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2,387,845

ELECTROACOUSTIC TRANSDUCER

Filed June 24, 1943

FIG. 1

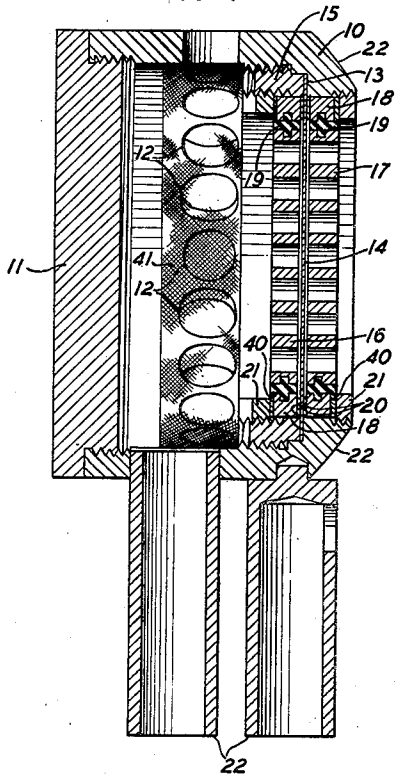


FIG. 3

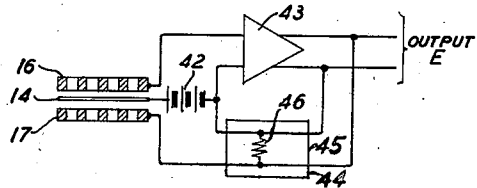


FIG. 4

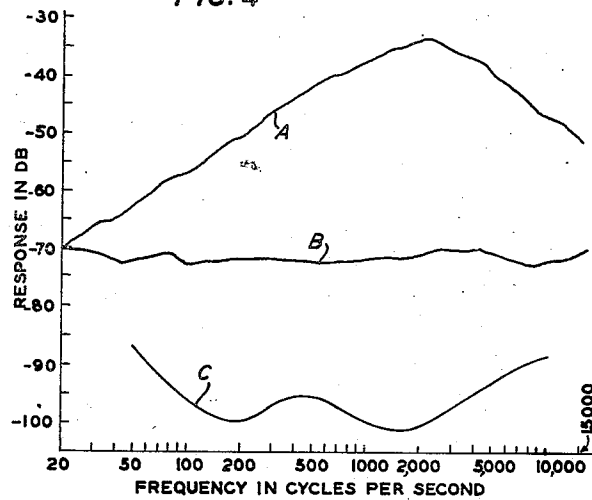
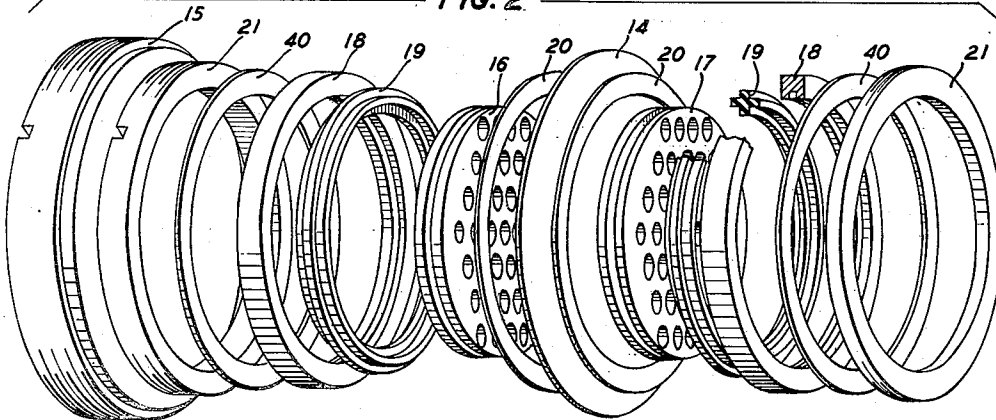


FIG. 2



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ELECTROACOUSTIC TRANSDUCER

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9 Claims. (Cl. 179-1)

This invention relates to electroacoustic transducers and, more particularly, to condenser microphones designed to have a preassigned directional characteristic, for example, a cardioid response pattern.

Basically, a microphone element comprises a diaphragm and means in cooperative relation therewith for translating vibrations of the diaphragm in accordance with sound waves effective upon the diaphragm into electrical variations corresponding to the diaphragm vibrations. In a microphone designed to have a prescribed, e. g. cardioid, directional pattern, both faces of the diaphragm are in communication with the atmosphere and means are provided for producing a phase shift between the two forces due to sound waves, applied to opposite faces of the diaphragm, whereby the output of the microphone is dependent upon the angle of incidence of sound waves thereon throughout a band of frequencies.

The diaphragm, of course, has a mechanical impedance which includes substantial reactance and, therefore, varies with frequency. Hence, generally speaking, the output of the microphone, in the absence of controls for the diaphragm motion, also varies with frequency. Furthermore, in directional, e. g. cardioid, microphones the phase shift introduced between the forces acting upon opposite faces of the diaphragm varies with frequency so that the resultant force effective upon the diaphragm, and hence the response, are dependent, in the absence of controls, upon frequency.

One general object of this invention is to improve the operating characteristics of electroacoustic transducers.

More specifically, one object of this invention is to increase the fidelity of translation of sound into electrical variations by a microphone.

Another object of the invention is to obtain a substantially uniform response throughout a wide range of frequencies for a microphone having a cardioid directional pattern.

A further object of this invention is to realize, in a cardioid microphone, substantially uniform directional discrimination throughout a wide range of frequencies.

Still another object of this invention is to obtain a high signal-to-noise ratio in a translating system including a microphone and an amplifier connected to the microphone.

A still further object of this invention is to segregate substantially completely, in a transducer comprising a microphone and an amplifier, a portion of the output of which is fed back to the

microphone to control the diaphragm motion, the fed back energy from the output side of the microphone.

In one illustrative embodiment of this invention, an electroacoustic transducer comprises a condenser microphone element including a diaphragm and a fixed electrode adjacent one face of the diaphragm, and a housing defining with the diaphragm a chamber adjacent the rear face of the diaphragm, the housing being provided with apertures covered with acoustic resistance material by way of which the rear face of the diaphragm is in communication with the atmosphere. The diaphragm and electrode are connected to the input of an amplifier having a substantially constant gain throughout the operating frequency range of the microphone element.

In accordance with one feature of this invention, the diaphragm motion is controlled by applying thereto a force proportional to the acoustic force effective upon the diaphragm and in opposition to the acoustic force throughout the operating frequency range.

More specifically, in accordance with one feature of this invention, the microphone element, amplifier and an electrical network connected between the output of the amplifier and the element are correlated to constitute a stabilized negative feedback system and the network is constructed so that the energy fed back to the element controls the diaphragm motion to maintain the ratio of the system output to the acoustic pressure of the sound field substantially constant throughout a wide range of frequencies. For example, in a microphone having a cardioid directive pattern, the parameters of the housing, chamber and apertures covered with acoustic resistance material are correlated so that the phase shift due thereto between the acoustic forces acting on opposite faces of the diaphragm is proportional to frequency and the feedback impedance is constructed so that its transmission characteristic likewise is proportional to frequency.

In accordance with another feature of this invention, the force due to feedback, applied to the diaphragm is applied by way of an auxiliary electrode opposite the other face of the diaphragm, that is, the face remote from the output electrode, and the diaphragm is made metallic whereby it constitutes an electrostatic shield between the output and auxiliary electrodes and substantially complete segregation of the output and feedback energies is realized.

The invention and the above-noted and other features thereof will be understood more clearly

and fully from the following detailed description with reference to the accompanying drawing in which:

Fig. 1 is a view in section of a microphone illustrative of one embodiment of this invention;

Fig. 2 is an exploded perspective view showing details of the diaphragm, electrode and support assembly in the device illustrated in Fig. 1;

Fig. 3 is a block circuit diagram illustrating the association of the microphone, the amplifier and the feedback network; and

Fig. 4 is a graph showing typical response-frequency characteristics of a microphone constructed in accordance with this invention.

Referring now to the drawing, the microphone illustrated in Figs. 1 and 2 comprises a circular housing 10 the base 11 of which is imperforate and the side wall of which is provided with a series of similar, equally spaced apertures 12. The housing is provided with an internal shoulder 13 against which a thin, circular, tensioned metallic diaphragm 14, for example of .00025 inch duralumin, is secured by a clamping ring 15.

Adjacent opposite faces of the diaphragm 14 are two similar, perforated metallic members 16 and 17 which are mounted from rings 18, for example of metal, by insulating, for example polystyrene, supports 19, the two rings 18 being spaced from the diaphragm 14 by washers 20 of such thickness as to establish predetermined substantially equal spacings between the diaphragm and the perforated members 16 and 17. These two members together with the supports 19 and rings 18 associated therewith are secured in position by clamping members 21 one of which is threaded to the casing 10 and the other of which is threaded to the clamping ring 15 as shown, suitable washers 40 being provided between the diaphragm and members 21. The clamping members 21 are utilized to tension the diaphragm and thereby tune it to a predetermined frequency.

The diaphragm 14 and metallic members 16 and 17 constitute electrodes of a condenser the electrode 16 serving as the output electrode. The electrodes 16 and 17 are biased at the same potential with respect to the diaphragm 14, as by a source 42 connected thereto by conductors, not shown, extending through conductive tubes 22 secured to the casing 10. Conveniently, the diaphragm, which is electrically connected to the casing, may be biased at a positive potential with respect to the electrodes 16 and 17.

The apertures 12 in the housing 10 are covered with an acoustic resistance material 41, such as acoustic silk, and together with the chamber bounded by the diaphragm and the housing constitute an acoustic network.

As illustrated in Fig. 3, the output of the microphone, that is, the voltage appearing between the diaphragm 14 and the output electrode 16, is supplied to an amplifier 43 constructed, in ways known in the art, to have a substantially constant transmission characteristic throughout the range of frequencies to be translated. A portion of the output of the amplifier 43 is fed back to the microphone by way of a network 44, to impress a potential, related to the amplifier output in the manner described hereinafter, between the auxiliary electrode 17 and the diaphragm 14. The network 44, in the specific system illustrated in Fig. 3, comprises a series condenser 45 and a shunt resistance 46.

The parameters of the microphone element 14, 16, 17, the amplifier 43 and network 44 are cor-

related in accordance with general principles known in the art (see, for example, the article, "Stabilized Feedback Amplifiers" by H. S. Black in *The Bell System Technical Journal*, January, 1934, page 1), so that these elements constitute a stabilized feedback system.

As is apparent, in the microphone illustrated in Fig. 1, the diaphragm is subjected to two forces due to sound waves, one due to sound waves which impinge upon the front face thereof, that is, the face toward the electrode 17, and the other due to sound waves which impinge upon the rear face of the diaphragm, that is, the face toward the electrode 16. The chamber adjacent the rear face of the diaphragm together with the silk-covered apertures 12 define an acoustic network comprising mass, stiffness and resistance in series with one another and with the diaphragm, the stiffness being determined by the volume of the chamber and the mass and resistance being determined principally by the interstices in the acoustic resistance material 41. This network, it will be seen, introduces a phase shift between the two acoustic forces acting upon the diaphragm.

Also, because of the path difference between the two faces of the diaphragm and the source of sound, another phase shift between the two forces results whose magnitude is dependent upon the angle of sound incidence. The network and housing parameters are correlated in accordance with principles known in the art so that, because of the phase shifts noted, the directional pattern of the microphone is of a prescribed form, for example substantially cardioid, throughout a wide range of frequencies, that is, the response is a maximum for sound waves incident upon the front face of the diaphragm and normal thereto, is a minimum, substantially zero, for sound waves traveling 180 degrees to this normal and is dependent upon the angle of incidence for other directions. The upper frequency limit of the band throughout which the phase shift is effective is determined in the main by the air path length between the two faces of the diaphragm. In a specific device of the construction illustrated in Fig. 1, the housing 10 may be of the order of $\frac{3}{8}$ inch in diameter, the path length may be of the order of $\frac{1}{2}$ inch and the mass, stiffness and resistance above noted may be of the order of 1.3×10^{-4} , 6.4×10^5 and 16.3, respectively, in acoustical units whereby the directional pattern of the microphone is cardioid throughout the range of frequencies up to substantially 10,000 cycles per second. Above this frequency, i. e., 10,000 cycles per second, directional discrimination is obtained principally due to diffraction effects of the microphone. As shown in Fig. 1, advantageously the front face portion 22 of the housing conforms substantially to a spherical surface element so that the diffraction effect obtained is substantially that of a disc, i. e., the diaphragm, associated with a spherical surface. By proper correlation of the factors involved, a substantially cardioid directional pattern throughout the frequency range up to substantially 20,000 cycles per second has been obtained.

It will be appreciated that the two phase shifts noted above, introduced between the two acoustic forces acting upon the diaphragm vary with frequency so that the resultant driving force applied to the diaphragm likewise varies with frequency. It has been determined that, in a cardioid microphone, if for sound incident normal to the front of the diaphragm the two phase shifts are made substantially equal throughout

the range of frequencies up to a frequency at which the stiffness reactance of the acoustic network is comparable in magnitude to the resistance of this network, a total phase shift proportional to frequency up to that frequency is obtained. For example, in the specific construction above described, a total phase shift proportional to frequency is obtained throughout the frequency range up to of the order of 10,000 cycles per second. Consequently, the resultant driving force applied to the diaphragm is proportional to frequency up to this frequency, e. g. 10,000 cycles per second.

The impedance of the diaphragm also varies with frequency, being, in the specific construction above described, predominantly a stiffness reactance up to the frequency to which the diaphragm is tuned, essentially resistive at and near this frequency and predominantly a mass reactance above this frequency. Consequently, the response of the microphone, without feedback, is dependent upon frequency, and, in the specific construction described above, wherein the two phase shifts are correlated as above set forth the response varies with frequency in the manner illustrated by curve A in Fig. 4, when no feedback force is applied to the diaphragm.

The microphone element 14, 16, 17, the amplifier 43 and the network 44 define an electro-mechanical system of the configuration of the $\mu\beta$ circuit described in the aforementioned article by H. S. Black, the diaphragm 14, back electrode 16 and amplifier 43 constituting the μ section of this circuit and the auxiliary electrode 17 and network 44 constituting the β section of this circuit. The force applied to the diaphragm by way of the auxiliary electrode 17 is dependent, of course, upon the force factor of the electrode 17 and the character of the network 44.

The response of this system as a whole expressed in terms of the output voltage of the system and the acoustic force effective upon the diaphragm, i. e. the force due to sound waves, is given by the equation

$$\frac{E}{p} = \frac{\mu}{1 - \mu\beta} \quad (1)$$

where E is the output voltage, p is the acoustic force acting upon the diaphragm, μ is the propagation constituent of the μ section of the circuit and β is the propagation constant of the β section. If the product $\mu\beta$ is very large in comparison to unity, a stabilized negative feedback system results and the right-hand side of Equation 1 may be written, for practical purposes, as

$$\frac{1}{\beta}$$

For this condition, i. e. $\mu\beta \gg 1$, Equation 1 may be written generally in terms of parameters of the microphone element and the network 44 as

$$\frac{E}{p} = \frac{d^2}{K_1 E_1 \frac{a_2}{a_1} B} \quad (2)$$

where

d =spacing between the diaphragm 14 and auxiliary electrode;

E_1 =polarizing voltage applied between the diaphragm 14 and electrode 17;

a_1 =area of the unclamped portion of the diaphragm 14;

a_2 =area of the electrode 17;

B =the propagation constant of the network 44;

K_1 =a constant, being 8.86×10^{-7} when d is in centimeters and E is in volts.

It is apparent from Equation 2 that the response characteristic of the system will be determined by the character of the network 44 inasmuch as the quantities a_1 , a_2 , d , K_1 and E_1 are constants in an actual device. Thus, if the acoustic force p were independent of frequency, the network parameter B should be independent of frequency, i. e., essentially resistive, in order that the response be independent of frequency.

As pointed out heretofore, in a device of the construction illustrated in Fig. 1, the acoustic force effective upon the diaphragm is proportional to frequency due to the phase shift introduced by the acoustic network and the path length between the front and back surfaces of the diaphragm. For such a device, therefore, the left-hand side of Equation 2 becomes

$$\frac{E}{K_2 \omega p_1}$$

where K_2 is a constant, ω is 2π times the frequency and p_1 is the free field acoustic force. Consequently, it will be seen that the attainment of a flat response characteristic for such a device requires that the network 44 have a transmission characteristic proportional to frequency and increasing at a prescribed rate with frequency. Hence, the network 44 in the system illustrated in Fig. 3 where the microphone element is of the construction illustrated in Fig. 1 and described hereinabove may be a series capacitance 45 and a shunt resistance 46. In an actual device, a network 44, having a transmission characteristic increasing substantially 6 decibels per octave has been found satisfactory, resulting in a response characteristic for sound incident upon the front face of the diaphragm and normal thereto of the form shown by curve B in Fig. 4 for the same device for which the response without feedback is of the form shown by curve A.

The feedback effect described above is largely independent of the angle of incidence of the sound waves upon the microphone. For example, the output of the same device having the characteristics illustrated by curves A and B, for sound incident at an angle of 140 degrees to the normal to the front face of the diaphragm varies but slightly with frequency throughout a wide range of frequencies as illustrated by the curve C in Fig. 4.

It is to be noted that the diaphragm 14 constitutes a substantially perfect shield between the two electrostatic fields on opposite sides thereof so that the energy fed back to the diaphragm through the impedance 44 and electrode 17 is segregated from the output side of the microphone element and affects the output only by the controlling action upon the motion of the diaphragm. Consequently, deleterious affecting of the phase and amplitude relations between the input to the amplifier and the energy fed back from the amplifier to the microphone element is prevented and stable operation and predetermined operating characteristics are realized.

The control of the diaphragm motion by feedback as described hereinabove, in addition to resulting in a uniform response throughout a wide frequency range enables realization of an improved signal-to-noise ratio over this range, as will be understood from the following considerations. The application of feedback in itself neither improves nor degrades the signal-to-noise ratio for such noise as is introduced in the system ahead of the plate circuit of the first stage of the amplifier. This fact together with

the efficacy of the feedback arrangement in controlling the diaphragm motion so that uniform response is obtained, allows changes in the mechanical parameters of the microphone resulting in an improved signal-to-noise ratio, which changes, in the absence of feedback, would result in a non-uniform response characteristic.

In general, in a device of the construction shown and described, the limit of the response obtainable at the higher frequencies in the range to be translated is dependent primarily upon the diaphragm mass. A reduction in mass results in an increased response at these frequencies and also in an increased signal-to-noise ratio at these frequencies. The response toward the lower end of the frequency range to be transmitted is dependent upon the diaphragm stiffness and a reduction in the stiffness results in an increased response and an improved signal-to-noise ratio at the lower end of the frequency range. Thus, in a device wherein the diaphragm motion is controlled by feedback, the diaphragm mass and stiffness can be correlated to obtain the optimum signal-to-noise ratio without resulting in non-uniformity of the response characteristic of the system. For a device of the construction shown and described, the optimum signal-to-noise ratio is realized, generally, when the area under the response curve of the device without feedback is a maximum.

The lower limit to which the diaphragm mass can be reduced is determined by the diaphragm material and the lower limit of the diaphragm stiffness obtainable is dictated in the main by the extent to which unbalance between the polarizing forces on the diaphragm can be eliminated practically. In an actual device of the construction shown and described, wherein the diaphragm was $\frac{1}{8}$ inch in free diameter, 0.00025 inch aluminum as the diaphragm material and tensioning of the diaphragm so that its resonance frequency was approximately 2000 cycles per second have been found to be satisfactory. As is apparent from curve A of Fig. 4, the area under the response curve for operation without feedback is large so that a high signal-to-noise ratio is obtained.

Although a specific embodiment of this invention has been shown and described, it will be understood that it is but illustrative and that various modifications may be made therein without departing from the scope and spirit of this invention as defined in the appended claims.

What is claimed is:

1. An electroacoustic transducer comprising a metallic diaphragm, electrode means on one side of said diaphragm and defining a condenser therewith for translating vibrations of said diaphragm in response to acoustic force effective thereon into electrical variations, an amplifier having its input connected to said means, and means for impressing upon said diaphragm a force substantially proportional to said acoustic force and in opposition thereto throughout the operating frequency range of said transducer, said last-mentioned means comprising an electrode member adjacent the opposite side of said diaphragm and defining a condenser therewith and an electrical impedance connecting said electrode member to the output of said amplifier.

2. An electroacoustic transducer comprising a condenser microphone element including a diaphragm and an output and an auxiliary electrode in cooperative relation with said diaphragm, an amplifier having its input connected to said dia-

phragm and output electrode, and an electrical impedance connected between the output of said amplifier and said auxiliary electrode and constituting with said amplifier and element a stabilized feedback system, said impedance having a transmission characteristic of the same form as the acoustic force-output characteristic of said element.

3. An electroacoustic transducer comprising a condenser microphone element including a diaphragm, an output electrode adjacent one face of said diaphragm and an auxiliary electrode adjacent the opposite face of said diaphragm, an amplifier having its input connected to said output electrode, and an electrical impedance connected between said auxiliary electrode and said amplifier and defining with said amplifier and element a stabilized negative feedback system, said impedance having a transmission characteristic of the same form as the acoustic force-output characteristic of said element.

4. An electroacoustic transducer comprising a microphone including a diaphragm having opposite faces in communication with a sound conveying medium and means in cooperative relation with said diaphragm for translating vibrations thereof in response to acoustic force effective thereon into electrical variations, acoustomechanical means for introducing a phase shift between the acoustic forces applied to the opposite faces of said diaphragm whereby the resultant force effective upon said diaphragm is dependent upon the angle of incidence of sound waves upon said microphone, and means for applying to said diaphragm a force proportional to said resultant force and in opposition thereto.

5. An electroacoustic transducer comprising a microphone including a diaphragm having opposite faces in communication with a sound conveying medium, means in cooperative relation with said diaphragm for translating vibrations thereof in response to acoustic force effective thereon into electrical variations, acoustomechanical means for producing a phase difference varying with frequency between the acoustic forces applied to the opposite faces of said diaphragm whereby the resultant acoustic force effective upon said diaphragm is dependent upon the angle of incidence of sound waves upon said microphone and varies with frequency, and means for applying to said diaphragm a force in opposition to and varying with frequency in the same manner as said resultant acoustic force.

6. An electroacoustic transducer comprising a microphone including a diaphragm having opposite faces in communication with a sound conveying medium, means in cooperative relation with said diaphragm for translating vibrations thereof in response to force effective thereon into electrical variations, acoustomechanical means for producing a phase difference between the acoustic forces acting upon the opposite faces of said diaphragm proportional to frequency throughout a preassigned range of frequencies and such that the directional pattern of said microphone is substantially cardioidal, and means for applying to said diaphragm a force proportional to frequency and in opposition to the resultant of said acoustic forces throughout said range of frequencies.

7. An electroacoustic transducer comprising a diaphragm having opposite faces in communication with the atmosphere, means cooperatively associated with said diaphragm for translating vibrations thereof into electrical variations,

means for producing a phase difference between the acoustic forces acting upon the opposite faces of said diaphragm comprising means constituting a barrier between said faces and means defining an acoustic network associated with said diaphragm, whereby the resultant of said acoustic forces is dependent upon the angle of incidence of sound waves upon said diaphragm, an amplifier connected to said first means, and means for applying to said diaphragm a force proportional to said resultant force and in opposition thereto comprising an electrode adjacent said diaphragm and defining a condenser therewith and an impedance connected between said electrode and the output of said amplifier.

8. An electroacoustic transducer comprising a microphone including a diaphragm having opposite faces in communication with the atmosphere, means cooperatively associated with said diaphragm for translating vibrations thereof into electrical variations, means for producing a phase shift proportional to frequency throughout a prescribed range of frequencies between the acoustic forces acting upon the opposite faces of said diaphragm such that the directional pattern of said microphone is substantially cardioid, an amplifier having its input connected to said first means, means adjacent said diaphragm for applying a force thereto, and an impedance connecting said force applying means to the out-

put of said amplifier and defining with said microphone and amplifier a stabilized negative feedback system, said impedance having a transmission characteristic proportional to frequency throughout said range of frequencies in substantially the same relation as the proportionality between said phase shift and frequency.

9. An electroacoustic transducer comprising a condenser microphone element including a diaphragm, an output electrode adjacent said diaphragm and an auxiliary electrode adjacent said diaphragm, said diaphragm having opposite faces in communication with the atmosphere, means for introducing a phase shift substantially linearly proportional to frequency throughout a preassigned range of frequencies, between the acoustic forces acting upon opposite sides of the diaphragm and such that the directional pattern of said element is substantially cardioid throughout said range of frequencies, said means comprising a housing defining with said diaphragm an acoustic phase shifting network, an amplifier having its input connected to said diaphragm and said output electrode, and an impedance connected between the output of said amplifier and said diaphragm and auxiliary electrode, said impedance being predominantly capacitative.

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