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Lindenberg

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[45] **July 1, 1975**

[54] **FULL RANGE ELECTROSTATIC LOUDSPEAKER FOR AUDIO FREQUENCIES**

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[21] Appl. No.: **393,789**

[52] **U.S. Cl.** ..... **179/111 R;** 179/180

[51] **Int. Cl.** **H04r 19/02**

[58] **Field of Search** ..... 179/111 R, 111 E, 106, 179/180

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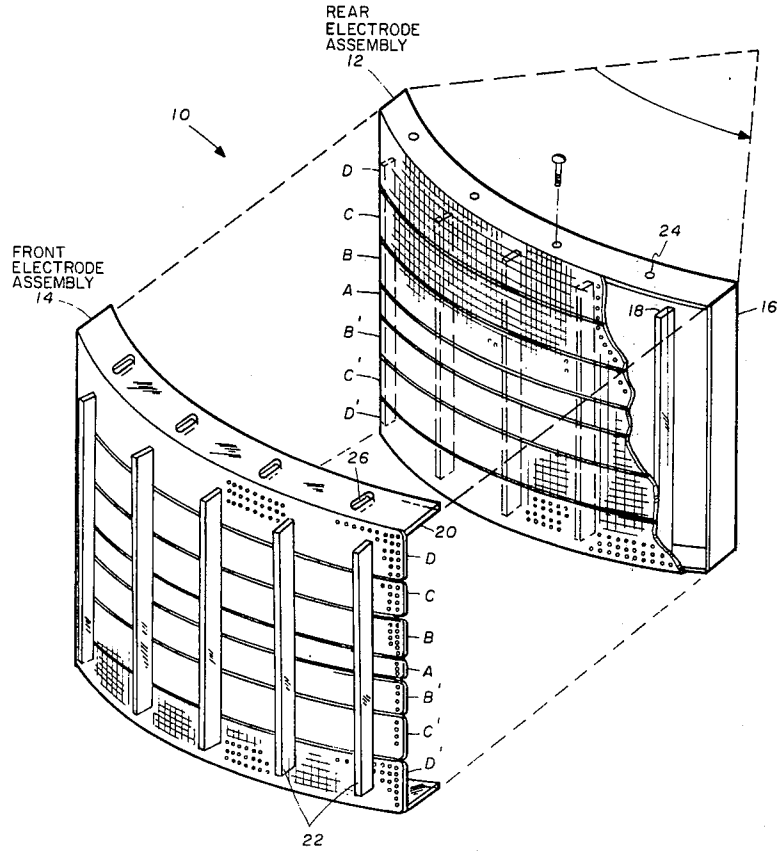
[57] **ABSTRACT**

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



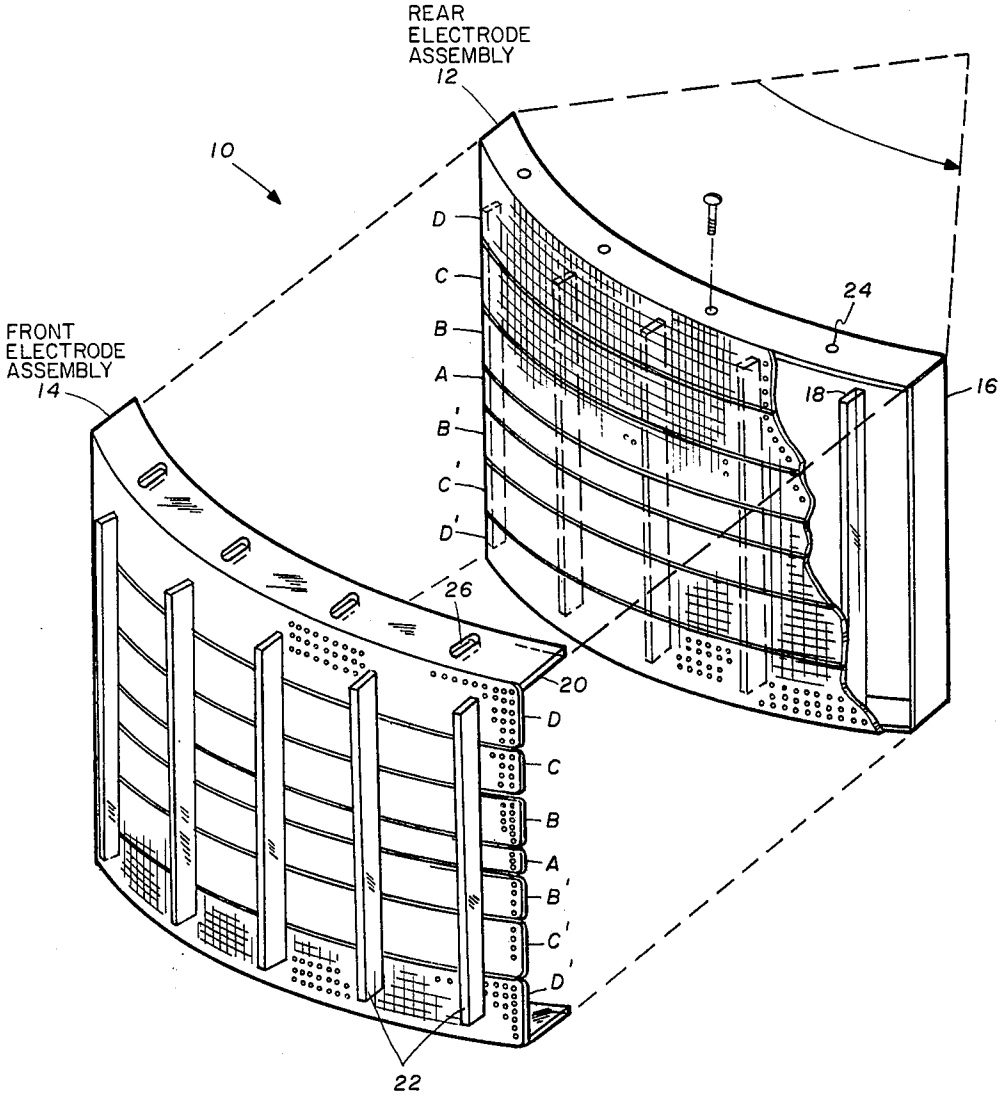

REAR
ELECTRODE
ASSEMBLY
12
10
D
C
B
A
B'
C'
D'
24
18
16
FRONT
ELECTRODE
ASSEMBLY
14
26
20
D
C
B
A
B'
C'
D'
22

FIG. 1

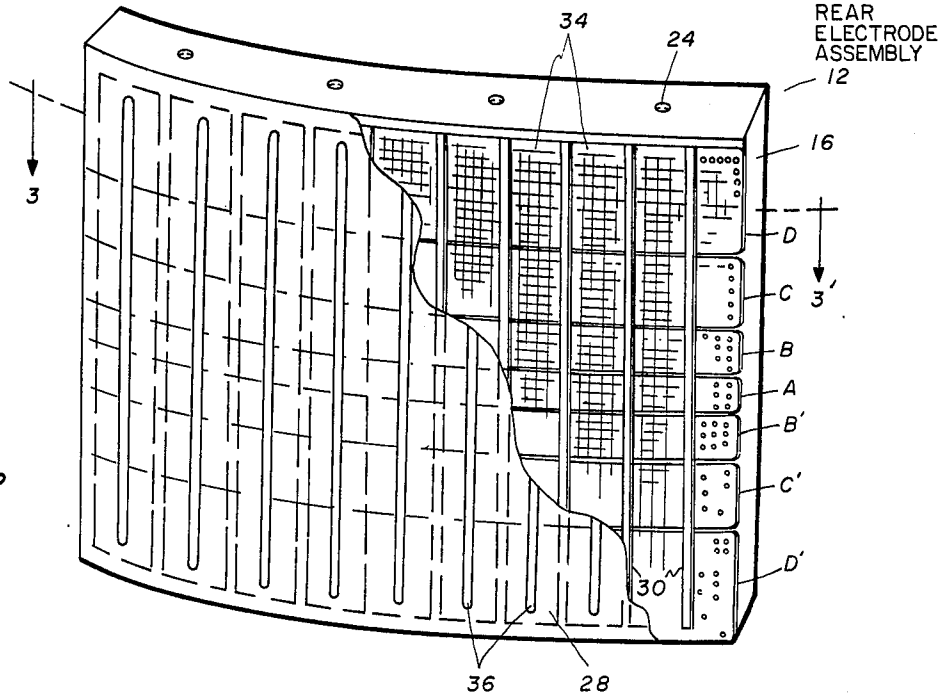


FIG. 2

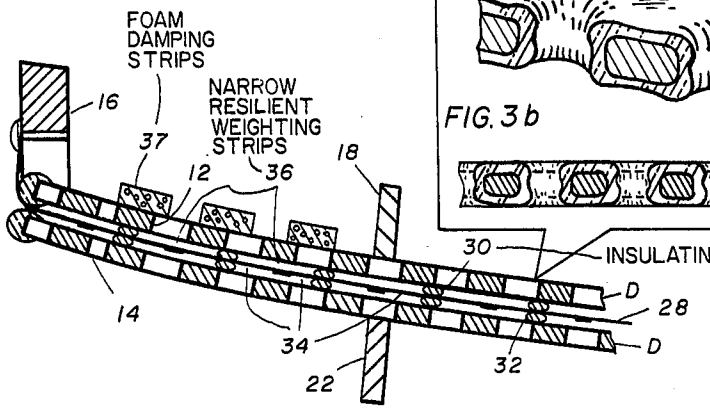


FIG. 3a

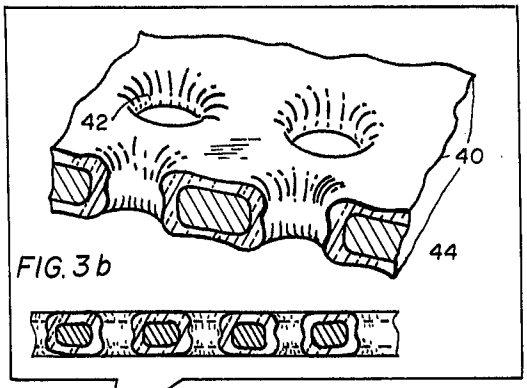


FIG. 3b

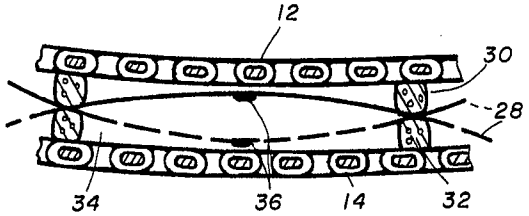


FIG. 4

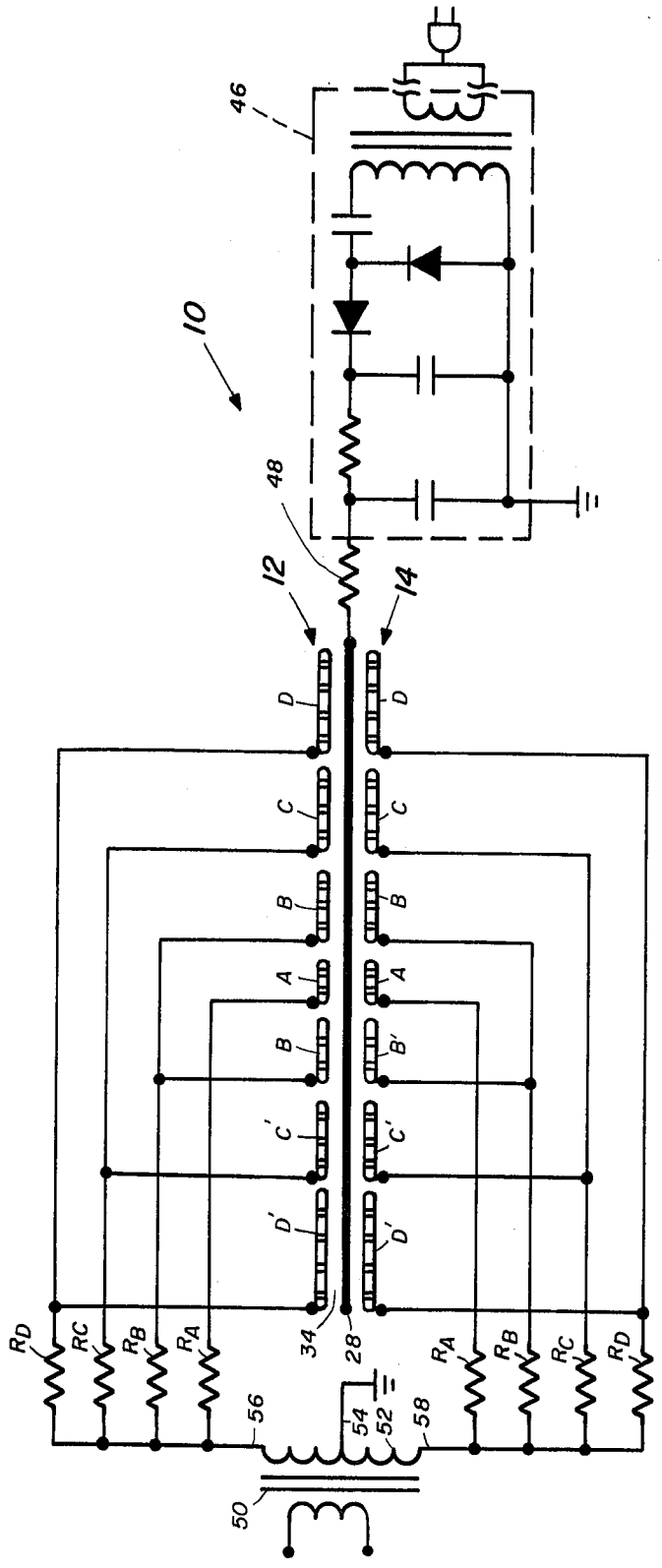
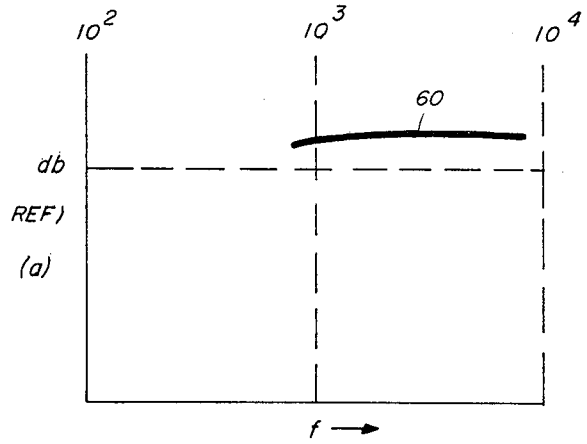
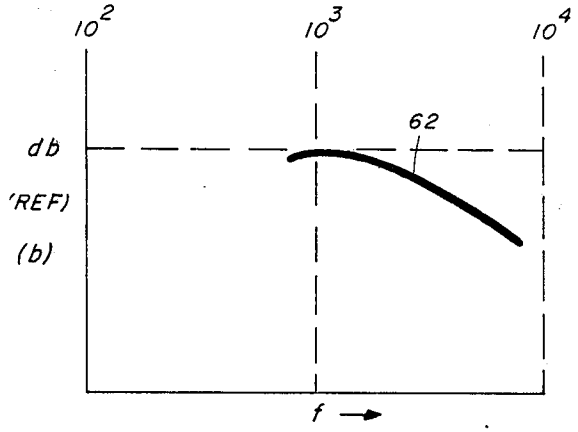

46
10
48
12
14
D
C
B
A
B
C'
D'
D
C
B
B'
C'
D'
R_D
RC
R_B
R_A
34
28
R_A
R_B
R_C
R_D
56
54
52
58
50

FIG 5





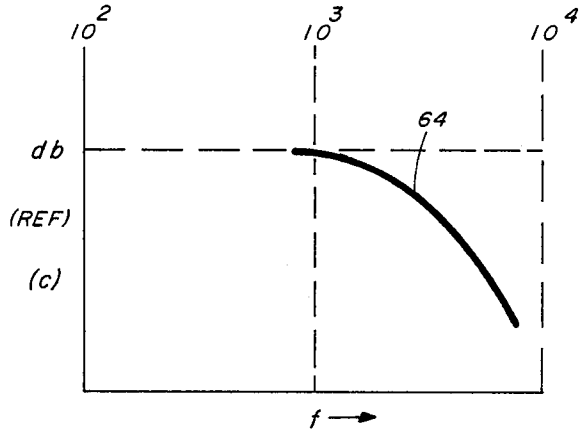
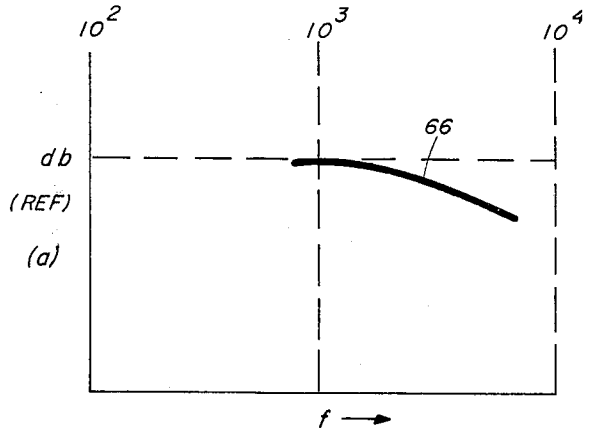
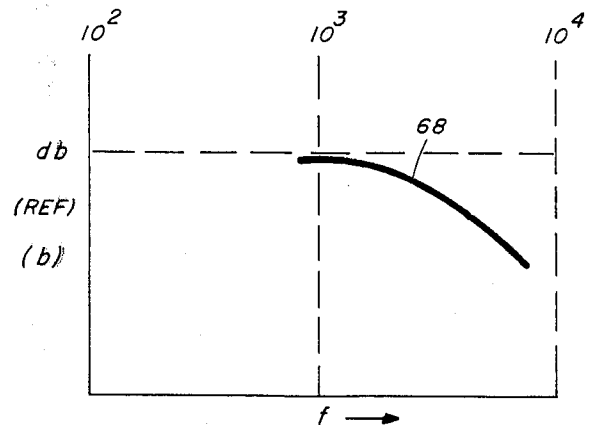


FIG. 6 (PRIOR ART)





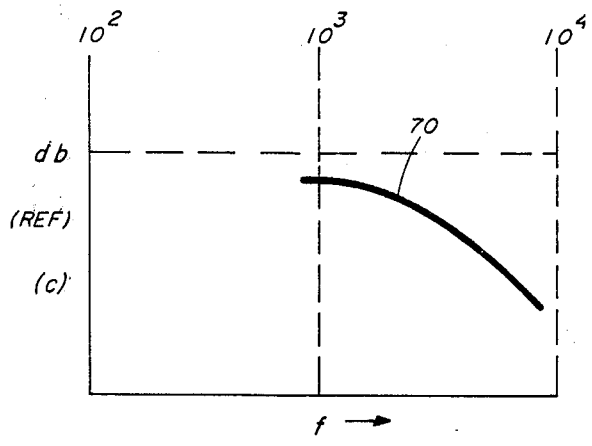


FIG. 7

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 mass-load 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 techniques 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 diaphragm 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

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 transverse 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 metallized 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 in the diaphragm being inertia controlled at frequencies 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 uniformaly 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 R_A, R_B, R_C and R_D 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 $R_A - R_D$ and terminal **58** is coupled to electrodes A–DD' through the associated resistors $R_A - R_D$.

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 $R_A - R_D$ 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 $R_A - R_D$ 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 1

Transverse Electrode Dimension	Resistive Value	Electrical Roll-off
A = 1.0 inch	R_A = 20 Kohm	20 KHz
B, B' each = 1.5 inches	R_B = 100 Kohm	8 KHz
C, C' each = 2.25 inches	R_C = 220 Kohm	1.6 KHz
D, D' each = 5.0 inches	R_D = 500 Kohm	0.7 KHz

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 $R_A - R_D$ 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. **6**(*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 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.

* * * * *