Feb. 3, 1953 A. M. WIGGINS 2,627,558

UNIDIRECTIONAL MICROPHONE

Filed July 22, 1946 4 Sheets-Sheet 1

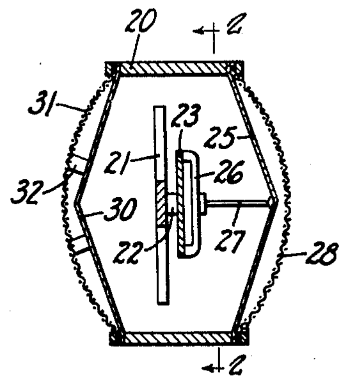

FIG.1

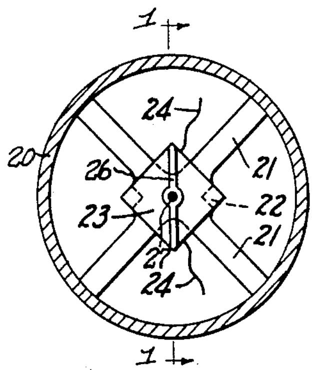

FIG.2

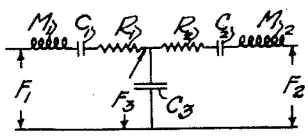

FIG.3

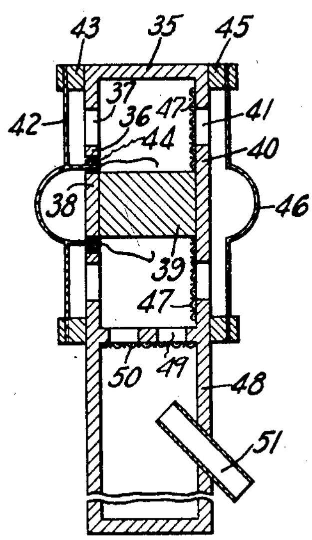

FIG.4

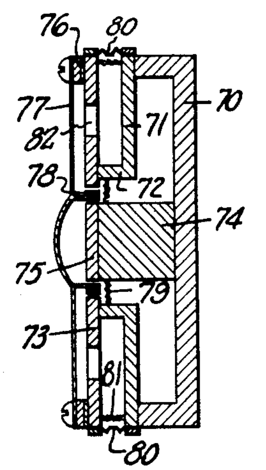

FIG.7

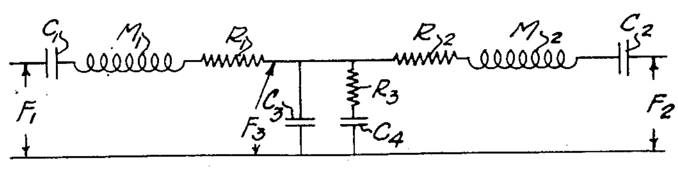

FIG.8

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UNIDIRECTIONAL MICROPHONE

Filed July 22, 1946 4 Sheets-Sheet 2

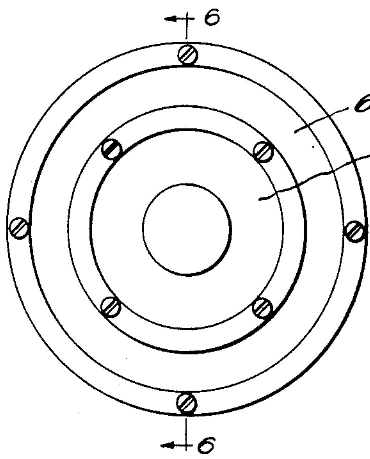

FIG. 5

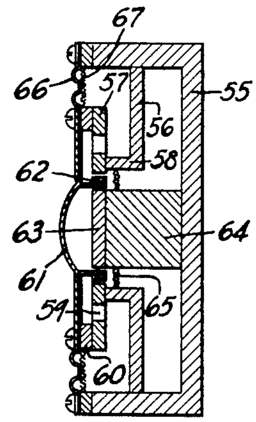

FIG. 6

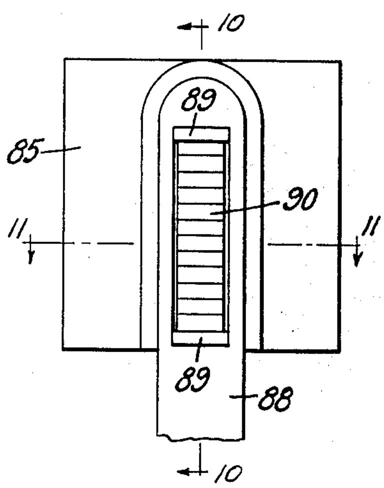

FIG. 9

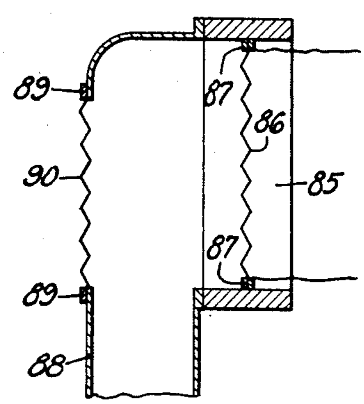

FIG. 10

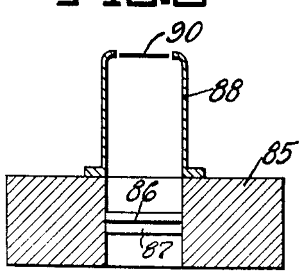

FIG. 11

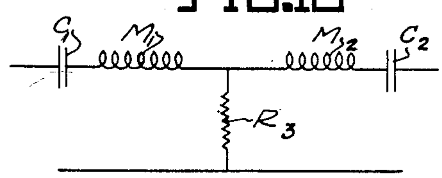

FIG. 12

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UNIDIRECTIONAL MICROPHONE

Filed July 22, 1946 4 Sheets-Sheet 3

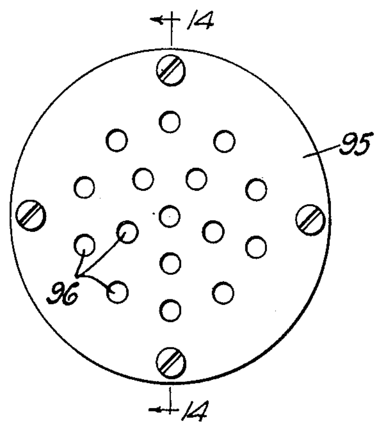

FIG.13

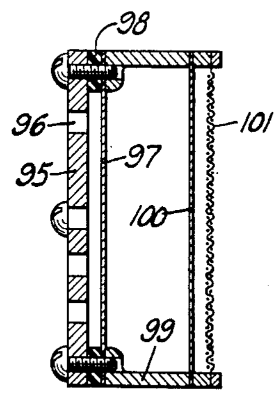

FIG.14

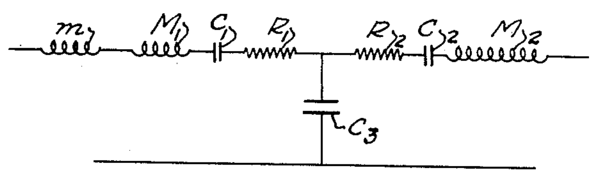

FIG.15

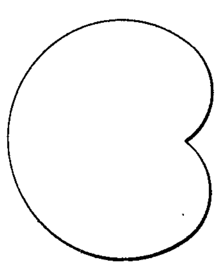

FIG.16

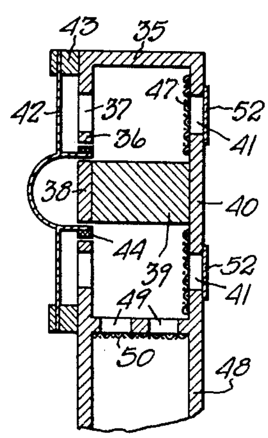

FIG.17

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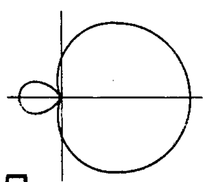

FIG. 18

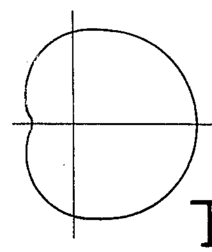

FIG. 19

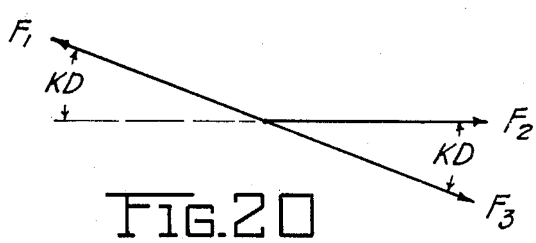

FIG. 20

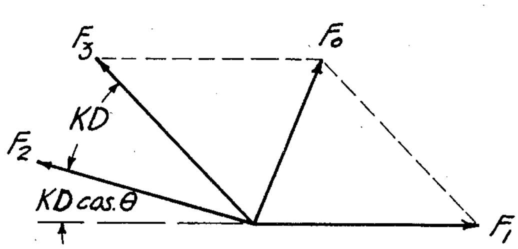

FIG. 21

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Patented Feb. 3, 1953 2,627,558

UNITED STATES PATENT OFFICE

2,627,558

UNIDIRECTIONAL MICROPHONE

Alpha M. Wiggins, Clay Township, St. Joseph County, Ind., assignor to Electro Voice, Incorporated, South Bend, Ind., a corporation of Indiana

Application July 22, 1946, Serial No. 685,337

12 Claims. (Cl. 179—115.5)

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This invention relates to a sound responsive device for converting sound waves into electrical energy. More particularly, it relates to a device or microphone having a unidirectional response characteristic, that is, which converts into electrical energy sound waves traveling in one direction while remaining comparatively inoperative with respect to or unresponsive to sound waves traveling in other directions. This application is a continuation in part of my copending application, Ser. No. 595,921, filed May 26, 1945.

Various types of unidirectional microphones have been developed heretofore. Such prior devices have generally employed one non-directional and one bi-directional unit in combination, or two similar microphones connected by an electrical phase-shifting network, or a single microphone unit having passages and other means defining an acoustical phase-shifting network for controlling the access of sound to one of the surfaces of its sound responsive element. The last named device operates on a pressure gradient principle which produces a force on the diaphragm proportional to frequency and requires placing of certain limitations on the moving element thereof in order to achieve both unidirectivity and uniform frequency response. I have discovered that a unidirectional sound response can be obtained by other means.

The primary object of the invention is to provide a transducer employing a combination of acoustical and mechanical networks to produce unidirectional response in a selected large frequency range.

A further object of the invention is to provide a unitary sound responsive device which is unidirectional in a selected frequency range and non-directional at frequencies outside the selected range, wherein the force on the sound responsive element thereof at frequencies below said range is independent of frequency.

A further object is to provide a unitary unidirectional sound responsive device which is sealed whereby liquid cannot enter it.

A further object is to provide a unitary sound responsive device having two vibratile elements of which one only is electrically operative and the other provides a mass reactance and mechanical resistance forming a predominant element in a network for shifting the phase of sound waves impinging thereon in proportion to their frequency.

A further object is to provide a unitary sound responsive device whose polar response pattern

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is in the nature of any preselected type of limaçon.

Other objects will be apparent from the description, drawings and appended claims.

In the drawings:

Fig. 1 is a longitudinal sectional view of a unidirectional crystal microphone taken on line 1—1 of Fig. 2.

Fig. 2 is a transverse sectional view taken on line 2—2 of Fig. 1.

Fig. 3 is an equivalent electrical circuit of the crystal type microphone of Fig. 1.

Fig. 4 is a sectional view, similar to Fig. 6, of a unidirectional dynamic microphone.

Fig. 5 is an end view of another unidirectional dynamic microphone.

Fig. 6 is a sectional view taken on line 6—6 of Fig. 5.

Fig. 7 is a sectional view, similar to Fig. 6, of a different embodiment of unidirectional dynamic microphone.

Fig. 8 is an equivalent electrical circuit of a dynamic unidirectional microphone as shown.

Fig. 9 is a rear elevation of a ribbon type unidirectional microphone.

Fig. 10 is a longitudinal sectional view taken on line 10—10 of Fig. 9.

Fig. 11 is a transverse sectional view taken on line 11—11 of Fig. 9.

Fig. 12 is an equivalent electric circuit of a ribbon type unidirectional microphone.

Fig. 13 is a face view of a unidirectional condenser microphone.

Fig. 14 is a transverse sectional view taken on line 14—14 of Fig. 13.

Fig. 15 is an equivalent electric circuit of a unidirectional condenser microphone.

Fig. 16 is a diagram illustrating the unidirectional characteristics of the device.

Fig. 17 is a view similar to Fig. 4, of another form of dynamic unidirectional microphone.

Fig. 18 is one polar response pattern obtainable with this invention.

Fig. 19 is another polar response pattern obtainable with this invention.

Fig. 20 is a vector diagram of the force acting upon the microphone for sound arriving axially from the rear of the microphone.

Fig. 21 is a vector diagram of the force acting upon the microphone for sounds arriving from any direction or angle θ.

Referring to the drawings, and particularly to Figs. 1 to 3, which illustrate a unidirectional crystal microphone, the numeral 20 designates a casing or frame which is preferably of tubular or open-ended form. Within this casing is secured a spider or other mounting 21 provided with laterally projecting lugs 22 for supporting a conventional piezoelectric element or crystal 23 at diametrically opposite points. Crystal 23 has the conventional electrical connections 24. The crystal is smaller than the casing and the spider is constructed to span the casing without forming any material obstruction therein. A conical diaphragm 25 spans one end of the casing which may be referred to as the front thereof. The diaphragm 25 and crystal 23 are interconnected by conventional means, here illustrated as a bridge member 26 secured at opposite sides of the crystal displaced approximately 90° from the lugs 22 and a rod or arm 27 projecting from the center of the bridge and bearing against the diaphragm 25 at its outer end. A screen 28 spans the end of casing 20 in spaced relation to diaphragm 25.

The opposite or rear end of casing 20 is spanned and sealed by a diaphragm 30 whose properties will be mentioned later. Diaphragm 30 has no connection with the piezoelectric element 23, and therefore may be referred to as a dead diaphragm. The diaphragm 30 is suitably damped either mechanically or acoustically. A mechanical damping arrangement is illustrated in Fig. 1, and constitutes a screen 31 spanning the casing 20 and spaced therefrom, and damping members 32, such as spaced rubber pads, are carried by the screen and bear against the diaphragm 30. An alternative damping means (not shown) is a silk or other porous material spanning the casing adjacent the diaphragm 30. Such porous material is selected for its ability to damp the diaphragm for sound waves passing therethrough for impingment upon the diaphragm 30, as distinguished from any property of inertance. In other words, the porous material is selected solely for its property of producing a desired resistance.

The critical property required of the diaphragm 30 is a mass which is correlated properly with the factors of its spacing from the diaphragm 25 and of the volume of the space enclosed between the two diaphragms. This mass is entirely independent of the mass of diaphragm 25, and bears no relation thereto. The diaphragm 30 is so selected that it provides a mass reactance and a mechanical resistance in response to sound of a frequency above its resonance point, which will cause a shift in phase or a lag for unidirectional purposes.

The device is so proportioned, with respect to the factors of the mass of diaphragm 30, the resistance of the damping means therefor, the spacing of the two diaphragms and the volume of the space between the diaphragms, that a unidirectional cardioid response characteristic, as illustrated diagrammaticaly in Fig. 16, is obtained, or a polar response characteristic of any selected type of limaçon, for example, as illustrated in Figs. 18 and 19, is obtained. More specifically, the device is so responsive to sound approaching in the direction faced by diaphragm 30, i. e., the rear of the device, that its effect upon the rear of diaphragm 25, after conversion by its impingement on the diaphragm 30, is characterized by phase identity with and cancelling reaction to the sound which passes around the device and impinges upon the front of diaphragm 25. In other words, upon impingement of sound approaching from the rear upon the diaphragm 30, the resistance and mass of the dead diaphragm 30 produces a phase shift of the impulses which reach or act upon the rear face of diaphragm 25 which is coordinated with the phase shifting or displacement of the sound which occurs in travel thereof through the longer path around the device to the front face of the diaphragm 25.

For sound which approaches from the front of the device, that which passes around the device and impinges upon the dead diaphragm, produces an effect upon the rear face of the diaphragm 25 in a phase-time relation to the effect of the sound upon the front face of diaphragm 25 which is determined by the size of the device and the values of the resistance and the mass of the dead diaphragm 30 to give maximum response for sounds approaching from the front in a direction parallel to the axis of casing 20 and diaphragm 25.

The resistance and the mass of the dead diaphragm 30 serve to produce a phase shifting reaction upon the impulses effective upon the rear face of the diaphragm 25 which is directly proportional to the frequency of the sound waves above the point at which the stiffness of the diaphragm 30 retards vibration thereof. Since the dimensions of the device are also a governing factor with respect to phase shifting, and phase shift is likewise proportional to frequency, the device is unidirectional at all frequencies above the stiffness controlled frequencies of the dead diaphragm and below frequencies whose wave length is at least four times the spacing of the two diaphragms 25 and 30. In other words, the range of frequencies within which the device has a unidirectional response is determined by the stiffness of the diaphragm 30 with respect to its lower limit and by the spacing of the two diaphragms with respect to its upper limit. Any unidirectivity due to diffraction has been disregarded in the foregoing considerations.

For sounds of frequencies well below the resonance point of the dead diaphragm 30, the dead diaphragm serves merely as a stiffness having a high mechanical impedance, so that the device is then a simple pressure microphone. Inasmuch as the E. M. F. generated on a piezoelectric element is proportional to the force on the diaphragm, the response of the device to sounds well below resonant frequency of diaphragm 30 is independent of frequency. For sounds of a frequency above the frequencies at which the stiffness of the dead diaphragm detards vibration thereof, the dead diaphragm becomes a mechanical impedance capable of producing phase shifting for unidirectivity. That is, the dead diaphragm automatically vitalizes for phase shifting and unidirectivity purposes. The force (considered as a mechanical term) which acts upon the live diaphragm under unidirectional conditions is proportional to frequency.

The vector diagram of the forces acting on the diaphragms of the microphone for sound incident axially from the rear is shown in Fig. 20. F_2 is the force on the outer face of the phase shifting diaphragm 30 as shown in Fig. 1. F_1 is the force on the outer face of diaphragm 25 which is in the opposite direction and displaced by an angle of KD, where K is $2/\lambda$, λ the wave length, and D the distance between the front and back diaphragms. The angle KD is the phase angle in radians produced by the sound traveling a distance D. F_3 is the force on the inner face of the live diaphragm 25 which is equal and opposite to F_1 for sound arriving axially from the rear due to the phase shift produced by the action of the dead diaphragm 30. The value of the mass and mechanical resistance of the dead diaphragm **30** which will produce a cardioid polar response may be calculated by use of the equivalent circuit shown in Fig. 3. F_1 is the force on the outer face of the live diaphragm **25**, F_2 the force on the outer face of the dead diaphragm **30** and F_3 the force on the inner face of the live diaphragm. M_1 is the mass of the live diaphragm **25** and crystal **23**, C_1 the compliance of the live diaphragm and crystal and R_1 the resistance associated with the diaphragm and crystal. M_2 is the mass of the phase shifting diaphragm **30**, C_2 the compliance of the diaphragm, and R_2 the resistance associated with the diaphragm. C_3 is the compliance of the volume of air between the two diaphragms. For unidirectional action of the microphone the force on the outer face of the live diaphragm must be equal and opposite to the force on the inner face for sounds arriving axially from the rear as shown in Fig. 20. Under these conditions the velocity of the live diaphragm is zero. Then from the equivalent circuit neglecting the compliance of the back diaphragm

$$\frac{F_2}{F_3}=\frac{R_2+j\omega M_2+\frac{1}{j\omega C_3}}{\frac{1}{j\omega C_3}} \qquad (1)$$

Where j equals $\sqrt{-1}$ and ω equals $2\pi f$ where f is the frequency. The phase displacement between F_1 and F_2 is KD. Assuming F_3 equals $-F_1$, and F_2 equals $F_3\epsilon^{jKD}$, where ϵ is the base of the natural logarithms, then

$$\frac{F_3\epsilon^{jKD}}{F_3}=\epsilon^{jKD}=j\omega C_3R_2-\omega C_3M_2+1 \qquad (2)$$

The acoustic capacitance CA of the volume between the two diaphragms is

$$C_A=\frac{V}{\rho c^2} \qquad (3)$$

where V is the volume in cubic centimeters, ρ the density of air and c the velocity of sound in air. The value of the mechanical compliance of this volume referred to the live diaphragm is

$$C_3=\frac{V}{\rho c^2A^2} \qquad (4)$$

Where A is the area of the diaphragm. By substituting this in Equation 2 and writing the unit vector in a different form, the equation becomes

$$\cos KD+j\sin KD=1-\frac{\omega^2MV}{\rho c^2A^2}-j\frac{\omega RV}{\rho c^2A^2} \qquad (5)$$

By separating real from imaginary quantities, two equations are obtained:

$$\cos KD=1-\frac{\omega^2MV}{\rho c^2A^2} \qquad (6)$$

$$\sin KD=\frac{\omega RV}{\rho c^2A^2} \qquad (7)$$

For small angles $\sin KD=KD$ and $K=\omega/c$

$$\frac{\omega D}{c}=\frac{\omega RV}{\rho c^2A^2} \qquad (8)$$

From this equation the mechanical resistance of the diaphragm must be

$$R=\frac{D\rho cA^2}{V} \qquad (9)$$

for unidirectional action of the microphone.

If KD is considerably smaller than 1, the cosine of the angle KD may be written

$$\cos KD=1-\frac{K^2D^2}{2}=1-\frac{\omega^2D^2}{2c^2} \qquad (10)$$

From Equations 6 and 10

$$1-\frac{\omega^2MV}{\rho c^2A^2}=1-\frac{\omega^2D^2}{2c^2} \qquad (11)$$

From this equation the mass of the dead diaphragm must be

$$M=\frac{D^2\rho A^2}{2V} \qquad (12)$$

For unidirectional action of the microphone.

If the mass and mechanical resistance are less than the above values, the phase shift will be less, producing a limaçon of the form shown in Fig. 18. The equation of this curve will be $a+b\cos\theta$ where a is less than b and θ is the angle of incidence. If the mass and mechanical resistance are more than the above values, the polar response will result in a limaçon of the form shown in Fig. 19 where the polar response will be $a+b\cos\theta$ and a will be greater than b.

A more generalized vector diagram for any angle of incidence is shown in Fig. 21. F_1 is the force on the outer face of the live diaphragm, and F_2 the force on the outer face of the dead diaphragm which is displaced by an angle $KD\cos\theta$, F_3 is the force on the inner face of the live diaphragm which is always displaced from F_2 by an angle KD due to the action of the mechanical impedence of the dead diaphragm. The vectorial sum of the forces acting on the outer and inner faces of the live diaphragm is equal to the resultant force F_o, on the live diaphragm. The equation for the phase relation of the force on the inner face of the live diaphragm to the force on the outer face may be written:

$$F_3=-F_1e^{-j(KD+KD\cos\theta)}$$

then

$$F_o=F_1+F_3=F_1-F_1e^{-jKD(1+\cos\theta)} \qquad (13)$$

For small angles of KD the force on the diaphragm is:

$$F_o=KDF_1(1+\cos\theta) \qquad (14)$$

This equation shows that the force on the diaphragm is proportional to frequency and the polar response is a cardioid.

An important characteristic of the sound responsive device or microphone constructed as herein described and illustrated is that the dead diaphragm does not produce an appreciable attenuation in magnitude, thereby giving a directional characteristic which is a limaçon. The transducer is distinguishable from transducers heretofore known wherein flexible waterproofing sheets have been used solely to span and seal the back of the device.

In one embodiment of this invention shown in Fig. 1, the distance between the front and back diaphragms was 1.25 centimeters. The diameter of the case was 4.75 centimeters. The volume of air between the two diaphragms was 20 cubic centimeters. The dead diaphragm was a formed aluminum diaphragm whose mass was .029 gram. The value of the mechanical resistance obtained from glass cloth covering the shield was 800 mechanical ohms.

It will be observed that this construction is completely sealed. Consequently, immersion of the device in water or other liquid will not damage it. This is a distinct advantage over unidirectional microphones which rely on acoustical networks for their unidirectivity and which consequently have openings through which liquid may enter them. Another advantage of the device is that the upper limit of the range at which the device will be unidirectional is readily controlled by adjusting the spacing between the two diaphragms. Consequently, the range may be made adjustable by simply providing a casing construction of telescoping parts or other construction adapted for axial elongation or selective adjustment lengthwise.

The principle of the invention, entailing the reliance upon the mass reactance and mechanical resistance of a dead diaphragm, can be applied to any type of microphone. Thus, a carbon button unit may be substituted for the piezo electric element of Figs. 1 and 2, and the same unidirectional properties can be obtained. In other types of microphones, the use of a dead diaphragm to provide a phase shifting mass reactance and mechanical resistance can be incorporated in different ways, some of which are illustrated herein.

Figs. 4 to 7 and 17 illustrate several applications of a dead diaphragm to a dynamic microphone to produce unidirectional results. The Fig. 4 construction comprises a cylindrical magnet 35 having an annular pole piece 36 provided with a plurality of large diameter openings 37 therein. Openings 37 are made of such large size that they have no inertance or phase shifting effect. A central pole piece 38 is positioned concentrically within the annular pole piece 36 and is mounted on a central magnet member 39 carried by the base 40 of magnet 35. Base 40 has a plurality of openings formed therein of substantially the same size as openings 37. A diaphragm 42 is suitably mounted at the front of the device adjacent to the pole pieces and spaced therefrom by a spacing ring 43. Diaphragm 42 mounts a coil 44 in the annular space between pole pieces 36 and 38 in the conventional manner.

A spacing ring 45 at the rear of the device serves to mount a second or dead diaphragm 46 in spaced relation to the rear magnet wall 40. A damping resistance member 47 is associated with the rear diaphragm and may comprise a silk screen or other porous member within the device and spanning the openings 41 of the magnet base.

An elongated tube 48 may be arranged to depend from the device. Openings 49 of large diameter provide for communication between the microphone chamber and the tube 48. A damping resistance 50 spans said openings. Also, if desired, a resonance tube 51 may be provided in tube 48 to accentuate the response to low frequency, but this is not essential.

Another manner in which the mass reactance and mechanical resistance of a dead diaphragm may be applied to a dynamic microphone is shown in Figs. 5 and 6. In this construction a cup-shaped magnetic body 55 is provided with a closed base and mounts an annular portion 56 which supports an annular pole piece 57 in spaced parallel relation thereto by means of a tubular extension 58. Pole piece 57 has a plurality of large openings 59 therein whose size prevents the occurrence of phase shifting therein. A spacer ring 60 of smaller diameter than the cup-shaped body is mounted on the pole piece 57 and mounts a diaphragm 61. A coil 62 is carried by the diaphragm 61 and positioned within the central opening of the pole piece. An inner pole piece 63 is positioned inside of coil 62 and is mounted on a central magnet member 64 carried by member 55. A damping resistance 65 is positioned to span the space between tubular element 58 and member 64 inwardly from coil 62. An annular diaphragm 66 spans the space between the spacer 60 and the outer peripheral wall of member 55. A suitable damping resistance 67 is arranged adjacent to the dead diaphragm 66.

A third construction which utilizes a dead diaphragm to provide unidirectivity by virtue of mass reactance and mechanical resistance is shown in Fig. 7. In this construction a shallow cup-shaped magnetic member 70 has an annular web or flange 71 terminating in a reduced diameter outwardly projecting annular portion 72 which mounts an annular pole piece 73. A central magnet part 74 is carried by member 70 and supports a pole piece 75 in concentric coplanar relation to pole piece 73. Pole piece 73 mounts a spacer 76 at its margin, and a diaphragm 77 is carried by said spacer. A coil 78 is carried by diaphragm 77 and positioned between pole pieces 73 and 75. A damping resistance 79 spans the space between annular member 72 and central magnet member 74 inwardly of coil 78. A ring type diaphragm 80 is mounted on, and spans the space between, the peripheral wall of member 70 and the margin of the pole piece 73. A damping resistance 81 is associated with the dead diaphragm 80. The pole piece 73 has a plurality of openings 82 therein of a diameter sufficiently large to avoid a phase shifting reaction therein.

In each of the different forms shown in Figs. 4 to 7, the dead diaphragm serves as a mass reactance and mechanical resistance for phase shifting purposes, to provide a unidirectional microphone response characteristic which is a cardioid of revolution or some other type of limaçon, in the same manner described above, assuming that the values are properly selected as mentioned above. The equivalent circuit for these constructions is shown in Fig. 8. As to the dynamic constructions, resistance value R_1 derives from the inherent resistance in the live diaphragm 42, 61 or 77 in the various embodiments; while the R_2 value derives from the resistance of the dead diaphragm plus that of the respective damping resistances 47, 67 and 81, or the R_3 value derives from the respective resistances 50, 65 or 79. All the other values are derived in the same manner as in Fig. 3. C_1 is the compliance of the diaphragms 42, 61 or 77; C_2 the compliance of the diaphragms 46, 52 or 80; C_3 the compliance of the small volume of air immediately below the diaphragms 42, 61 or 77; C_4 the compliance of the large volume of air enclosed in tube 48, and enclosed behind damping sheets 65 or 79, respectively. The volume C_3 is quite small, so the effect of this compliance will be negligible except at the very high frequencies. The vector diagram of the forces acting on this microphone is the same as shown in Fig. 20 for sound arriving axially from the rear. Under these conditions

$$\frac{F_2}{F_3}=\frac{R_2+j\omega M_2+R_3+\frac{1}{j\omega C_4}}{R_3+\frac{1}{j\omega C_4}} \qquad (15)$$

The phase displacement between F_2 and F_3 is KD.

$$F_2=F_3e^{jKD}=F_3\ (\cos KD+j \sin KD) \qquad (16)$$

$$\cos KD+j\sin KD=\frac{R_2+R_3+\frac{1}{j\omega C_4}+j\omega M_2}{R_3+j\frac{1}{\omega C_4}} \qquad (17)$$

since

$$K=\frac{\omega}{c}$$

where c is the velocity of sound, and for small angles sin $KD=KD$ and

$$\cos KD=1-\frac{K^2D^2}{2}=1-\frac{\omega^2D^2}{2c^2}$$

this may be written

$$1-\frac{\omega^2D^2}{2c^2}+j\frac{\omega D}{c}=\frac{R_2+R_3+\frac{1}{j\omega C_4}+j\omega M_2}{R_3+\frac{1}{j\omega C_4}} \qquad (18)$$

$$1-\frac{\omega^2D^2}{2C_2}+j\frac{\omega D}{c}=\frac{R_3R_2+R_3^2+j\omega M_2R_3+j\frac{R_2}{\omega C_4}+\frac{1}{\omega^2C_4^2}-\frac{M_2}{C_4}}{R_3^2+\frac{1}{\omega^2c^2}} \qquad (19)$$

By separating real from imaginary quantities, two equations are obtained:

$$\frac{\omega D}{c}=\frac{\omega M_2R_2+\frac{R_2}{\omega C_4}}{R_3^2+\frac{1}{\omega^2C_4^2}} \qquad (20)$$

$$1-\frac{\omega^2D^2}{2c^2}=\frac{R_3R_2+R_3^2+\frac{1}{\omega^2C_4^2}2-\frac{M_2}{C_4}}{R_3^2+\frac{1}{\omega^2C_4^2}} \qquad (21)$$

For very low frequencies the mechanical impedance of the back diaphragm is essentially a resistance R_2, and the impedance of the volume C_4 becomes large in comparison to the resistance R_3. Under these conditions the resistance R_2 of the diaphragm may be determined from (20)

$$R_2=\frac{D}{C_4c} \qquad (22)$$

The compliance of the volume of air back of the diaphragm is given by

$$C_4=\frac{V}{\rho c^2A^2} \qquad (23)$$

The resistance R_2 of the dead diaphragm is given by

$$R_2=\frac{D\rho cA^2}{V} \qquad (24)$$

which is the same as that given by Equation 9 for the case of the crystal microphone.

For high frequencies the reactance of the compliance C_4 is small compared to R_3 and the resistance R_2 is small compared to the reactance of the mass M_2. From Equation 20 the mass of the back diaphragm must be

$$M_2=\frac{DR_3}{c} \qquad (25)$$

Just as in the crystal microphone, the polar response may be modified by changing the mechanical impedance of the back diaphragm. If the value of mass and mechanical resistance is less than the above value, the polar response will be similar to the limaçon shown in Fig. 18; while if it is above this value, the polar curve will be similar to that shown in Fig. 19.

In one embodiment of the dynamic microphone the distance between the front and back was one centimeter, the volume of air C_4 behind the diaphragm was 56 cubic centimeters. The damping resistance leading to the large volume of air was 1500 mechanical ohms when referred to the live diaphragm. The mass of the back diaphragm was .045 gram. The resistance inherent in the back diaphragm which was constructed of a plastic sheet material was enough to produce enough phase shift at the low frequencies without the addition of cloth damping.

Among the advantages of the Fig. 4 embodiment is the fact that the tube 46 may be used to enlarge the confined air chamber in the device and thereby to relieve the stiffness effect upon the live diaphragm by reducing the rate at which air in the chamber is compressed incident to vibration of the diaphragm. The response characteristics with respect to the range of frequencies at which unidirectivity occurs, and with respect to response independent of frequency for sounds well below the resonance of the dead diaphragm, are the same for these embodiments as above described. Also the sealed construction, except where a resonance tube is employed, is a characteristic of each of these embodiments.

The embodiment of the invention illustrated in Fig. 17 is the same as that in Fig. 4, with the exception that the dead diaphragm of Fig. 4 is omitted. The same reference numerals applied in Fig. 4 are used for similar parts in Fig. 17. In its stead a film or diaphragm 52 is applied to span and seal each of the openings 41 in the back 40 of the casing. The member 52 may be a plastic film, such as a thin film of a vinyl resin, which is marginally cemented or adhered to the back 40 around each opening 41. Alternatively, of course, a single film or diaphragm may span the back, in which event the marginal cementing around each opening is desirable. The film or diaphragm members 52, when properly selected as to mass and other properties, serve the same function as the dead diaphragm 46 of the Fig. 4 construction, and the equivalent circuit of Fig. 8 applies thereto.

The manner in which the dead diaphragm principle to obtain unidirectional response may be incorporated in a ribbon type of microphone is illustrated in Figs. 9 to 11, inclusive. A magnetic frame 85 provides an elongated passage therethrough. Within this passage is positioned the voltage generating element 86, in the nature of a thin flexible conductor or ribbon which is corrugated transversely as is conventional. Suitable electrical connections branch from this ribbon. Any convenient mounting members 87 may be utilized to mount and support the ribbon 86 in operative position, i. e. with just enough clearance at its side edges to permit it to operate freely in the frame passage. An elongated depending damped pipe or tube 88 is connected to the rear face of the frame 85 to completely span and close the rear end of the ribbon-receiving passage thereof. The tube 88 has an elongated opening in its rear upper end portion and suitable mounting means 89 are positioned at the ends of said opening to mount a dead diaphragm 90 of the ribbon type which fits within the tube opening with only such clearance at its sides as to permit it to operate freely within said opening in response to sound waves impinging thereon or of the flexible sheeting type which completely spans and seals the opening in the tube.

The equivalent circuit for this type of device is illustrated in Fig. 12. A characteristic of the device is that the ribbons 86 and 90 each have a large capacitance and a negligible capacitive reactance. The resistance R is derived from the damping resistance of the tube 88.

If the labyrinth is treated as a pure resistance the mass of the back diaphragm may be calculated from Equation 25. The resistance required in the back diaphragm will be negligible due to the fact that the labyrinth is very nearly a pure resistance. In one embodiment of this type of microphone a labyrinth 36 inches long with a cross section of 3/8" x 3/8" was used. Tufts of wool were placed at intervals of about every inch along the labyrinth. A diaphragm of .02 gram mass was used.

Unidirectional response can also be obtained by applying the mass reactance and mechanical resistance phase shifting principle to a condenser microphone, as illustrated in Figs. 12 to 14. The electrode 95 which forms one element of the condenser is provided with a plurality of passages 96 therethrough, all of large diameter. A diaphragm 97 is mounted in capacitive relation to the electrode, as by a spacer ring 98. These condenser elements are provided with suitable electric leads or connections and are mounted upon one end of a casing 99. A dead diaphragm 100 spans the opposite end of casing 99. A suitable resistance 101 is associated with the diaphragm 100.

The equivalent circuit of this construction is shown in Fig. 15. It will be observed that the circuit is characterized by the addition of the inertance *m* resulting from the presence of the holes 96 in electrode 95 to the mass M, of the live diaphragm 97. The circuit is further characterized by a large capacitance value C^3 resulting from the closed chamber between the diaphragms. The values of the mass and mechanical resistance of the diaphragm 100 and resistance 101 will be the same as in the crystal embodiment in Fig. 1.

In each of the various embodiments of this invention, the dead diaphragm may be either a single diaphragm element or a combination of diaphragms or elements so correlated and constructed as to provide the desired phase shifting. Wherever the specifications or the claims refer to such a dead diaphragm or element, it will be understood that a multiple or combination element, as well as a single element, is contemplated within the scope of this invention.

I claim:

1. A sound responsive device comprising a casing, two spaced vibratile sound responsive members carried by said casing and cooperating therewith to define a sealed chamber, one of said members being adapted to translate its vibrations into electrical energy, the other member having a mass reactance and a resistance so proportioned with the value of the compliance of said chamber as to produce a phase shift in the sound pressure applied thereto equal to a constant ratio of the shift produced by the travel of sound through the distance between the two sound responsive members externally of the device the mass of said other member being approximately

$$M=\frac{D^2\rho A^2}{2V}$$

and the resistance of said other member being approximately

$$R=\frac{D\rho c A^2}{V}$$

where D is the distance between said spaced sound responsive members, ρ is the density of air, A is the area of the member, c is the velocity of sound, and V is the volume of the chamber in cubic centimeters.

2. A sound responsive device comprising a vibratile sound responsive member adapted to translate its vibrations into electrical energy, and means cooperating with said member to define a closed chamber, said means including a vibratile portion having a mass and resistance of a value sufficient to impart to said device a directional characteristic which is a cardioid of revolution the mechanical resistance of said vibratile portion being

$$R=\frac{D\rho c A^2}{V}$$

and the mass being

$$M=\frac{D^2\rho A^2}{2V}$$

where D is the distance between said vibratile sound responsive member and said vibratile portion, ρ is the density of air, c is the velocity of sound in air, A is the area, and V is the volume of the chamber in cubic centimeters.

3. A sound responsive device comprising a member defining a chamber and including a vibratile wall portion, and a vibratile sound responsive member closing said chamber spaced less than one-fourth of the wave length of the highest frequency at which unidirectional response is desired, said wall portion having a mass and resistance proportioned to shift the phase of sound impulses impinging thereon in proportion to frequency for unidirectional response of said sound responsive member the mass of said wall portion being approximately

$$M=\frac{D^2\rho A^2}{2V}$$

and the resistance of said wall portion being approximately

$$R=\frac{D\rho c A^2}{V}$$

where D is the distance between said spaced vibratile members, ρ is the density of air, A is the area of the member, and c is the velocity of sound, and V is the volume of the chamber in cubic centimeters.

4. A sound responsive device comprising a casing, a pair of spaced diaphragms spanning and sealing said casing, means for converting the vibrations of one only of said diaphragms into electrical energy, the other diaphragm serving to translate by the relation of its mechanical impedance to the compliance and resistance of the fluid within the casing the phase of wave energy applied to the inner surface of said converting diaphragm so as to produce a directional characteristic which is a cardioid of revolution said compliance being

$$C=\frac{V}{\rho c^2 A^2}$$

and said resistance being

$$R=\frac{D\rho c A^2}{V}$$

wherein V is the volume of the casing in cubic centimeters, ρ is the density of the fluid, c is the velocity of sound, D is the distance between said diaphragms, and A is the area of the diaphragm whose vibrations are converted into electrical energy.

5. In a sound translating device comprising a structure defining a chamber having spaced openings, a pair of sound responsive members each mounted in one of said openings, means for converting the vibrations of only one of said members into electrical energy, the other member having a mass and resistance so proportioned as to impart to said device a directional characteristic which is a limaçon said mass being less than

$$M=\frac{D^2A^2\rho}{2V}$$

and said resistance being less than

$$R=\frac{D\rho cA^2}{V}$$

where D is the distance between said sound responsive members, ρ is the density of air in said chamber, A is the area of the other member, c is the velocity of sound, and V is the volume of the chamber in cubic centimeters.

6. A sound responsive device comprising a casing defining a chamber having a pair of openings, a diaphragm mounted at each opening, means for converting the vibrations of only one diaphragm into electrical energy, a damping resistance in said chamber associated with the other diaphragm, said last named diaphragm having a mass reactance whose value is correlated with the value of said resistance according to the formula

$$M=\frac{DR}{c}$$

where M is the mass of said other diapragm, D is the distance between said diaphragms, R is said damping resistance, and c is the velocity of sound to produce a unidirectional response of said first diaphragm.

7. In a microphone, a casing having a pair of spaced openings, means spanning one opening and adapted to vibrate in response to sound and translate its vibrations into electrical energy, and a flexible member spanning the other opening and resonant at and above a predetermined frequency and having a mass and a resistance of such a value as to impart to said device a directional characteristic which is a cardioid of revolution, said device being unidirectional for all frequencies above the frequencies at which the stiffness of said flexible member retards vibration thereof and being non-directional at frequencies well below the resonant frequency of said flexible member when the stiffness of said member is the controlling factor the mass of said flexible member being

$$M=\frac{D^2\rho A^2}{2V}$$

and its resistance being

$$R=\frac{D\rho cA^2}{V}$$

where D is the distance between said vibrating means and said flexible member, ρ is the density of fluid in said casing, A is the area of the flexible member, c is the velocity of sound, and V is the volume of the casing in cubic centimeters.

8. In a sound translating device, a housing having two spaced openings, two vibratile elements each spanning a housing opening and spaced apart and cooperating with said housing to confine a closed volume of fluid therebetween, one of said elements being adapted to translate its vibrations into electrical energy, the other element having a mass and resistance so proportioned to the displacement between the two diaphragms and the other perameters of the device that it shifts the phase of the sound pressure applied thereto substantially equal to a constant times the phase shift produced by the travel of sound through the distance between the two diaphragms externally of the device at all wave lengths substantially greater than the dimensions of the device to produce a polar response pattern in the nature of a limaçon the mass of said other element being approximately

$$M=\frac{D^2\rho A^2}{2V}$$

and the resistance of said other element being approximately

$$R=\frac{D\rho cA^2}{V}$$

where D is the distance between said vibratile elements, ρ is the density of said fluid, A is the area of the last named vibratile element, c is the velocity of sound, and V is the volume of said housing in cubic centimeters.

9. In a sound translating device, means for producing a magnetic field, a conductor mounted in said field, a pipe mounted behind said conductor constituting a terminating acoustic resistance for said conductor, said conductor substantially closing the mouth of said pipe, said pipe having an opening behind said conductor, a vibratile element substantially spanning said opening and having a mass proportioned with the acoustic resistance of said pipe whereby the phase of sound impinging thereon is shifted by an amount equal to a constant value of the phase shift occurring in the travel of sound around the device from said conductor to the said vibratile element said mass being

$$M=\frac{DR}{c}$$

where D is the distance between said conductor and said vibratile element, R is the resistance of said pipe, and c is the velocity of sound, said vibratile damping element having a negligible resistance and said pipe being substantially a pure resistance.

10. In a sound translating device, means for producing a magnetic field, a conductor mounted in said field, means defining a large chamber having a restricted portion partially bounded by said conductor and having an opening, a vibratile element substantially spanning said opening in spaced relation to said conductor, a resistance in said chamber-defining means located substantially at said restricted portion, said vibratile element having a mass proportioned to said resistance and the constants of the device whereby the phase of sound acting thereon is shifted to produce a polar response pattern which is a limaçon of revolution the mass reactance of said vibratile element being

$$M=\frac{DR}{c}$$

where D is the distance between said conductor and said vibratile member, R is said resistance and c is the velocity of sound.

11. In a sound translating device, means for producing a magnetic field, a conductor mounted in said field, a pipe mounted behind said conductor constituting a terminating acoustic resistance for said conductor, said conductor substantially closing the mouth of said pipe, said pipe having an opening behind said conductor, a vibratile element substantially spanning said opening and having a mass proportioned to the acoustic resistance of said pipe so as to produce a directional characteristic which is a carioid of revolution said pipe being substantially a pure resistance and said vibratile element having a negligible resistance, the mass reactance of said vibratile element being

$$M=\frac{DR}{c}$$

where D is the distance between said conductor and said vibratile member R is the damping resistance of said pipe, and c is the velocity of sound.

12. In a sound translating device, means for producing a magnetic field, a conductor mounted in said field, a pipe mounted behind said conductor and constituting a terminating acoustic resistance for said conductor, said conductor substantially closing the mouth of said pipe, said pipe having an opening behind said conductor, and a vibratile element substantially spanning said opening and having a mass of a value to impart to said device a directional characteristic which is a limaçon said mass corresponding to the formula

$$M=\frac{DR}{c}$$

where D is the distance between said conductor and said vibratile element, R is the damping resistance of said pipe, and c is the velocity of sound.

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