FULL RANGE ELECTROSTATIC LOUDSPEAKER FOR AUDIO FREQUENCIES

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Filed: Sept. 4, 1973
Appl. No.: 393,789

U.S. Cl. 179/111 R; 179/180
Int. Cl. H04r 19/02
Field of Search 179/111 R, 111 E, 106, 179/180

REFERENCES CITED

UNITED STATES PATENTS
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2,975,243 3/1961 Katella
3,654,403 4/1972 Bobb
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537,931 7/1941 United Kingdom

ABSTRACT

A single diaphragm electrostatic loudspeaker having multiple opposing pairs of electrodes which are graded in size, the speaker further including means for electrically controlling the high frequency response of each electrode pair so as to achieve an overall uniform response.

The diaphragm is acoustically damped and selectively tuned by mass loading to achieve inertia control below a designated frequency, thus extending the loudspeaker’s useful response into the low frequency range.

A typical form and construction for the loudspeaker is disclosed which also provides for relatively uniform sound dispersion throughout designated horizontal and vertical angles of coverage.

16 Claims, 8 Drawing Figures
FIG. 1
FULL RANGE ELECTROSTATIC LOUDSPEAKER FOR AUDIO FREQUENCIES

BACKGROUND OF THE INVENTION

1. Field of the Invention
The present invention relates generally to electro-acoustic devices, and in particular, relates to electrostatic loudspeakers.

2. Description of the Prior Art
Electrostatic loudspeakers are generally classified as either single-sided or push-pull. Both types employ a very thin, flexible diaphragm in close proximity to a stationary electrode. The entire diaphragm is at least partially conductive and has a polarizing potential applied thereto. In the case of a push-pull device, the diaphragm may be positioned between two stationary electrodes. In operation, the audio signal is applied between the electrodes, creating a charge between the electrodes which varies depending upon the signal amplitude. When the necessary charge differential is present between the polarized diaphragm and the electrodes, the diaphragm, due to its low mass, will vibrate and thereby acoustically reproduce the audio represented by the signal applied to the electrodes.

Attempts at commercial electrostatic loudspeakers have met with some success. However, because the half wave length of low bass frequencies is several feet (for example, over ten feet at fifty Hertz), full frequency electrostatic loudspeakers have necessarily been so large as to completely dominate the surrounding decor.

There have been suggestions in the prior art to massload the diaphragm in order to reduce the active high frequency propagation area to achieve low frequency capability with diaphragms of relatively modest dimensions. For example, D. T. N. Williamson, et al., disclose, in U.S. Pat. No. 3,008,014, mass-loading buttons spaced across the surface of the diaphragm.

Historically, electrostatic loudspeakers have also been subject to other limitations. Professor Frederick V. Hunt, in ELECTOACOUSTICS, No. 5 of the Harvard Monographs in Applied Science, Harvard University Press, 1954, devotes Chapter 6, pages 108-212 to a discussion of the history and technique used with electrostatic loudspeakers. Professor Hunt discusses many prior art references, including United States and foreign patents, which teach techniques for avoiding some of the difficulties previously experienced with electrostatic loudspeakers. Of particular interest, Professor Hunt suggested that the effective diaphragm area could be varied automatically with frequency, perhaps by an electrical segmentation of the stationary electrode.

There are also other prior art references which suggest segmented electrodes. Vogt, in French Pat. No. 711,807, teaches a concentric electrode arrangement in a pushpull device, in which the outer concentric electrode pair is biased negative with the inner electrode pair being biased with opposite polarities (one positive, one negative). Bobb, in U.S. Pat. No. 3,654,403, also discloses an arrangement employing segmented stationary electrodes. Malme, in U.S. Pat. No. 3,014,098, teaches an electrostatic speaker employing a tensioned-wire stationary electrode.

Professor Hunt et al. have also suggested the electrical segmentation of the diaphragm and the use of a matching impedance circuit to obtain uniform frequency response in an electrostatic speaker. See, Technical Memorandum No. 17, Office of Naval Research Contract N5 ORI-76, Project Order X, reported from the Acoustics Research Laboratory, Harvard University.

SUMMARY OF THE INVENTION

The present invention contemplates an electrostatic loudspeaker comprising a diaphragm which is at least partially conductive with polarizing means electrically coupled thereto. Two electrodes are spaced adjacent to first and second respective portions of the diaphragm, the speaker further comprising means for electrically controlling the frequency response of each electrode.

THE DRAWING

FIG. 1 is an expanded perspective view, partially cut away, of an embodiment of an electrostatic loudspeaker in accordance with the present invention with the diaphragm omitted for purposes of illustration.

FIG. 2 is a perspective front view of a rear electrode assembly in accordance with the embodiment of FIG. 1, with the diaphragm in place and partially cut away. FIG. 3(a) is a partial cross-section of the electrostatic loudspeaker of the embodiment of FIGS. 1 and 2 as taken along the line 3-3' of the rear electrode in FIG. 2. FIG. 3(b) is an enlarged perspective view of a portion of the electrodes shown in FIGS. 1, 2 and 3(a). FIG. 4 is another cross-section similar to that of FIG. 3(a).

FIG. 5 is a schematic circuit diagram of the electrostatic loudspeaker according to the present invention.

FIG. 6 is a family of curves illustrating the middle and high frequency response of an electrostatic loudspeaker in accordance with the prior art.

FIG. 7 is a family of curves illustrating the middle and high frequency response of a speaker in accordance with the present invention.

DETAILED DESCRIPTION OF THE INVENTION

An embodiment of an electrostatic loudspeaker in accordance with this invention will now be described with reference to FIGS. 1-3. While the push-pull electrostatic loudspeaker is specifically described, it will be appreciated by those skilled in the art that the present invention may also be employed with a single-sided arrangement.

Reference is made to FIG. 1. The electrostatic loudspeaker 10 includes a rear electrode assembly 12 and a front electrode assembly 14. The speaker 10 further includes a diaphragm positioned between the electrode assemblies 12, 14; however, the diaphragm is removed in FIG. 1 to illustrate the rear electrode assembly, and will be described in detail below with reference to FIGS. 2, 3(a), 4 and 5. The rear electrode assembly 12 is supported by a rigid insulating frame 16. Suitably, the frame 16 outlines a section of a cylinder in which the curvature thereof includes about 80° of arc.

In accordance with this invention, the rear electrode assembly 12 includes a plurality of segmented electrodes fixed to the frame 16. In this example, the segmented electrodes include four electrodes A, B, C and D, the outer three electrodes including two segments, one segment being identified in FIG. 1 by the corresponding prime letter (B', C' and D', respectively). Each of the outer three electrodes BB', CC' and DD' surrounds a substantial portion of the periphery of the
next adjacent electrode. That is, electrode DD' substantially surrounds electrode CC', electrode CC' substantially surrounds electrode BB' and electrode BB' substantially surrounds electrode A. The electrodes A-DD' may assume a variety of configurations, such as concentric rings, ovals, rectangles, and so forth. However, the parallel electrode arrangement of FIG. 1 is preferred because this parallel segmented electrode arrangement provides a uniform vertical dispersion of acoustical energy both in terms of amplitude and frequency response. In conjunction with this parallel segmented electrode arrangement, the cylindrical section form of the loudspeaker 10 provides the desired uniform horizontal dispersion. All of the electrodes A-DD' comprise acoustically transparent material; for example, a rigid metal plate having spaced holes therein is suitable. The electrodes A-DD' are affixed to the sides of the frame 12 and are held in rigid, spaced relationship by insulating ribs 18 extending transversely to all of the electrodes.

The front electrode assembly 14 also includes a frame 20 supporting a set of electrodes A, BB' CC' and DD' opposed to, and having shapes and dimensions like the corresponding electrodes A, BB' CC' and DD' of the rear electrode assembly 12. The electrodes A-DD' of the front electrode assembly 14 are also held in rigid, spaced relationship by transverse insulating ribs 22. The dimensions of the front frame 20 are such as to allow that frame to fit snugly over the frame 16 of the rear electrode assembly 12. The rear electrode 12 includes tapped holes 24 and corresponding fasteners, such as screws which are adapted to engage apertures 26 in the front electrode frame 20 and thereby hold the two frames 16, 20 in fixed relationship but allowing for adjustments to the spacing between the two frames.

An important aspect of this invention contemplates the correlation of the dimensions of each electrode, as related to wavelength of certain audio frequencies, with means for electrically controlling the high frequency roll-off of each electrode. Briefly, the vertical dimension of each electrode A-DD' and the impedance of a matching network described below is preselected so as to achieve an overall uniform frequency response. Thus, while no specific dimension is critical, the transverse vertical and the horizontal dimensions of all of the electrodes A-DD' and the active diaphragm area are critical relative to, and in proportion to each other since these relationships determine the frequency response for the speaker 10. These relationships will be more completely described below with reference to FIGS. 5, 6 and 7.

Reference is now made to FIGS. 2, 3(a) and 4, in which the diaphragm is interposed between insulating spacing strips 30, 32 which are respectively fixed to the rear electrode assembly 12 and the front electrode assembly 14 transverse across all of the electrodes A-DD'. The diaphragm 28 preferably comprises a very thin, flexible plastic film such as Mylar metalized for conductivity on one or both sides thereof. The transverse strips 30, 32 thus define a series of parallel bays 34, each bay having a portion of the diaphragm tensioned across portions of all of the electrodes A-DD' of both electrode assemblies 12, 14. As is more clearly shown in FIG. 4, a narrow, resilient weighting strip 36 is affixed to one or both sides and down the middle of each portion of the diaphragm 28 in each bay 34. During motion of the diaphragm 28 in each bay 34, the weighting strips 36 mass-load the diaphragm and extend the low frequency characteristic thereof. By maintaining the weighting strips 36 very narrow, the effective diaphragm area at high frequencies may approximate the diaphragm area at low frequencies. Further, by proper selection of the mass of each weighting strip 36 relative to the diaphragm tension, the low frequency limit of the speaker 10 can be controlled so as to extend the low frequency below the acoustical roll-off of the outer electrode DD'. In this example the diaphragm is made to resonate at fifty Hertz. However, the resonance frequency created by such tuning can be unpleasant to the listener, and it is therefore desirable to employ acoustical damping means, such as the segmented strips 37 shown in FIG. 3(a), to damp this resonant frequency. The proper choice of resonant frequency, mass, and damping results below that where radiation resistance starts to fall off.

Noting the inset of FIG. 3(b), there is shown a representative fragment of all of the electrodes A-DD'. The fragment, referred to as 40, comprises a metal such as aluminum, for example, having holes 42 therein, which render the electrode acoustically transparent. A dielectric layer 44 is disposed uniformly on the fragment 40 and around the periphery of the holes 42. As shown in the views of FIGS. 1, 2, 3(a) and particularly in FIG. 3(b), the corners and the holes 42 in each electrode A-DD' are rounded so as to lessen the potential for corona arcing, since, as is well-known, such arcing tends to occur most often at sharp corners and edges having small cross-sectional areas. Thus, it is particularly desirable, as shown in FIG. 3(b), to deposit the dielectric layer 44 more thickly at the edges of the holes 42 than along the flat areas. This may be accomplished by the electrostatic deposition of the dielectric insulating coating.

The manner in which the acoustical and electrical characteristics of each electrode are controlled and correlated to obtain a uniform frequency response will now be described with reference to FIGS. 5, 6 and 7.

In FIG. 5, one bay 34 between the rear and front electrode assemblies 12, 14 respectively, is shown in cross-section with the corresponding electrode segments A-DD'. The loudspeaker 10 further includes a polarizing high voltage D.C. power supply 46 electrically coupled to the diaphragm 28 through a resistor 48. The high voltage power supply 46 may be constructed by known techniques.

The loudspeaker 10 further includes an audio transformer 50 the primary winding of which is adapted to be coupled to the output of a commercially available audio amplifier. The secondary windings 52 of the transformer 50 include a grounded center tap 54. Each of the two terminals 56, 58 of the secondary windings 52 are coupled through resistors R1, R2, R1 and R2 to the corresponding electrodes A-DD' of one of the electrode assemblies 12, 14. Specifically, terminal 56 of the secondary winding 52 is coupled to electrodes A-DD' of the rear electrode assembly 17 through the associated resistors R1, R2 and terminal 58 is coupled to electrodes A-DD' through the associated resistors R1, R2.

As is well known, each electrode A-DD' of the rear electrode assembly 12 and the corresponding electrode A-DD' of the front electrode assembly 14 defines a capacitance. By an appropriate correlation between the
values of resistors \( R_1 - R_6 \) and the width of each electrode A-DD', the overall uniformity of the frequency response of the loudspeaker 10 is controlled. More specifically, the RC network defined by the combination of each resistor \( R_1 - R_6 \), with the corresponding electrode to electrode capacitance is balanced so as to obtain a relatively uniform frequency response for all audio frequencies.

By way of example only, the following transverse electrode dimensions and resistor values set forth in Table 1 below have been employed to achieve a relatively uniform frequency response.

<table>
<thead>
<tr>
<th>Transverse Electrode Dimension</th>
<th>Resistive Value</th>
<th>Electrical Roll-off</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 1.0 inch</td>
<td>( R_1 = 20 ) Kohm</td>
<td>20 KHz</td>
</tr>
<tr>
<td>B, B' each = 1.5 inches</td>
<td>( R_{B, B'} = 100 ) Kohm</td>
<td>8 KHz</td>
</tr>
<tr>
<td>( C, C' ) each = 2.25 inches</td>
<td>( R_{C, C'} = 220 ) Kohm</td>
<td>1.6 KHz</td>
</tr>
<tr>
<td>D, D' each = 5.0 inches</td>
<td>( R_{D, D'} = 500 ) Kohm</td>
<td>0.7 KHz</td>
</tr>
</tbody>
</table>

It is understood that the effective diaphragm area for any given frequency is equal to the sum total of the area of the electrodes energized at that frequency. In the arrangement represented by FIG. 5 and Table 1, for example, the effective diaphragm area when electrode CC' is energized is equal to the sum of widths of electrodes A, BB' and CC' which represents a total of 8.5 inches (A + B + B' + C + C'). Thus, the balancing network represented by the resistors \( R_1 - R_6 \) rolls off the high frequency response for each electrode A-DD' for those frequencies above that frequency having a half wavelength represented by the sum of the transverse dimensions of the included electrodes.

Electrode DD', representing the total width of all electrodes, has an acoustical low frequency roll-off starting at 350 Hertz. Because of the mass-loading of the weighting strips 36, the low frequency response may be substantially extended below the acoustical roll-off of electrode DD'. When employing this mass-loading technique, the diaphragm 28 tends to be inertia controlled at frequencies in the range below the acoustical roll-off of electrode DD'. The acoustical damping created by the foam strips 37 controls excess diaphragm motion at resonance and smooths the low frequency response.

FIGS. (a)-(c) illustrates a set of actual curves representative of the middle and high frequency response of an electrostatic loudspeaker but without segmented electrodes or the resistor network shown in FIG. 5. Thus configured, the acoustical dispersion characteristics represent the prior art push-pull electrostatic speakers employing a monolithic electrode on either side of the diaphragm.

The curve 60 at FIG. 6(a) represents the acoustic energy (in db) measured "on axis", i.e., along a line normal to the center of the diaphragm 28. The curve 62 at FIG. 6(b) illustrates the measurement of acoustic energy 15° off-axis, and the curve 64 at FIG. 6(c) illustrates a similar measurement made 30° off-axis, each measured vertically.

Curves 66, 68 and 79 of FIGS. 7(a), (b) and (c), respectively, illustrate an actual set of corresponding measurements of the speaker of the present invention, employing the resistive network shown in FIG. 5. From a comparison of FIGS. 6(a)-(c) and 7(a)-(c), respectively, several advantages of the speaker of the present invention can be readily ascertained. For example, at FIGS. 6(a)-(c), it is seen that on-axis response tends to accentuate the higher frequencies, while at listening positions above or below axis the high frequencies are severely attenuated, a phenomenon quite unpleasant to the listener. Thus, it can be seen that the electrostatic speaker of the present invention has a relatively uniform frequency response and is less directional in the vertical direction than a speaker not employing the resistive balancing network. Furthermore, the cylindrical form of the speaker 10 provides a uniform horizontal dispersion through the included angle.

I claim:

1. An electrostatic speaker, comprising: an electrode assembly comprising a section of a cylinder; a diaphragm tensioned across a curved surface of said electrode assembly; means for changing the area of said diaphragm energized with changes in audio frequency, said means including a plurality of curved parallel electrodes about said electrode assembly, said electrodes extending parallel to each other and perpendicular to the axis of said cylinder, and forming said cylindrical section; and wherein some of said electrodes comprising two segments spaced on opposite sides of, and surrounding a substantial portion of a next adjacent electrode.

2. An electrostatic speaker as recited in claim 1 further comprising supporting ribs joined transverse to all of said electrodes.

3. An electrostatic speaker as recited in claim 1 further comprising another electrode assembly comprising a cylindrical section adjacent to said one electrode assembly with said diaphragm tensioned therebetween.

4. An electrostatic speaker as recited in claim 3 further comprising a plurality of curved electrodes about said another electrode assembly opposing and corresponding in shape and dimension to said electrodes of said one electrode assembly.

5. An electrostatic speaker as recited in claim 4 further comprising opposing insulated spacing strips fixed to each electrode assembly transverse to said electrodes with said diaphragm therebetween.

6. An electrostatic speaker as recited in claim 5 further comprising weighting strips fixed to said diaphragm between said spacing strips.

7. An electrostatic speaker as recited in claim 4 wherein said electrodes comprise a central electrode of a smallest transverse dimension and an adjacent electrode of greater transverse dimension, said adjacent electrode including two segments each on opposite sides of said central electrode.

8. An electrostatic speaker as recited in claim 7 wherein said changing means further comprises electrical balancing means for rolling off the high frequency response of said adjacent electrode for those frequencies above that frequency having a half wavelength represented by the transverse dimension of said central electrode.

9. An electrostatic speaker as recited in claim 8 wherein said changing means further comprises: another electrode having two segments substantially surrounding said adjacent electrode; and wherein said balancing means includes means for rolling off the high frequency response of said another electrode for those frequencies above that frequency...
having a wavelength represented by the sum of the transverse dimensions of said central and adjacent electrodes.

10. An electrostatic speaker as recited in claim 9 wherein said balancing means comprises:

a first impedance means coupled with both segments of said adjacent electrode; and wherein said first and second impedance means are balanced with the inter-electrode capacitance of each said electrode to achieve an overall uniform frequency response.

11. An electrostatic speaker as recited in claim 1 further comprising acoustically resistive means adjacent a side of one of said electrodes and opposite said diaphragm.

12. An electrostatic speaker as recited in claim 1 wherein each said electrode comprises an acoustically transparent material.

13. An electrostatic speaker as recited in claim 12 wherein said acoustically transparent material comprises a metal plate having spaced holes therein.

14. An electrostatic speaker as recited in claim 13 further comprising a dielectric layer encapsulating each said electrode, said dielectric layer being substantially thicker around the periphery of said holes.

15. An electrostatic speaker as recited in claim 14 wherein said diaphragm comprises an insulating sheet having a conductive layer thereon.

16. An electrostatic transducer comprising:

a single, flexible diaphragm;

means for suspending said diaphragm as a cylindrical section having an axis extending in a first direction;

means for energizing said diaphragm for a predetermined range of audio frequencies;

means for sequentially reducing the area of said diaphragm energized with increases in said audio frequencies by reducing the dimension of said energized area only in a direction substantially parallel with said first direction; and wherein only a narrow belt of said diaphragm relative to the overall area of said diaphragm is energized for the highest of said audio frequencies.

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