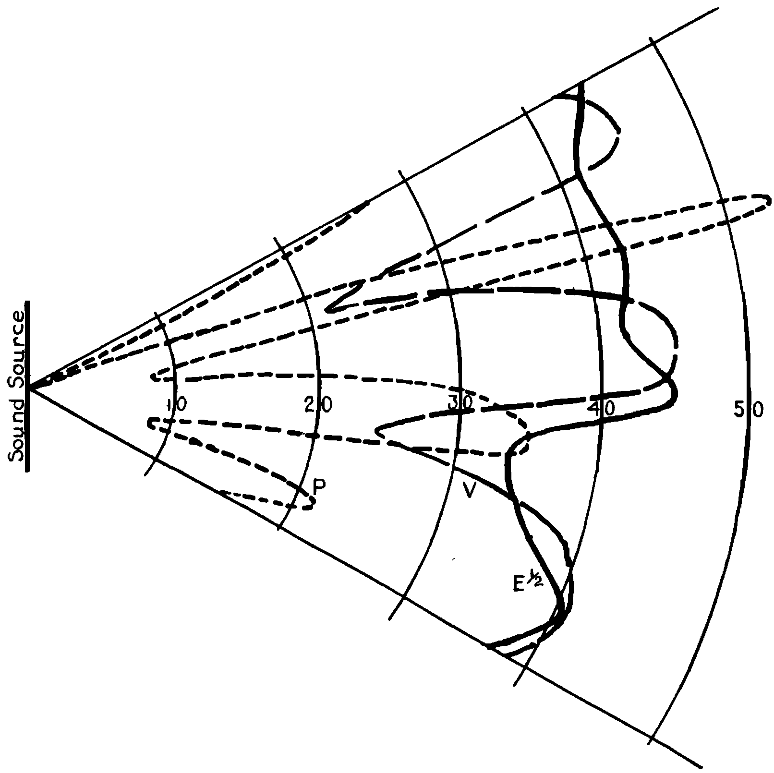

FIG. 13. *Showing P, V and $E^{1/2}$ along arc G 10 feet from speaker. 6 inch cone radiating from one side. f=290~.*

RIBBON MICROPHONE ROTATING ON ITS AXIS EQUIVALENT TO TWO MICROPHONES IN CANCELLING STANDING WAVE PATTERNS IN A ROOM

The difficulty of obtaining a true picture of the sound in a closed room because of irregularities due to interference is well known. A system has been suggested in the preceding section which requires three or four microphones, each having a separate amplifier, if a continuous measurement is to be made. A single amplifier may of course be used if three or four readings may be taken, one after the other, and added subsequently. It is a matter of interest that a single ribbon microphone, rotated on its own axis so that it occupies very little more space than the microphone which is standing still, can be used to take continuous readings equivalent to that obtained by means of two microphones. This is possible as evident from the following considerations. It has been shown that readings taken with a ribbon microphone where the microphone is

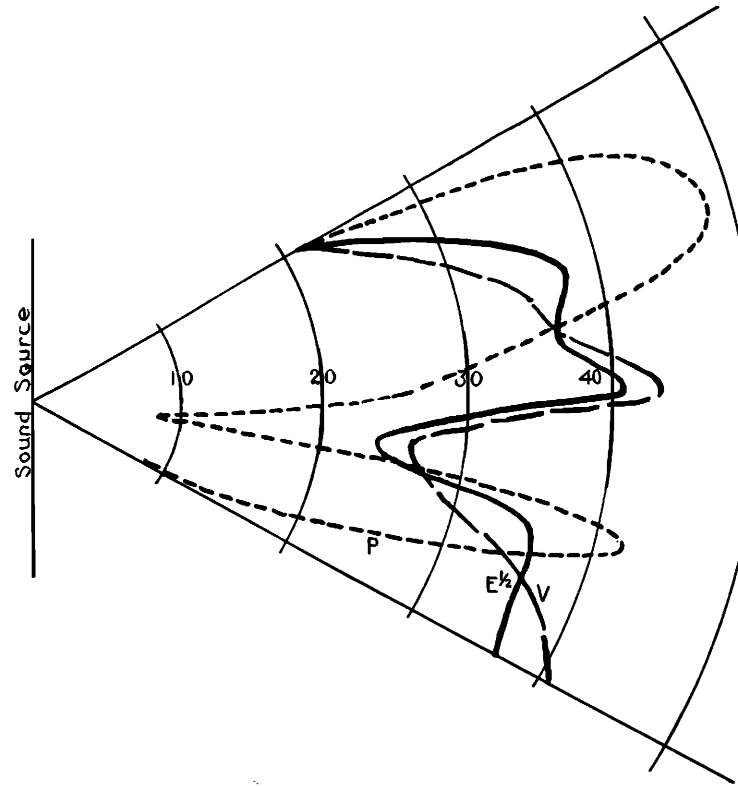

FIG. 14. *Showing P, V, and* $E^{1/2}$ *along arc G 10 feet from speaker. 12 inch cone in 3×3 feet baffle.* $f=290\sim$.

rotated into positions where the plane of the ribbon differs by 90°, lead readings which are equivalent to two separate microphones disposed at random. It has also been shown that when rotated about an axis, all pairs of 90° positions having their outputs squared and added give the same sum. If the microphone is rotated continuously about an axis and red into an amplifier with a square law detector, the readings sweep through all pairs of 90° positions and if the microphone is rotated rapidly enough in comparison with the speed of response of the thermocouple and meter, a continuous reading is obtained which is equivalent to that of two microphones placed at random.

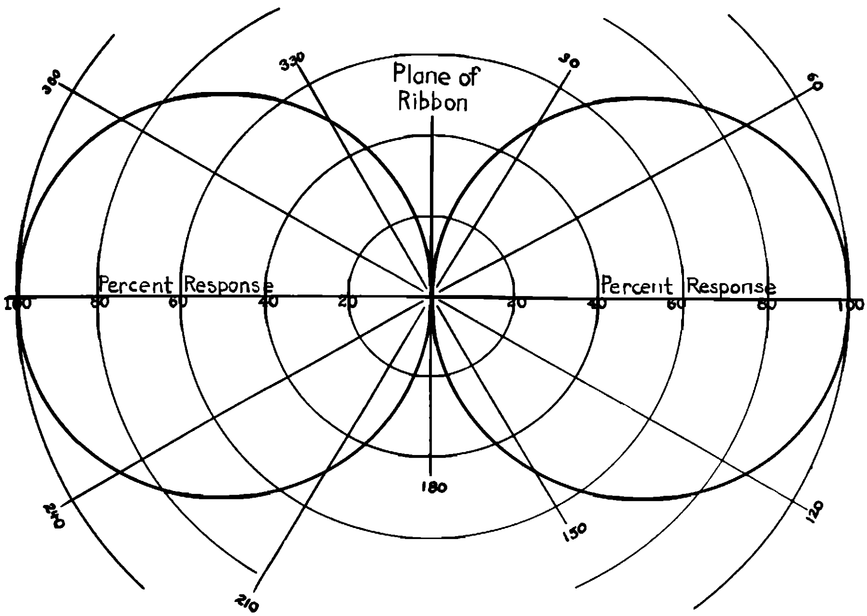

FIG. 15. *Directional characteristic of ribbon microphone.*

ENERGY FLOW MICROPHONE

Another use for a pressure gradient microphone in conjunction with a pressure microphone has been suggested by H. F. Olson as a means for measuring energy flow in a sound field. The energy flow in a given direction can be determined by taking the time average of the instantaneous product of the pressure and the velocity in the direction in which the flow is desired. Since the pressure gradient microphone measures velocity, it can be combined with a pressure microphone by using electrical circuits in which the product of the two outputs are taken to give a reading which is proportional to the energy flow perpendicular to the axis of pickup of the velocity microphone. Care must be taken to compensate for any phase shift which takes place in going from the acoustic wave to the electrical wave, since the amount of transmission of energy depends very largely on the relation of the velocity and pressure components in the sound wave.