July 21, 1959 A. A. JANSZEN 2,896,025

ELECTROSTATIC LOUDSPEAKER

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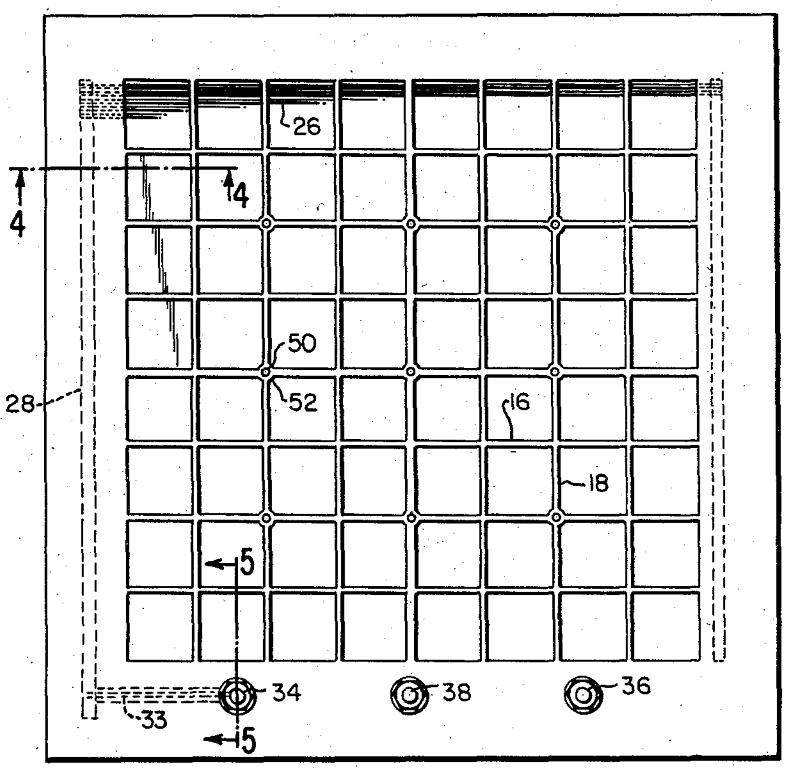

Fig. 1

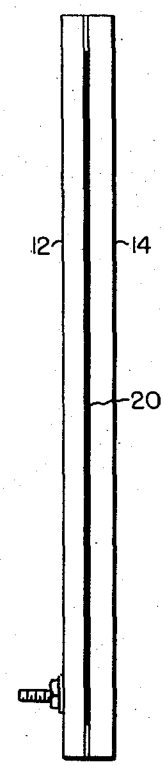

Fig. 2

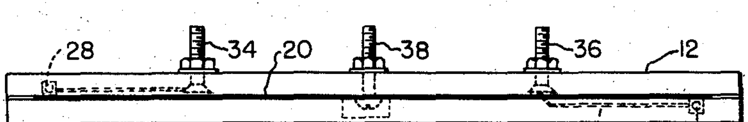

Fig. 3

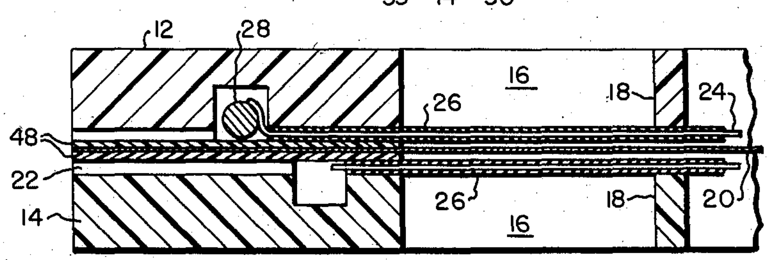

Fig. 4

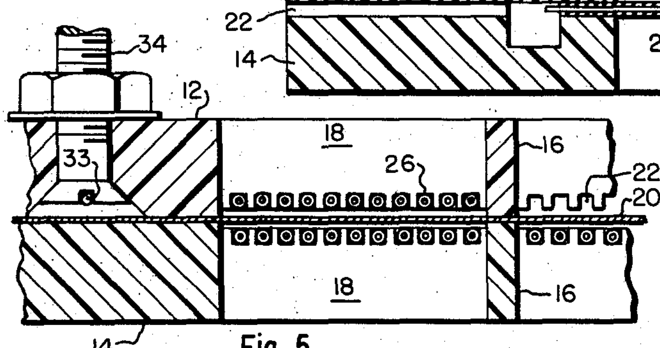

Fig. 5

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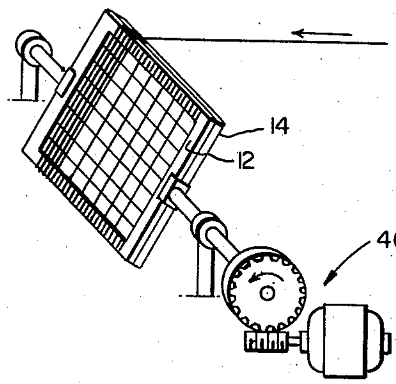
Fig. 6



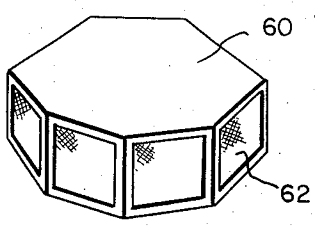
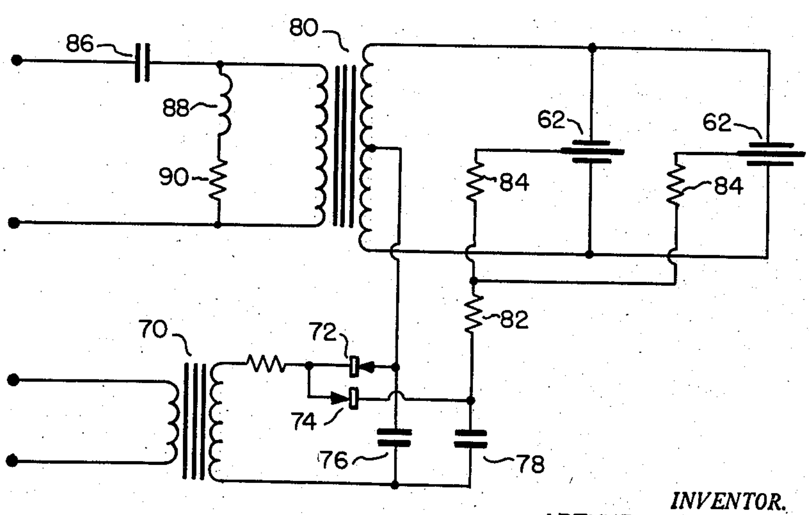


Fig. 7

Fig. 8



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ELECTROSTATIC LOUDSPEAKER

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14 Claims. (Cl. 179—111)

The present invention relates to electrostatic loudspeakers.

In my prior Patent No. 2,631,196 issued March 10, 1953, there is described an electrostatic loudspeaker construction wherein the movable diaphragm is mounted in closely spaced relation to an acoustically transparent stationary or back electrode formed by a mesh or zigzag arrangement of wire in which the successive lengths are sufficiently close together to provide a substantially uniform electrical field at the diaphragm. As a further feature of my prior patent, the electrode wires are insulated in such fashion as to permit the air gap between diaphragm and electrode to be operated at or near the ionization potential. As a result of the large electrostatic forces which are developed from the application of a high electric field, it is possible to obtain from the loudspeaker a high acoustic power output per unit area over a wide range of audio frequencies.

To take full advantage of the teachings of my prior patent and to make possible the production of electrostatic loudspeaker units that are substantially unaffected in their performance by temperature changes and consequent thermal expansion and contraction of the structure, the present invention has as an object the provision of an electrostatic loudspeaker unit embodying a novel and effective form of wire grid electrodes.

The invention likewise has as an object the provision of novel mounting and supporting means for the electroacoustic diaphragm and adjacent open grid electrodes, dividing both the diaphragm and the electrodes into small areas or regions in each of which a highly precise spacial relationship may be provided and maintained, so as to make possible an efficient electrostatic loudspeaker having resonances outside the range being reproduced and capable of smooth and faithful response over a wide frequency range.

More specifically, it is an object of the present invention to provide a novel fixed electrode construction wherein a plurality of spaced wires are utilized, the wires being supported in a manner that enables the spacing between diaphragm and electrode to be maintained at optimum, substantially unaffected by relative thermal expansion and contraction of the wire elements and the supporting frame.

Still another feature of the invention involves a grid electrode construction wherein the conductive elements may be effectively insulated so as to permit break-down free operation for long periods of time and under a wide range of conditions, with a high potential applied across the air gap between diaphragm and electrodes.

As another feature, the invention involves the provision of a push-pull electrostatic transducer wherein the diaphragm is disposed between closely-spaced fixed electrodes, with electrode-supporting frames between which the diaphragm is clamped not only at its margins but also at intermediate points.

A further feature of the invention relates to an electrostatic loudspeaker and method of making the same,

wherein the fabrication, though requiring careful manipulation at certain stages of the assembly, nevertheless permits electrostatic loudspeaker units of high efficiency and performance capabilities to be manufactured with precision and with assurance of stability.

In accordance with these and other objects as will hereinafter appear, a feature of the present invention involves an electrostatic loudspeaker unit wherein the diaphragm is supported by a rigid frame structure that also provides support for the diaphragm in intermediate regions to afford extremely precise positioning of the diaphragm while dividing the latter into separate radiating elements of small area. Another feature of the invention involves utilizing the same rigid structure and integral intermediate diaphragm-engaging means for positioning the wire elements of the grid electrode so that the wire elements may be positioned in accurate, close spatial relationship to the diaphragm.

Another important feature of the invention involves mounting the wire elements of the fixed electrode within minute tubular insulating supports, the supports being so mounted as to permit relative motion of the wire elements within the insulating supports without lateral distortion and consequent impairment of the close and precise spacing between electrode and diaphragms.

Still another feature of the invention involves a construction of diaphragm and electrode mounting means which permits the fabrication of the wire electrodes in place on their supports as a readily realizable manufacturing step that results in the forming of both electrodes simultaneously and with the wires positioned with extreme accuracy.

Other features of the invention will appear in the detailed decription, to be read in conjunction with the accompanying drawings in which

Fig. 1 is a front view of an elecrostatic loudspeaker unit constructed in accordance with the present invention.

Fig. 2 is a side edge view of the unit shown in Fig. 1.

Fig. 3 is a bottom edge view of the unit.

Fig. 4 is an enlarged sectional detail of a portion of the unit taken along the line 4—4 of Fig. 1.

Fig. 5 is an enlarged sectional view of another portion of the unit taken along the line 5—5 of Fig. 1.

Fig. 6 is an oblique view showing an intermediate stage of assembly.

Fig. 7 is a view of a mounting and enclosure for the electrostatic loudspeaker units of the invention, to form an effective radiator for the middle and upper portion of the audio frequency spectrum.

Fig. 8 is a schematic diagram of a suitable matching network and power supply for the loudspeaker.

The electrostatic loudspeaker units of the present invention resemble those disclosed in my prior Patent No. 2,631,196, through the use of a very thin flexible diaphragm which serves as one electrode, while another electrode is provided by a plurality of parallel wires spaced in close relation to the diaphragm. A high bias potential is maintained across the air gap between electrodes, the bulk resistivity and dimensions of the diaphragm and of the insulating coating on the wire electrodes being such that most of the applied bias potential appears across the air gap. As a result, the loudspeaker is enabled faithfully and efficiently to translate into acoustic output the electrical signals applied to the electrodes.

As described in the patent, it is desirable to maintain across the air gap between the electrodes and the moving diaphragm a bias potential which is at or near the ionizing potential of the air in the gap. In general, this involves a potential gradient of the order of 100,000 to 150,000 volts per inch. It is also necessary to have as a coating for the wire electrodes a dielectric material having a high dielectric constant and appropriate thickness, so as to cause the greater part of the signal voltage as well as the bias voltage to appear across the air gap.

In order to obtain the desired high potential gradient across the electrode gap without requiring a special high voltage power supply, it is necessary to utilize very small spacing between the fixed electrodes and the moving diaphragm. This spacing, though greater than the excursions of the diaphragm during operation within design power levels, is nevertheless so small as to present special problems in constructing and maintaining the electrode relationship. Furthermore, the electrodes must be such as to permit free radiation of the sound output from the diaphragm. This is achieved by employing as the fixed electrodes a grid of spaced wires, each wire being enclosed in an insulating sheath of dielectric material, the spacing of the wires from one another being sufficient to render the electrode acoustically transparent while still affording a substantially uniform electric field across the gap between the electrode plane and the diaphragm.

An individual loudspeaker unit, according to the preferred embodiment, consists of a diaphragm supported equidistant between a pair of wire grid electrodes, so as to permit a balanced or push-pull excitation from the driving source. As illustrated in the drawings, a speaker unit embodies a pair of rectangular frames **12** and **14** of molded dielectric material. These frames, except for minor differences in respect to terminal connections, are identical in order that when secured together they may remain flat under varying conditions of temperature and the like.

The frames consist of a margin or boundary region of appreciable width, and integral web or lattice elements disposed preferably but not necessarily in rectilinear fashion to divide the region within the boundary into squares of the order of one inch or less. For purposes of subsequent identification, the web elements running laterally in Fig. 1 will be identified by reference character **16**, and the vertically extending webs by **18**.

The flexible diaphragm **20** which constitutes the movable radiating element of the speaker is secured between the frames and is preferably of vinylidine-chloride of the order of .0004" in thickness, provided with a conductive coating in the nature of a dag coating. It will be observed in the enlarged sectional detail views of Figs. 4 and 5 that the lateral web elements **16** engage the diaphragm at regions intermediate the margins, while the inner edges of the web elements **18** are spaced from and provide clearance for the diaphragm. As as result, the diaphragm is free to vibrate in mechanically independent regions while being supported along lines parallel to and intermediate the top and bottom margins of the frame, as viewed in Fig. 1.

The webs **18** are utilized to support the wire elements that form the fixed electrodes, and for this purpose the webs are notched, preferably by ganged slotting saws for precision, to a uniform depth relative to the plane of the inner, diaphragm-supporting face of the frame. The notches **22** are of a width to accommodate the wire **24** and insulating sheath **26** during the winding operation to be described, and are of a depth to allow the surface of the sheath to lie flush with the edge surface of the web, as shown in Fig. 5. By way of example a spacing of the order of 0.01" between the fixed electrodes and the diaphragm, to allow for diaphragm excursion, has been found appropriate in the illustrated embodiment.

The wire elements of the electrode grid are soldered to conductive bars **28** and **30** received in slots formed in the inner faces of the side margins of the frames. It will be observed that the bars are not positioned adjacent one another in the assembled unit but are at opposite ends thereof to minimize capacitance. Connections **33** from the bars extend to terminals **34** and **36**, while connection to the conductive coating of the diaphragm is provided by terminal **38**.

As an important feature of the invention, only one end of each of the wires **24** forming an electrode grid is secured to a conductive bar. At the other end the wires are free of any longitudinal anchoring. In view of the extreme accuracy with which it is desired to position the electrode elements relative to the diaphragm, it might be expected that anchoring of the wire elements under considerable tension would constitute the desired arrangement. On the contrary, it has been found that superior results, with freedom from the effects of the relatively greater thermal expansion and contraction of the supporting frame, are attained by mounting the wires in such fashion that there is freedom for relative longitudinal sliding movement between sheath and wire. As a result of the precise support provided by the frame with notched intermediate webs to which the sheaths of the wires may be secured by cementing, the wires are maintained in straight, precisely spaced relation at all times, even though the unit be subjected to wide extremes of temperature. In effect, there is provided a floating electrode structure which will not warp, sag, or distort because of differences in the thermal coefficients of expansion of the various materials that make up the loudspeaker unit, particularly the wires and the frame.

To form the electrodes, it is convenient to secure a pair of frames in back-to-back relation with the slotted grooves facing outward and in parallel alignment on the two outer surfaces. A single strand of insulated electrode wire (A.W.G. No. 28, tinned copper, with vinyl chloride insulation has been successfully employed) is then wound around the pair of framing members, care being taken to see that the wire is wound successively in the parallel grooves on each side. This method of assembly may be most easily practiced by placing the pair of frames in a rotatable power driven jig (illustrated generally at **46** in Fig. 6). As the winding proceeds, the wires are laid in adjacent grooves, and crimped in a sharp bend around the end of the frame.

Prior to winding, the wire is stretched to approximately 1.06 times its original length to cause straightening and stiffening. This also has the effect of reducing its diameter slightly. During the winding, the wire is maintained under sufficient tension to produce the sharp bend around the frame edges.

Upon completion of the winding step, the insulation on the wires is severed in the region of the slots for conductive bars **28** and **30** and pushed back sufficiently to permit subsequent soldering of one end of each wire to the bar. This is carried out while the continuous winding surrounds the frames. Because of the stretching that has been imparted to the wire prior to winding, the insulating sheath when cut at each end tends to shrink longitudinally, with consequent enlargement substantially to its original diameter, thereby freeing the wire within so that relative longitudinal sliding movement can freely occur as required by relative thermal expansion and contraction of frame and wire.

The insulating sheaths are then cemented to the frame at all crossing points of the webs **18**, using a suitable resin-base cement. Seating of the wires to the full depth of the slots in the web insures that the proper spacing will result between the finished electrode and the diaphragm.

After the insulating sheaths of the wires have been cemented in place, the wires may be cut by a high speed slotting saw along lines inwardly of the frame edge. The single bus bars **28** and **30** for each electrode may be inserted in their slots and the wires soldered to the bars. Following this, insulating strips **48** are laid over the ends of the wires and bus bars in preparation for assembly of the frames and diaphragm.

The diaphragm is coated with a graphite suspension or dag coating of a character that affords a high surface resistivity. The coated area is slightly smaller in area than the webbed region within the side margins of the frame, with a narrow extension of the coating to make contact with terminal **38**. The diaphragm is secured around inner edges of one frame under tension. The tension on the diaphragm and the size of the free areas of the diaphragm between supporting webs is such as to cause any natural or resonant frequency to lie below the range of frequencies to be reproduced by the loudspeaker. Tensioning of the diaphragm to the desired amount is conveniently carried out by supporting the diaphragm in a temporary tensioning frame or hoop and loosely coupling it acoustically to a source of sound vibrating at the desired resonant frequency. When the diaphragm has been properly tensioned it will itself vibrate in resonance. The tensioned diaphragm is then positioned between frames, electrodes on the inside, one or both frames having their inner faces coated with adhesive prior to assembly. To insure rigid bonding between frames in addition to marginal clamping, small staking elements or pins **50** may be inserted through the enlarged bosses **52** provided at intervals at the intersection of vertical and horizontal webs of the frame. These regions permit the diaphragm to be pierced by the securing pins without disturbing the diaphragm.

By reason of the symmetrical construction, involving identical frame elements and wire electrodes on each side of the diaphragm, the unit is substantially free of any warping or twisting tendencies. Furthermore, since the wire elements are not under tension, but are unanchored at one end and free to slide within their dielectric tubular sheaths, relative expansion and contraction of the supporting frame and wires does not disturb the electrode-diaphragm spacing, nor permanently deform any part of the structure.

While electrostatic loudspeakers of the type described may be employed as radiators for the entire audio frequency spectrum, it is generally advantageous to utilize some other form of transducer for the lower frequencies, and to employ the electrostatic transducer for the upper frequencies, for example from 800 or 1,000 cycles up to the upper limit of audibility. In such case, a conventional cone-type electrodynamic unit, mounted in suitable baffle means, may provide the response for the lower frequencies.

While a single electrostatic unit may be employed as the high frequency radiator, more than one is generally preferable for power handling and to permit greater spread of radiation. Where several elements are employed, these may be disposed at an angle to one another, as illustrated by the loudspeaker shown in Fig. 7, wherein the case **60** is in the shape of a polygon formed by truncating a 90° segment of a circle. In the front of the case are arranged four electrostatic loudspeaker units **62** disposed at approximately 30° to one another for effective distribution of sound energy.

The case may contain the coupling network for the speaker units, as well as the power supply to furnish the polarizing potential. The units which have been described will function effectively with a polarizing voltage of approximately 1,000 volts, D.C., and this polarizing potential may be obtained from a 110 v. A.C. supply by a small step-up transformer **70** and voltage doubler circuit employing rectifiers **72**, **74** and capacitors **76**, **78**. This D.C. potential is applied between the center of the output winding of the audio coupling transformer **80** and the diaphragm through a resistor **82**, which may be of the order of 100 megohms. The polarizing potential, being direct current, is applied to both air gaps effectively in parallel. In the case of multiple electrostatic units, isolating resistors **84** are employed in the supply to each diaphragm. These may be approximately 5 megohms each. The current required is extremely small, and the polarizing potential may be left on continuously, if desired.

The matching network for coupling the electrostatic units to the output of the amplifier includes provision for excluding the lower frequencies, for example below 800 or 1,000 cycles depending on the selected cross-over point between the low and high frequency units. The network comprises, in addition to the coupling transformer **80**, a series capacitor **86** and shunt inductance **88** with resistor **90**.

For coupling to the 16 ohm output of the amplifier, the coupling transformer may have a turns ratio of approximately 50/1, secondary to primary. This will be suitable to provide, from an amplifier operating at reasonable power levels, voltage peaks at the speaker of the order of 2000 volts, representing 100% modulation for a bias potention of 1000 volts. To provide low frequency cutoff at the desired frequency of 800–1000 cycles, the capacitor **82** may have a capacity approximately 20,000 times that of the electrostatic unit (or units in parallel). The inductance **88** will generally have a value less than one-half the inductance of the transformer primary, measured with the secondary open. By way of example, a value of 3 mh. has been employed in a representative network. Resistor **90** may be of he order of 10 ohms. For a representative electrostatic loudspeaker assembly, this will place the resonant frequency of the L-C combination at approximately 1000 cycles, and within the desired region for low-frequency cut-off.

The electrostatic loudspeaker of the present invention is effective to reproduce complex waveforms with remarkable fidelity. As compared with other types of electracoustic transducers, the response is characterized by substantial freedom from peaks and dips over the entire frequency range. This freedom from resonances and other spurious responses, together with the extremely high damping resulting from the low mass and heavy loading or coupling to the air, provides extremely good transient response, free of "ringing" or hangover effects.

As a consequence of the special electrode construction, wherein the individual electrode elements, straightened by stretching, are disposed in slidable relation to their insulating sheaths so as to be independent of relative dimensional changes in wire and frame, the loudspeaker unit is capable of withstanding wide variations in temperature without temporarily or permanently altering its performance capabilities. Furthermore, the construction is such as to permit manufacture with the requisite precision and with a high degree of uniformity.

While the invention has been described in terms of a particular illustrative embodiment, the invention is not so limited, and comprehends other forms, constructions and methods of manufacture within the scope of the appended claims.

I claim:

1. An electrostatic transducer comprising a flexible diaphragm of high resistivity, a frame on which the diaphragm is supported, a plurality of conductive electrodes, electrical connections to the diaphragm and to the electrodes, and dielectric insulating sheaths for the electrodes, the sheaths being supported by the frame in closely spaced relation to the diaphragm with the electrodes slidable within the sheaths to accommodate relative dimensional changes between electrodes and frame.

2. An elestrostatic transducer comprising a flexible diaphragm of high resistivity, a frame on which the diaphragm is supported, a grid of wires, electrical connections to the diaphragm and to the wires, and dielectric insulating sheaths on said wires and carried by the frame to support the wires in closely spaced relation to the diaphragm, each wire being longitudinally anchored at one point only.

3. An electrostatic transducer according to claim 2 having the wires slidably received within their dielectric insulation.

4. An electrostatic transducer according to claim 2 having the wires longitudinally anchored relative to the frame at one end only.

5. An electrostatic loudspeaker comprising a flexible

diaphragm of high resistivity, supporting frames on each side of said diaphragm, a plurality of electrode-supporting webs in each frame, a plurality of parallel electrode wires extending across the webs, electrical connections to the wires and to the diaphragm, a dielectric sheath on each wire, means for supporting the diaphragm in closely spaced relation to the electrode wires to provide an air gap, and means anchoring one end of the electrode wires to the frame, the other portions of the wires being slidable within the dielectric sheath to permit longitudinal movement relative to the frame.

6. An electrostatic transducer comprising a thin diaphragm of high resistivity, supporting frames between which the diaphragm is supported in tension, each frame having integral webs engaging the diaphragm intermediate the margins of the frame to support the diaphragm for independent vibration in a plurality of separate areas, other webs spaced from the plane of the diaphragm, a pair of electrodes each comprising a grid of spaced wires carried by said other webs in closely spaced relation to the diaphragm on each side thereof, the wires having an insulating sheath of dielectric material within which the wires are relatively slidable, electrical connections to the diaphragm and to the wires, said connections including a conductor at one end of each grid, to which one end of each wire is anchored.

7. An electrostatic transducer according to claim 6 having the sheaths surrounding the wires shorter than the wires.

8. An electrostatic transducer according to claim 6 having the sheaths surrounding the wires secured to the frame.

9. An electrostatic transducer according to claim 6 in which the ends of the wires remote from the anchored ends extend beyond the sheaths into an open area in the margin of the frame.

10. An electrostatic transducer according to claim 6 having the conductor bar of one frame remote from the conductor bar of the other frame.

11. An electrostatic transducer according to claim 6 having the frames secured together at points intermediate the margin by means penetrating the diaphragm.

12. An electrostatic transducer according to claim 6 having enlarged areas in the frames in the region of web intersections, and staking means extending through the diaphragm and into the web intersections to secure the frames in regions intermediate the margins.

13. An electrostatic transducer according to claim 6 having a diaphragm of vinylidine chloride.

14. An electrostatic transducer comprising a thin diaphragm of high resistivity, supporting frames between which the diaphragm is supported in tension, each frame having integral webs engaging the diaphragm intermediate the margins of the frame to support the diaphragm for independent vibration in a plurality of separate areas, other webs spaced from the plane of the diaphragm, a pair of electrodes each comprising a grid of spaced wires carried by said other webs in closely spaced relation to the diaphragm on each side thereof, the wires having an insulating sheath of dielectric material within which the wires are relatively slidable, the webs having notches within which the sheathed wires are disposed, means securing the sheaths to the webs, electrical connections to the diaphragm and to the wires, the wires being anchored to the frame at one portion only of each wire to permit relative sliding movement between sheath and wires at other portions of the wires.

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