United States Patent

Wright

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[45] **June 6, 1972**

[54] AUDIO SYSTEM INCLUDING ELECTROSTATIC LOUDSPEAKER

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[22] Filed: **Dec. 8, 1969**

[21] Appl. No.: **883,143**

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

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

[58] **Field of Search** ..... 179/111, 1 R, 1 F, 1 FS

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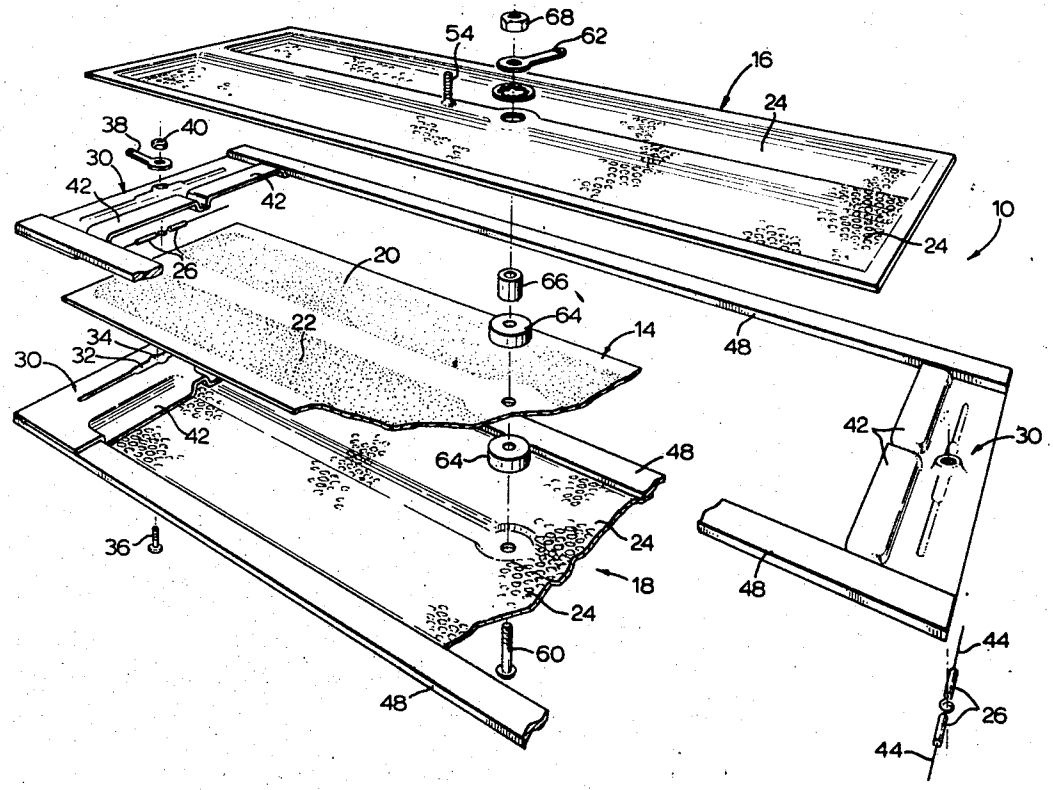
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Assistant Examiner—Thomas L. Kundert
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[57] **ABSTRACT**

An audio system including the last stage of the audio amplifier as an audio frequency voltage output source, a DC source providing a substantially constant charge so as to define and maintain an electrostatic field, and an electrostatic loudspeaker wherein the electrostatic field is maintained between electrodes and the audio frequency voltage output is impressed on the electrostatic field. Negative feedback from the audio voltage output may be provided.

The electrostatic loudspeaker is assembled so as to include spacer blocks on either side of a movable diaphragm, and clamped between two rigid, outer electrodes. An electrical connection is passed through the spacer blocks so that both outer electrodes may have electrical connections made to each, respectively, on one common side of the loudspeaker assembly.

17 Claims, 14 Drawing Figures



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SHEET 1 OF 4

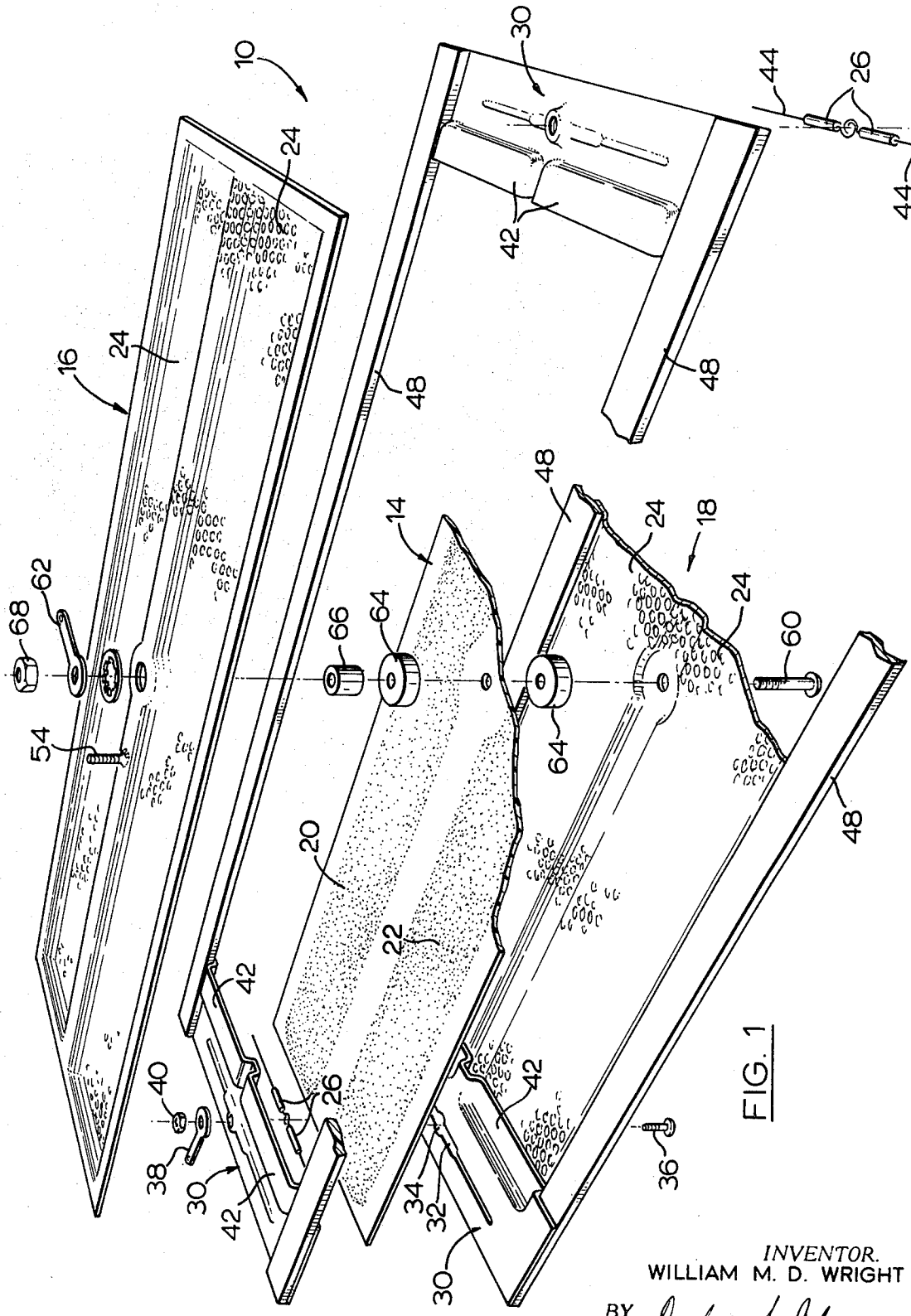


FIG. 1

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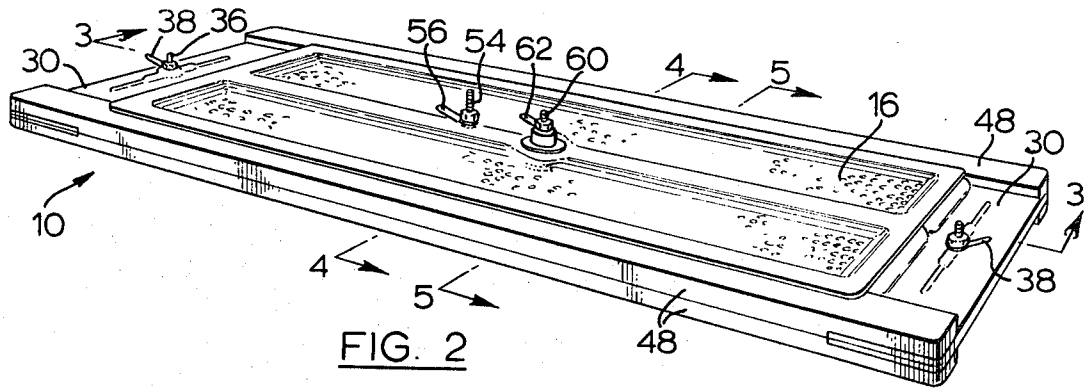


FIG. 2

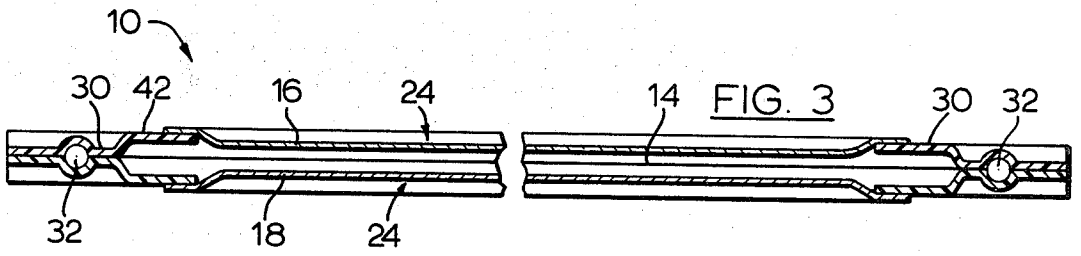


FIG. 3

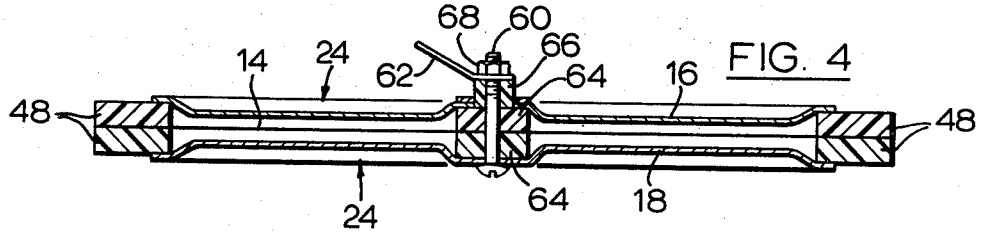


FIG. 4

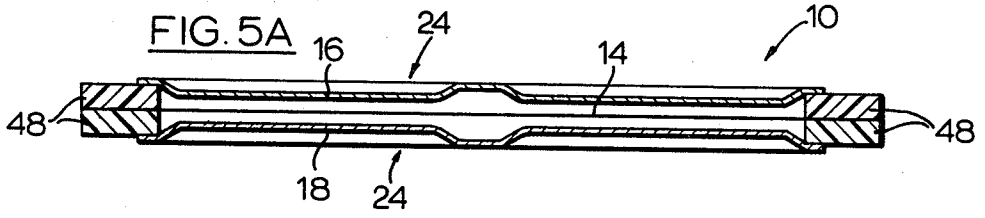


FIG. 5A

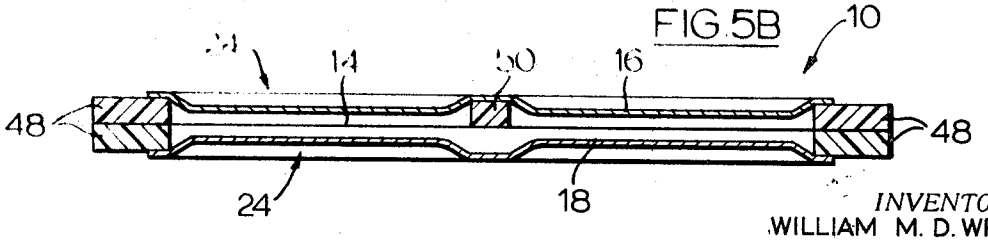


FIG. 5B

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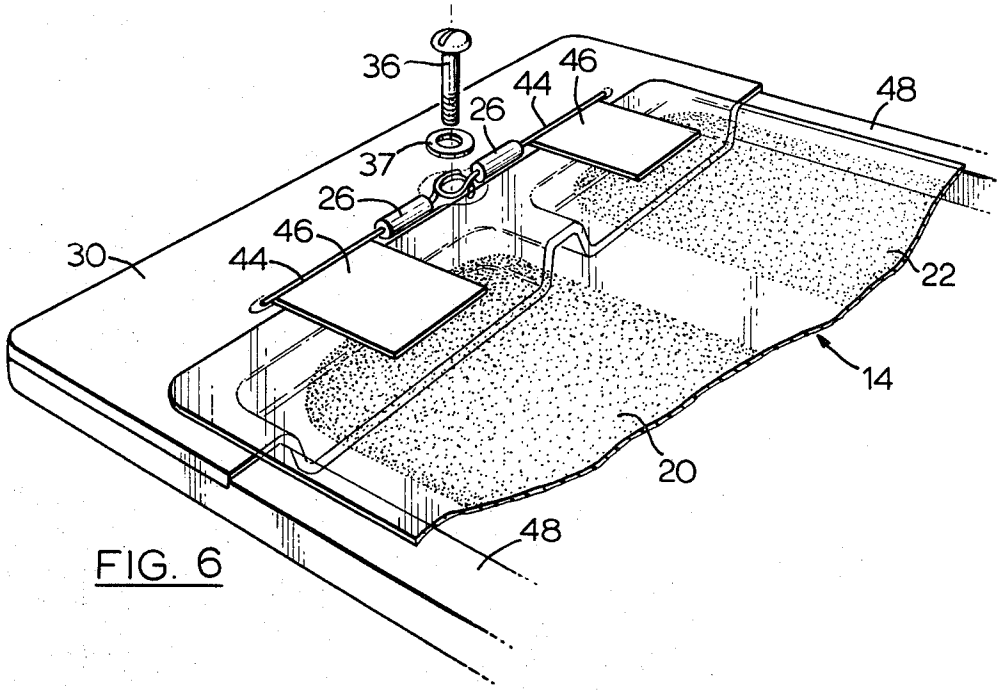


FIG. 6

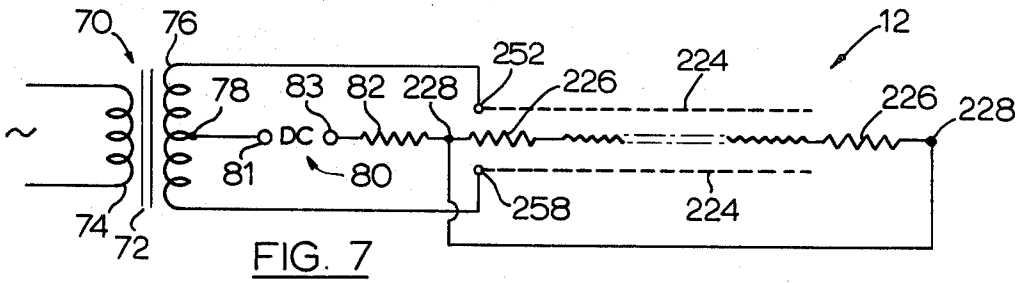


FIG. 7

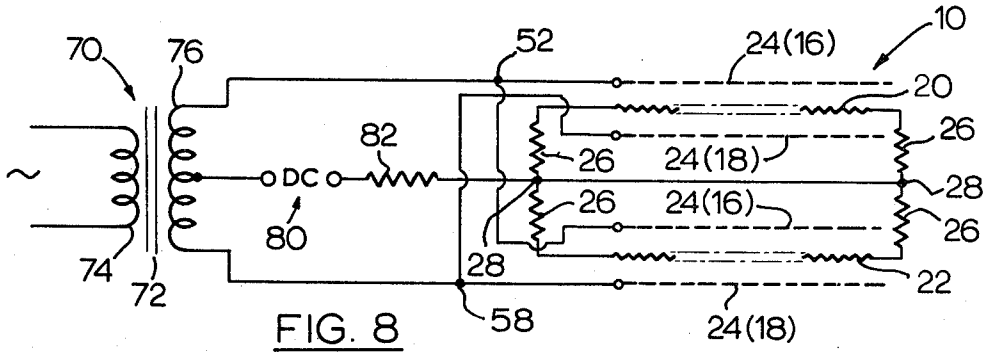


FIG. 8

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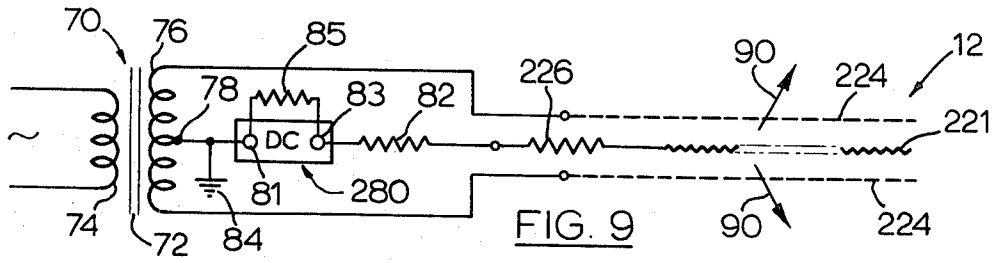


FIG. 9

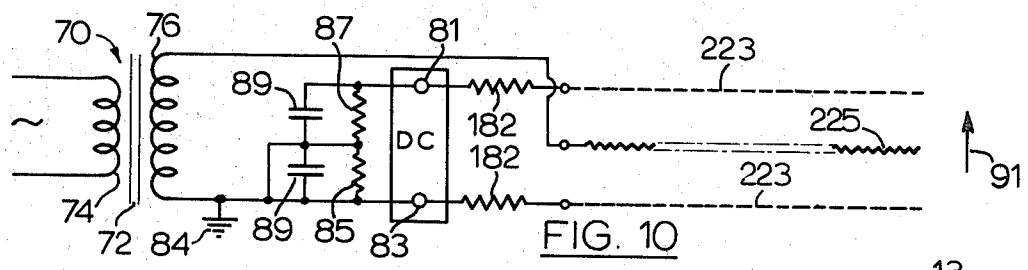


FIG. 10

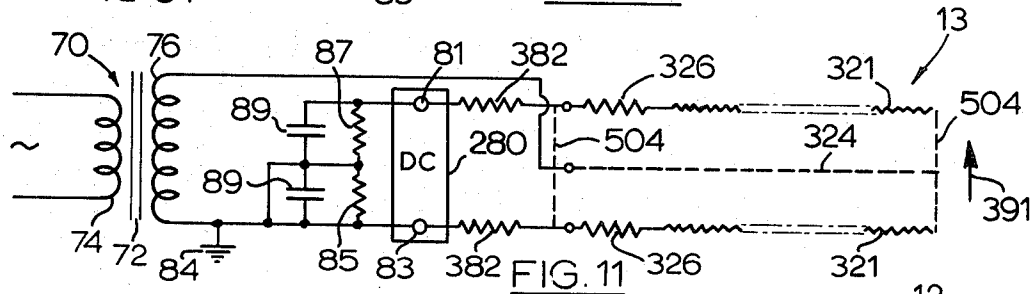


FIG. 11

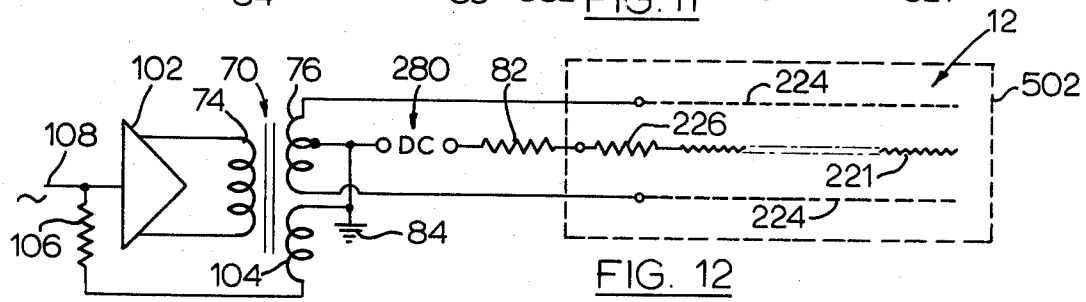


FIG. 12

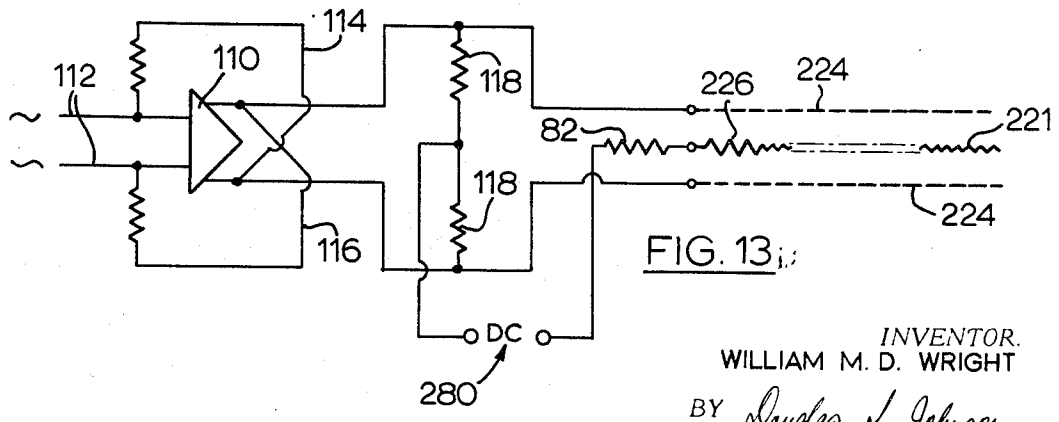


FIG. 13

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AUDIO SYSTEM INCLUDING ELECTROSTATIC LOUDSPEAKER

FIELD OF THE INVENTION

This invention relates to an audio system which comprises an audio frequency voltage output source and an electromechanical transducer having an audible output; and more particularly, the invention relates to a substantially constant charge electrostatic loudspeaker and its relationship to the audio power output driving the speaker in an audio system.

The present invention is related especially to electrostatic loudspeakers having three electrodes in spaced parallel relationship, at least one of which is a thin, movable diaphragm. Electrostatic fields are established between the center electrode and the two outside electrodes, which fields may be either additive or opposing, depending upon the circuit configuration.

BACKGROUND OF THE INVENTION

The efficiency and fidelity of the audio output of an electrostatic electro-acoustical transducer, i.e. an electrostatic loudspeaker, are both increased and enhanced where the area of each of the electrodes is large as compared to the spacings between them — say, 100 square inches to 0.25 inch — and it becomes important that the electrodes be rigidly mounted. Of course, allowance must be taken for the physical excursions of the movable diaphragm which, when held from its periphery, may move as a plane surface, a modified catenary or a catenary when the frequency of the impressed signal is above, at, or below the resonant frequency of the speaker. Further, the provision of relatively thin electrodes, both diaphragm electrodes and rigid metal electrodes as discussed hereafter, permits a high acoustical resolution with substantial acoustic transparency, while also permitting the maintenance of a smooth field gradient between electrodes. When a smooth field gradient is maintained between electrodes of an electrostatic speaker, and when the parallel and rigid relationship of the electrodes is also maintained, the unit may then be operated with high field and/or signal voltage gradients without surface voltage breakdown and without dielectric breakdown until the dielectric strength of the medium in which the electrodes are operating is reached.

It has been a fault of known electrostatic speakers that they could not be operated at high signal voltages without risking surface voltage breakdown. It has also been a fault of known electrostatic speakers that connections made to the front electrode of such a speaker were necessarily mechanically effected at that electrode. When the electrostatic speakers were enclosed behind grills or speaker cloth, etc., no problems were encountered; but in time the perforated metal or wire cloth electrodes which were very often used in electrostatic speakers became usable by interior decorators in decorative panels, etc., and electrical connections made thereto then became unsightly.

The electrical characteristics of electrostatic loudspeakers have very often been disregarded, except for matching of the loudspeaker to the output of an audio amplifier at a given frequency; and the usual considerations of capacitive loading, treble roll-off, etc., have also usually been taken into account. There has, however, been little effort made to actively incorporate the electrostatic speaker and its associated drive circuitry as a feedback source to the last stage of an audio output amplifier, thereby improving the damping characteristics, transient response, etc. of the audio amplifier.

This invention, therefore, serves to provide an audio system including an electrostatic loudspeaker which overcomes the shortcomings discussed above.

SUMMARY OF THE INVENTION

It is an object of this invention to provide an audio system including an electrostatic loudspeaker which can be easily assembled, and which provides an efficient, acoustically accurate audio output.

A further object of this invention is to provide an assembly for an electrostatic loudspeaker whereby all of the necessary electrical connections thereto may be made at one side thereof.

A further object of this invention is to provide an audio system including an audio output voltage source and an electro-mechanical transducer having a DC, substantially constant charge field impressed thereupon.

A still further object of this invention is to provide various alternatives for establishing a DC field and for impressing an audio frequency signal on an electrostatic loudspeaker.

Yet another object of this invention is to provide a loudspeaker which is operable in a gaseous medium other than air.

BRIEF DESCRIPTION OF THE DRAWINGS:

These and other features and objects of the invention are discussed more fully hereafter, in association with the accompanying drawings, in which:

FIG. **1** is an exploded view, partially in cross-section, of the major components of one embodiment of an electrostatic speaker made in accordance with this invention.

FIG. **2** is a perspective view of an assembled electrostatic speaker similar to that of FIG. **1**.

FIG. **3** is a cross-sectional view in a length-wise direction taken along the line **3—3** of FIG. **2**.

FIG. **4** is a cross-section in a cross-wise direction taken along the line **4—4** in FIG. **2**.

FIG. **5A** is a cross-section in a cross-wise direction taken along the line **5—5** in FIG. **2**.

FIG. **5B** is a cross-section similar to that of FIG. **5A**, and showing an alternative, preferred, embodiment of the electrostatic speaker of FIG. **2**.

FIG. **6** is a perspective, cross-sectional view of a portion of an electrostatic speaker assembled in accordance with this invention.

FIG. **7** is a simplified circuit showing the electrical connections to a preferred embodiment of the electrostatic speaker of this invention in an audio output system according to this invention, and operating in a preferred mode.

FIG. **8** is a simplified circuit diagram showing an audio system according to this invention in a preferred mode, and utilizing an electrostatic speaker similar to that shown in FIGS. **1** to **6**.

FIG. **9** is an alternative, simplified circuit diagram for a preferred mode of operation of the audio system according to this invention.

FIG. **10** is a simplified circuit diagram showing an alternate mode of operation of the audio system of this invention.

FIG. **11** is a simplified circuit diagram showing yet another mode of operation of the audio system according to this invention.

FIG. **12** is a simplified circuit diagram showing one form of negative feedback in an audio system according to this invention; and

FIG. **13** is a simplified circuit diagram showing another mode of negative feedback in an audio system according to this invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

An electrostatic speaker **10** is illustrated in FIGS. **1** to **6**; and is indicated in FIG. **8**. For purposes of simplicity, as will be discussed hereafter, a simplified circuit presentation of the speaker **10** is shown at **12** in FIGS. **7**, **9**, **10**, **12** and **13**.

The electrostatic speaker **10**, (and the electrostatic speaker **12**) basically comprises a thin, pliant, diaphragm **14** and two metal electrodes **16** and **18**. At least one side of the diaphragm **14** is coated with a highly resistive electrically conductive layer as at **20** and **22** in FIG. **1**. Each high resistivity electrically conductive layer on the surface of diaphragm **14** may be formed from a graphite suspension in a suitable wetting agent, or a carbon/molybdenum suspension, or any suitable high resistivity coatings as are well known in the electrostatic speaker

art; and the high resistivity electrically conductive layer is suitably brushed in suspension onto the required portions of the surface of the diaphragm and permitted to dry. The resistivity of the high resistivity electrically conductive portions of the surface of diaphragm **14** is at least 100 megohms per unit square.

The electrodes **16** and **18** are suitably formed of perforated metal, metal screen or wire cloth, and are mechanically rigid especially in comparison to the diaphragm **14**. In the preferred embodiment shown, dished portions **24** are formed in each of the electrodes **16** and **18**. It will be noted that each dish **24** is formed so that the bottom thereof is substantially planar, with the bottoms of adjacent dishes **24** formed in any one of the electrodes **16** or **18** being substantially coplanar. As will be noted hereafter, the assembly of the preferred electrostatic speaker illustrated in FIGS. **1** to **6** assures a substantially parallel and mechanically rigid relationship of the diaphragm **14** (when at rest) with the electrodes **16** and **18**.

The material from which the electrodes **16** and **18** are made is chosen so as to be electrically conductive and substantially acoustically transparent, as well as mechanically rigid. The electrodes **16** and **18** may conveniently be stamped or pressed using well known metal working techniques. The diaphragm **14** may be formed from a sheet of thin, pliant, plastic material having sufficient tear strength to retain its integrity during operation; and may conveniently be made from such materials as saran, Pliofilm or mylar.

The preferred embodiment of the electrostatic speaker **10** has two adjacent dished portions **24** formed in each of the electrodes **16** and **18**, and two adjacent conductive portions **20** and **22** on at least one of the surfaces of diaphragm **14**. The area covered by each of the conductive portions **20** or **22** is slightly less than the area of any one of the dished portions **24**.

Turning briefly to FIGS. **7** and **8**, the electrostatic speaker **10** is represented in FIG. **8** with the various dished portions **24** and the conductive layers **20** and **22** being designated in that Figure. Resistors **26** are indicated in FIG. **8** and shown pictorially in FIG. **1**. The resistance of each of the resistors **26** is identical to that of each of the other resistors, within reasonable tolerance. In FIG. **8**, the designation **16** or **18** in brackets after the designations **24** refers to the metal electrode in which each respective dished portion **24** is to be found. It will be noted, therefore, that each of the dished portions **24** in electrode **16** is electrically, equi-potentially connected to the other dished portion **24**; and similarly with the dished portions **24** in the electrode **18**. Likewise, with respect to the junction point **28** which is illustrated at either end of the circuit representation of speaker **10** in FIG. **8**, the high resistivity electrically conductive portions **20** and **22** of the diaphragm **14** are each, respectively, electrically away from the junction point **28** by the value of each resistor **26**. In other words, each half of the electrostatic speaker **10** is electrically identical to the other half, and those halves are therefore represented by one circuit designation of a speaker **12** illustrated in FIG. **7**. Thus, speaker **12** comprises screens **224** (the work 'screen' as used herein designates the dished portion **24** of either of the electrodes **16** or **18**, or the equivalent thereof) along with electrically conductive layer **221** on the diaphragm which is situated between the screens **224** together with resistors **226** at either end thereof. Likewise, the circuit representation of electrostatic speaker **12** in FIGS. **9**, **10**, **12** and **13** omits the right-hand representation of the junction point **228** which is electrically identical to, although physically separated from, the left-hand junction point **228**. The electro-mechanical transduction or electro-acoustical power transformations which are accomplished in the electrostatic speakers according to this invention are most easily understood with reference to the simplified circuit representations thereof as shown particularly in FIGS. **9** through **13**, and as discussed hereafter.

The physical, mechanical assembly of the preferred embodiment of the electrostatic speaker according to this invention, as illustrated in FIGS. **1** through **6** (including a preferred alternative embodiment as shown in FIG. **5B**) is discussed below:

After the high resistivity electrically conductive layer or coating **20** and **22** is placed in the designated portions on at least one of the surfaces of diaphragm **14**, the diaphragm is placed between two pairs of end shells **30**. Each of the end shells **30** is conveniently vacuum formed of a suitable, electrically insulating plastic; and has recesses **32** formed therein which will accommodate each of the resistors **26** and hole **34** through which suitable fastening means such as screw **36** may be passed to be later fastened with lug **38** and nut **40**. Cups **42** are conveniently formed in end shelves **30** to support the ends of electrodes **16** and **18**, as illustrated in FIG. **3**.

FIG. **6** illustrates a preferred method of attachment of the resistors **26** into the electrical circuit of the speaker **10**, and the left-hand upper end shall **30** as shown in FIG. **1** is illustrated in upside-down position in FIG. **6**. It is noted that the diaphragm **14** is supported over at least a portion of the underside (that is, the up side as illustrated) of the end shell **30**. The support of the diaphragm **14** may be temporary at this time, as is discussed in greater detail hereafter. In any event, it is noted that bolt **36** passing through washer **37** effects an electrical connection to the inner pigtails of each of resistors **26**, and the outer pigtails **44** of resistors **26** extend away from the bolt **36** in the manner shown. A foil strip **46**, or a strip of silver paint or other suitable conductive paint or lacquer, is passed from each pigtail **44** to either of the high resistivity electrically conductive layers **20** or **22** respectively. A good, physically pliant electrical connection from resistor **26** to either of the high resistivity conductive portions **20** or **22** of diaphragm **14** is thereby assured. As noted above, similar mechanical and electrical connections are made at the other end (i.e. the right-hand end as illustrated in FIG. **1**) of the electrostatic speaker as shown.

In any event, the electrostatic speaker is assembled so that the conductive portions **20** or **22** of the diaphragm **14** underlie the dished portions **24** of the electrodes **16** and **18**; and the electrodes **16** and **18**, the diaphragm **14**, the end shells **30** with resistors **26** and bolts **36**, etc. are then assembled together with side braces **48** so that the various electrodes, diaphragm, etc., have the respective inter-related positions one to another as illustrated in FIGS. **1**, **2**, **3**, **5A** and **6**. Epoxy cement is spread around the periphery of each of the electrodes **16** and **18** where they will contact end shells **30** or side braces **48**, and between the end shells and the side braces so as to securely and rigidly hold the diaphragm **14** in place as well as the electrodes **16** and **18**; and the entire assembly is clamped together and set aside until the epoxy cement has cured. Other suitable cements or assembly techniques may be used provided that they do not introduce unwanted audible or electrical interference with the operation of the electrostatic speaker as discussed hereafter.

A preferred embodiment of the electrostatic speaker illustrated includes a stiffener rib **50** which extends down the center between the dished portions **24** of either of the electrodes **16** and **18** (or both, but in this case electrode **16**); and the stiffener rib **50** is securely fastened by cement or otherwise to the portions of the electrode with which it contacts, and to the diaphragm **14**. Thus, the mechanical assembly of the electrostatic speaker in accordance with the embodiment illustrated in FIG. **5B** provides essentially two speakers side by side with the diaphragm **14** rigidly held in each one of them and having a span width less than one half the width of the diaphragm span width as illustrated in FIG. **5A**. The power handling capacity of a speaker made according to the embodiment illustrated in FIG. **5B** is therefore enhanced over that of a speaker as illustrated in FIG. **5A**, because the excursions taken at the center of the diaphragm under any given power/field conditions are less for the FIG. **5B** configuration as opposed to the FIG. **5A** configuration or embodiment.

Referring briefly to FIG. **2** and to FIGS. **7** or **8**, it will be noted that the junction points **28** or **228** are effected, mechanically, by bolts **36**. Similarly, the junction point **52** or **252** is conveniently, mechanically effected by bolt **54** with lug **56**, shown in FIG. **2** on electrode **16**. The junction point **58** or **258** may conveniently be effected by bolt **60** together with lug **62** and nut **68** in the manner discussed hereafter.

Referring especially to FIGS. 1 and 4, it will be noted that the bolt 60 extends upwardly through a pair of aligned insulating spacer blocks 64 which are placed on either side of the diaphragm 14. A further spacer block 66 may be placed above the electrode 16 so as to place the lug 62 well above the surface of electrode 16. Nut 68 is turned down on the bolt 60, and a clamping action is then achieved between the underside of the head of the bolt — which is contacting the outside surface of the electrode 18 — and the underside of the nut 68 and lug 62. Thus, as the nut 68 is turned down over the bolt 60, a mechanical clamping of electrodes 16 to 18 is assured. However, because of the insulative properties of spacer blocks 64 and 66, the lug 62 is electrically connected to electrode 18 but electrically insulated from electrode 16. It is now seen that the electrical connection to each of electrodes 16 and 18 may be conveniently made on one side of the electrostatic speaker 10 or 12. Also, as noted, the junction points 28 or 228 are mechanically situated on the same side of the electrostatic speaker 10 or 12 through bolts 36, together with lugs 38 and nuts 40.

The electro-acoustical operation of the audio system according to this invention is discussed below: Reference is made to FIGS. 7 and 9, which as discussed above and with the exceptions noted below, are identical. Particularly, the circuits of FIGS. 7 and 9 show an input transformer 70 to the audio system circuit; and the transformer has a core 72, primary winding 74 and secondary winding 76. (The audio frequency transformer 70 is also shown in FIGS. 8, 10, 11 and 13.) In the usual circumstance, the audio frequency transformer 72 is a step up transformer; but in any event, the transformer is an audio frequency voltage output source in which an audio frequency voltage appears across the secondary winding 76. Also, of course, the audio frequency transformer 70 may be replaced with transformer-less, usually transistorized, audio output circuitry of the type well known in the audio amplifier art.

The circuit of FIG. 7 includes a center-tap 78 on the secondary winding 76 of transformer 70, and a DC input 80 having terminals 81 and 83. A resistor 82 is inserted in the line between terminal 83 and junction point 228 on speaker 12.

The center-tap 78 is also made on secondary winding 76 in FIG. 9, and a DC source 280 is inserted between resistor 82 and center-tap 78, and having terminals 81 and 83, as before. Additionally, DC source 280 is shown as having a resistor 85 across its output terminals 81 and 82; but the resistor 85 across the output of DC source 280 is shown merely to indicate that the source may be regarded as having a very high output impedance. Of course, if the voltage output from DC source 280 is absolutely ripple free, it would be impossible to measure any impedance as indicated at resistor 85. Finally, a ground connection to ground 84 is shown so that the center-tap 78 and the terminal 81 are at ground potential.

It is not indicated which of terminals 81 and 83 is positive and which is negative; nor does the polarity of the DC source materially effect the operation of the audio system of this invention and particularly the operation of the electrostatic speaker. It will be noted that the screens 224 of electrostatic speaker 12 in FIG. 9 are also at ground potential, DC-wise; and, subject to charging current limitations and other, extremely small, current flow circumstances during operation — all of which current limitations may slightly effect potential because of resistors 82 and 226 — the potential of the conductive layer 221 on the diaphragm of the electrostatic speaker 12 is essentially that of terminal 83 of DC source 280. (It should be stressed that the electrostatic speaker 12 is essentially one in which an electrostatic, DC field is maintained; so that the physical inter-position of the diaphragm 14 on one side or the other of its high resistivity electrically conductive layer 221, and between it and one of the screens 224, will have no effect as to the maintenance of an electrostatic field therebetween.)

The value of the resistor 82 is chosen so that the time constant for the circuit comprising the diaphragm to electrode capacitances, in parallel, and shunted by the isolating resistor 26, will be substantially longer than the period of the lowest operating frequency impressed on the electrostatic speaker. The value of the resistor 82 may typically be between 50 and 1,000 megohms.

The value of each isolation resistor 26 or 226 is chosen so that, having regard to the capacitance of the electrostatic speaker — which capacitance value may be readily determined knowing all of the parameters as to area of the electrodes, spacing therebetween, dielectric strength, etc. — the time constant of the RC circuit formed by the resistor 26 or 226 and the capacitance of the electrostatic speaker 10 or 12 will be such that, during operation of the speaker, the discharging effects which may be happening at one of the high resistivity conductive layers on the diaphragm will not substantially alter or affect the operation (and the charge) of the other high resistivity conductive layer on the diaphragm. At noted, the two conductive portions 20 and 22 of diaphragm 14 are connected in the same DC charging circuit; and the isolating resistors 26 effectively isolate any capacitance discharge or AC operating phenomena of the one conductive portion from the other. Typically, the value of each isolating resistor 26 may be between 20 and 100 megohms.

The quality of the DC voltage which is delivered from the DC source 80 or 280 may vary; but usually a high voltage DC generator is provided having a DC output with less than 10 percent ripple. The effect of ripple, especially high percentage ripple in a DC output where the peak-to-peak value of that ripple may approach the peak-to-peak signal voltages, may be noticable especially when the DC is derived from a rectified AC having a base frequency within the audible range, and usually from 60 to 440 Hz.

In any event, for purposes of this discussion, it is assumed that each of screens 224 of electrostatic speaker 12 in FIG. 9 is at ground potential and that the high resistivity electrically conductive layer 221 on the diaphragm is negative with respect to ground so that an electrostatic, DC, field is established between the conductive layer 221 and each of the screens 227 in an outwards direction as indicated by arrows 90. There are, therefore, two opposed electrostatic fields, one on either side of the high resistivity electrically conductive layer 221 of diaphragm 14. When no AC signal is applied to the screens 224, the audio system and particularly the electrostatic speaker 12, is quiescent, and there is no audible power output from the electrostatic speaker 12. However, assume that an audio frequency signal is impressed on primary winding 74 of transformer 70, which signal appears across the secondary winding 76. For ease of discussion, the audio system of the circuit in FIG. 9 will be considered at one instant in time, and it will be assumed that the audio frequency signal (whether it is of simple or complex wave form is immaterial) is positive going at the instant of time in question. Because the secondary winding 76 is center-tapped, and assuming a polarity of the windings 74 and 76 so that the top end of winding 76 goes positive when the top end of winding 74 goes positive, then the top end of winding 76 and top screen 224 are positive going and the bottom end of winding 76 and bottom screen 224 are negative going with respect to ground 84 at the particular instant being spoken of.

The value of the voltage output of the DC source 280 is chosen so that, having regard to all of the physical parameters of the electrostatic speaker 12, an electrostatic, DC, field is established as shown at arrows 90 having a field gradient of from 10 to 40 Kv per inch. Likewise, the audio frequency voltage output source (in this case transformer 70) is chosen so that the audio frequency signal applied across the screens 224 of electrostatic speaker 12 may, at peak signal voltages, provide an instantaneous field having a field gradient of up to 40 Kv per inch.

In any event, having regard once again to the effect of the field as indicated at arrows 90 in FIG. 9, and the effect of the signal voltages impressed on screens 224 at the instant in question, it will now be noted that the negative going signal on the lower screen 224 will have the effect of instantaneously reducing the electric field established between conductive

layer **221** and lower screen **224**; with the physical effect that the diaphragm begins a physical excursion towards the lower screen **224**. In addition, the positive going signal applied to the upper screen **224** has an additive effect to the DC field established between the conductive layer **221** of diaphragm **14** and the upper screen **224**. The physical manifestation of the additive effect of the instantaneous signal field upon the established electrostatic field is that the diaphragm **14** begins a physical excursion downwards away from the upper screen **224**. That is, the audio signal applied across the screens **224** as shown in FIG. **9**, is additive with the electrostatic fields established as indicated at arrows **90**, with respect to the net effect on the physical motion of diaphragm **14**. Therefore, an audible power output from the electrostatic speaker **12** and the audio system of FIG. **9** may be realized in real time by virtue of the physical motion of the diaphragm **14** under the effect of the established electrostatic field and the audio frequency field superimposed thereon.

No consideration is made of the specific problems of compliance, mass inertia, etc., of the diaphragm **14** in this invention, Such problems which directly effect the physical motion and mechanical suspension of the diaphragm are well considered in the literature, such as Wright U.S. Pat. No. 3,135,838, issued June 2, 1964; Bobb U.S. Pat. No. 2,878,323, issued March 17, 1959; or Williamson et al U.S. Pat. Nos. 3,008,013 and 3,008,014, issued Nov. 7, 1961. Also, as mentioned above, the material of the screens **224** — that is the material of the metal electrodes **16** and **18** — is such as to be mechanically substantially rigid and acoustically substantially transparent.

The center-tap of secondary winding **76** and the DC connection thereto and through the winding to the screens **224**, can accommodate a physically symmetrical assembly of the electrostatic speaker **12**. In this way, the opposed electrostatic fields can be easily established in the electrostatic speaker, and the audio frequency signals impressed on the screens **224** then act additively on the opposed fields, as discussed above.

The preceeding discussion is relevant to the electrostatic speakers **10** and **12**, and to the circuitry, as illustrated in FIGS. **7**, **8** and **9**.

In another embodiment of the invention, as illustrated in FIG. **10**, the electrostatic field is established between screens **223** which are isolated from each other in a DC sense, but which are electrically connected in an AC sense. Specifically, it will be noted that there is a center-tap **87** on resistor **85**, which center-tap is grounded at **84**. In the sense of the DC portion of the circuit illustrated in FIG. **10**, therefore, the terminal **81** and the upper screen **223** attached thereto are positive with respect to ground; and likewise the terminal **83** and the lower screen **233** attached thereto are negative with respect to ground. There is, therefore, an electrostatic field established between the lower and upper screens **223** in the direction indicated by arrow **91**. DC blocking capacitors **89** are connected from terminals **81** and **83** respectively to ground; and the value of capacitors **89** is chosen so that they represent an AC shunt to any signal within the audio frequency which would be impressed thereupon. Therefore, the screens **223** are electrically connected in an AC sense and isolated in a DC, electrostatic, sense.

The screens **223** and diaphragm coating **225** of the electrostatic speaker **15** of FIG. **10** have high and low impedances, respectively. That is, in this embodiment, the screens **223** have a high resistivity per unit square — in the order of 100 megohms or more — and the conductive layer **225** on the diaphragm has a low resistance.

The screens may be made by coating a mechanically stiff, acoustically transparent and electrically insulating plate member with high resistivity coating as previously discussed; or by such means as vacuum depositing a very thin metallic or semiconductive layer on the plate member. The diaphragm may have a low resistance layer such as foil or conductive paint or lacquer placed on it in the working portion of its effective, suspended area.

In the circuit of FIG. **10**, the isolating resistors **182** are placed between the output of the DC source **280** and each of the high resistivity screens **223**, respectively. There is no separate resistance placed in the circuit between the upper end of secondary winding **76** and the low resistance layer **225** on the diaphragm.

It was noted above that field established between screens **223** acts upwardly in the direction indicated by arrow **91**. It may be convenient to regard the field as being the additive combination of two fields; viz., the field between lower screen **223** and diaphragm **225**, and the field between diaphragm **225** and upper screen **223**.

Having regard to a signal impressed upon the audio frequency voltage output source (i.e. transformer **70**) in FIG. **10**, it is convenient to regard an instantaneous condition of the transformer when the upper end of both primary and secondary windings **74** and **76** respectively are positive going. For that purpose, it is convenient to regard the lower end of the primary and secondary windings as being connected to ground. In any event, it will be noted that as the upper end of the secondary winding **76** is positive going, an instantaneous field gradient is established between the conductive layer **225** and the screens **223** such that the signal field gradient is directed from ground potential to the higher potential; and therefore the signal field gradient is directed from each of the screens **223** towards the conductive layer **225**. However, having regard to the electrostatic fields and the effect of the signal voltage field gradient thereupon as each occurs between one of the screens **223** and the conductive layer **225**, it will be noted that since the electrostatic field is directed upwards from lower screen **223** to the conductive layer **225**, a positive going signal on the conductive layer **225** with respect to the lower screen **223** will cause the diaphragm to begin an upwards excursion away from the lower screen **223**. Likewise, there is an additive, electrostatic field extending upwardly from the conductive layer **225** towards the upper screen **223** as discussed above; and when the signal voltage gradient appears between those electrodes at the instant chosen, the conductive layer **225** is positive going with respect to the upper screen **223** — or in other words, the upper screen **223** may be considered to be negative going with respect to the conductive layer **225** — and therefore, the interaction of the electrostatic field with the signal voltage field is manifested by an upward excursion of the diaphragm towards the upper screen **223**. The net effects of the signal voltage gradient with the electrostatic field on the diaphragm are, once again, additive; and an audible power output from the electrostatic speaker **15** is heard.

Yet another embodiment of the audio system according to this invention is illustrated in simplified circuit form in FIG. **11**, having speaker **13** designated therein. It will be noted that the AC and DC portions of the circuit of FIG. **11** are substantially the same as in FIG. **10**, with the net result that an upwards directed electrostatic field may be considered to be established as indicated at arrow **391**. However, it will be noted in the circuit of FIG. **11** that isolating resistors **382** are connected to the output side of the DC power source **280** at terminals **81** and **83** thereof, and that the isolating resistor **382** are in turn connected each respectively to an input resistor **326** which in turn is connected to a high resistivity electrically conductive layer **321**. Obviously, the high resistivity electrically conductive layers **321** are to be found, respectively, on a pair of diaphragms which would be mounted having a fixed spacing and with as great mechanical rigidity as possible when in a quiescent state. A single, mechanically rigid and acoustically substantially transparent screen **324** is mechanically, rigidly fixed between the diaphragms on which the high resistivity conductive layers **321** are found.

In the audio system illustrated in FIG. **11**, the electrostatic field is directed as indicated by arrow **391** across the screen **324** which is DC-wise, at ground potential. Therefore, because the screen **224** is rigid and the diaphragms are movable, when the DC field between the diaphragms is switched on, one of the high resistivity conductive layers on one of the diaphragms

(in this case the lower diaphragm) is negative with respect to ground and the other is positive; with the net result that an instantaneous migration of each of the diaphragms towards the center screen **324** is manifested. Thus, when the DC field between the diaphragms in the circuit of FIG. **11** is turned on, the spacing therebetween becomes slightly less than the non-operative spacing.

The electrical operation of the audio system of FIG. **11** is essentially the same as that described above with respect to FIG. **10**; except that each of the diaphragms moves in accordance with the effect of the interaction of the signal voltage field gradient with the DC field. However, as discussed above, the effects of a —say — positive going signal on screen **324** with respect to either of the diaphragms **321** would be additive so that the diaphragms would each move in one direction or the other at any given instant of time.

It should also be noted from FIGS. **12** and **13** that the electro-mechanical transducers—i.e., the electrostatic speakers **12** — of the audio system shown in simplified circuit form in either of those figures are electrically connected to a negative feedback input to the audio frequency voltage output source. Thus, in FIG. **12**, a last stage amplifier is shown at **102** feeding the audio frequency transformer **70** on the secondary side of which there is an additional winding **104**. One end of the additional winding **104** is grounded and the other end is connected through resistor **106** to the input to the last stage amplifier **102**. By properly choosing the polarity of the additional winding **104** on the secondary side of the transformer **70**, a negative feedback to the signal line **108** is established. Of course, the grounded end of the additional winding **104** also is equipotentially connected to the screens **224** of the electrostatic speaker **12**. The operation of the circuit of FIG. **12** is substantially as described above with respect to any of FIGS. **7**, **8** or **9**, and the effect of the negative feedback to the last stage of the audio amplifier which is a part of the audio frequency voltage output source of the audio system, is well know.

Likewise, a transformer-less audio frequency voltage output source **110** is illustrated in FIG. **13** having push-pull input **112** and having cross-connected negative feedback **114, 116**. In this case, the output voltage of the source **110** appears across a voltage divider comprising resistors **118** so that a balanced, substantially center-capped voltage divider means appears with the DC source **280** connected thereto. The remaining connection to the screens **224** and high resistivity electrically conductive layer **221** of the diaphragm **14** of electrostatic speaker **12**, through isolating resistor **82** and input resistor **226** are as discussed above; and the operation of the circuit is also as discussed above.

Any of the electro-mechanical transducers **10, 12** or **13** — that is, the electrostatic speakers — may be operated in a gaseous medium other than air. Preferably, the dielectric strength of that gaseous medium is at least equal to that of air. In the case of a speaker such as electrostatic speaker **12**, it may be placed in a sealed enclosure having membrane or diaphragm side or sides of the proper compliance, etc. One such enclosure is shown schematically in FIG. **12** around electrostatic speaker **12** at **502**.

It should be noted that the speaker **13** illustrated in FIG. **11** and discussed above may be hermetically sealed as at **504** so that two of the surfaces of the sealed enclosures are comprised essentially of the diaphragms on which the high resistivity conductive layers **321** are to be found. In either case — that is in the case of an hermetically sealed speaker **13** having seals **504**, or a speaker **12** in an hermetically sealed enclosure **502** — the gaseous medium may be one whose density is either greater or less than that of air. One gaseous medium whose density is considerably greater than that of air and whose dielectric strength is higher to that of air and which, therefore, provides considerably altered acoustical qualities to a speaker, particularly at lower frequencies, is sulphur hexafluoride. Other gaseous mediums may also be used; and indeed a gaseous medium having a dielectric strength less than that of air may be used provided the necessary design considerations with respect to electrode spacing are taken account of.

All of the above discussion assumes an electrostatic field, with little or no charging current to maintain the electrostatic field after the electrostatic speaker has been initially energized. That is, when the DC source which establishes and maintains the electrostatic field is first turned on and the electrodes to which it is connected are uncharged, a charging current will occur until the electrodes are charged and the field established. Because the electrostatic speaker has finite volume and surface resistances, as well as finite dimensional limits, there may be very slight currents from the DC charge to the electrodes to maintain the electrostatic fields; but the fields that are established and maintained can be assumed to be steady, electrostatic fields, and the current drain necessary to maintain the electrostatic fields is immaterial to the operation of any of the circuits discussed above.

The operation of any of the electrostatic speakers in any of the audio systems of the circuits discussed above is substantially linear with respect to the audio frequency signal source. This is explained as follows. Assume a field gradient $\bar{E}$ established between electrodes having fixed, constant spacing (d); and assume a voltage (e) applied between the electrodes. The magnitude of the field gradient $\bar{E}$ is proportional to the spacing and the voltage, and therefore,

$$\bar{E} = K_1 \cdot e/d \qquad \text{(Equation 1)}$$

or

$$\bar{E} = K_2 \cdot e \qquad \text{(Equation 2)}$$

where K_1 and K_2 are system constants.

Next, as discussed above, assume that there is no meaningful current flowing in the electrostatic field charging circuit, so that the electrostatic field is constant, and the charge maintaining it is constant. Any isolated charge Q which has a constant magnitude or magnitude per unit area will have no effect on the field gradient. However, the electromotive force $\bar{F}$ acting on that charge will be proportional to the magnitude of the charge and gradient so that

$$\bar{F} = K_3 (\bar{E} \cdot Q) \qquad \text{(Equation 3)}$$

where K_3 is a system constant. Therefore,

$$\bar{F} = K_3 . Q . K_2 . e \qquad \text{(Equation 4)}$$

where K_3 is another system constant; and for constant Q,

$$K_3 \cdot Q \cdot K_2 = K_4 \qquad \text{(Equation 5)}$$

and

$$\bar{F} = K_4 \cdot e \qquad \text{(Equation 6)}$$

Thus, where there is a constant electrostatic field having a constant charge and a fixed spacing, and therefore having a constant electrostatic field gradient; the magnitude of the electromotive force acting on a charge in the field gradient will be proportional to the applied voltage on that field. As noted, the applied voltage on the electrostatic field is the voltage derived from the audio frequency voltage output source; in other words, the audio signal in the audio system of this invention.

It should also be noted that the input impedance of the electromechanical transducer of this invention (i.e. the electrostatic speaker) is substantially capacitive. Any resistive component that may be noticed appears primarily because of the radiation resistance of the transducer, rather than as the result of any mass reactance of the diaphragm or any compliance reactance thereof. This is essentially so, because the diaphragm is very light.

It can now be noted therefore that operation of the audio system according to this invention — especially when power amplification means are employed having negative voltage feedback, so as to provide output voltage proportional to its input voltage — may be such that the audible power output from the audio system is nearly directed proportional to the input signal applied — in the first instance — to an audio power amplifier from which the aforestated output voltage is derived. In other words, especially where the means providing the output voltage is relatively insensitive insofar as variations

of its loading may be concerned, and having in mind all of the power delivery and power handling limitations of audio amplifiers — even those of the highest quality — the proportionality of the audio output to the applied signal is direct to a very high degree.

There are audio amplifiers known in the market place having very high quality and having highly proportional output signals relative to their input signals. However, the linearity of the audio amplifiers has very often been much higher than that of the speakers which they were driving, with the result that the cost of audio system has very often been higher, proportionately, to the quality of audio output therefrom than would be the cost of otherwise comparable audio systems according to the present invention.

The physical emplacement of the electrodes and diaphragm of the preferred embodiment of the electro-mechanical transducer (electrostatic speaker) according to this invention give effect to a smooth change in field gradient between the supporting structure, and especially the end shells **30**, and the "active" area of the electro-mechanical transducer which includes the high resistivity conductive portions of the diaphragm and the screens associated therewith. Because the audio system including the electro-mechanical transducer is essentially a constant charge device, the physical action of the diaphragm(s) is substantially proportional to the impressed audio frequency signal voltage.

It has further been seen that the electrostatic loudspeaker which forms a part of this invention is easily and accurately assembled so as to assure the proper functioning thereof. It has been noted that all of the electrical connections to the electro-mechanical transducer which are necessary in an audio system in accordance with this invention may be made on one side only of the electrostatic speaker comprising the electro-mechanical transducer. Still further, a rigid, mechanical clamping means is provided for an electrostatic speaker; thereby enhancing the efficiency, clarity and power handling capacity of the speaker.

Finally, various alternative circuit arrangements have been shown for providing the DC and signal voltage feeds to the electro-mechanical transducer so that the transducer may operate in one of several modes of operation having respect to the electrostatic field which is formed therein. Also, it has been shown that the electro-mechanical transducer which constitutes a portion of this invention may be operated in the gaseous medium other than air; and one embodiment of an electrostatic speaker has been shown, which can, itself, be hermetically sealed to contain a gaseous medium therein other than air.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. An audio system including an audio frequency voltage output source and an electro-mechanical transducer means electrically connected thereto and having an audible power output:

wherein a substantially balanced, center-tapped voltage divider means is connected across said voltage output source, and said center-tap is connected through a DC source and a high resistance electrical input to thin, pliant and movable diaphragm means in said electro-mechanical transducer means;

said diaphragm means having two major surfaces and being electrically conductive with high resistivity over at least one major portion of at least one of said major surfaces;

said diaphragm being mechanically suspended between substantially parallel, mechanically rigid, electrically conductive and acoustically substantially transparent plate means; said plate means being electrically connected across said audio frequency voltage output source; each said at least one major portion of said at least one major surface of said diaphragm means being bounded at its periphery by a portion of said diaphragm surface which is substantially electrically non-conductive.

2. The audio system of claim **1** where each of said plate means is dished so that each said at least one major portion of said at least one major surface of said diaphragm means substantially underlies a dished portion of each said plate means.

3. The audio system of claim **2** where said DC source provides a substantially constant charge to the high resistivity electrically conductive portion of said at least one major surface of said diaphragm means.

4. The audio system of claim **3** where said audio frequency voltage output source has a negative feedback input therefrom, and where said electro-mechanical transducer means is electrically connected to said negative feedback input

5. The audio system of claim **3** where said audio frequency voltage output source is capable of producing a complex audio output signal having a signal voltage providing a field gradient of up to 40 Kv per inch; and where said DC source provides a DC field having a field gradient of from 10 to 40 Kv per inch.

6. The audio system of claim **3** where said electro-mechanical transducer means includes at least one pair of aligned, highly insulative spacer blocks, one on each side of said diaphragm and compressively held between the diaphragm surface and the respective plate means spaced therefrom.

7. The audio system of claim **6** further comprising electrically conductive means extending through a pair of aligned spacer blocks and electrically connecting the plate means on a first side of said electro-mechanical transducer means with electrical connector means projecting above the plate means on the second side thereof, so that said electrical connector means is electrically insulated from the plate means on said second side of said electro-mechanical transducer.

8. The audio system of claim **4** where said audio frequency voltage output source is capable of producing a complex audio output signal having a voltage providing a field gradient of up to **40** Kv per inch; and where said DC source provides a DC field having a field gradient of from 10 to 40 Kv per inch.

9. The audio system of claim **6** where the resistance of said high resistance input to said movable diaphragm means is at least 10 megohms; and the resistivity of said at least one high resistivity electrically conductive surface of said diaphragm is at least 100 megohms per unit square.

10. The audio system of claim **8** where the resistance of said high resistance input to said movable diaphragm means is at least 10 megohms; and the resistivity of said at least one high resistivity electrically conductive surface of said diaphragm is at least 100 megohms per unit square.

11. The audio system of claim **2** including a further, sealed, enclosure, therefor, outside said plate means, said enclosure having a gaseous medium other than air therein with a dielectric strength at least equal to that of air.

12. The audio system of claim **11** where said gaseous medium is sulphur hexafluoride.

13. An audio system including an audio frequency voltage output source and an electro-mechanical transducer means electrically connected thereto and having an audible power output:

a high output impedance DC source having positive and negative sides and a grounded center-tap so that said positive side is positive with respect to ground and said negative side is negative with respect to ground;

said electro-mechanical transducer means comprising thin, pliant and movable diaphragm means mechanically suspended between a pair of substantially parallel, mechanically rigid, electrically conductive and acoustically substantially transparent plate means;

said diaphragm means having two major surfaces and being electrically conductive over at least one major portion of at least one of said major surfaces; each said at least one major portion of said at least one major surface of said diaphragm means being bounded at its periphery by a portion of said diaphragm surface which is substantially electrically non-conductive.

said negative and positive sides of said DC source being connected through high resistance electrical input means to one each of said plates, respectively, said plates each having two major surfaces, and having high resistivity;

14. The audio system of claim **13** where said DC source provides a substantially constant charge to said plate means.

15. The audio system of claim **14** where said electro-mechanical transducer means includes at least one pair of aligned, highly insulative spacer blocks, one on each side of said diaphragm and compressively held between the diaphragm surface and the respective plate means spaced therefrom.

16. The audio system of claim **15** further comprising electrically conductive means extending through a pair of aligned spacer blocks and electrically connecting the plate means on a first side of said electro-mechanical transducer means with electrical connector means projecting above the plate means on the second side thereof, so that said electrical connector means is electrically insulated from the plate means on said second side of said electro-mechanical transducer.

17. The audio system of claim **16** where the resistance of said high resistance input to said plate means is at least 10 megohms; and the resistivity of said plates is at least 100 megohms per unit square.

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