April 8, 1941. B. BAUMZWEIGER 2,237,298

CONVERSION OF WAVE MOTION INTO ELECTRICAL ENERGY

Filed Sept. 29, 1938 4 Sheets-Sheet 1

Fig. 1.

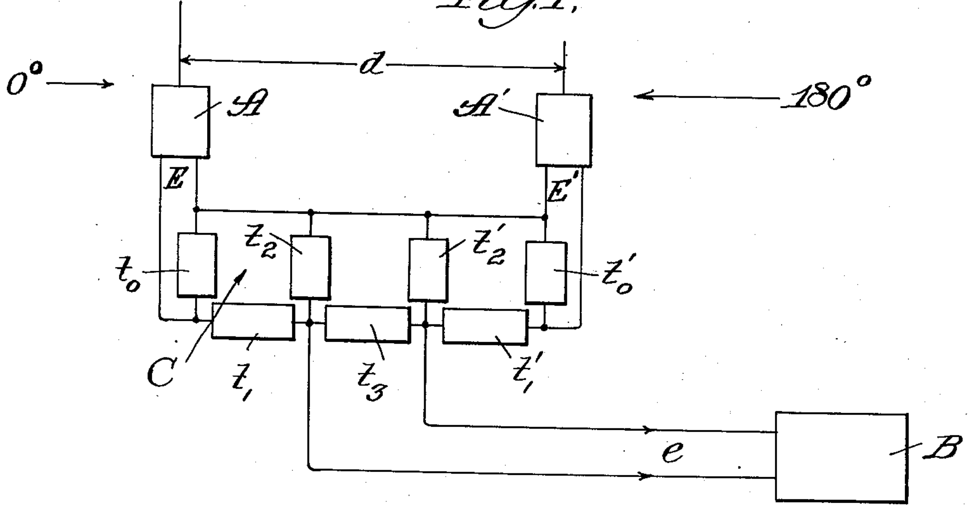


Fig. 2.

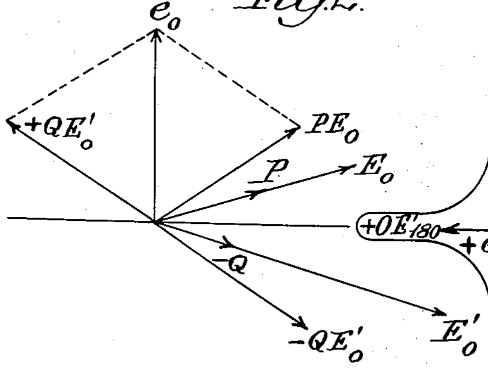


Fig. 3.

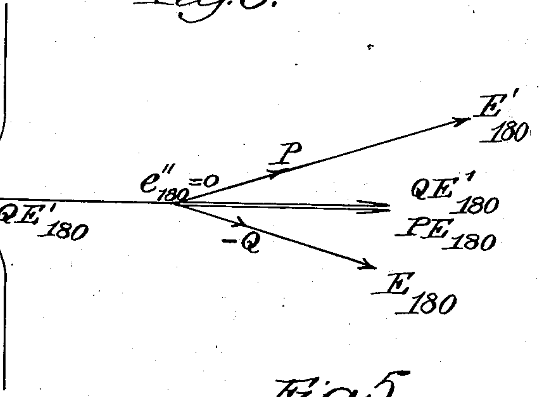


Fig. 4.

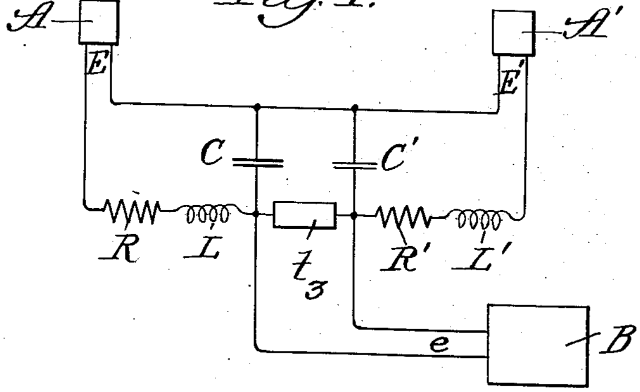
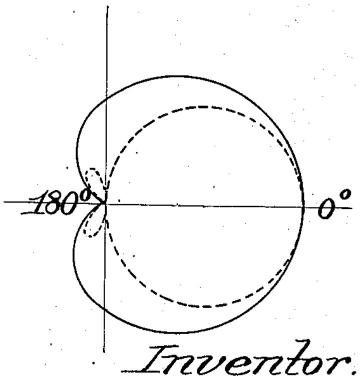


Fig. 5.



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CONVERSION OF WAVE MOTION INTO ELECTRICAL ENERGY

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Fig. 6. Fig. 7.

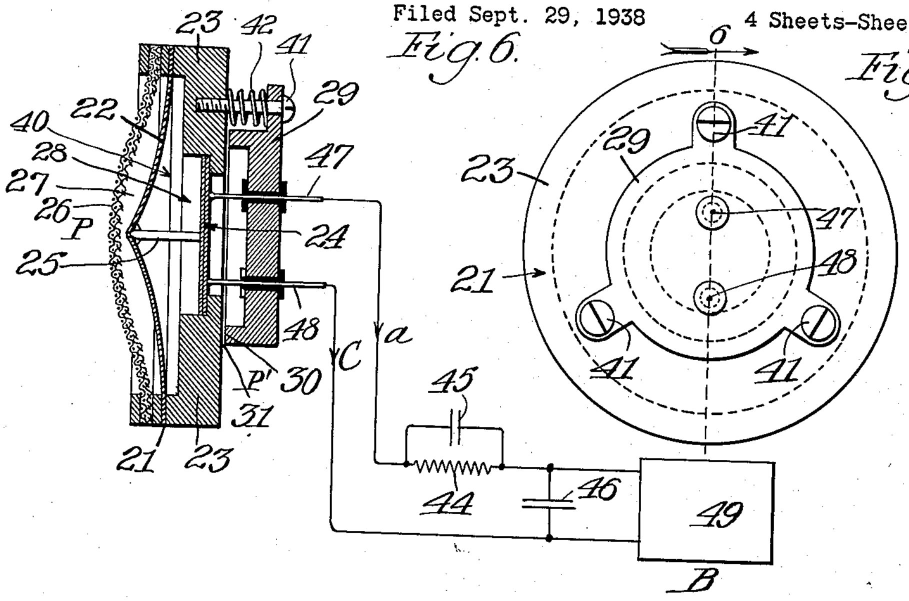

Fig. 8.

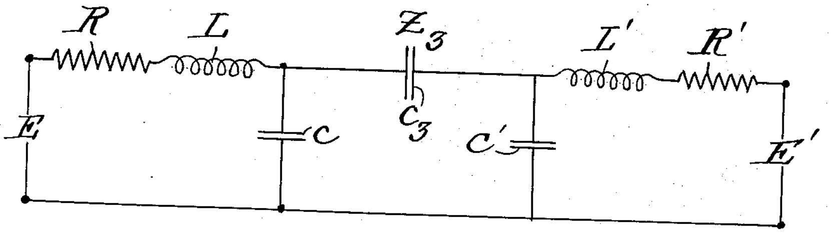

Fig. 9.

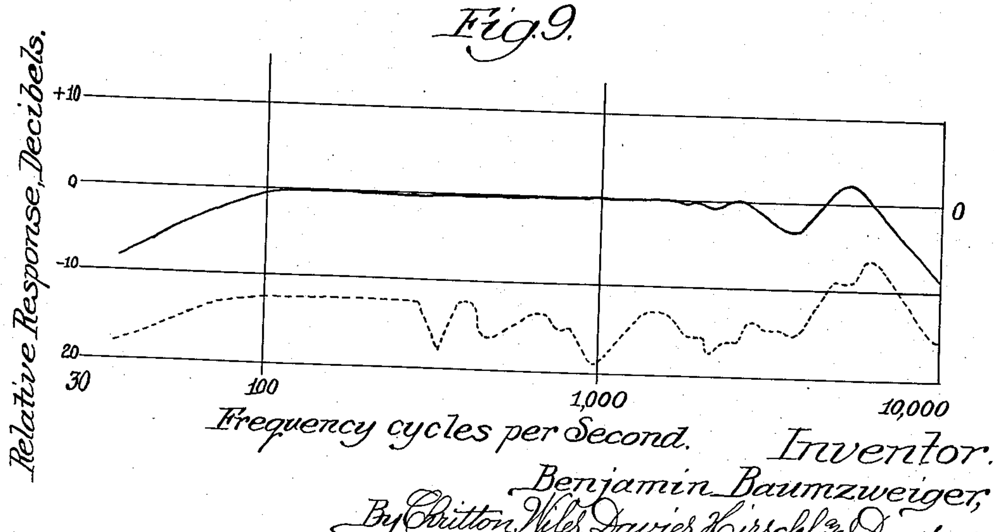

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Fig. 11.

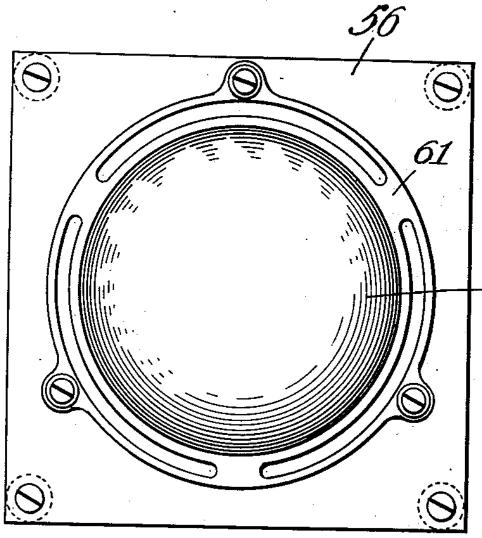


Fig. 10.

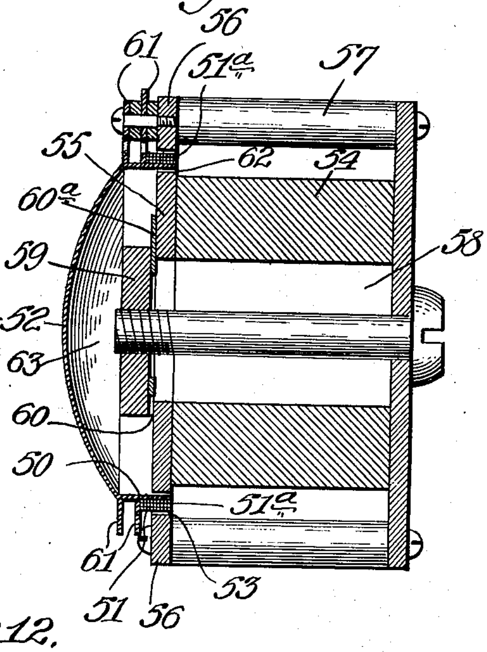
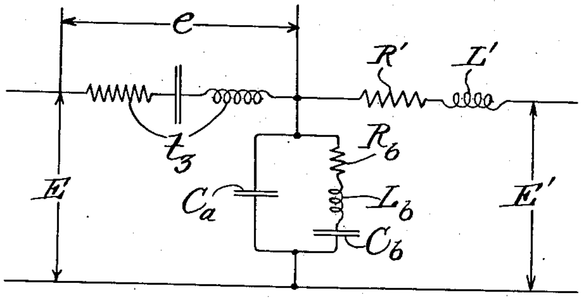


Fig. 12.



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CONVERSION OF WAVE MOTION INTO ELECTRICAL ENERGY

Filed Sept. 29, 1938 4 Sheets-Sheet 4

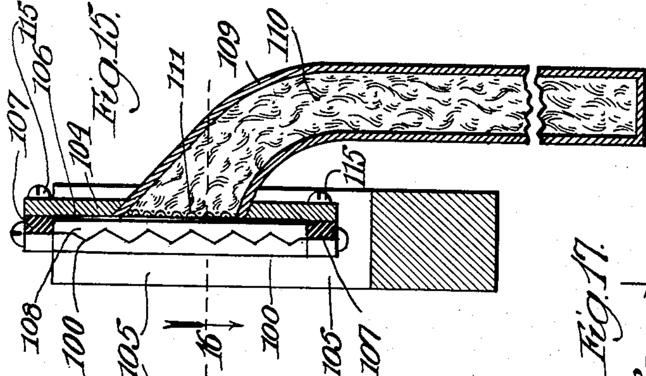
Fig. 15.

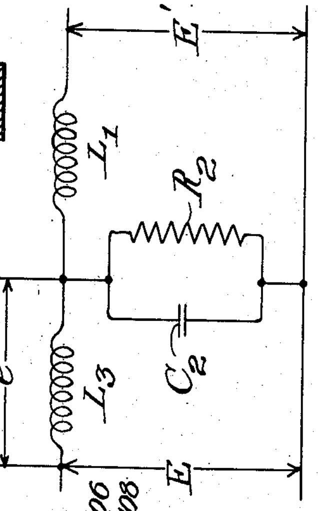
Fig. 17.

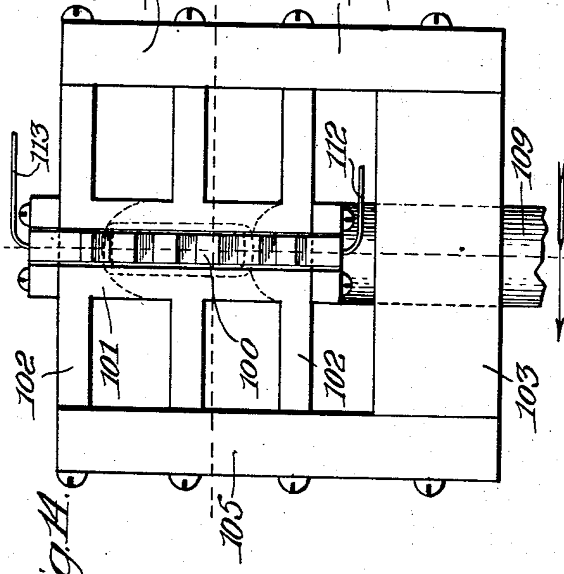
Fig. 14.

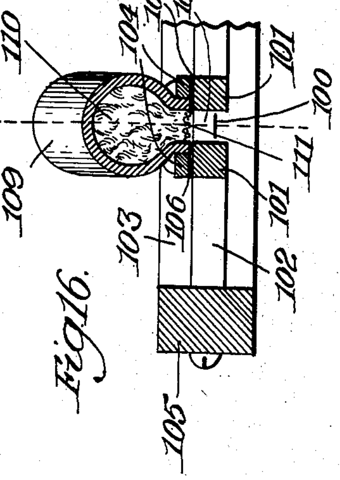
Fig. 16.

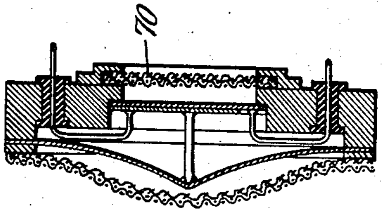
Fig. 13.

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Patented Apr. 8, 1941 **2,237,298**

UNITED STATES PATENT OFFICE

2,237,298

CONVERSION OF WAVE MOTION INTO ELECTRICAL ENERGY

Benjamin Baumzweiger, Chicago, Ill., now by change of name Benjamin B. Bauer, assignor to S. N. Shure and Frances Shure, trustees, doing business as Shure Brothers, a partnership

Application September 29, 1938, Serial No. 232,439

18 Claims. (Cl. 179—1)

This invention relates to apparatus for conversion of wave motion into electrical energy and the converse. More particularly it relates to instruments of unidirectional nature, i. e., in which the instrument is active preferentially in one direction only, throughout an extensive range of frequencies, being relatively inoperative in other directions.

Unidirectional operation has previously been obtained in both the transmitting and receiving transducers through a combination of a unit having a nondirectional (circular) polar sensitivity pattern with one having a bidirectional (cosine-law) polar sensitivity pattern. A combination of two such units causes the resulting polar sensitivity pattern to be unidirectional (cardioid) in shape, and it has been applied extensively in the past to transmitting antennas, microphone apparatus, etc. For this latter application, one of the units is commonly made to operate on the pressure component of the sound wave (pressure transducer) and the other upon the pressure-difference of the sound wave (velocity transducer). Addition or cancellation of the voltages generated in each unit occurs depending upon whether the incidence of sound is from the front (0° incidence) or from the rear (180° incidence) of the instrument. Obviously, the voltages generated by both units for the 180° incidence should be substantially equal and opposite in phase throughout the frequency range in which the cancellation is desired, which because of inherent differences in construction and operating principle is a difficult thing to obtain in microphones operating upon dissimilar components of the sound wave.

One important object of my invention is to provide a unidirectional transducer operating over a wide frequency range and comprising in part two transducing elements operating on the same component of the sound wave, thus doing away with the necessity of subtracting outputs of two transducing elements working on dissimilar components of the sound wave.

Another object is to provide a unidirectional transducer with marked unidirectional properties over the operating range of frequencies.

A further object is to obtain an instrument with unidirectional sensitivity pattern by the action of wave effects at two points in a sound wave, using one transducer element only. Other objects of my invention will become apparent as this specification proceeds.

Figure 1 is a diagrammatic layout of generalized apparatus embodying my invention; Fig. 2, a vector diagram showing the voltage relationships for a zero degree incidence of sound; Fig. 3, a similar view to Fig. 2 but representing the 180° incidence of sound; Fig. 4, a diagrammatic view of a specific embodiment comprehended within the diagram of Fig. 1; Fig. 5, a polar diagram illustrating the directional characteristics of the transducer of Fig. 4; Fig. 6, a diagrammatic and sectional view of a unidirectional crystal microphone; Fig. 7, a rear view in elevation of the same; Fig. 8, an equivalent electrical circuit of the microphone shown in Fig. 6; Fig. 9, a frequency response curve of the microphone shown in Fig. 6, the upper curve showing the front side response and the lower dotted line showing the decrease of response for the rear incidence sound; Fig. 10, a part sectional view of a unidirectional dynamic microphone; Fig. 11, a front view of the same; Fig. 12, a diagrammatic view of the equivalent electrical circuit of the microphone shown in Fig. 10; Fig. 13, a cross-sectional view of the unidirectional crystal microphone equipped with an acoustical resistance formed of cloth; Fig. 14, a front elevation of a unidirectional moving conductor microphone; Fig. 15, a sectional view, the section being taken as indicated at line 15 of Fig. 14; Fig. 16, a sectional view, the section being taken as indicated at line 16 of Fig. 14; and Fig. 17, a diagrammatic view of the equivalent electrical circuit of the microphone shown in Fig. 14.

My invention is principally applicable to production and reception of sound waves in air, although it will become apparent to those skilled in the art that it may be equally applicable to wave phenomena in other media. The transducer element or elements employed may be either of the reversible type, such as piezoelectric crystal, moving coil, moving armature or condenser type, or of the non-reversible type such as, for example, the carbon-type. The theory set forth herein is applicable to receiving apparatus, such as loudspeakers, as well as to transmitting apparatus such as microphones. If transducers of the reversible type are employed, one instrument could serve interchangeably, both as a transmitter and as a receiver.

The nature of my invention is such that it can be best explained by reference to the following equivalent electrical networks and circuit equations. Fig. 1 is a schematic representation of two electroacoustic transducers A and A', generating respectively voltages E and E', and the interconnecting electrical network C. The transducers, which may operate on any function of the sound wave whatsoever, are spaced by an effective acoustical distance *d* which in general should be smaller than, or comparable to, one-quarter wavelength of the highest frequency at which unidirectional action is desired, although it will be shown later that transducers may be constructed having unidirectional properties at frequencies higher than that specified above by virtue of diffraction and other wave effects. C is a generalized network shown in an equivalent

π section, composed of impedances Z_0, Z_1, Z_2, and Z_0', Z_1', and Z_2'. The impedance Z_3 is connected to the receiver B which may be an amplifier or any other receiving device. For simplicity, the internal impedances of the transducers A and A′ are here considered negligible, although if this is not the case the proper internal impedances should be inserted in the network in carrying out the analysis.

The sound wave is considered as a plane wave which may be incident from any angle $\theta°$ from the normal 0° incidence indicated with the corresponding arrow in Fig. 1. The voltage developed by the transducers A and A′ is indicated as E and E′ respectively. Subscripts (θ), (0) and (180) are used to designate voltages developed for any angle of incidence $\theta°$, for normal front (0°) or for the rear (180°) incidence of sound, respectively. The respective voltages generated by the transducers A and A′ will be displaced in phase by an angle given by the equation:

$$\phi_0=\frac{\omega d}{C_v}\cos\theta \qquad \text{(I)}$$

in which

ϕ_θ is the phase angle between the voltages E and E′

ω is the expression $2\pi f$

f is the frequency, cycles per second

θ is the angle of incidence of sound

C_v is the velocity of the sound wave

Applying circuit analysis to the equivalent circuit of Fig. 1, it may be shown that the voltage e delivered to the receiving apparatus, is given by the equation:

$$e=\frac{\left(1+\frac{Z_1'}{Z_2'}\right)E-\left(1+\frac{Z_1}{Z_2}\right)E'}{\frac{Z_1}{Z_3}\left(1+\frac{Z_1'}{Z_2'}\right)+\left(1+\frac{Z_1}{Z_2}\right)\left(1+\frac{Z_1'}{Z_2'}\right)+\frac{Z_1'}{Z_3}\left(1+\frac{Z_1}{Z_2}\right)} \qquad \text{(II)}$$

It may be shown, furthermore, that the voltage drop across any branch in a network composed of linear elements, due to the action of two sources A and B connected at any two points, may always be expressed as the sum of the partial voltage drops due to each source acting alone. Thus, for the network of Fig. 1, the portion of e due to E can be expressed as PE where P is the coefficient of E in Equation II divided by the denominator, and the portion of e due to E′ can be expressed as QE′ where Q is the coefficient of E′ in Equation II divided by the denominator. It is seen therefore that the expression for the voltage delivered to the receiving apparatus can be indicated in the form:

$$e=PE+QE' \qquad \text{(III)}$$

Any expression involving network elements, having the function of P and Q in Equation III, is herein called the network factor.

To obtain unidirectional action, the voltage e_{180} should become zero. Therefore, the condition to be met is:

$$e_{180}=PE_{180}+QE'_{180}=0 \qquad \text{(IV)}$$

and hence the relation between coefficients P and Q should be such that:

$$-\frac{P}{Q}=\frac{E'_{180}}{E_{180}} \qquad \text{(V)}$$

and the nature of the network components is to be chosen to substantially maintain this relation throughout the frequency range in which the unidirectional action is desired.

Equation V is perfectly general and may be applied to any unidirectional transducing system having two generators and in interconnecting network, delivering the translated energy to a receiver. For the particular case of the network of Fig. 1, the values of network factors P and Q specified above may be inserted into, e. g., (V), giving the following relationship to be fulfilled:

$$\frac{1+\frac{Z_1'}{Z_2'}}{1+\frac{Z_1}{Z_2}}=\frac{E'_{180}}{E_{180}} \qquad \text{(VI)}$$

Before describing more specific embodiments of my invention, its operation will be further clarified by the following explanation made in reference to Figs. 2 and 3, which are vector diagrams representing the voltage relations for front and rear incidence of sound upon the instrument of Fig. 1.

For the purpose of explanation, it is assumed that voltages E and E′, generated by the similar generators A and A′, are of unequal magnitudes, although this is not necessarily the case. The voltage E_0 is shown leading the voltage E'_0 through an angle ϕ determined by Equation I, while the voltage E_{180} is shown lagging behind E'_{180} by the same angle, since reversal of the direction of incidence brings about reversal of the relative phase positions of the generated voltages. The network factors P and −Q are shown of the same relative magnitudes and angular position as the rear (180°) incidence voltages E'_{180} and E_{180} respectively, as specified by Equation V.

The 0° (front-incidence) condition is shown in Fig. 2. The voltage E_0 is operated upon the vector P to give the vector PE_0 which is the contribution of the generator A to the total output voltage. The voltage E'_0 is operated upon by vector −Q giving the vector $-QE'_0$ which is the contribution of the generator A′ to the total output voltage. QE'_0 is added to PE_0 giving the resultant output voltage e_0.

The (180°) rear incidence condition is shown in Fig. 3. The voltage E_{180} is operated upon by the vector P giving the vector PE_{180} which is the contribution of the generator A to the total output voltage. The voltage E'_{180} is operated upon by the vector −Q giving the vector $-QE'_{180}$ which is the contribution of the generator A′ to the total output voltage. It should be noticed that for the rear incidence condition, the voltages PE_{180} and QE'_{180} are out of phase and of equal magnitude, and hence when the latter is added to the former, the resulting total output voltage is zero.

A specific example of network selection will be given in reference to Fig. 4. This network is the same as that of Fig. 1, with the following element values:

$$\left.\begin{aligned}Z_0&=\infty\\ Z'_0&=\infty\\ Z_1&=R+j\omega L\\ Z_2&=\frac{1}{j\omega C}\\ Z'_1&=R'+j\omega L'\\ Z'_2&=\frac{1}{j\omega C'}\end{aligned}\right\} \qquad \text{(VII)}$$

It will be assumed here that the voltages E and E' are two vectors of equal magnitude and displaced by an angle ϕ whose value is determined from Equation I, their ratio being therefore equal to a unit vector at the angle ϕ. Substituting this value of angle into the right hand side of Equation VI, and that of the network elements of (VII) into the left hand side of Equation VI, it is evident that the desired relationship is:

$$\frac{1-\omega^2L'C'+j\omega C'R'}{1-\omega^2LC+j\omega CR}=\left|\underline{\frac{\omega d}{C_v}}\right. \qquad \text{(VIII)}$$

The left hand member of the Equation VIII represents a quotient of two vectors, each of which may be made very nearly a vector operating at an angle proportional to frequency, if the relationship between resistance, inductance and capacitance is such that:

$$L=\frac{CR^2}{2} \text{ and } L'=\frac{C'R'^2}{2} \qquad \text{(IX)}$$

since substituting these values into Equation IX gives the following relation:

$$\left|\underline{\frac{\omega d}{C_v}}\right.=\frac{1-\frac{\omega^2C'^2R'^2}{2}+j\omega C'R'}{1-\frac{\omega^2C^2R^2}{2}+j\omega CR} \qquad \text{(X)}$$

It should be observed that the numerator and the denominator of Equation X are the major terms of the expansion for the cosine and the sine functions: hence, as long as:

$$\omega C'R'<<1 \text{ and } \omega CR<<1 \qquad \text{(XI)}$$

The Equation X may be rewritten

$$\left|\underline{\frac{\omega d}{C_v}}\right.=\frac{\cos \omega C'R'+j \sin \omega C'R'}{\cos \omega CR+j \sin \omega CR}=$$
$$\cos \omega(R'C'-CR)+j \sin \omega(C'R'-CR)=$$
$$\left|\underline{\omega(C'R'-CR)}\right. \qquad \text{(XII)}$$

The frequency term ω drops out of this equation, and therefore the condition for unidirectivity will be obtained if

$$\frac{d}{C_v}=R'C'-RC \qquad \text{(XIII)}$$

The distance d and the velocity of sound C_v being known, R, R', C, and C' may be selected by the use of Equation XIII. Then values of L and L' may be computed from Equation IX. Since the Equation XII holds as long as the expressions (XI) are true, then by choice of sufficiently small distance d, unidirectional action may be obtained throughout a wide range of frequencies. I have found that Equation XII is valid up to frequencies at which d is not larger than one-quarter the wavelength of sound; thus, if d is equal to approximately 1.5 cm., undirectional action is obtained for all frequencies up to approximately 5,000 cycles per second.

The type of polar directivity pattern obtained with the use of my invention depends upon the operational principle of the transducers A and A'. This may be shown by solving the Equation V for Q and substituting into Equation III, which gives:

$$e=P\left(E-\frac{E_{180}}{E'_{180}}E'\right)=PE'\left(\frac{E}{E'}-\frac{E_{180}}{E'_{180}}\right) \qquad \text{(XIV)}$$

Since A and A' are similar generators, the ratio of voltages E and E' will be a vector K having constant magnitude and acting at the angle ϕ_θ; therefore, the ratio of E_{180} and E'_{180} will be a vector K at an angle ϕ_{180}; therefore:

$$e=PE'(K\left|\underline{\phi_\theta}\right.-K\left|\underline{\phi_{180}}\right.)=PE'K(\left|\underline{\phi_\theta}\right.-\left|\underline{\phi_{180}}\right.) \qquad \text{(XV)}$$

The expression in parenthesis of Equation XV, at frequencies for which d is small compared to one-quarter wavelength of sound, may be shown to approximately equal the algebraic sum of the angles ϕ_θ and ϕ_{180}. Substituting the values of these angles given by Equation I,

$$e=PE'K\frac{\omega d}{C_v}(1+\cos \theta) \qquad \text{(XVI)}$$

If the character of the transducers A and A' is such that the voltage generated is independent of the incidence of sound (pressure-operated or non-directional transducers), the polar characteristic of the combination will be a cardioid of revolution expressed by the quantity in parenthesis in Equation XVI. This polar characteristic is shown graphically in solid line in Fig. 5.

If the voltage E and E' varies as the cosine of the angle of incidence, which will occur if transducers are of the bidirectional or "velocity-type," then $E'=E'_0 \cos \theta$ and:

$$e=PE'_0K\frac{\omega d}{C_v}[\cos \theta(1+\cos \theta)] \qquad \text{(XVII)}$$

The quantity in brackets of Equation XVI represents the polar characteristic shown graphically in dotted line in Fig. 5. It is seen, therefore, that combining two velocity-type transducers and the network described results in an electroacoustic transducing instrument of very marked unidirectional properties. It will be observed that my invention may make use of any two transducers operating on the same wave function, even if their transducing principles were dissimilar.

Instead of providing the electrical network directly at the output of the transducers, it is possible to first amplify these outputs with two independent amplifiers and combine the outputs after the amplification. This procedure would be considered of the nature of an equivalent.

Instead of employing two transducers and an electrical network to obtain unidirectional operation, my invention makes such operation possible through modifying wave disturbances at two points in space by means of equivalent acoustical networks and impressing these disturbances upon one electroacoustical transducer. An embodiment of my invention employing this alternative is shown in cross section and rear elevation in Figs. 6 and 7. The transducer assembly consists of a diaphragm **22** suitably supported in a casing **23** which also contains the piezoelectric crystal **24**. The forces developed by sound phessure at the diaphragm are transmitted to the crystal by means of a connecting member **25**, and the electrical energy developed therein is received from the crystal by means of conductors **47** and **48**. The front side of the diaphragm is provided with an acoustical damping screen **26** constituted of a suitable wire-screen support having one or more thicknesses of cloth forming acoustical resistance and inertance. Between the diaphragm **22** and screen **26**, there is a cavity **27** having an acoustical compliance C.

The casing **23** has a circular opening **28** which serves as a housing for the piezoelectric crystal and also forms part of the acoustical network. The housing **23**, the back plate **29**, and the diaphragm **22** provide a cavity **40**. At the rear side of the case by means of screws **41** is held a cover **29** provided with ridge **30**, the proper spacing being obtained by adjustment against compression of spring **42**. Thus, a narrow passage **31** is formed, having acoustical resistance and an inertance. P denotes the sound pressure at the outside of the damping screen; P′ denotes the sound pressure at the outside of the passage **31**. The effective acoustical path between these pressures is called *d*. I have found that, at frequencies of sound for which the diameter of the casing **23** is smaller than one-half wave-length, the pressures P and P′ are essentially equal and separated by a phase angle given by Equation I.

The equivalent electrical circuit of the transducer and its associated acoustical network appears in Fig. 8 in which R and L, and R′ and L′ are the acoustical resistances and inertances of the screen **26** and the passage **31**, respectively; C and C′ are acoustical compliances of the cavities **27** and **40** respectively. Z_3 is the impedance of the transducer element itself. As a simplifying assumption, the impedance Z_3 is considered as formed by the capacitance C_3 corresponding to the stiffness of the crystal **24**, and the reactions of the medium are neglected. The voltage *e* developed across Z_3 represents the resultant pressure upon the piezoelectric crystal. It may be observed that this equivalent circuit is entirely identical with that of Fig. 4, and therefore all of the equations derived previously may be applied to it. Thence, the acoustic capacitance, resistance and inertance terms are selected in reference to Equations IX and XIII to provide the unidirectional action desired. The terms R, L, and C due to screen **26** and cavity **27** are small compared with terms R′, L′ and C′ due to passage **31** and cavity **40**, hence the last term of the right hand side of Equation XIII will not have a great bearing upon the unidirectional action of the microphone. I have found that in some cases it is convenient to leave the damping screen **26** out altogether, and when this is done the constants R′ and C′ of the Equation XIII have to be readjusted slightly to compensate for disappearance of the last term. I have found that in a microphone with the casing **23** having a diameter of 6 cm. and the cavity **40** having a volume of 8 cc., the effective distance *d′* is 3.5 cm. and satisfactory operation is obtained when the passage **31** has a circumferential length of 10 cm., a radial length of 0.1 cm. and a thickness of 0.01 cm. These dimensions give an approximate acoustic capacitance C′ or 5.7×10^{-6} cm.^{5} per dyne and an approximate acoustic resistance of R′ of 18 acoustical ohms. Since C′, R′ and *d′* are not calculable with good degree of accuracy in terms of the physical dimensions of the instrument, I prefer to calculate the approximate dimensions for these terms, and obtain the final values by adjusting the thickness of the passage **31** by means of the screw **41** until correct unidirectional action is obtained. Obviously an alternative procedure would be to adjust instead the volume of the cavity **40** or the length of the distance *d* which could be done by provisions for adjustably altering the size of the case **23**.

Instead of obtaining resistance R′ by means of the passage **31**, it is possible to substitute the cover **29** with a suitable foraminous supporting member such as a wire-screen disc having a number of thicknesses of cloth or felt or similar porous material attached to it, completely covering the opening **28**, as shown more clearly in Fig. 13. The cloth illustrated is designated by the numeral **70**. Fig. 13 is similar to Fig. 6 except as to the use of the cloth screen **70** in place of the narrow passage **31**. By a suitable choice of the thickness and porosity of the material employed, the proper value of acoustic impedance may be obtained. Sometimes it is difficult to select a material having the exact ratio of resistance to inertance specified in Equation IX; however, it is seen from Equation X that the squared terms are second-order terms in expansion for cosine function, and therefore the exact relationship between the inertance term L′ and the resistance and capacitance terms R′ and C′ is not a vital one in obtaining the unidirectional operation of the instrument at low frequencies, and reasonable departure therefrom will affect the unidirectional action but slightly. The important adjustment, however, is the one between the terms expressed in Equation XIII.

I have mentioned previously that the Equation XII is valid up to frequencies at which *d* is not larger than approximately one-quarter wavelength of sound. This corresponds, for the instrument of Fig. 6, to a frequency of approximately 2500 cycles per second. It should not be assumed, however, that above said frequency the unidirectional action ceases, because above 2500 cycles per second, the instrument tends to become highly unidirectional in favor of sounds arriving from the front because of diffraction and the so-called "baffle-effect" due to the size of the case **23**. The unidirectional action is therefore obtained essentially throughout all of the important frequency range.

I have found that when a plane wave of constant intensity and varying frequency is impressed upon the front side of the instrument of Fig. 6, the resulting alternating force upon the crystal **24** is approximately proportional to frequency up to the frequency at which one-quarter wavelength equals the effective distance *d′*, becoming approximately independent of frequency for frequencies at which one-quarter wavelength is larger than the effective distance *d′*. Since the voltage developed in a crystal is proportional to the force applied, I found it useful to provide a compensating electrical network which would deliver an output voltage substantially independent of frequency at the receiving apparatus. This network consists of a parallel combination of a condenser **45** and a resistance **44**, both in series with a larger condenser **46**; said network is connected across the terminals **47** and **48** of the crystal, the receiver **49** being connected across the larger condenser.

Fig. 9 shows the frequency response obtained with this microphone and electrical network for plane wave incident upon the front (upper curve) and the rear (lower curve) of the instrument, indicating the type of discrimination obtained at all frequencies. The polar directivity pattern is a cardioid shown in solid lines in Fig. 5.

It may be found convenient in many instances to provide the desired electrical compensation in the receiver **49**. For applications in which it is desired to give predominance to higher frequencies of sound, the compensating network may be entirely dispensed with.

Another embodiment of my invention is shown in the part sectional elevation in Fig. 10 and front elevation in Fig. 11. A moving coil consisting of a circular bobbin **50** having a winding **51** and a dome-shaped diaphragm or cover **52** is arranged to move in an air gap **53** of a magnetic structure, thereby transforming its mechanical motions into electrical energy which is received from the winding **51** by means of conductors 51ª. The magnetic structure consists of a cylindrical permanent magnet 54 provided at one pole with an internal circular pole piece 55, and having an external pole piece 56 connected to the other pole of the magnet by means of several connecting rods 57 which provide enough cross sectional area to conduct the magnetic flux, and do not appreciably interfere at the same time with the free access of the sound waves to the inner pole shoe 55. Associated with the magnetic structure, however not performing flux carrying functions, is a circular plate 59 which defines the cylindrical chamber 58 and also by means of shims 60ª forms a narrow passage 60 which establishes communication between this chamber and the volume within the moving coil.

The coil is suspended on a suitable elastic suspension 61 which permits axial motions in the air gap. The external diameter of the inner pole piece 55 is slightly smaller than the internal diameter of the bobbin, thus forming a narrow passage 62 leading into the cavity 63 which is defined by the moving coil. The stiffness of the suspension 61 is low so that the coil assembly is resonated at a low frequency, preferably in the neighborhood of 60 cycles per second. The resonant effect is not very pronounced, however, because of the damping resulting from motion of air in the passage 62.

The equivalent electrical circuit of the instrument placed in a sound wave is given in Fig. 12. E is the equivalent of sound pressure upon the front of the diaphragm 52. E′ is the equivalent of the pressure of the sound wave at the passage 62; Z_3 is acoutical impedance of the coil and its suspension; R′ and L′, the resistance and inertance terms of the passage 62; C_a is the acoustic compliance of the cavity 63; R_b and L_b, the acoustic impedance of the passage 60; C_b, the acoustical compliance of the chamber 58; as in the preceding embodiment, the reactions of the medium are neglected. The effective acoustical distance between the pressures E and E′ will be called *d*, and for frequencies at which this distance is less than a quarter wavelength of sound, E and E′ may be considered equal in magnitude and displaced by an angle ϕ given in Equation I.

Comparing structures illustrated in Fig. 6 and Fig. 10, it will be noticed that the latter is similar to the former with the screen 26 removed, since the impedance of the narrow passage 31 in Fig. 6 corresponds to that of the passage 62 in Fig. 10, and the compliance of the cavity 40 in Fig. 6 corresponds to the total compliance of the cavities 58 and 63 in Fig. 10. This similarity may be further seen by comparing the equivalent circuits of Fig. 8 and Fig. 12, the former with the impedances R, L. and C (corresponding to the damping screen 26 and cavity 27 in Fig. 6) removed. Comparing these equivalent circuits, the series impedances R′ and L′ of Fig. 8 correspond with the impedances of the same calling in Fig. 12, and the capacity C′ of Fig. 8 corresponds to the total capacity of the condensers C_a and C_b in Fig. 12. Therefore Equation XIII may be used to determine the correct proportion between the resistance and compliance units in the structure of Fig. 10, the last term of the right hand member of the equation being set equal to zero since the front screen is not used in this embodiment. However, in the moving coil structure of Fig. 10, it is not feasible to make the passage 62 narrow enough to obtain the correct ratio between resistance and inertance as expressed in Equation IX and this would affect adversely the unidirectional properties of the microphone in the middle range of audio frequencies. I have found that by subdividing the compliance element into two approximately equal parts shown as C_a and C_b interconnected by a series impedance having a resistance value R_b approximately three times the value of R′ and an inertance value L_b approximately equal to L′, the unidirectivity Equation VI is very closely satisfied throughout substantially all of the audio-frequency range.

I have found that in a microphone as illustrated in Fig. 10 having an external pole piece 56 approximately 3.8 cm. square and a moving coil approximately 2.8 cm. in diameter, the equivalent front-to-back distance *d* is approximately 2.5 cm., and with a total volume of cavities 58 and 63 of 6 cc. correct operation is obtained if the passage 62 has an axial length of 0.16 cm. and a thickness of 0.013 cm., and the passage 60 has a circumferential length of 4.5 cm., a radial length of 0.16 cm. and a thickness of 0.007 cm. These dimensions give an approximate acoustic value of C_a and C_b of 2.1×10^{-6} cm.^{5} per dyne each, R′ and R_b of 17.3 and 50 acoustical ohms, respectively, L′ and L_b of .0015 gram per cm.^{4}. These terms are not calulable with high degree of accuracy and minor adjustments are required to obtain satisfactory operation which is similar to that indicated by the performance curves of Fig. 9. It will be understood that through judicious application of previously given theory and equations, the above dimensions may be considerably altered without departing from the scope of my invention.

A still further embodiment of my invention employing a moving conductor as a transducing element is shown in front elevation in Fig. 14. The voltage generating element is a light metallic conductor or ribbon 100 which may be corrugated to increase its flexibility, supported at its two ends on insulating supporting members 107 and adapted to move between pole pieces 101 of a magnetic structure and convert these motions into electrical energy which is received by means of conductors 112 and 113. The ribbon is almost as wide as the space between the pole pieces, being separated therefrom only enough to move freely therebetween. Figs. 15 and 16 which are cross sectional views of the instrument along the lines 15 and 16 in Fig. 14, respectively, show that the pole pieces 101 and the ribbon 100 form a cavity 108 which is inclosed at the rear by a plate 104 suitably attached to the supporting member 107 by means of screws 115. The cavity 108 is in communication with the exterior by means of passages 106 formed between the pole pieces 101 and the back plate 104, the width of said passages being determined by suitably adjusting the position of the supporting members 107 behind the pole pieces 101. The passages 106 have such proportions as to constitute essentially an acoustical mass element. The cavity 108 is provided with a parallel dissipative element formed by a pipe or conduit 109 of suitable cross section and length fitted at the near end into the back plate 104 and closed at the far end. The conduit is filled with dissipative material 110, such as loosely packed felt, wool, or cotton, which is retained at the near end with a wire screen 111 or similar foraminous retaining member. It will be evident, however, that other suitable means may be used to produce the parallel resistance effect. The sound pressure at the front or exposed part of the ribbon will be called P and that at the entrance of the passage 106 will be called P′.

The effective acoustical distance between these pressures will be called *d*.

The equivalent electrical circuit of this microphone is shown in Fig. 17. E and E′ represent the sound pressures P and P′ respectively, L_0 represents the acoustical impedance of the ribbon which is assumed to be a mass, and *e* is the force developed across the ribbon due to E and E′, L_1 is the mass of the passage 106, C_2 is the compliance of the cavity 108, and R_2 is the resistance of the conduit 109.

Equation II may be applied to this circuit by substituting the appropriate value of the impedances. Following a reasoning similar to that employed with Equations IX to XII, it may be shown that unidirectional action is obtained if

$$C_2=\frac{L_1}{2R_2^2} \qquad \text{(XVIII)}$$

and, in addition,

$$\frac{d}{C_v}=\frac{L_1}{R_2}\ \cdots \qquad \text{(XIX)}$$

I have found that in a microphone of this description having an equivalent front-to-back distance *d* of 2 cm. satisfactory operation is obtained if the volume of the cavity 108 is 1.2 cm., total length of the slit 106 is 10 cm., its transverse width 0.8 cm., and its thickness 0.06 cm., and the conduit 109 has an approximate cross sectional area of 1.25 sq. cm. and a length of several feet, being filled with loosely packed lambs' wool. This corresponds to the following constants in the equivalent circuit of Fig. 17: capacitance C_2, 0.85×10^{-6} microfarads; inductance L_1, .002 henry; resistance R_2, 34 ohms. These constants may be considerably altered within the range of validity of Equations XVIII and XIX without departing from the spirit of my invention.

I claim:

1. In a unidirectional electroacoustic transducer operating in a medium, means having two pressure-sensitive surfaces adapted to vibrate and translate its vibrations into electrical energy, one of said surfaces being substantially exposed to the medium, a structure forming a cavity in conjunction with the second of said surfaces, a passage defining acoustical resistance and inertance establishing communication between said cavity and the medium and located at such distance from said exposed surface that the ratio of said distance to the wave velocity in the medium substantially equals the product of acoustical compliance of said cavity and resistance of said passage in any consistent system of units.

2. In an electroacoustic transducer operating in an elastic medium, means having pressure-sensitive sides adapted to vibrate and translate its vibrations into electrical energy, a structure including phase-shifting acoustical network elements providing unequal access of the sound pressures to said sides and establishing cooperatively with said means an equivalent acoustical distance, one of said sound pressures undergoing a phase shift, due to the action of said network, substantially equal to the angle between the pressures in a wave traveling said distance in the medium itself throughout a range of frequencies.

3. In a microphone, means adapted to be acted upon by direct sound waves and by waves the phase of which has been shifted, an acoustical phase-shifting network having an inlet spaced from said first-mentioned means, said network shifting the phase of sound pressure at its inlet through an angle proportional to frequency, and means cooperating with said first-mentioned means for translating the effects of said direct sound waves and said phase-shifted sound waves into electrical energy.

4. In a microphone, means having two pressure-sensitive surfaces adapted to vibrate and translate vibrations into electrical energy, one of said surfaces being substantially exposed to the transmitting medium, a structure forming a cavity providing acoustical compliance in conjunction with the other of said surfaces and having sound permeable means communicating with the external medium, said second means defining acoustical resistance and inertance, said compliance, resistance and inertance having their relationship in such proportion that the ratio of sound pressure in the medium at said passage to the sound pressure developed in said cavity is a vector substantially proportional to frequency throughout a range of audio frequencies.

5. In an electroacoustic transducer, a member having two pressure sensitive surfaces adapted to vibrate and translate vibrations into electrical energy, one of said surfaces being substantially exposed to the medium, a structure forming a cavity in conjunction with the other of said surfaces, and a sound permeable means defining acoustical resistance and reactance establishing communication between said cavity and the medium at an effective acoustical distance from said exposed surface of approximately one-quarter wavelength of a frequency within the upper range to be translated, the acoustical resistance and reactance of said sound permeable means being so selected in respect to the volume of said cavity and said acoustical distance that the transducer is notably more sensitive in the direction facing said exposed surface than in all other directions.

6. In a sound translating device, a moving body adapted to vibrate and convert its vibrations into electrical variations, a casing supporting said body and having a cavity, said body forming one of the walls of the cavity, and communicating means between said cavity and the atmosphere, said means defining principally acoustical resistance and adapted in conjunction with said cavity to shift the phase of sound at all wavelengths substantially larger than the dimensions of said casing.

7. In a microphone, a moving body adapted to vibrate and translate its vibrations into electrical variations, a casing supporting said body and having a cavity, said body forming one of the walls of the cavity, and substantially direct communicating means between said cavity and the atmosphere, said means comprising a supporting member and a porous material defining principally acoustical resistance secured thereon.

8. In a microphone, vibratory means having two pressure-sensitive surfaces and comprising in part a piezo-electric crystal, one of said surfaces being exposed to the atmosphere, a casing supporting said means and having a cavity, said means being adjacent to said cavity, and substantially direct communicating means between said cavity and the atmosphere, said communicating means defining acoustical impedance and adapted in conjunction with said cavity to shift the phase of sound at all wavelengths substantially greater than the dimensions of said casing.

9. In a transducer, a diaphragm adapted to vibrate and convert its vibrations into electrical variations, one of the sides of said diaphragm be-

ing substantially exposed to the atmosphere, a casing supporting said diaphragm and having a cavity, said diaphragm forming one of the walls of the cavity, and communicating means providing acoustical impedance between said cavity and the atmosphere, said means comprising a passage, dissipative means associated with the passage, and means for adjusting the impedance by variation of the dimensions of the passage.

10. In a transducer, a moving body having two pressure-sensitive sides, one of which is substantially exposed to the atmosphere, adapted to vibrate and convert its vibrations into electrical variations, a casing supporting said body and having a cavity, and substantially direct communicating means providing acoustical impedance between said cavity and the atmosphere, said means comprising a passage, dissipative means associated with said passage, and means for adjusting said impedance.

11. A sound translating device comprising vibratory means having two pressure-sensitive surfaces and adapted to translate its motions into electrical energy, a casing supporting said means and having a cavity in conjunction with one of the surfaces of said vibratory means, a passage comprising acoustical resistance and intertance leading into a second cavity and substantially direct communicating means between said first cavity and the atmosphere, said communicating means defining acoustical resistance and inertance, said passages being adapted in conjunction with said cavities to shift the phase of sound pressure at all wavelengths of sound substantially larger than the dimensions of said casing.

12. A sound translating device comprising vibratory means adapted to translate its axial motions into electrical energy and having two pressure-sensitive surfaces, a casing supporting said vibratory means and having a cavity, one of the surfaces of said vibratory means being enclosed by said cavity and the other surfaces being substantially exposed to the atmosphere, a passage comprising acoustical impedance leading from said first cavity into a second cavity and substantially direct communicating means between said first cavity and the atmosphere, said means defining acoustical impedance, the axially projected area of the exposed surface of said vibratory means being substantially equal to the axially projected area of the enclosed surface of said means.

13. In a method of obtaining unidirectional operation in a single unit electroacoustic transducer having two pressure-sensitive surfaces and an enclosure incorporating adjustable sound permeable means defining acoustical impedance and enclosing one of said surfaces, the step of adjustably varying said sound permeable means to the impedance value at which said transducer is most sensitive to sounds arriving from one direction.

14. In a method of obtaining unidirectional operation in a single unit electroacoustic transducer having two pressure-sensitive surfaces and an enclosure incorporating an outlet to sound adapted to support an impedance forming means of porous material associated with said outlet, the step of selecting said impedance material providing an impedance at which said transducer is most sensitive to sounds arriving from one direction.

15. In a microphone, vibratory means having two pressure-sensitive surfaces and comprising in part a piezo-electric crystal, one of said surfaces being substantially exposed to the atmosphere, a casing supporting said means and having a cavity, the vibratory means being adjacent to said cavity, and substantially direct communicating means comprising a passage having acoustical impedance connecting said cavity and the atmosphere, and means for adjusting said impedance.

16. In a microphone, a diaphragm, a coil attached thereto, a magnetic structure having an air-gap in which said coil may vibrate, said diaphragm partially enclosing a cavity interconnected with a second cavity, said first cavity having a substantially direct passage to the atmosphere, the outlet of said passage being located at a distance from said diaphragm of from 1 to 5 cm.

17. In a sound translating device, means having two pressure-sensitive surfaces adapted to vibrate and translate its vibrations into electrical energy, one of said surfaces being exposed to the atmosphere, a casing supporting said means and having a cavity, said means being adjacent to said cavity, and substantially direct communicating means between said cavity and the atmosphere, said communicating means defining acoustical impedance and adapted in conjunction with said cavity to shift the phase of sound at all wavelengths substantially greater than the dimensions of said casing.

18. In a microphone, vibratory means having two pressure-sensitive surfaces and comprising in part a piezoelectric crystal, one of said surfaces being substantially exposed to the atmosphere, a casing supporting said means and having a cavity, said means being adjacent to said cavity, and substantially direct communicating means between said cavity and the atmosphere, said communicating means comprising a supporting member and a porous material defining principally acoustical resistance secured thereon and adapted in conjunction with said cavity to shift the phase of sound at all wavelengths substantially greater than the dimensions of said casing.

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