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**United States Patent** [19][11] **Patent Number:** **5,450,497****Paddock**[45] **Date of Patent:** **Sep. 12, 1995**[54] **AUDIO TRANSDUCER IMPROVEMENTS**[75] **Inventor:** **Paul W. Paddock, McMinnville, Oreg.**[73] **Assignee:** **Linaeum Corporation, Portland, Oreg.**[21] **Appl. No.:** **882,144**[22] **Filed:** **May 11, 1992**[51] **Int. Cl.<sup>6</sup>** ..... **H04R 25/00**[52] **U.S. Cl.** ..... **381/191; 381/202; 381/186**[58] **Field of Search** ..... 381/202, 194, 196, 190, 381/191, 116, 113, 174, 173, 186, 182; 310/324; 181/163, 164, 168, 169[56] **References Cited****U.S. PATENT DOCUMENTS**

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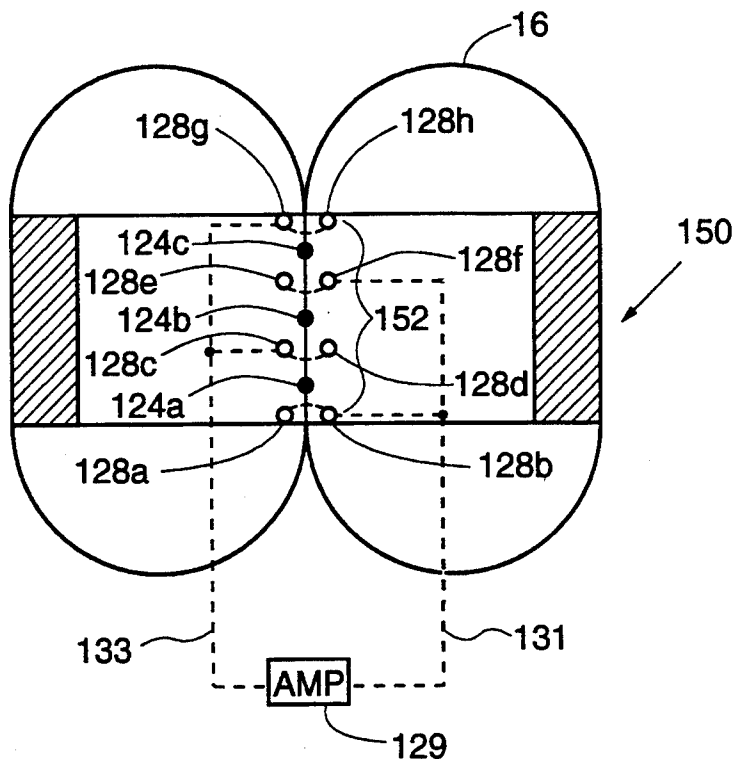
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Campbell Leigh & Whinston

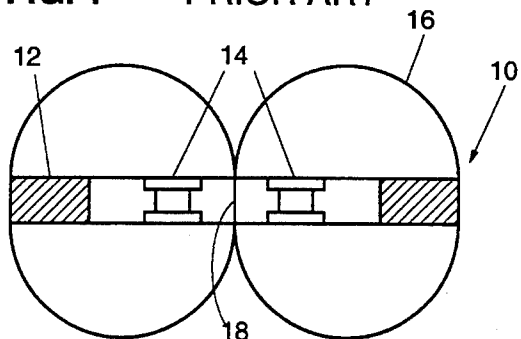
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**ABSTRACT**

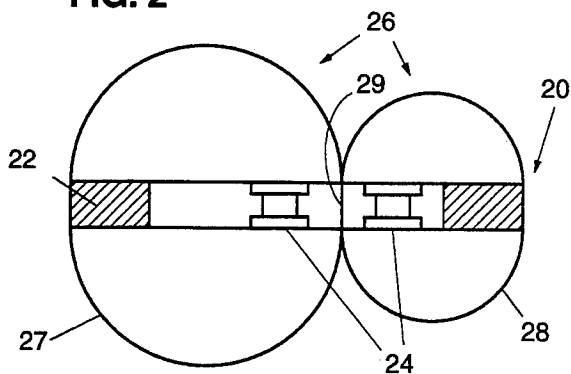
An audio transducer having a cylindrical diaphragm molded with contoured ridges. The diaphragm includes at least two lobes, each extending from a central expanse to the transducer frame. The lobes may have different radii and different angular arc lengths. A driver attached at the central expanse may include a double-sided etched coil, or may be provided by an electrostatic driver having a charged filament attached to the diaphragm. The transducer diaphragm may include a central third lobe having different size and structural characteristics to provide added low frequency response. The transducer may be configured to provide omnipolar sound radiation with opposed spaced-apart semi-circular cylindrical diaphragms arranged to pulse symmetrically toward and away from each other.

**5 Claims, 10 Drawing Sheets**

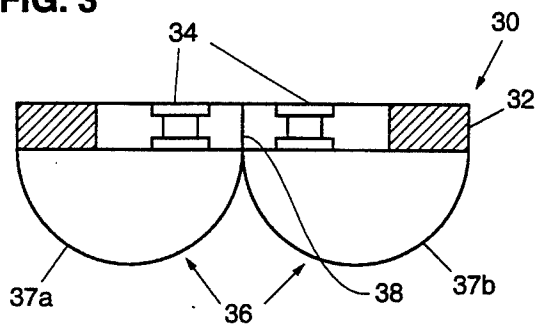
**FIG. 1** PRIOR ART



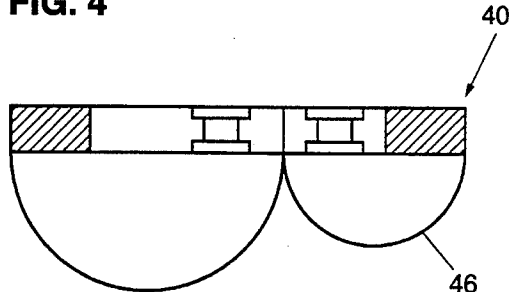
**FIG. 2**



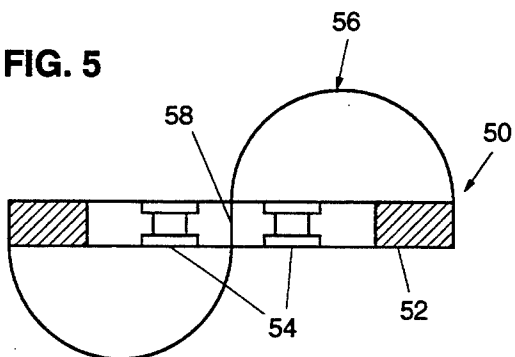
**FIG. 3**



**FIG. 4**



**FIG. 5**



**FIG. 6**

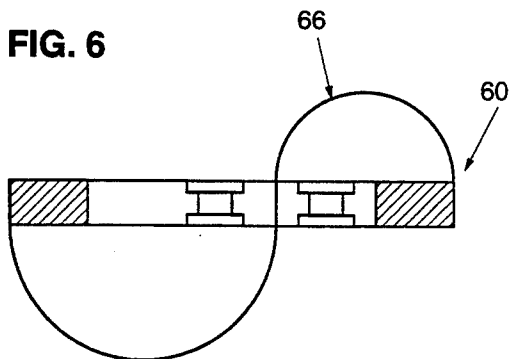


FIG. 7

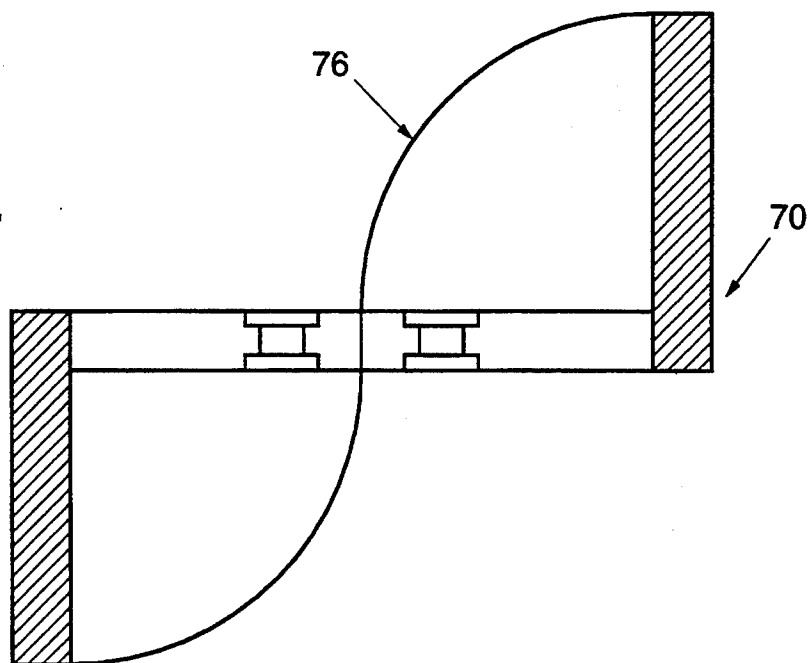


FIG. 8

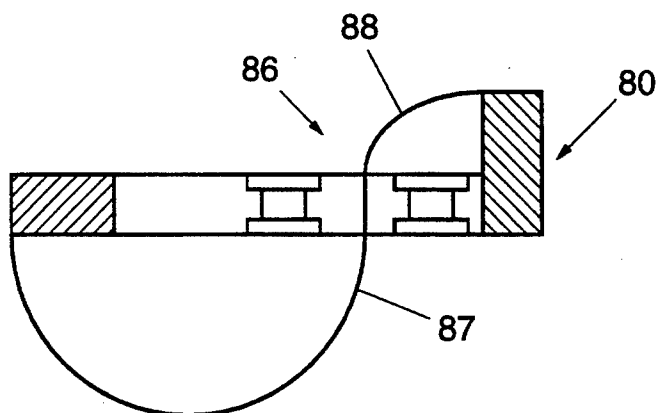


FIG. 9

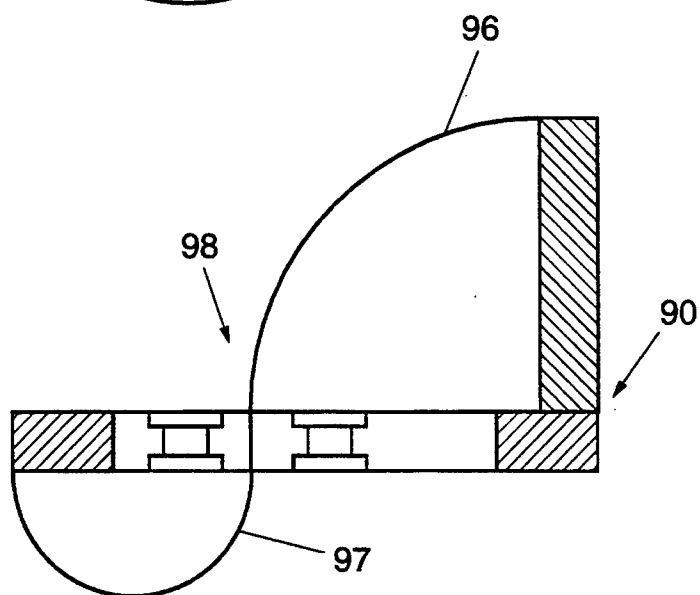


FIG. 10

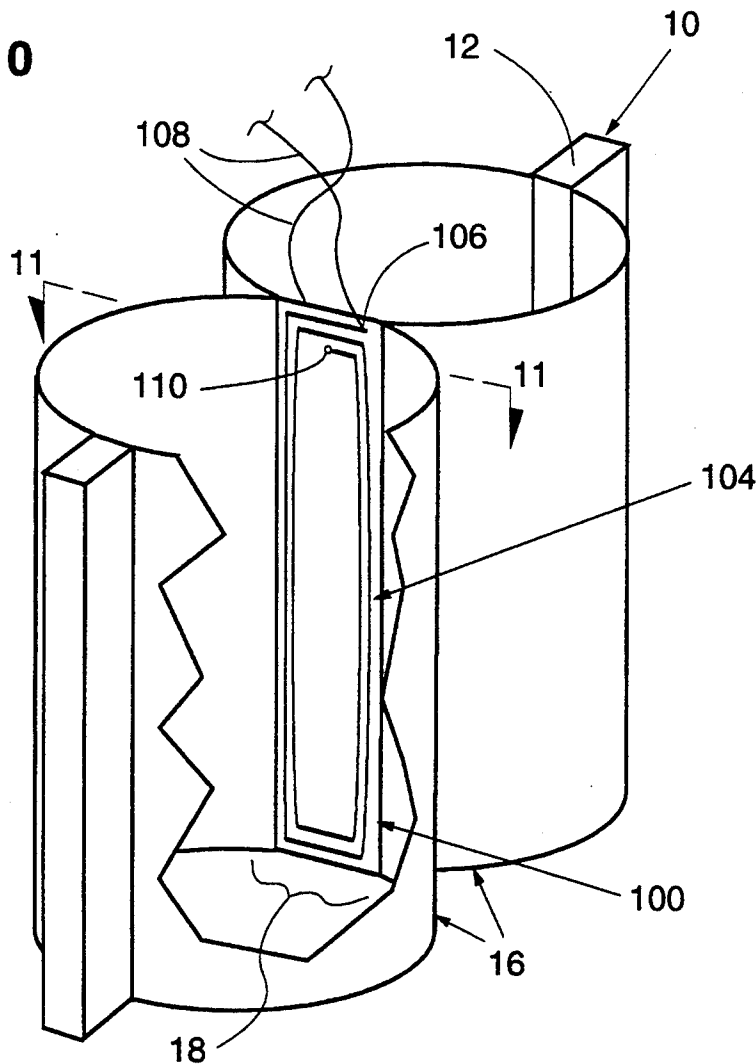


FIG. 11

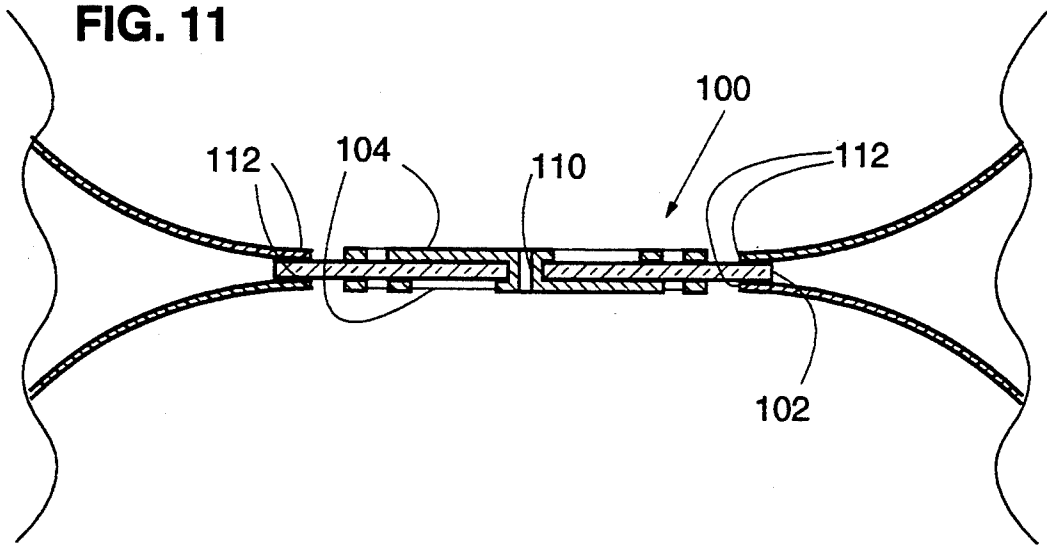


FIG. 12

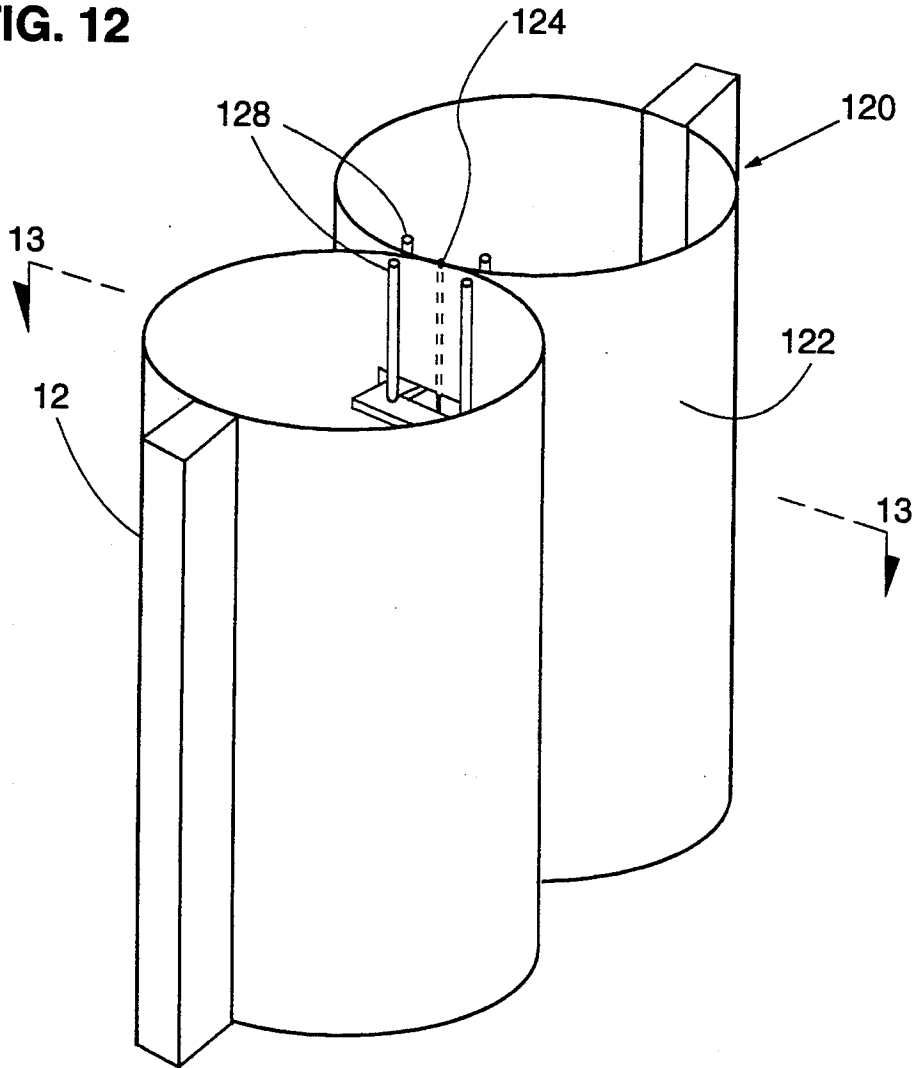


FIG. 13

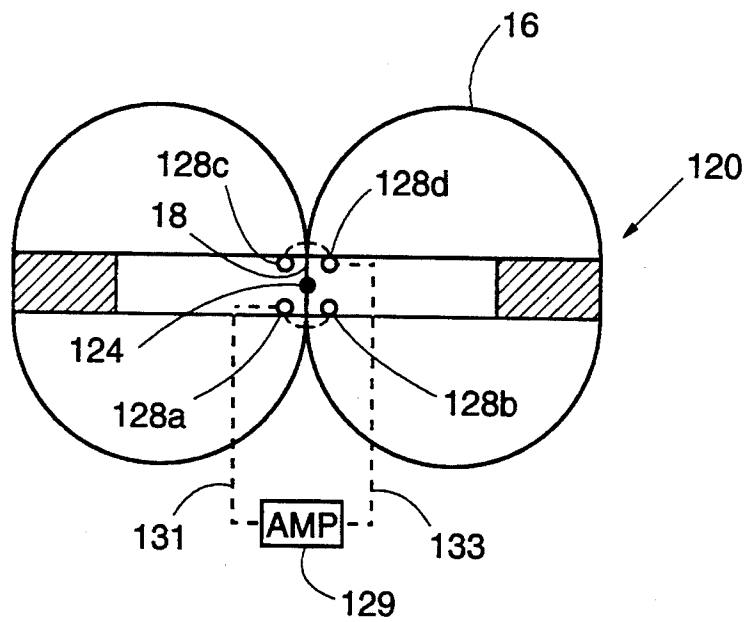


FIG. 14

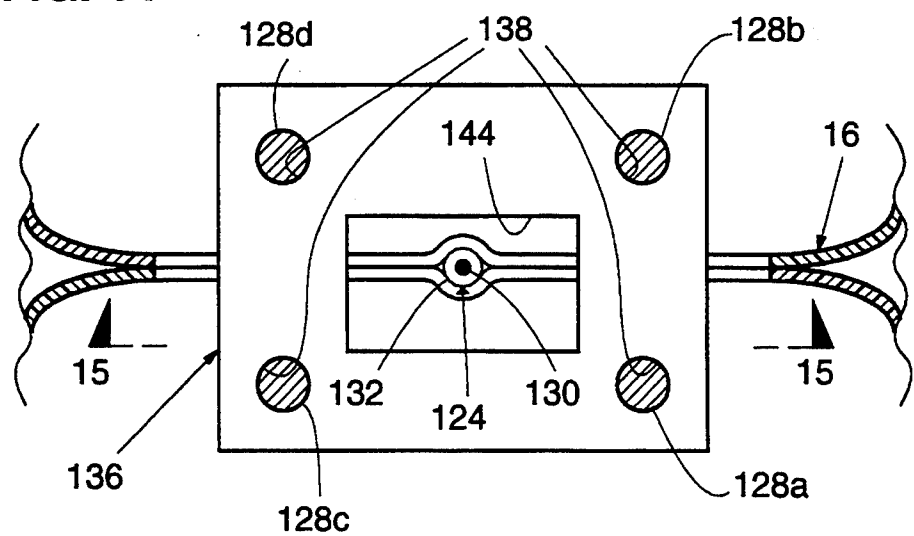


FIG. 15

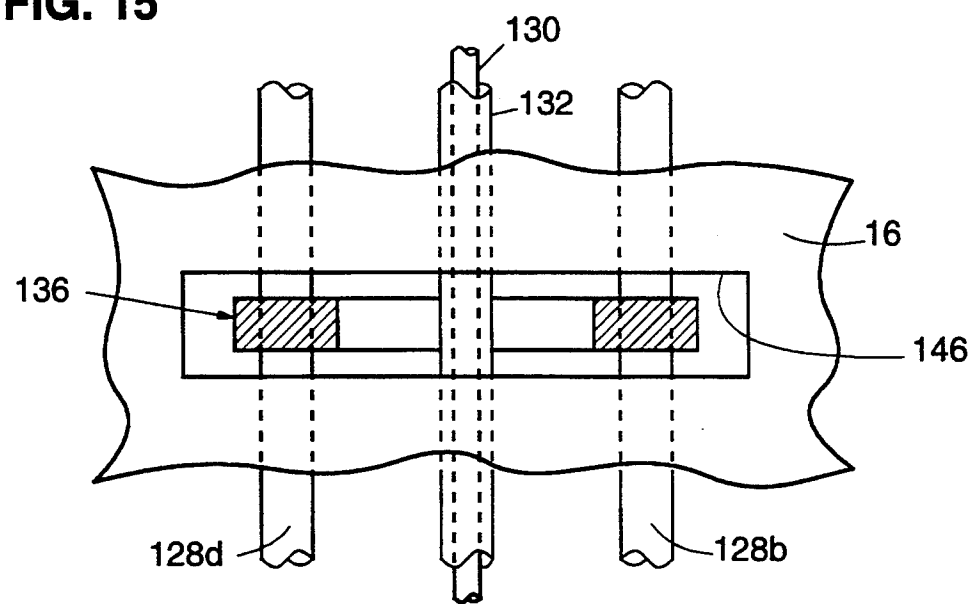


FIG. 16

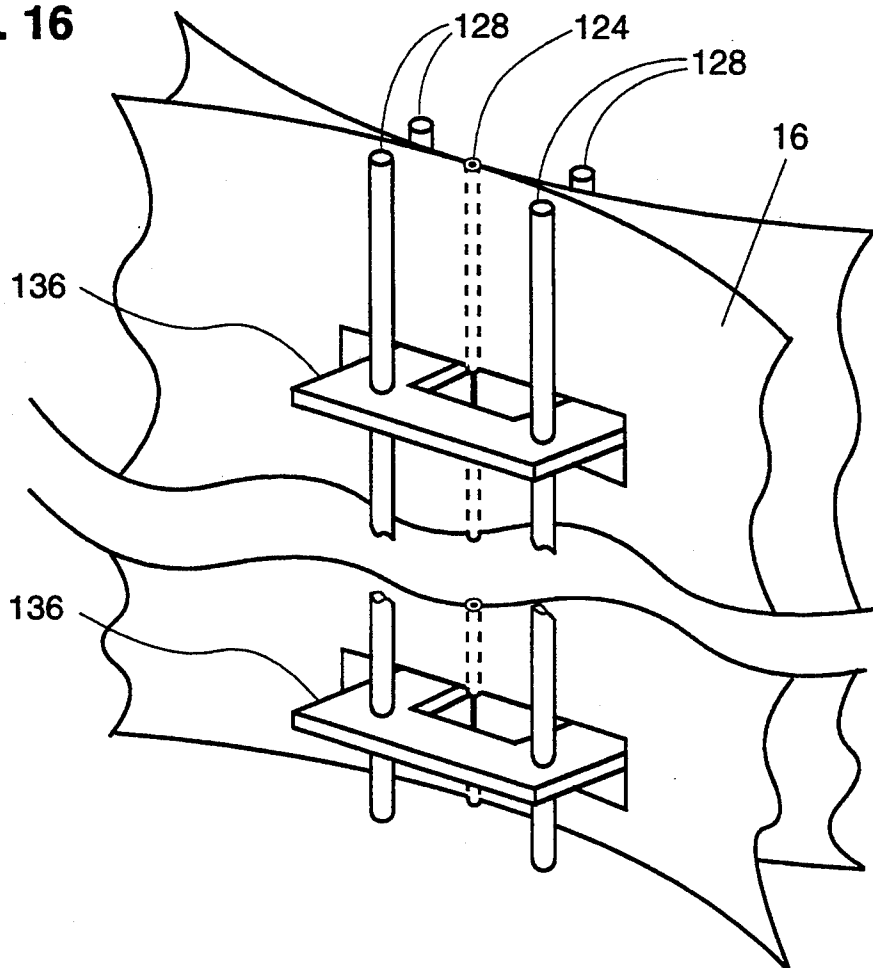


FIG. 17

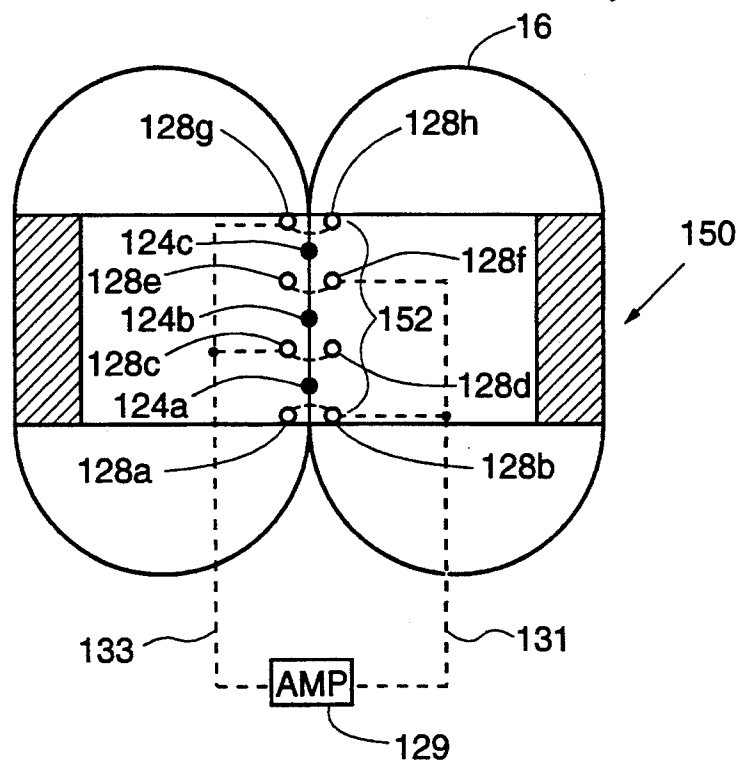


FIG. 18

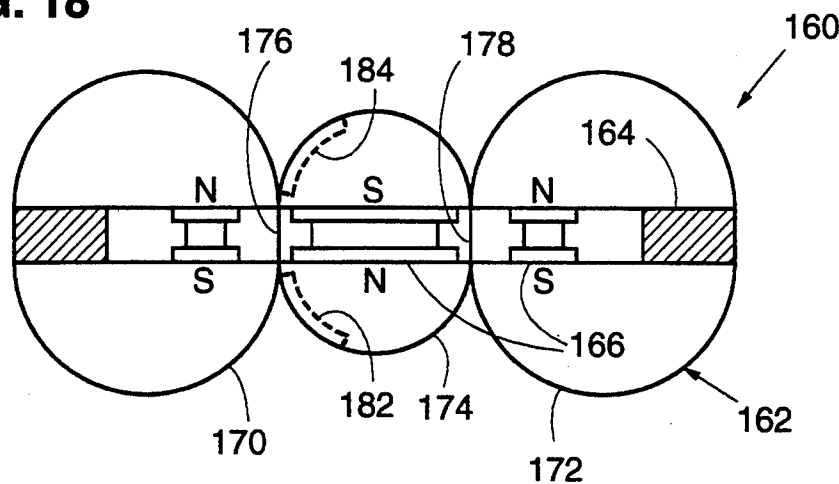


FIG. 19

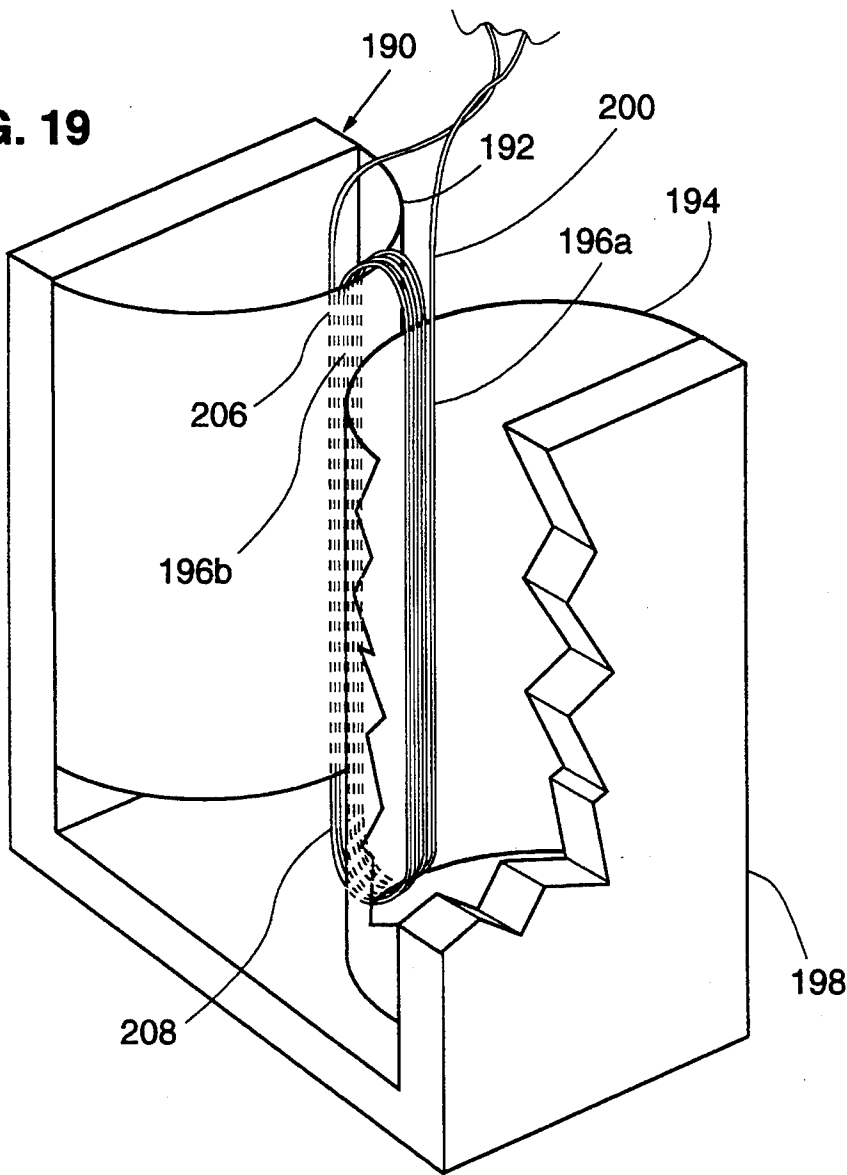




FIG. 20

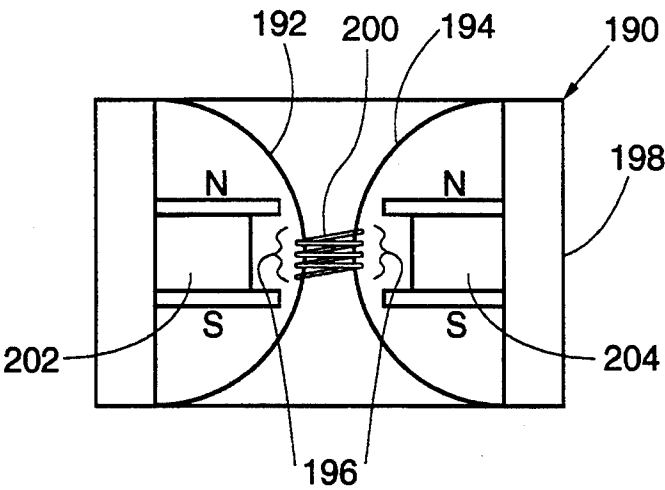


FIG. 21

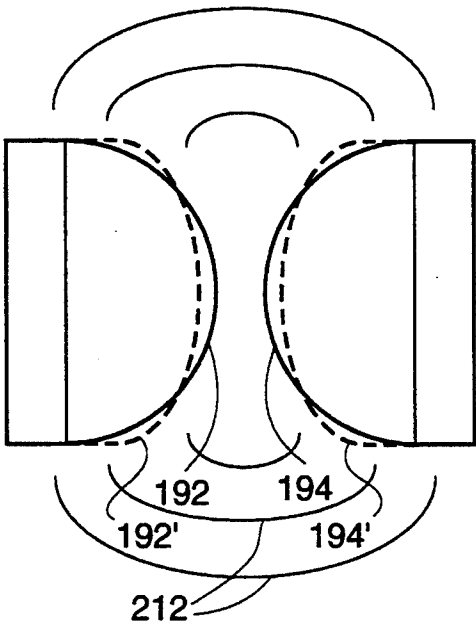


FIG. 22

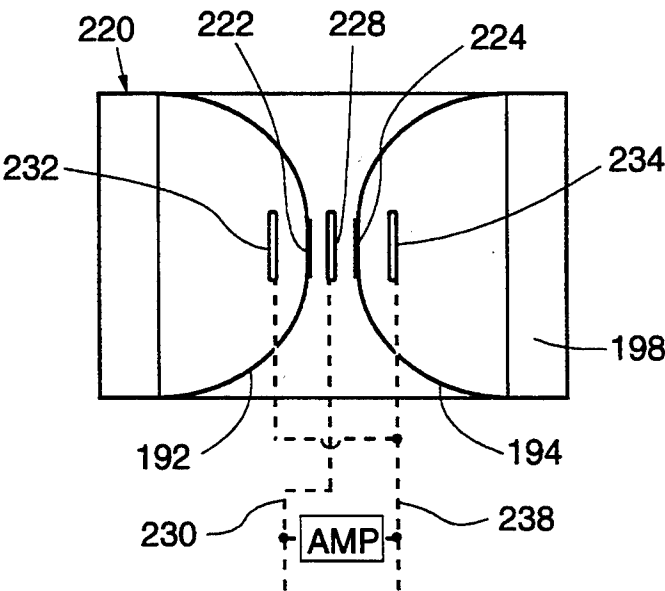


FIG. 23

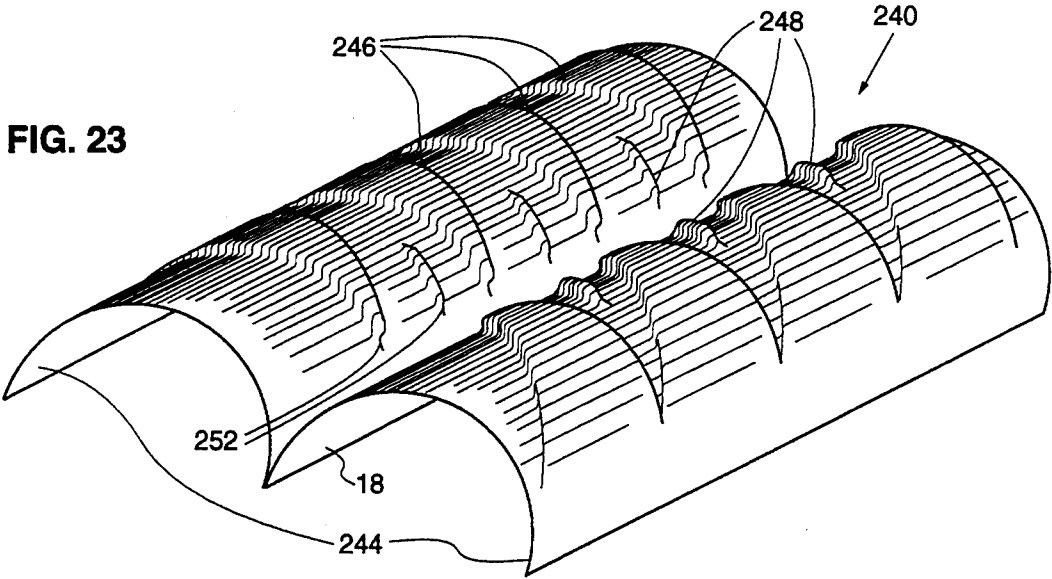


FIG. 24

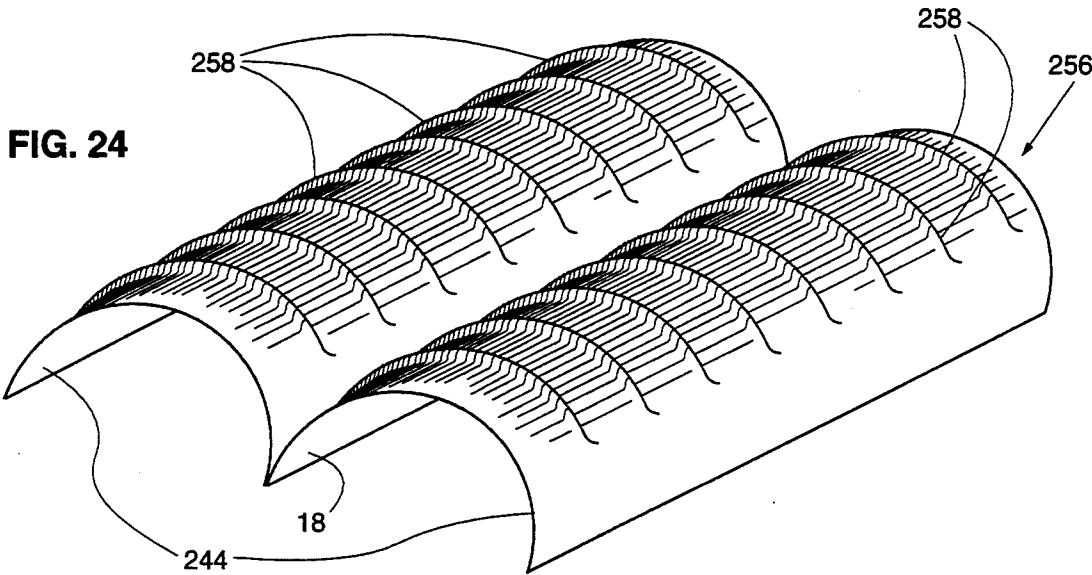


FIG. 25

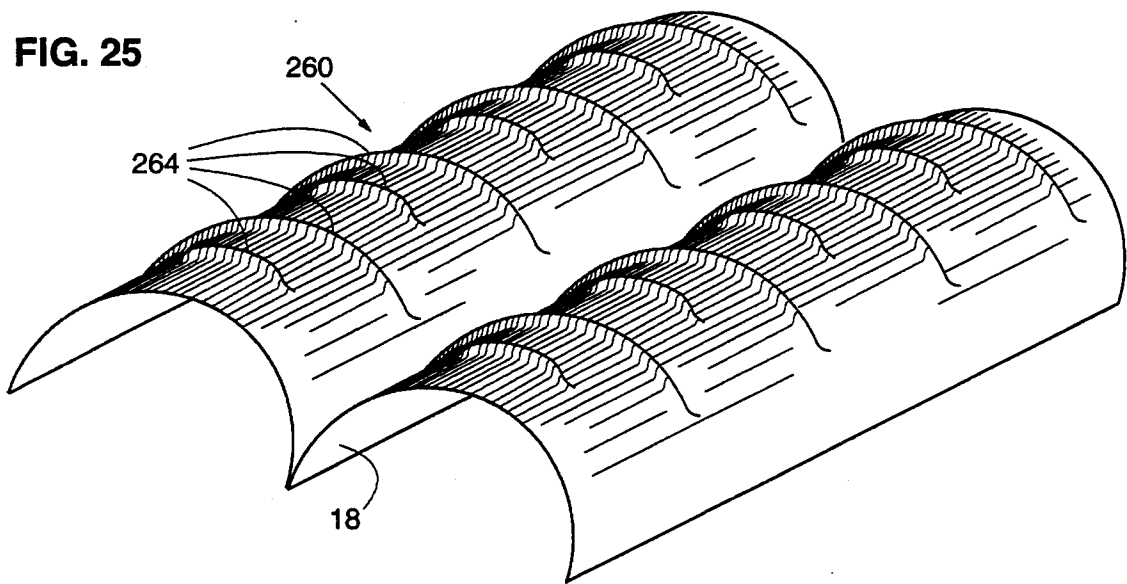
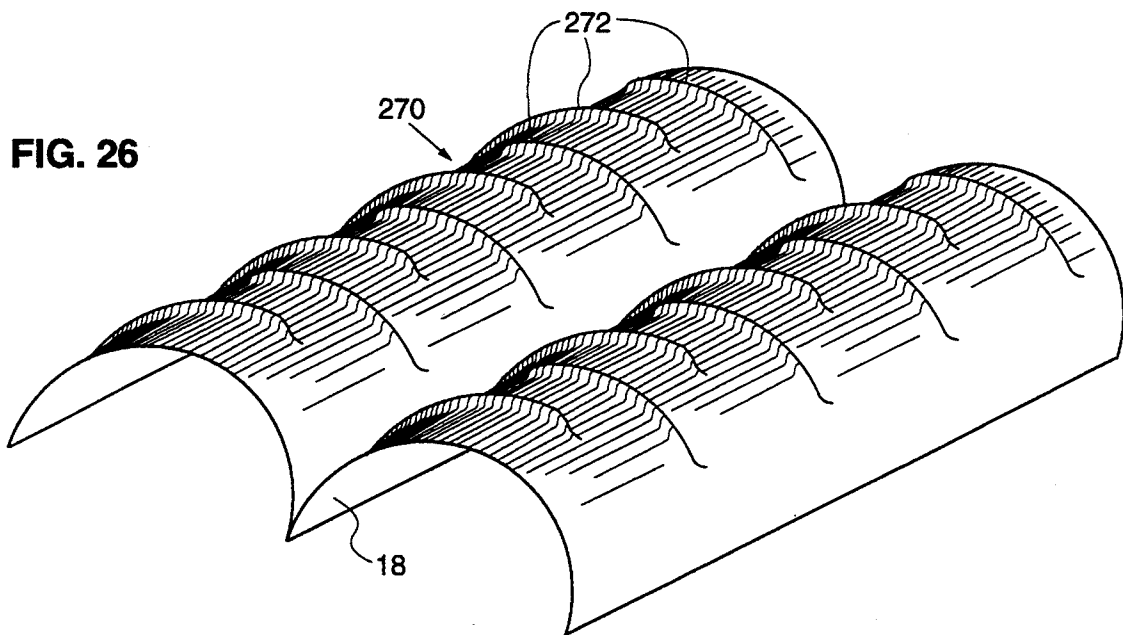


FIG. 26



## AUDIO TRANSDUCER IMPROVEMENTS

## TECHNICAL FIELD

This invention generally relates to audio transducers. More particularly, the invention relates to improvements in the design of a transducer having a cylindrical or partially cylindrical arcuate diaphragm defined by a cross-sectional profile projected on an axis to define a generally cylindrical diaphragm.

## BACKGROUND OF THE ART

U.S. Pat. Nos. 4,584,439 and 4,903,308, and pending U.S. patent application Ser. Nos. 07/499,492 filed Mar. 29, 1990; 07/436,914 filed Nov. 14, 1989; 07/708,924 filed Apr. 11, 1991; and 07/730,172 filed Jul. 12, 1991, are incorporated herein by reference, as they disclose variations and refinements of an audio transducer having a diaphragm that can be generally described as "cylindrical" in the broadest sense of the term. That is, the diaphragm is defined by a two-dimensional cross-sectional profile that is projected on an axis to form a three-dimensional diaphragm having a constant cross-section. The cross-sectional profile need not be circular but may be an open or closed polygon or curve. These cylindrical diaphragms may generally be formed from flat sheets that are curved so that all lines normal to the curved surface remain perpendicular to the axis of projection. The diaphragms in the disclosed patents typically include a pair of tangentially abutting circular or semi-circular cross-sectional tube-shaped webs.

In operation, these cylindrical diaphragm transducers generate sound by a "rolling motion" in which an electromagnetic coil attached to the diaphragm interacts with a fixed magnetic field to move in a direction perpendicular to the axis of projection of the diaphragm. Each of various portions of the diaphragm accommodate the coil motion relative to a fixed frame by selectively tightening and loosening its radius of curvature to achieve the rolling motion.

While the transducers of the above-referenced applications and patents are reasonably efficient, with a relatively flat frequency response over a large bandwidth of approximately 5 octaves, there remains a need for additional improvements in the performance criteria of efficiency, bandwidth and response flatness. In addition, there is a need to reduce manufacturing costs and to further increase product quality by simplifying the manufacture of such a device.

## SUMMARY OF THE INVENTION

The primary object of this invention is to provide an improved transducer having features that independently and in concert overcome the difficulties and shortcomings of the prior art and which fulfills the aforementioned needs.

This object may be satisfied by providing a transducer having a cylindrical diaphragm and one or more of the following improvements: an asymmetric or unbalanced diaphragm, a monopolar diaphragm, an S-shaped diaphragm, opposed and spaced-apart diaphragm webs for omnipolar output, an etched coil, an electrostatic drive element, a three-lobed diaphragm, and molded contoured diaphragms with stiffening ridges.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a sectional schematic top view of a prior art transducer.

FIG. 2 is a sectional schematic top view of a transducer having an asymmetric diaphragm in accordance with one embodiment of the present invention.

FIG. 3 is a sectional schematic top view of a symmetrical monopolar transducer in accordance with a second embodiment of the present invention.

FIG. 4 is a sectional schematic top view of an asymmetric monopolar transducer in accordance with a third embodiment of the present invention.

FIG. 5 is a sectional schematic top view of a transducer having a balanced S-shaped diaphragm in accordance with a fourth embodiment of the present invention.

FIG. 6 is a sectional schematic top view of a transducer having an unbalanced S-shaped diaphragm in accordance with a fifth embodiment of the present invention.

FIG. 7 is a sectional schematic top view of a transducer having a balanced truncated S-shaped diaphragm in accordance with a sixth embodiment of the present invention.

FIG. 8 is a sectional schematic top view of a transducer having an unbalanced partially truncated S-shaped diaphragm in accordance with a seventh embodiment of the present invention.

FIG. 9 is a sectional schematic top view of a transducer having an unbalanced partially truncated S-shaped diaphragm in accordance with an eighth embodiment of the present invention.

FIG. 10 is a fragmentary perspective view of a transducer having an etched coil in accordance with a ninth embodiment of the present invention.

FIG. 11 is an enlarged cross-sectional view taken along line 11—11 of FIG. 10.

FIG. 12 is a perspective view of an electrostatic transducer having a cylindrical diaphragm in accordance with a tenth embodiment of the present invention.

FIG. 13 is a schematic cross-sectional top view taken along line 13—13 of FIG. 12.

FIG. 14 is an enlarged partial cross-sectional view taken along line 13—13 of FIG. 12.

FIG. 15 is an enlarged cross-sectional view taken along line 15—15 of FIG. 14.

FIG. 16 is an enlarged fragmentary perspective view of the electrostatic drive portion of the transducer of FIG. 12.

FIG. 17 is a schematic cross-sectional top view of an electrostatic transducer having multiple drive elements in accordance with an eleventh embodiment of the present invention.

FIG. 18 is a schematic cross-sectional top view of a low frequency transducer having three cylindrical diaphragm lobes in accordance with a twelfth embodiment of the present invention.

FIG. 19 is a fragmentary perspective view of an omnipolar transducer in accordance with a thirteenth embodiment of the present invention, with magnet means omitted.

FIG. 20 is a cross-sectional schematic top view taken along line 20—20 of FIG. 19.

FIG. 21 is a top schematic view of the transducer of FIG. 19 showing the operation thereof.

FIG. 22 is a schematic cross-sectional top view of an omnipolar transducer having an electrostatic drive in

accordance with a fourteenth embodiment of the present invention.

FIG. 23 is a perspective view of a molded diaphragm in accordance with a fifteenth embodiment of the present invention.

FIG. 24 is a perspective view of an alternative molded diaphragm.

FIG. 25 is a perspective view of an alternative molded diaphragm.

FIG. 26 is a perspective view of an alternative molded diaphragm.

#### DETAILED DESCRIPTION OF THE INVENTION

FIG. 1 illustrates a schematic cross-sectional view of a prior art transducer illustrated in FIG. 1 of U.S. Pat. No. 4,903,308 to Paddock et al. The prior art transducer 10 includes a rigid frame 12 carrying magnets 14. A symmetrical two-lobed "figure-eight" shaped diaphragm 16 has two intercoupled circular sections tangentially abutting at a central expanse 18 that carries an electromagnetic coil. In this schematic view, the diaphragm is viewed along its axis of projection to show its cross-sectional profile. The remote ends of each web are connected to opposite ends of the frame 12. The transducer 10 is bilaterally symmetrical, giving it predictable and balanced acoustic properties. However, any acoustic faults in any one portion of the diaphragm are thus likely to occur in corresponding symmetrical portions, with the undesirable consequences of such faults being magnified multi-fold.

It will be appreciated that unless otherwise specified, the actual construction details of the prior art transducer of FIG. 1 and transducer designs described below are identical to what is disclosed in U.S. Pat. No. 4,903,308. Additional information for constructing these transducer designs can be found in U.S. Pat. No. 4,584,439.

FIG. 2 shows an asymmetric transducer 20 having a frame 22, magnets 24 secured to the frame, and an asymmetrical "figure-eight" shaped diaphragm 26 secured at its remote ends to the frame. One generally circular first lobe 27 of the diaphragm 26 is larger than an adjacent smaller second lobe 28, with the lobes tangentially abutting at a central expanse 29 between the magnets 24. The two lobes are interconnected at the central expanse. While the asymmetric diaphragm 26 may be formed of a single uniform material, it is preferred that the two lobes be formed of materials having different thicknesses and flexibility properties. Because of spring forces in the diaphragm, it tends to return to a centered position in the absence of external forces. Preferably, the lobes have similar spring constants to provide a net balanced spring force, and so that the central expanse naturally follows a straight path during the rolling motion of the diaphragm. This may be achieved by selecting a thicker and stiffer material for the larger first lobe 27 than for the smaller second lobe 28. Alternatively, the entire diaphragm may be formed of a single sheet of material with molded stiffening ridges to provide needed rigidity, as will be discussed below. The diaphragm preferably is provided with damping means such as damping strips adhered to the inner concave surface of the diaphragm (as shown in the '308 patent) or alternative damping means as described below.

FIG. 3 shows a monopolar transducer 30 having a frame 32 carrying magnets 34 and having a flexible cylindrical diaphragm 36 attached to the frame. The

diaphragm 36 is formed in a "numeral-three" profile with a pair of semi-circular lobes 37a, 37b attached at their distal ends to the frame and tangentially abutting at a central expanse 38 disposed between the magnets 34. The transducer 30 is a monopolar design and generates sound from only one side, so that it may be attached to a large flat surface, such as a wall or the front of a speaker cabinet (not shown), with the convex lobes projecting away from the surface. Because of the inherent tendency of the semi-circular lobes of the diaphragm 36 to straighten out, the lobes are securely glued together at the central expanse so that the diaphragm retains its shape while at rest. Also, the lobes may be preformed in the curved state so that they remain curved when unstressed.

FIG. 4 shows a transducer 40 having a "numeral-three" shaped diaphragm 46 similar to that of diaphragm 36 shown in FIG. 3, but with asymmetrically shaped lobes. Consequently, the transducer achieves the advantages of asymmetry in a monopolar design.

FIG. 5 shows a transducer 50 having a frame 52 with magnets 54 attached to the frame. A substantially S-shaped diaphragm 56 attached to the frame has two substantially semi-circular lobes, with each lobe being convex outward away from opposite sides of the frame. The lobes are joined at a central expanse 58 between the magnets 54. Because of the inherent tendency of an S-shaped diaphragm to straighten out to a flattened state, the diaphragm 56 is preferably molded to its desired S-shape so that it retains its shape at rest without internal stresses. In contrast to the diaphragms previously described, the diaphragm 56 may be constructed of a continuous single sheet or multi-layer sheet which forms both lobes, rather than two separate and distinct sheets (multi-layer or otherwise) which are interconnected at the central expanse to form the two lobes.

FIGS. 6-9 illustrate variations of the S-shaped diaphragm. FIG. 6 shows a transducer 60 having a substantially S-shaped diaphragm 66 with lobes of different sizes analogous to the asymmetrical transducers shown in FIGS. 2 and 4.

FIG. 7 shows a transducer 70 having a substantially S-shaped diaphragm 76 in which each lobe forms a quarter circle, as opposed to the semi-circular lobes illustrated in FIG. 5. The transducer 70 has some similarity to the bipolar transducer disclosed in U.S. Pat. No. 4,584,439 to Paddock.

FIG. 8 shows a transducer 80 having a generally S-shaped diaphragm 86 with a forward-facing semi-circular lobe 87 having a first radius and a rearward facing quarter-circle lobe 88 having a second radius smaller than the first radius. As discussed above with respect to the asymmetrical transducer of FIG. 2, the different lobes are preferably formed of materials having different stiffness and other mechanical properties to achieve a balanced rolling motion.

FIG. 9 shows a transducer 90 having an S-shaped diaphragm 96 similar to that of FIG. 8, except that it has a semi-circular front lobe 97 with a radius smaller than a quarter-circle rear lobe 98. It is also contemplated that the embodiments of FIGS. 8 and 9 may be rotated by 180 degrees so that the quarter-circle lobe of either embodiment faces forward.

FIG. 10 shows a modified version of the transducer 10 of FIG. 1, with an etched coil assembly 100 attached to the diaphragm 16 at the central expanse 18. These modifications may be employed in any of the diaphragm profiles disclosed or suggested above. As shown in

FIG. 11, the coil assembly 100 is formed in a multi-layer laminated design like that used for production of conventional two-sided printed circuit boards. A thin substrate 102 formed of a glass epoxy material or others such as Kapton common to printed circuit boards includes a pair of conductive coils 104 etched from copper foil laminated to opposite sides of the substrate 102. The substrate may range upward from 0.0025 inch thick, with 0.005 inch being preferred. One ounce copper foil provides adequate current carrying capacity, with trace widths of between 0.004-0.010 inch for the long vertical traces; the short transverse traces may be somewhat wider. Overall impedance of the coil may be varied by adjusting the width of the transverse traces. In the preferred embodiment, each coil is capable of carrying 2 amps of current continuously. Because the assembly is commonly fabricated for very stressful manufacturing processor, it is not susceptible to delamination at temperatures that occur in an audio transducer environment.

Each coil 104 includes a trace end contact 106 suitable for attachment to wiring 108 (shown in FIG. 10) that connects to an amplifier output. A metallized through-hole 110 defined in the substrate 102 permits the connection of the inner terminus of one coil to the inner terminus of the other coil on the opposite side of the substrate. As a result, there is no need for lead wires to provide a crossover for connecting to the interior of the coil. Also, the number of turns is effectively doubled, with the current flowing in one orbital direction. The coil assembly 100 is preferably adhered to inner diaphragm edges 112 as shown in FIG. 11 to allow the coils 104 to remain exposed to air for heat dissipation. The etched coil assembly may also be used in conjunction with any of the asymmetrical, S-shaped or monopolar embodiments shown in FIGS. 2 through 9.

FIG. 12 shows an electrostatic transducer 120 having a cylindrical diaphragm 122 with a substantially "figure-eight" profile, similar to the prior art transducer 10 shown in FIG. 1. The electromagnetic drive system of the prior art device is replaced by an electrostatic drive. In the electrostatic transducer 120 of FIG. 12, a highly charged filament 124 is attached to the diaphragm at the central expanse and runs the full height of the diaphragm without interruption. The filament is electrically connected to a high voltage of about 2-10 kv, and remains constantly charged during operation. A set of conductive rods 128 is fixed to the transducer frame 12 and connected to the variable signal outputs of an amplifier 129. The charged filament 124 is thereby electrostatically attracted to and repulsed by the variably charged rods with a force sufficient to create motion in the diaphragm for generating sound.

FIG. 13 shows the electrostatic transducer 120 in cross-section. To achieve a balanced, controlled diaphragm motion, the drive rods 128 are arranged in a rectangular array. Each drive rod runs parallel to the projection axis of the diaphragm 16. A left front drive rod 128a and right front drive rod 128b are positioned adjacent the central expanse 18 on opposite sides thereof and generally forward of the filament 124. The front drive rods 128a and 128b are electrically connected together and are connected to a first amplifier output line 131. A left rear drive rod 128c and right rear drive rod 128d are similarly positioned on opposite sides of the central expanse, but to the rear of the filament 124. The rear drive rods 128c and 128d are electrically connected to each other and to a second amplifier out-

put line 133, with the amplifier being connected to an input signal and creating a variable potential voltage difference between the front and rear drive rod pairs.

The charged filament 124 is preferably sandwiched between the tangentially abutting diaphragm lobes. In embodiments having S-shaped diaphragm profiles, such as those shown in FIGS. 5-9, the filament may be attached to one side of the diaphragm or laminated between layers of a multi-layer diaphragm.

As shown in FIG. 14, the filament 124 includes a conductive core 130 surrounded by an insulating cladding layer 132. The core is preferably formed of graphite-impregnated thread or other electrically conductive material to retain a charge. The cladding layer 132 is preferably formed of a thin tube of glass or other dielectric material that is not susceptible to dielectric breakdown at high voltages in the range of up to 5-10 kv. Without the cladding layer, the conductive core would be susceptible to arcing at high voltage, leading to ozone generation and other related problems. While a voltage of 2 kv may be adequate to achieve acceptable performance, higher voltages will provide commensurate increases in speaker efficiency, reducing amplifier cost and power requirements.

As shown in FIG. 14, one or more rod retention clips 136 may be used to laterally interconnect rods 128a, 128b, 128c, 128d. The clip 136 is formed of insulating material, such as a resilient plastic, to mechanically align the rods 128 and to eliminate unwanted vibrations thereof. The clip 136 defines a set of rod apertures 138 through which rods 128a-d are received. The clip defines a central space 144 for receiving the charged filament 124 and to permit a range of motion. Because the clip completely encircles the charged filament, the filament must be threaded through each clip prior to lamination with the diaphragm. Alternatively, the clip may be U-shaped so that it may be installed after the filament is laminated with the diaphragm and may further include flexible snap connections for receiving the rods without requiring the rods to be threaded through the apertures 138. To prevent vibration and loosening, the rods are preferably adhesively attached to the clip after assembly.

FIG. 15 further shows the clip 136 in a vertically aligned relationship with the diaphragm 16. The diaphragm defines an oblong or rectangular aperture 146 that is sufficiently large to provide clearance for the clip 136 and so that the diaphragm may vibrate in a sufficiently wide range of motion to generate sound without contacting the clip.

FIG. 16 shows a central portion of the diaphragm 16 in which two clips 136 are attached to rods 128a, 128b, 128c, 128d to provide alignment. This approach is useful for very tall transducers, an application to which the electrostatic approach is particularly well suited. Many clips are employed in a tall transducer, with the clips being spaced apart by 3 to 6 inches. An electromagnetic coil driven speaker of this type suffers from increasing impedance as the coil length is extended. Thus, a transducer several feet tall must be manufactured in several distinct sections. However, the electrostatic transducer has no such limitations.

FIG. 17 shows an electrostatic transducer 150 using ganged components for improved efficiency. The transducer 150 has three charged filaments 124a, 124b and 124c mounted on an enlarged central expanse 152 of the diaphragm 16. Drive rods 128a-128h are arranged in pairs in alternation with the filaments, with the mem-

bers of each pair being positioned in opposite sides of the central expanse 152. So that all of the components act in concert to provide efficient, high output sound, the central filament 124b is charged to a high voltage polarity opposite that of filaments 124a and 124c. Drive rods 128a, 128b, 128e and 128f are connected to a first output 131 of amplifier 129; rods 128c, 128d, 128g and 128h are connected to the opposite amplifier output 133. The ganged approach illustrated in FIG. 17 is shown as having three filaments, but it is contemplated that this number may be two, four or more.

The electrostatic drive construction is illustrated in conjunction with a symmetrical bipolar "figure-eight" profile diaphragm, as shown in FIGS. 1-13. However, the electrostatic principle may be applied to any transducer having a cylindrical diaphragm, such as those illustrated in FIGS. 2-9. The ganged construction illustrated in FIG. 17 has a similarly wide applicability and need not be limited to the illustrated embodiment.

FIG. 18 shows a low range transducer 160 having a three-lobed diaphragm 162. The transducer 160 includes a frame 164 supporting three sets of magnets 166. The diaphragm 162 includes two primary peripheral lobes 170, 172 formed of a flexible material, as used in two-lobed diaphragms of the prior art. A central lobe 174 has a smaller radius than the peripheral lobes 170, 172 and tangentially abuts each peripheral lobe at a respective central expanse 176, 178 that carries a coil for production of sound generally in the manner disclosed in the prior art. With the peripheral magnets being oriented in similar polarity and the central magnets oriented oppositely, the coils attached to each central expanse 176, 178 are connected in opposite polarity so that both coils act in concert to create a synchronized driving motion.

The transducer 160 may be configured as a woofer for producing primarily low frequency sounds, or alternatively may serve as a wide bandwidth device with a frequency range extending to substantially lower frequencies than would be possible with a two-lobed diaphragm.

For use as a woofer only, the central lobe material may be a relatively heavy and stiff material for maximum efficiency. The central area behaves as a piston and generates low frequency sound in concert with the peripheral lobes 170, 172, which operate in a rolling motion, as described in the prior art. Because the central lobe 174 functions ideally as a piston, wave motion across the central lobe is undesirable and may be controlled through use of a damping material such as felt, which may be attached to the entire inner surface of the central lobe 174.

For the transducer 160 to function as a wide bandwidth device, the central lobe 174 is formed of a thin, flexible material that may be appreciably thinner than the flexible material forming the peripheral lobes 170 and 172. Such a thin material will be sufficiently rigid at low frequencies due to the tighter radius in which it is bent. At low frequencies, the full range transducer 160 operates essentially as the woofer embodiment discussed above. At high frequencies, the central lobe responds flexibly to wave motion. Accordingly, the central lobe 174 must be damped adjacent to one central expanse 176 by a pair of felt strips 182, 184 attached to the interior of the central lobe 174. Without such damping, each central expanse would function as a separate sound source with the sound generated by each objectionably interfering with that generated by the other.

Alternatively, to avoid interference, the input to one of the coils may be electronically filtered to eliminate interference-generating high frequencies.

FIG. 19 shows a compression omnipole wave generator transducer 190 having opposed semi-cylindrical diaphragms 192, 194 with opposed, central coil-carrying portions 196a, 196b. Distal edge portions of the diaphragms are mounted to a frame 198. An electromagnetic coil 200 is attached to the diaphragm and forms a series of adjacent loops, each one of which runs up the first diaphragm 192 and down the second diaphragm 194. Accordingly, at any given time, all current flowing through the coil is flowing in a single direction in the wire portions of the coil 200 attached to the first diaphragm 192, while the current is flowing in the opposite direction through all the wire portions of the coil attached to the second diaphragm 194.

FIG. 20 shows a cross-sectional schematic view of the omnipole transducer 190, which has magnets 202, 204 attached to the frame 198 within the respective diaphragms 192, 194. The magnets are oriented in similar polarity so that the north pole of the first magnet 202 is directly opposite the north pole of the second magnet 204, with the south poles being similarly opposed. While the coil 200 is securely adhered to the diaphragms where the vertical wire portions run adjacent the magnet structures, the coil 200 includes slack upper and lower loops 206, 208 to permit the central coil-carrying portions 196 of the diaphragm freely to move toward and away from each other as a varying current passes through the coil.

In FIG. 21, the diaphragms 192, 194 (shown in solid lines) are shown in the extended position more closely spaced than when in the flexed positions 192', 194' (shown in dashed lines). This opposed motion creates compression and rarefaction of air within the space between the diaphragms. Consequently, acoustic waves 212 are emitted from the space between the diaphragms in a widely dispersed pattern on each side of the transducer. The combination of the acoustic waves, which constructively interact with each other as they emanate from the front and rear, gives the transducer an omnipolar response. In other words, the sound pressure generated by the transducer in a response to a given signal does not appreciably vary as the listener moves in a horizontal 360 degree circle centered on the transducer. The transducer 190 may be constructed in a vertically elongated configuration to create an effective omnipolar line source, that is, one that emulates a theoretical radially-pulsing cylinder.

Alternatively, as shown in FIG. 22, an electrostatic omnipole transducer 220 may be constructed according to the principles of the electrostatic transducer of FIG. 13. The electrostatic omnipole transducer 220 has similarly charged planar elements 222, 224 attached respectively to diaphragms 192, 194. The planar elements are wired to a high voltage power supply (not shown). A central plate 228 occupies the line of symmetry between the diaphragms and is connected to a first amplifier output 230. A pair of similar outer plates 232, 234 are positioned symmetrically within the respective diaphragms 192, 194 and are each electrically connected to a second amplifier output 238. The central plate 228 experiences balanced forces, making substantial reinforcement unnecessary. The outer plates 232, 234 may be secured along their height to the frame 198. Alternatively, all the plates may be replaced by similarly con-

nected vertical rods, as shown in the embodiment of FIG. 13.

In any cylindrical diaphragm system such as those disclosed above, as well as those of the prior art, it is necessary to control the flexibility and resonances of the diaphragms. In the bipolar cylindrical transducer 10 illustrated in FIG. 1, as well as in many of the other transducers disclosed herein, a wide frequency range is achievable. However, this range is limited at the high and low ends by contrary factors.

For theoretically ideal, efficient high frequency response, the central expanse 18 should approach infinitely low mass and high rigidity so that it may move crisply and responsively to an input signal of a limited power. The distance between the central expanse 18 and the diaphragm ends attached to the frame 12 is sufficiently long compared to the wavelength of high frequency vibrations that such waves are damped within the diaphragm well before they reach the diaphragm outer edges and have an opportunity to reflect back and interfere with subsequently generated waves. Also, because the diaphragm moves only a very small amount to generate high frequencies, flexibility is not critical.

At low frequencies, on the other hand, the diaphragm moves an appreciable amount, requiring flexibility. Furthermore, the long wavelengths involved may propagate within the diaphragm to the frame and reflect back to interfere with subsequently generated waves, creating unacceptable resonances at various frequencies if left undamped. Therefore, the ideal diaphragm for producing low frequencies is thick, non-resonant and flexible. In the prior art, these contrary objectives of high- and low-frequency production have been reconciled with reasonable success because rigidity for high frequency production is essential only near the central expanse, while flexibility and wave damping is necessary only in the diaphragm regions remote from the central expanse.

FIG. 23 shows a contoured diaphragm 240 in "numeral-three" configuration for a monopole transducer. To provide rigidity near the central expanse 18 and flexibility near the remote end 244, each lobe of the diaphragm 240 is molded from a single sheet of thermoplastic with a set of raised ridges 246. These ridges are broad and gently contoured near the remote end 244 to permit flexibility, and are narrow and more sharply contoured near the central expanse 18 to provide rigidity, even with a thin, otherwise flexible material. The ridges also have a taller profile near the central expanse and a lower profile near the remote end 244. Additional rigidity enhancing narrow ridges 248 may be positioned adjacent the central expanse for additional rigidity.

The contoured diaphragm 240 is preferably vacuum-formed onto a cylindrical form (not shown) shaped like the desired resulting diaphragm. This provides a diaphragm that is stress-free when at rest. If the diaphragm were formed in a generally planar position, it would become stressed as it was curved into the final cylindrical form. When so formed, it would have an outer surface in tension and inner surface in compression, resulting in different wave propagation rates.

Each ridge 246, 248 has a tapered end 252 adjacent the central expanse 18 so that waves propagating from the central expanse through the diaphragm do not appreciably reflect off the leading edge of the ridge. The ridges provide for controllability of the diaphragm's

flexibility without the time-consuming and efficiency-impairing addition of mass, such as the damping strips shown in the prior art. The ridges need not have a regular or symmetrical appearance. In fact, a designer may analyze a prototype diaphragm for undesirable resonances and selectively place ridges to eliminate the resonances. For instance, a region showing excessive flexibility may be provided with narrower, taller, more rigid ridges.

Other contemplated variations are illustrated in FIGS. 24-26. FIG. 24 shows a diaphragm 256 having a plurality of parallel linear ridges 258 molded therein. Each ridge 258 spans nearly the entire distance between the central expanse 18 and one of the remote ends 244. Each ridge is gently tapered at its ends to avoid reflections of propagating waves caused by abrupt transitions.

FIG. 25 shows a diaphragm 260 having parallel ridges 264 in an alternating arrangement, with full length ridges as shown in FIG. 24 being interspersed with shorter ridges to provide a wider transitional zone between the ridge-free areas and the ridge areas. FIG. 26 shows a diaphragm 270 providing a similar effect, but with intermediate length ridges 272 of the same length being positioned alternately proximate to and distal from the central expanse 18.

Any or all of the above features and improvements may be employed in embodiments also including features of the prior transducers. For instance, the diaphragm may include support or suspension members such as elastic cords or tab cut-outs folded from the diaphragm and adhered to the magnet or frame structure. Also, the diaphragm may be formed of either single or multiple layers of different materials and may also include adhesive damping strips applied to selected regions of the diaphragm inner surface. It should also be noted that the narrow magnet spacing of the prior systems is preferred; the schematic drawings in this application show a wider magnet gap to facilitate illustration.

Having illustrated and described the principles of my invention by what is presently a preferred embodiment, it should be apparent to those persons skilled in the art that the illustrated embodiment may be modified without departing from such principles. For instance, while the contoured diaphragms of FIGS. 23-26 are illustrated in the context of monopole transducers, the contours may similarly be applied in asymmetrical, S-shaped, or dipolar transducers. The various features and improvements disclosed herein may be combined in many combinations, such as a preferred embodiment having an electrostatic drive with an S-shaped diaphragm having a small radius semi-circular front lobe and a large radius quarter-circle rear lobe, and having contours molded into the diaphragm to provide added rigidity to the rear lobe. Innumerable other permutations of the features disclosed herein are contemplated to provide alternative embodiments. I claim as my invention not only the illustrated embodiment, but all such modifications, variations and equivalents thereof as come within the true spirit and scope of the following claims.

I claim:

1. An electrostatic audio transducer comprising:
  - a frame;
  - a flexible diaphragm having first and second ends attached to the frame, the diaphragm extending along an axis of projection and having a first lobe and a second lobe each having a sectional profile, perpendicular to the axis of projection, that is at



11

least a portion of a circle, the first and second lobes being tangentially joined to each other at a central expanse extending parallel to the axis of projection; chargeable element attached to the central expanse parallel to the axis of protection, the chargeable element being suitable for carrying an electrostatic charge; and

a conductive drive structure attached to the frame adjacent and substantially parallel to the chargeable element, the drive structure being connectable to an electrical signal to selectively attract and repel the chargeable element so as to cause movement of the central expanse in a direction perpendicular to the axis of projection and in a manner causing a rolling motion of the diaphragm, in said direction relative to the frame, sufficient to produce sound waves.

2. The transducer of claim 1 wherein the drive structure comprises a plurality of electrically conductive rods extending parallel to the chargeable element.

3. The transducer of claim 1 wherein the chargeable element comprises a linear electrically conductive rod.

12

4. The transducer of claim 1 wherein the chargeable element is movable, in response to electrical signals passing through the conductive drive structure, in a substantially planar path and the drive structure is positioned laterally outside of the planar path.

5. An audio transducer comprising:  
a frame; and

a flexible sound-producing diaphragm having first and second ends attached to the frame, the diaphragm extending along an axis of projection and having a first lobe and a second lobe each having a sectional profile, perpendicular to the axis of projection, that is at least a portion of a circle, the first and second lobes being tangentially joined to each other at a central expanse extending parallel to the axis of projection to provide the diaphragm with a substantially S-shaped sectional profile, wherein the first lobe has a first radius of curvature and the second lobe has a second radius of curvature smaller than the first radius of curvature, and the first lobe is stiffer than the second lobe sufficiently to provide a net balanced spring force to the central expanse.

\* \* \* \* \*

UNITED STATES PATENT AND TRADEMARK OFFICE  
**CERTIFICATE OF CORRECTION**

PATENT NO. : 5,450,497

DATED : September 12, 1995

INVENTOR(S) : Paul W. Paddock

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

On the Cover Page:

Under the heading "[56] References Cited - FOREIGN PATENT DOCUMENTS" insert the following:

--6094600 5/1985 Japan . . . 381/173--.

Column 5, line 9, "0,005" should be --0.005--.

Column 5, line 11, "0,004-0,010" should be --0.004-0.010--.

Signed and Sealed this  
Twenty-first Day of May, 1996

Attest:



BRUCE LEHMAN

Attesting Officer

Commissioner of Patents and Trademarks



US005249237A

**United States Patent** [19]**Paddock**[11] **Patent Number:** **5,249,237**[45] **Date of Patent:** **Sep. 28, 1993**[54] **AUDIO TRANSDUCER IMPROVEMENTS**[75] **Inventor:** **Paul W. Paddock**, McMinnville,  
Oreg.[73] **Assignee:** **Linnaeum Corporation**, Portland,  
Oreg.[21] **Appl. No.:** **708,924**[22] **Filed:** **May 31, 1991**[51] **Int. Cl.<sup>5</sup>** ..... **H04R 25/00**[52] **U.S. Cl.** ..... **381/202; 381/194;**  
381/199[58] **Field of Search** ..... 381/202, 204, 194, 195,  
381/199, 89, 197[56] **References Cited****U.S. PATENT DOCUMENTS**

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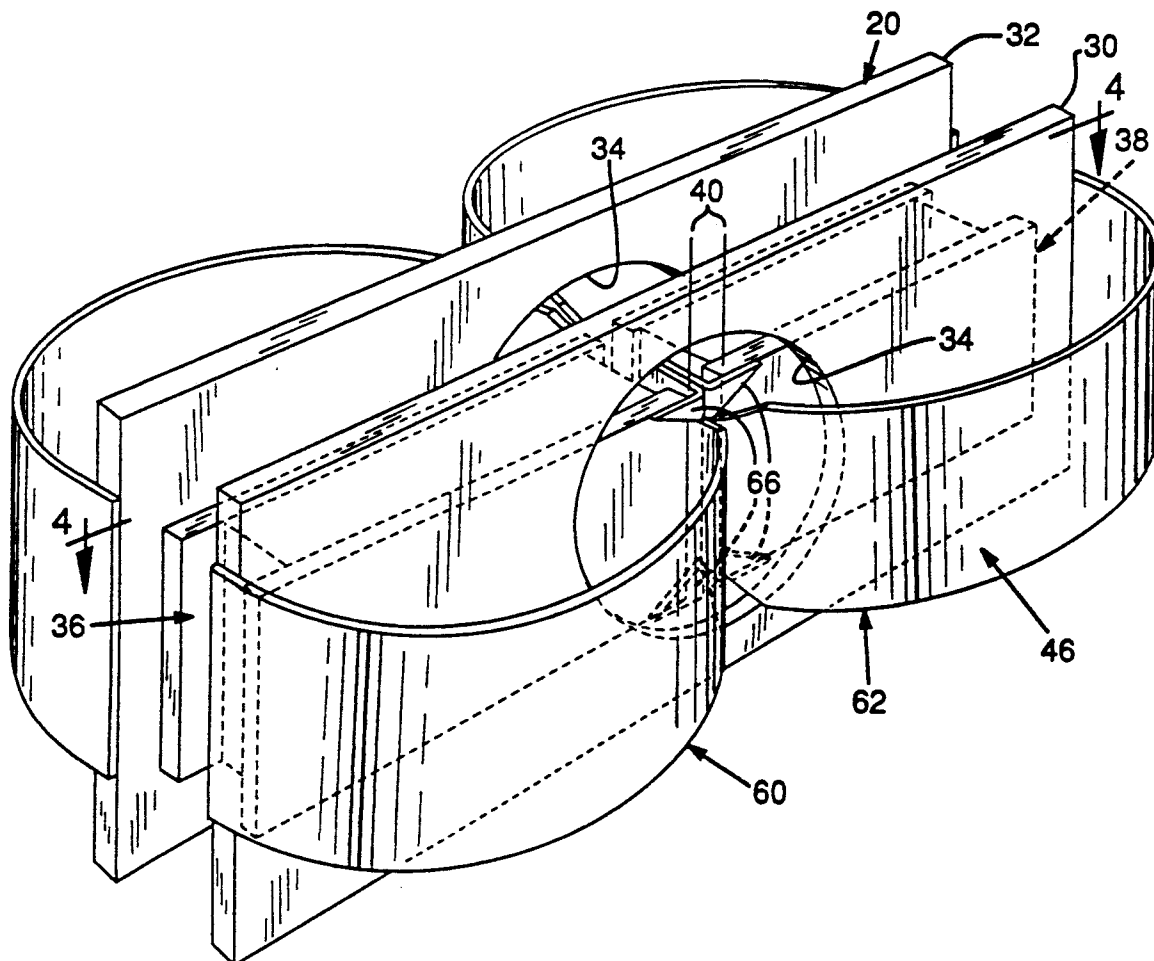
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*Primary Examiner*—Jin F. Ng*Assistant Examiner*—Huyen D. Le*Attorney, Agent, or Firm*—Klarquist, Sparkman,  
Campbell, Leigh & Whinston[57] **ABSTRACT**

An audio transducer having a pair of magnets supported to provide a magnet gap within which a flexible diaphragm supporting an electrical coil is received. The diaphragm is formed of a pair of flexible cylindrical webs joined at their centers to support the coil within the magnet gap. The diaphragm is provided with a row of perforations on either side of the gap to provide flexibility and is aligned centrally within the gap by tab portions partially cut from the diaphragm and folded to be adhered to the magnets.

**19 Claims, 6 Drawing Sheets**

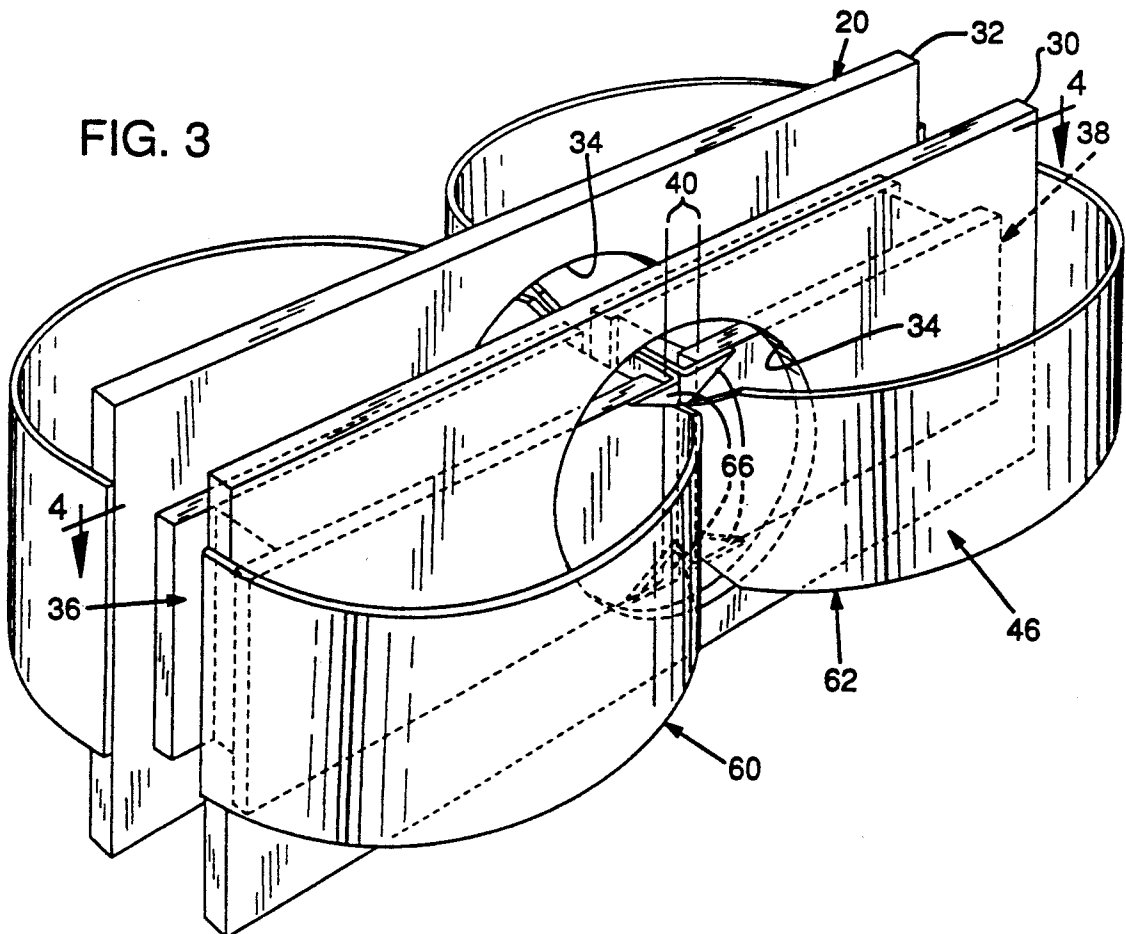
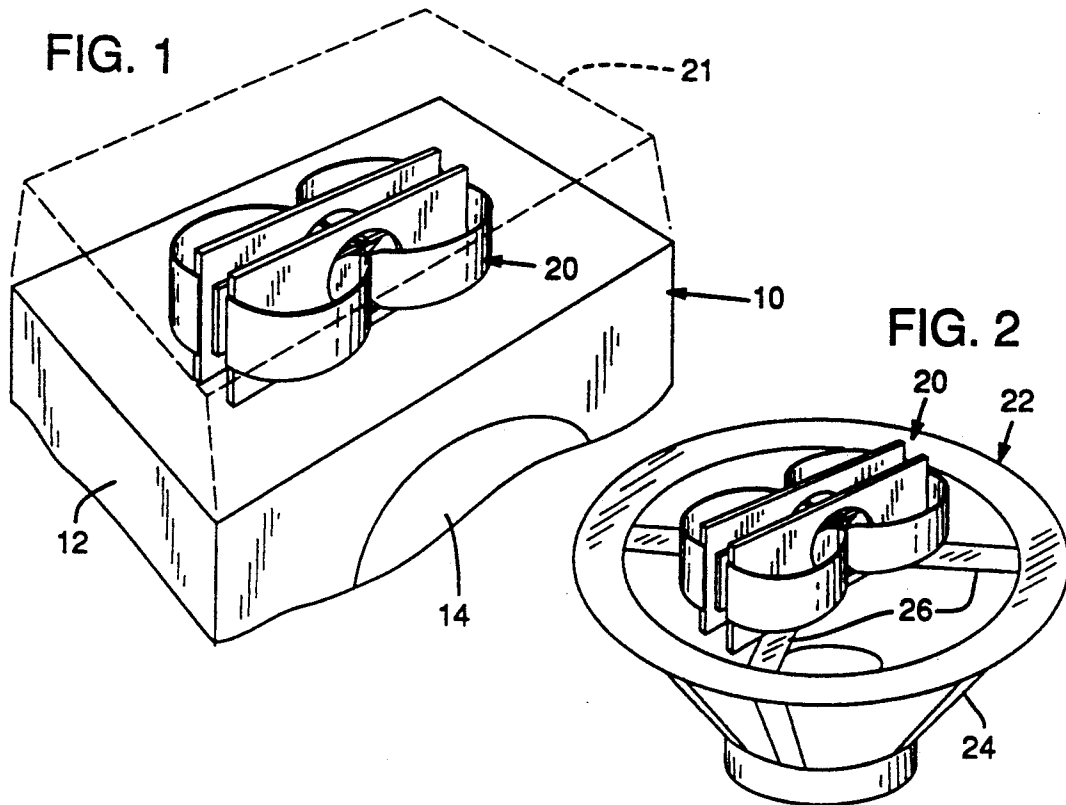




FIG. 6

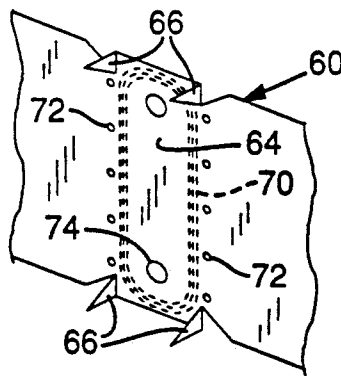


FIG. 14

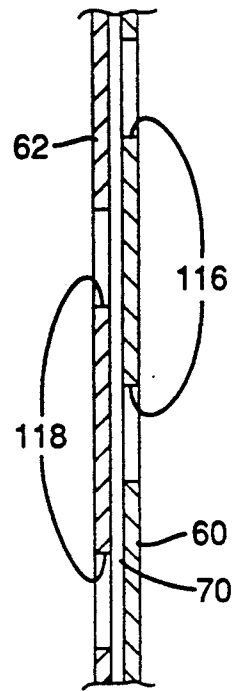


FIG. 7

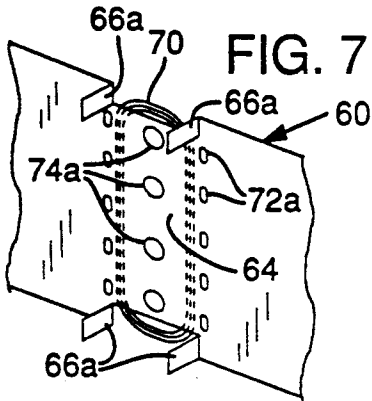


FIG. 12

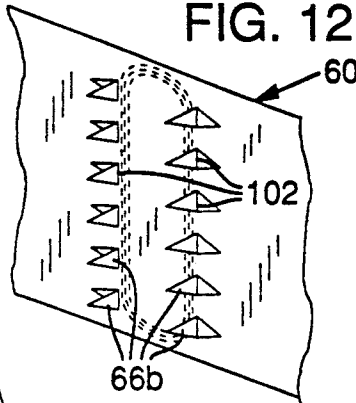


FIG. 13

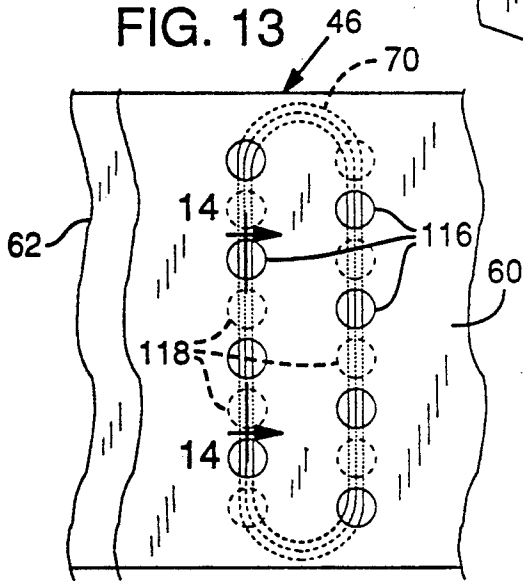


FIG. 15

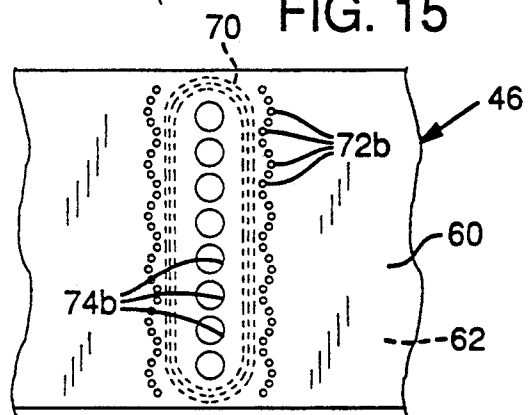


FIG. 16

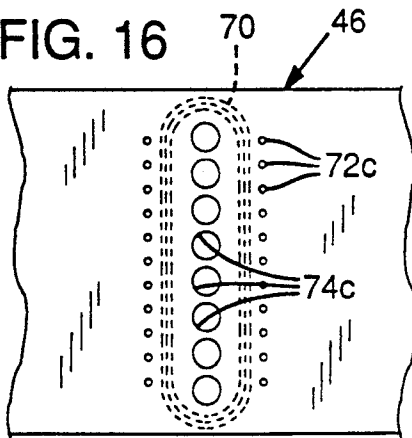


FIG. 17

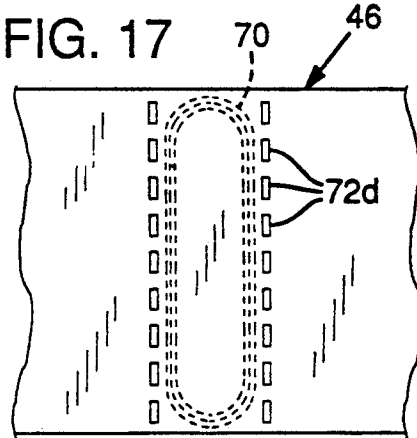


FIG. 8

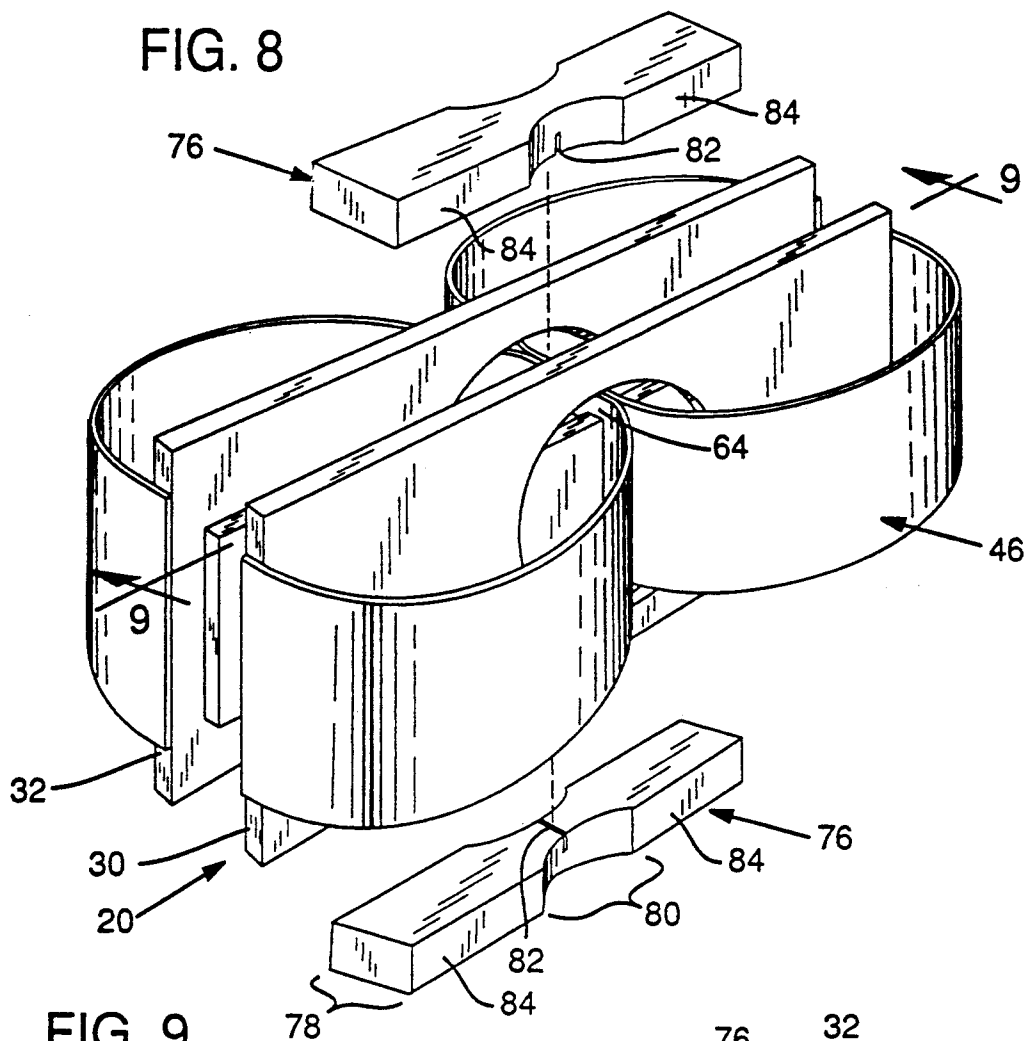


FIG. 9

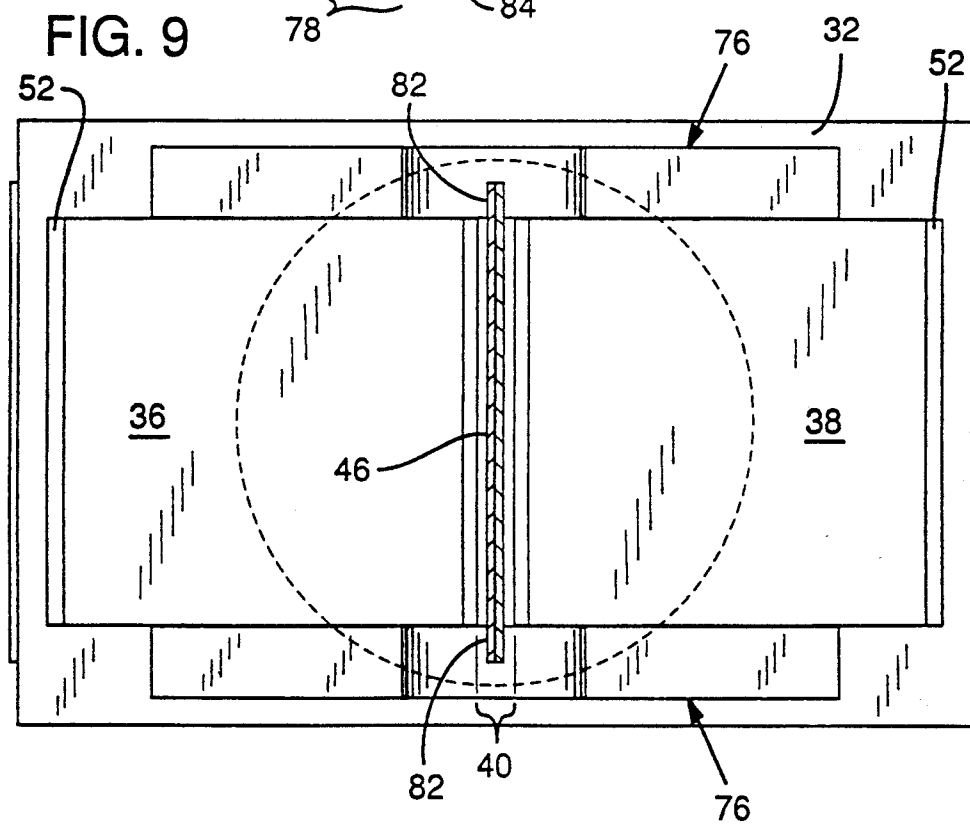


FIG. 10

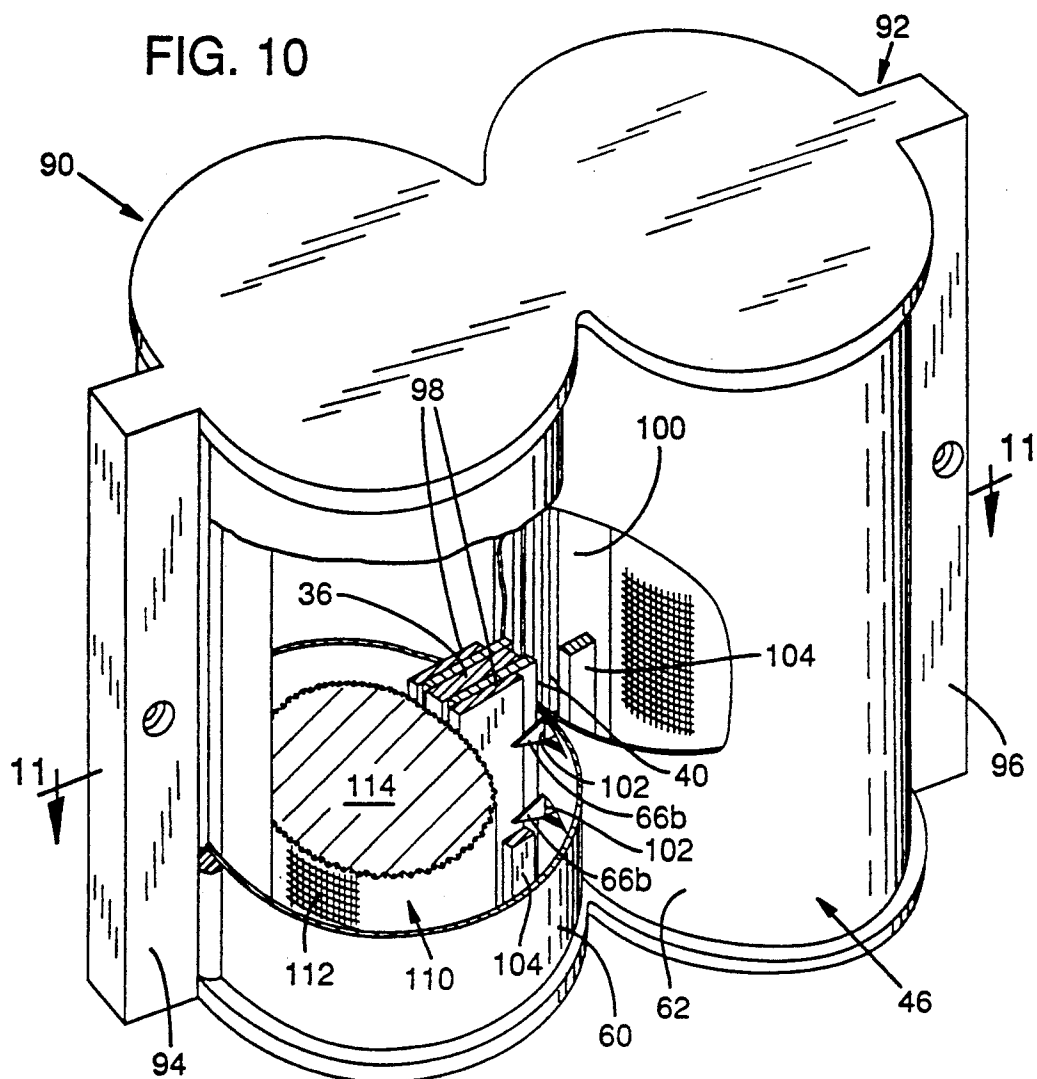
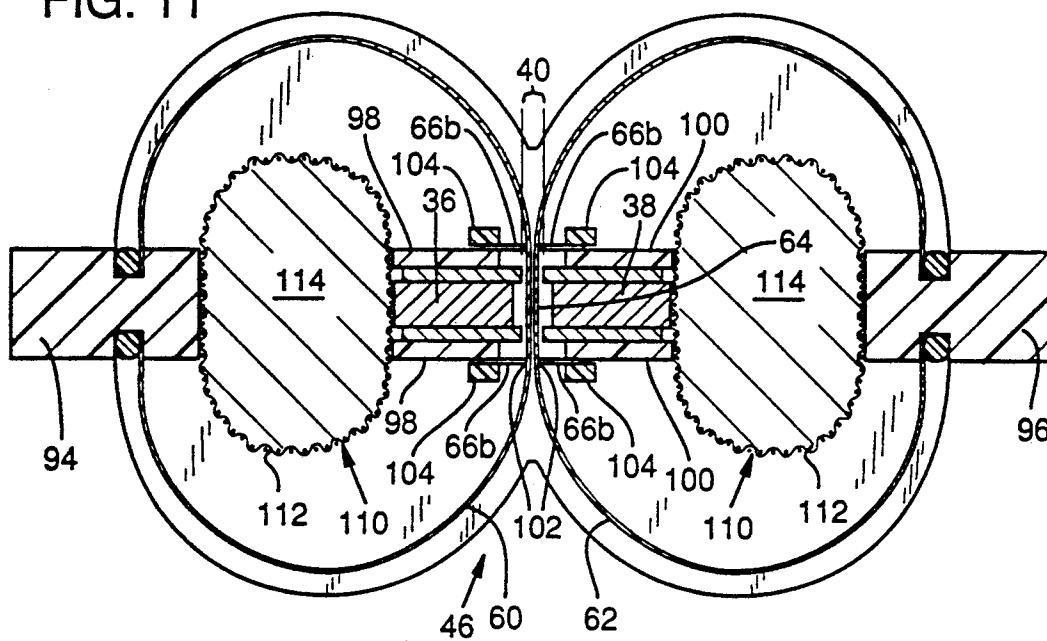
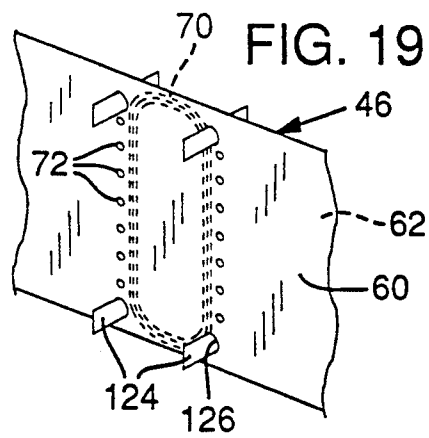
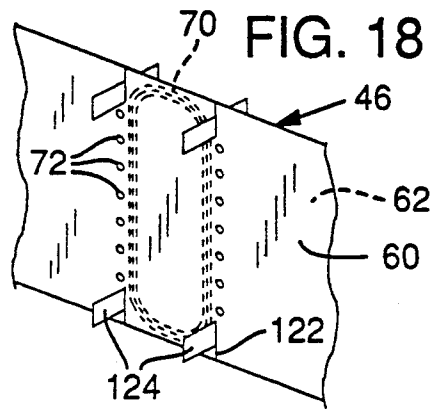


FIG. 11







## AUDIO TRANSDUCER IMPROVEMENTS

### Technical Field

This invention generally relates to audio transducers. More particularly, the invention relates to improvements in the design of a transducer with at least one arcuate diaphragm.

### BACKGROUND OF THE ART

U.S. Pat. No. 4,903,308, which is incorporated herein by reference, discloses an audio transducer used for producing mid-range to high range frequencies. This transducer has a pair of elongated resilient webs whose intermediate portions are joined together forming an expanse that extends generally in a plane, with the expanse supported for movement in the direction of the plane. This transducer is particularly well suited for high end consumer audio markets in which cost is not a substantial concern. Therefore, the complexity of the assembly and the precise manufacturing processes required do not prevent this transducer from being highly effective and marketable. In addition, overall efficiency of the existing transducer need not be maximized due to the generally adequate power capabilities of typical home audio amplifiers.

The foregoing transducer design is not as well suited for applications in which the manufacturing cost is critical and power is limited, as in portable stereo and car stereo applications. This is true of many other prior transducer designs as well. It is always desirable to reduce manufacturing cost and to increase efficiency for any application, particularly without sacrificing performance. Also, any transducer may be improved by widening its frequency range, especially by improving its high frequency efficiency.

A fundamental problem in extending the range of frequencies in any transducer is the seemingly unavoidable trade-off between the high and low frequency performance of the transducer. Measures to improve high frequency response, such as the use of lighter diaphragm materials, have the effect of diminishing output efficiency at the lower range of the transducer. Measures to improve low frequency response, such as the use of stiffer diaphragm materials, cause high frequency losses.

All prior art devices can benefit by reducing manufacturing costs. High performance transducers generally have numerous complex parts which must be carefully aligned in a labor- and skill-intensive manufacturing process that requires many assembly steps.

A further disadvantage of many prior transducers is that the speaker coil does not easily dissipate the heat that is generated when the transducer is driven under high load conditions. The coil is typically covered by material that thermally insulates the coil.

A further drawback in many prior transducers is the less than optimum high frequency efficiency due to the moving mass of the rigid portion of the diaphragm.

A further disadvantage in the prior art is the efficiency limitation caused by the lack of precision of alignment of the diaphragm relative to the magnet structure. To provide maximum efficiency, the magnets should be closely spaced adjacent the coil. This is especially critical with small, high frequency drivers, which typically use fewer coil turns and, thus, require a high strength magnetic field. The limitation of the prior art, however, is that imprecise positioning of the diaphragm

and coil relative to the magnet creates a risk of the diaphragm contacting the magnet structure as the diaphragm vibrates or as misalignment occurs over time and use. Thus, a wide gap is required to tolerate imprecise alignment of the diaphragm and to prevent the unacceptably distorted output that occurs when the diaphragm contacts the magnet.

In the above the above-referenced prior art transducer, the diaphragms are aligned centrally in the magnet gap by a set of elastic cords, each spanning from one magnet to the other and passing through a small hole defined in the diaphragm. Although the elastic cords are sized to tightly fit the holes defined in the diaphragm, the diaphragm may slightly shift over time. This shift is tolerated by using a wider magnet gap, which results in a lower efficiency transducer unsuitable for applications such as automotive and portable stereos. An additional characteristic of this suspension approach is that the added mass of the elastic cords tends to slightly diminish the high frequency performance of the transducer.

A further characteristic of the prior art transducer making it less than ideal for portable applications, is the further reduced efficiency caused by the larger magnet pole plates, which must extend beyond the magnets to provide a rigid position for the magnets to be secured to each other across the magnet gap above and below the diaphragm, and without interfering with the diaphragm. The securing bars used for this purpose tend to limit the width of the diaphragm, resulting in limited efficiency.

A further disadvantage of all prior art audio transducers is that the diaphragm material has a less than desirable strength-to-weight ratio. In addition, the flexible materials such as the plastics and papers that are commonly used for such applications have a low resistance to solvents and acids and are highly susceptible to degradation in various types of radiation, particularly ultraviolet light as is found in outdoor applications, such as automotive installations.

A further disadvantage of the diaphragm materials used in the prior art is that the plastics and plastic coated papers commonly used have a surface that is generally incompatible with many adhesives, making manufacturing difficult by limiting adhesive choices to those adhesives with other undesirable properties.

### SUMMARY OF INVENTION

An object of this invention, therefore, is to provide an improved transducer featuring a construction which overcomes the difficulties and shortcomings indicated.

More specifically, an object of the invention is to provide a transducer with an improved high frequency response without a loss of efficiency or performance at the low end of the transducer frequency range.

Another object of the invention is to provide a high performance transducer that may be inexpensively manufactured, having a small number of parts and requiring few complex manufacturing processes.

Still another object of the invention is provide a transducer wherein the speaker coil may easily dissipate accumulated heat.

A further object of the invention is to provide a transducer having a rigid moving mass of reduced weight.

Yet another object of the invention is provide a transducer wherein the diaphragm may be easily and precisely aligned within the magnet gap to safely permit a

narrowed magnet gap such that the alignment remains fixed over use and time.

It is a further object of the invention to provide a transducer with a diaphragm alignment system that does not add appreciable mass to the transducer and which is sufficiently lightweight to avoid damping the vibration of the diaphragm.

It is a further object of the invention to provide a transducer having a rigid magnet alignment structure that does not limit the width of the diaphragm employed.

A further object of the invention is provide a transducer with a diaphragm constructed from a material that has a high strength-to-weight ratio, is resistant to solvents and acids, which resists degradation on exposure to ultraviolet radiation, which has a surface that is compatible with a wide variety of standard adhesives, and which is highly thermally transmissive without warpage at high temperatures and temperature differentials.

These and other objects and advantages of the invention will become more fully apparent as the description which follows is read in conjunction with the accompanying drawings.

### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of a transducer according to the present invention used in one application as a high frequency transducer attached to a standard low-frequency speaker with a cone driver.

FIG. 2 is a perspective view of the transducer of FIG. 1 as mounted to an automobile low frequency cone driver.

FIG. 3 is a perspective view of the transducer of FIG. 1.

FIG. 4 is a cross-sectional view taken along line 4—4 of FIG. 3.

FIG. 5 is an enlarged cross-sectional view taken along line 4—4 of FIG. 3 showing the structure in the vicinity of the electrical coil.

FIG. 6 is a fragmentary perspective view of an alternate diaphragm embodiment of the apparatus of FIG. 3 in preassembled form with triangular tangs extended.

FIG. 7 shows a fragmentary perspective view of an alternate diaphragm embodiment in preassembled form with rectangular tangs extended.

FIG. 8 is a partially exploded perspective view of the transducer of FIG. 3 with an alternative diaphragm centering arrangement.

FIG. 9 is a cross-sectional view taken along line 9—9 of FIG. 8.

FIG. 10 is a fragmentary perspective view of a mid- and high-frequency transducer constructed in accordance with another embodiment of the invention.

FIG. 11 is a cross-sectional view taken along line 11—11 of FIG. 10.

FIG. 12 is a fragmentary perspective view of an alternate diaphragm embodiment of the apparatus of FIG. 10 in preassembled form with alignment tangs extended.

FIG. 13 is fragmentary side view of an alternative diaphragm embodiment of the apparatus of FIG. 10.

FIG. 14 is an enlarged cross-sectional view of the diaphragm of FIG. 13 taken along line 14—14 of FIG. 13.

FIG. 15 is a fragmentary side view of an alternate diaphragm embodiment of the apparatus of FIG. 10.

FIG. 16 is a fragmentary side view of a further alternate diaphragm embodiment of the apparatus of FIG. 10.

FIG. 17 is a fragmentary side view of a further alternate diaphragm embodiment of the apparatus of FIG. 10.

FIG. 18 is a fragmentary perspective view of an alternative diaphragm alignment arrangement of the apparatus of FIG. 3.

FIG. 19 is a fragmentary perspective view of a further alternative diaphragm alignment arrangement of the apparatus of FIG. 3.

### DETAILED DESCRIPTION OF THE INVENTION

FIG. 1 shows a book shelf speaker 10 embodying the present invention in the application. The speaker includes a standard box-type enclosure 12 with a cone driver 14 for producing low- and mid-range frequencies. A high frequency transducer 20 in accordance with the present invention is mounted to the top of the enclosure 12. The driver 14 and high frequency transducer 20 are electrically connected to a standard cross-over network (not shown) so that the high frequency transducer 20 receives frequencies over 2,000 Hz and the driver 14 receives frequencies below 2,000 Hz. This cross-over point may be varied to suit the needs of the particular application. An acoustically transparent grille 21 (shown in dashed lines) may be provided to protect the speaker from dust and damage, and to provide an aesthetic appearance.

As a second exemplary application of the present invention, FIG. 2 shows an automotive speaker 22 for mounting in a typical rear deck position of an automobile interior. A standard upward facing cone-type low- or mid-range driver 24, such as a typical 6"×9" woofer, is oriented horizontally with its diaphragm facing upward. The high frequency transducer 20 is rigidly suspended above the diaphragm of the driver 24 by horizontal brackets 26 that allow substantial open space for the sound emitted by the driver 24 to be upwardly projected. The high frequency transducer 20 thereby protrudes above the rear deck (not shown) and transmits sound directly forward toward the automobile passengers. The high frequency transducer 20 and driver 24 are interconnected by a cross-over network (not shown) as discussed above with reference to speaker 10 of FIG. 1. A protective grille (not shown) may be used to shroud the speaker 22.

As shown in FIG. 3, the high frequency transducer 20 is generally of a rigid, layered construction. This construction includes a chassis or frame having a front chassis plate 30 and a rear chassis plate 32. Plates 30, 32 are vertically oriented rectangular plates made preferably of a rigid plastic material. The plates are identical to one another and oriented in a parallel, laterally spaced relationship. Each plate defines a circular central aperture 34 having a diameter that is a substantial fraction of the height of the chassis plates 30, 32, to permit passage of large items without sacrificing rigidity. The apertures of the plates are in registration with one another. A first magnet assembly 36 and a second magnet assembly 38 are supportively sandwiched between the chassis plates 30, 32 with the chassis plates adhesively affixed thereto to provide a rigid chassis structure. The magnet assemblies 36, 38 thereby provide a fixed magnetic field suitable for interaction with a coil carrying an electrical current as will be discussed below. The magnet assem-

blies 36, 38 are rigid rectangular structures arranged symmetrically and orthogonally between the chassis plates 30, 32 to define a magnet gap 40 of constant width therebetween. The magnet gap 40 extends vertically the full height of the magnet assemblies and if extended laterally, would bisect the central apertures 34. Thus, the centers of the apertures are aligned with the magnet gap.

To maximize speaker efficiency, the magnet gap should be as narrow as possible while allowing sufficient clearance to permit passage of a planar diaphragm 46 as will be discussed below. The ideal gap width varies depending on the size of the transducer and application being fulfilled. The magnet gap 40 may range between 0.020 and 0.062 inch, with a spacing of inch being preferred in the particular high frequency transducer 20 illustrated.

As shown in FIG. 4, each magnet assembly 36, 38 comprises a magnetic core 48, 50, respectively, with a pair of rigid, ferro-magnetic metal pole plates 52 affixed to the opposite sides of each magnetic core. The pole plates 52 are generally coextensive with the magnetic cores 48, 50, extending slightly beyond the magnetic cores in the direction of the magnet gap 40 so that the separation between opposed pole plates 52 defines the magnet gap. The magnetic cores 52 are magnetically oriented so that each pole plate is of opposite magnetic polarity from the other pole plate attached to the same magnetic core and so that each pole plate 52 is also magnetically opposite from its counterpart across the magnet gap 40.

It will be apparent from the foregoing that each chassis plate is adhered to one of the pole plates of each magnet assembly to provide a sandwich construction which is perfectly symmetrical.

The diaphragm 46 is formed of a pair of elongate resilient webs 60, 62. The paired structure provides a symmetrical structure, but a single diaphragm may be used where this characteristic is unnecessary. Each web includes flexible curved portions forming the end of each web, joined to and extending from an intermediate, generally planar central portion 64 also indicated in FIG. 5. Web 60 includes a front curved portion 60a, a rear curved portion 60b and a central expanse 60c. Web 62 includes a front curved portion 62a, a rear curved portion 62b and a central expanse 62c. The central expanses 60c, 62c of the two webs are joined together, as with an adhesive, to form the central portion 64. The central portion 64 is an essentially rigid unit functioning as a narrow beam, and is movable generally in the plane occupied by the expanse. That is, it moves perpendicularly to the plane of the chassis plates 30, 32. Thus, the central portion is movable laterally relative to the transducer as a whole.

The diaphragm 46 is preferably constructed of an aramid fiber paper sheet such as Nomex®, produced by DuPont, but other flexible, lightweight, high-strength, environmentally stable materials may be used.

The central portion 64 of the diaphragm 46 is suspended centrally within the magnet gap 40 by the flexible curved portions 60a, 60b, 62a, 62b. The end of each flexible curved portion is attached adhesively to a respective end portion 30a, 30b, 32a, 32b of each chassis plate 30, 32 so that each flexible portion forms a semi-circular shape, giving the diaphragm the general shape of a figure-eight when viewed from above or below. The curved portions of each web define curved surfaces which extend through respective central apertures 34

to meet at the expanse. The curved portions 60a, 60b, 62a, 62b primarily act as flexible suspension members and not as sound radiating surfaces. This is particularly true at high frequencies, at which only the portions of the diaphragm 46 closest to the center portion 64 are actively radiating sound. Thus, alternate suspension devices may be used without impairing the function of the invention, particularly at high frequencies.

FIG. 5 shows the central portion 64 of the diaphragm 46 that resides within the magnetic gap 40. As will be discussed below with reference to FIG. 6, a set of tab portions or tangs 66 are partially cut from the diaphragm 46 and folded perpendicular to the central portion 64 of the diaphragm so that they extend in planes substantially coincident with the exterior surfaces of the pole plates 52, to which the free ends of the tangs 66 are adhesively attached. The central apertures 34 are large enough to expose a sufficiently large area of the exterior surfaces of the pole plates 52 to permit the tangs to be attached thereto. As a result, the central portion 64 is maintained in the central location between the magnets while being free to move laterally within its own plane by a sufficient amount to produce high audio frequencies. The tangs 66 prevent longitudinal movement of the central portion 64 of the diaphragm 46, while permitting unimpaired lateral movement in the plane of the central portion 64.

FIG. 5 further illustrates an electromagnetic coil 70 laminated between the central expanses 60c, 62c of the web 60, 62 to become a rigid portion of the central portion 64. The vertical portions (shown in cross-section) of the coil 70 are positioned in the regions immediately between the pairs of opposed pole plates 52.

FIG. 6 shows web 60 in a straightened, partially preassembled condition with triangular tangs 66 cut and folded in position for attachment to the magnet pole pieces 52. In this embodiment, one edge of each tang is an extension of either the upper or lower portion of the web, depending on whether the tang is the upper or lower tang. The coil 70 (shown in dashed lines) is an elongate looped coil of wire forming a vertically oriented generally oblong or rectangular shape, with a pair of opposed straight, vertically oriented wire segment portions being spaced apart to align with the magnet pole pieces 52. Similar tangs are cut in web 62 (not shown) and folded in the opposite direction as those shown, providing a symmetrical diaphragm.

As further shown in FIG. 6, the diaphragm 46 is provided with a vertical row of hinge perforations 72 on each side of the coil 70. The perforations are preferably aligned with the folded tangs 66 and are positioned within about  $\frac{1}{4}$  inch of the coil 70 and hence within about  $\frac{1}{4}$  inch of the joined expanse portion. The tangs are integral extensions of the web formed by folding pre-slitted tab-like portions of the web. Positioning the perforations 72 close to the coil 70 effectively reduces the mass of the rigid center portion 64 of the diaphragm 46. The perforations 72 may be circular as shown or, alternatively, may be any other shape including oblong, square or elliptical and may alternatively be sheared line segments with no diaphragm material removed. FIG. 6 further shows the center portion 64 defining mass reduction holes 74, the advantages of which are discussed below with reference to FIG. 7.

Each row of perforations acts like a hinge to permit a less constrained, more responsive movement of the central diaphragm expanse portion 64. The size of the perforations is not critical, only the proportion of mate-

rial removed affects the key property of hinge-like flexibility at the edges of the center portion 64. Along the hinge center line of each row of hinge perforations 72, the sum of the linear dimensions of the perforations is preferably between about 10% and 50% of the full linear dimension of the web 60 along the same vertical line. With current materials used, the perforations define a pair of hinge lines at which the web material is preferably about 80% connected and 20% perforated. Thus, it is apparent that the web shown in FIG. 6 is less than 20% perforated and thus less than optimum. The foregoing parameters likely will become better defined with further experimentation.

The added hinge-like flexibility provided by the perforations 72, permits the efficiency of the transducer at very high frequencies to be substantially increased as the rigid central portion 64 of the diaphragm 46 is able to move more independently of the mass of the web curved portions 60a, 60b, 62a, 62b. In addition, the reduced mass resulting from the removal of the diaphragm material is the close vicinity of the central portion may also contribute to this effect. Experimental analysis has shown a 3 to 6 db increase in output over the 12 to 24 kHz high frequency range, with no sacrifice in efficiency at the low end of the transducer's output. Previous attempts to provide an improved high frequency efficiency, such as using a lighter and more flexible diaphragm material, have resulted in an undesirable drop off in low frequency performance.

FIG. 7 shows a web 60 having an alternative arrangement of tangs 66a and perforations 72a. In this embodiment, the tangs are rectangular and folded perpendicularly outward from their original pre-folded positions in the center portion 64 of the diaphragm 46 covering the end portions of the coil 70. While it is generally desirable that the coil be supported by and rigidly affixed to the webs 60 and 62, this is only important along the vertical portions of the coil (shown in dashed lines), which magnetically interact with the magnets shown in FIGS. 3 and 4. The exposed end portions of the coil 70 need not be supported. A further advantage of the FIG. 7 web construction is that the exposed end portions of coil 70 dissipate accumulated heat more effectively, as they are directly exposed to the environment.

The perforations 72 are shown in FIG. 7 as oblongs aligned axially in a vertical row, but any shape may be used as discussed above with reference to FIG. 6. As in FIG. 6, FIG. 7 shows only a single web 60. A similar web 62 would be adhered at the central portion 64 to create a sandwich, with the coil 70 between the webs. FIG. 7 also shows central mass reduction perforations 74 defined in the central portion 64 of the diaphragm, and centered entirely within the coil 70 to reduce the mass of the central portion 64. The central portion 64 is rigid and functions essentially as a planar beam translating in its own plane. The mass reduction provided decreases the inertia of the central portion 64 and results in a slight improvement in high frequency efficiency, with a subjectively perceptible increase in the quality of sound perceived as quickness.

FIGS. 8 and 9 show the high frequency transducer 20 with an alternative diaphragm centering mechanism. Instead of the tangs 66 formed of the diaphragm 46 to align the diaphragm within the magnet gap 40, as shown in FIGS. 3-7, the embodiment of FIG. 8 uses a pair of elongated foam members 76 to retain the central portion 64 of the diaphragm centrally within the magnet gap 40. Each foam member has a width 78 sized to closely fit

between the front and rear chassis plates 30, 32. Each foam member 76 has a slitted central neck portion 80 with a reduced width. A slit 82 is cut across the width of the neck portion to a depth of about one-half the thickness of the foam member. The foam members 76 are attached to the high frequency transducer 20 by mating the slits 82 with the corresponding top and bottom edges of the central portion 64 of the diaphragm 46 and adhesively securing the sides 84 of the foam member 76 to the inner surfaces of the chassis plates so that the foam members rest against the magnets 36, 38 and are entirely positioned between the chassis plates 30, 32. In addition, the slits 82 are adhesively secured to corresponding edges of center portion 64 of the diaphragm 46.

The diaphragm 46 is thereby retained perfectly centered within the magnet gap 40 by the slits 82 provided in the elongated foam members 76. Because the foam members 76 are formed of a lightweight open cell foam having a low resistance to small displacements, they have a negligible damping effect on high frequency vibrations of the diaphragm 46, yet they preserve a central alignment of the diaphragm 46 that is not susceptible to shifting over time.

FIGS. 10 and 11 show a wide range, mid- to high-frequency transducer 90 embodying the invention as an essentially improved version of the audio transducer disclosed in U.S. Pat. No. 4,903,308. Transducer 90 operates on the same general principal as the high frequency transducer 20, with a diaphragm 46 formed by webs 60, 62, as a figure-eight shape. The central portion 64 of the diaphragm 46 passes through the magnet gap 40 (FIG. 11) with a coil 70 (not shown) sandwiched between the webs 60, 62 and residing within the magnet gap in the manner precisely described. In this larger embodiment of the transducer 90, a larger chassis 92 retains the diaphragm 46 and the magnet assemblies 36, 38. The chassis 92 is formed generally of spaced apart vertical diaphragm retaining members 94, 96 and two opposed pairs of central opposed vertical magnet retaining members 98, 100 located between the diaphragm retaining members 94, 96. The magnet retaining members 98 comprise a pair of rigid vertical planar members spaced apart sufficiently so that magnet assembly 36 may be rigidly affixed therebetween to define the magnet gap 40 with the opposite magnet assembly 38, which is similarly affixed between the opposing pair of magnet retaining members 100.

FIGS. 10 and 11 further show a diaphragm centering means including triangular alignment tangs 66b formed by V-shaped cuts in each web 60, 62. The apex of each "V" forms a free end that points horizontally away from the central portion 64 of the diaphragm 46. The base of each "V," that is, the portion closest to the central portion 64 of the diaphragm 46 and integrally attached to the diaphragm at a fold line 102, extends substantially perpendicularly from the web in a plane parallel to the exposed exterior surface of the adjacent magnet retaining pair member 98, 100 so that the tang 66b may be adhered to or secured against the adjacent retaining member. With the diaphragm 46 suitably centered in the magnet gap 40, the free end tips of the tangs are adhered or clamped to the exposed surfaces of the magnet retaining pair members 98, 100 and covered by rigid elongated tang retaining members 104, which are adhesively affixed to the magnet retaining pair members 98, 100 so that the tips of the tang 66 are sandwiched therebetween. The cuts forming the tangs 66 have the

additional advantage of providing a flexible hinge line as discussed above with respect to the hinge perforations 72 and 72a of FIGS. 6 and 7. Additional perforations (not shown) between tangs 66b may be provided to increase the diaphragm's flexibility still further.

FIGS. 10 and 11 also show a pair of cylindrical acoustic dampers 110 oriented vertically and positioned between the respective diaphragm retaining member 94, 96 and magnet retaining pair 98, 100 in each chamber defined by the respective circular web 60, 62. Each damper 110 is formed by a cylindrical tube of perforated webbing, such as a flexible plastic mesh 112, which is filled with a core of lightweight fibrous stuffing 114. The stuffing 114 may be any suitable material, such as wool, felt, cellulose fiber or fiberglass. The dampers prevent internal acoustic reflections and vibrations from degrading the output sound.

FIG. 12 shows preassembled web 60 of the embodiment of FIGS. 10 and 11 with the tangs 66b shown as "V" cuts and folded along fold lines 102. Tangs 66 are arranged in two vertically aligned rows, one row on each side and located about  $\frac{1}{4}$  inch from coil 70. Like tangs 66, tangs 66b are formed as integral folded extensions of the diaphragm.

FIGS. 13 and 14 show an alternative configuration of the diaphragm 46 for use on the mid- to high-frequency range transducer 90 of FIGS. 10 and 11. Web 60 is provided with a plurality of circular holes 116 arranged in vertical rows registered with the linear vertical portions of the coil 70. The holes 116 are spaced apart in each row by a center-to-center distance greater than twice the diameter of the holes. The holes are staggered in each row so that the holes in one row are aligned with the mid points between centers of adjacent holes in the opposite row. The web 62 is provided with an identical set of holes 118, shown in dashed lines. Webs 60, 62 are registered with the holes 116, 118 aligned in reverse registration so that each hole 116 overlies a solid unbroken portion of adjacent web 62 and each hole 118 underlies a solid, unbroken portion of adjacent web 60. Therefore, there are no openings passing entirely through both webs 60, 62. The coil 70 is adhesively laminated between the webs 60, 62 so that its vertical linear sections are generally aligned with the rows of holes 116, 118. Because of the arrangement of holes 116, 118, every point along the entire length of the coil 70 is adhered either to web 60 or web 62 or both. This prevents any undesirable relative motion between the coil 70 and the webs 60, 62. Because the webs 60, 62 are adhered only to the coil, and not to each other in the region beyond the periphery of the coil, the holes 116, 118 provide the hinge-like flexibility discussed above, and produce high frequency efficiency improvements without sacrificing low frequency efficiency. In addition, heat in the coil 70 is readily dissipated by the substantial portions exposed to air through the holes 116, 118, while performance is maintained with a rigidly attached coil.

FIG. 15 shows an alternative diaphragm arrangement for the transducer 90 of FIGS. 10 and 11. An articulated row of perforations 72b is defined entirely through the diaphragm 46, penetrating both webs 60, 62 on both sides of the coil 70. The perforations as shown are circular, but numerous other shapes are contemplated and may be substituted. The holes 72b of this embodiment are separated by at least a minimal distance from the coil 70 to ensure that the coil is entirely adhered to the diaphragm 46. At least a portion of some of the perfora-

tions preferably are within at least about  $\frac{1}{4}$  inch of the coil 70 to provide optimal flexibility in the diaphragm 46 for high frequency efficiency. FIG. 15 further shows a centrally aligned row of mass reduction perforations 74b positioned in a vertical row within the coil 70. The perforations 74b may pass entirely through the diaphragm 46 or may each be defined only in a single web 60 or 62 so that through holes are not provided through the diaphragm. In an alternative embodiment, a thin film or sheet of thin material may be provided between the webs 60, 62 to close the perforations 74b while allowing the advantages of substantial weight reduction.

FIG. 16 shows an additional alternative embodiment, with diaphragm 46 having hinge perforations 72c defined in the diaphragm 46 as small diameter circular holes in a linear configuration. In this embodiment shown, about 20% of each row is perforated while about 80% of the diaphragm remains connected at each row. FIG. 16 further shows the optional mass reduction perforations 74c.

FIG. 17 shows a further alternative diaphragm 46 embodiment having elongated rectangular perforations 72d that provide a hinge-line of approximately 50% perforated length and 50% connected length.

It will be appreciated that the perforations 72 located along the outside vertical edges of coil 70 can have a wide variety of shapes and sizes. The perforations 72, for example, have a diameter of about  $\frac{3}{32}$  inch and are spaced apart about  $\frac{1}{4}$  inch. Perforations 72a have a length of about  $\frac{1}{8}$  inch and are spaced apart about  $\frac{1}{4}$  inch. Similarly, perforations 72b have a diameter of about  $\frac{1}{8}$  inch and a spacing of about  $\frac{1}{4}$ , and perforations 72c have a diameter of about  $\frac{3}{16}$  inch and a spacing of about  $\frac{1}{2}$  inch.

The increased flexibility and compliance which the perforations 72 provide the diaphragm is, in part, a function of the distance of the perforations from the vertical edge of the coil (which edge also defines the edge of the rigid central portion formed by adhering the two webs together). The perforations preferably eliminate diaphragm material along a hinge line within about  $\frac{1}{4}$  inch and, most preferably, within  $\frac{1}{8}$  inch or less of the vertical edges of the central joined-together portion of the webs. As this distance increases, spacing the perforations further from the coil, the increased flexibility and compliance drops off because the perforations are located farther from "hinge zone" on either side of the rigid beam-like central portion and hence farther from the primary high frequency radiator zone.

As the perforations move toward the coil to the point where they overlap the coil and extend into the rigid central portion area, the perforations cease to contribute increased flexibility but still improve the diaphragm performance to some extent by reducing the mass of the central portion which oscillates in response to the changing magnetic field.

For balance, it is important that the perforation pattern on both sides of a vertical line bisecting the coil be substantially symmetric. When web 60 in FIG. 13 is considered by itself, the perforations 116 do not provide a perfectly symmetric pattern as just noted. However, the webs 60 and 62 together do provide a balanced symmetry as FIG. 13 illustrates. It is also desirable that the perforation patterns above and below a horizontal line bisecting the coil also be symmetric.

FIG. 18 shows an alternative approach for suspending and aligning the diaphragm 46 in the magnet gap 40.

The diaphragm defines a pair of vertical slits 122 at both the upper and lower edges thereof, with the slits being aligned to register with the magnet pole plate surfaces 52 when the diaphragm is installed. An elongated rectangular tab 124 is inserted into each slit 122 so that it extends perpendicularly by an equal amount from each side of the diaphragm. Each tab is preferably formed of a strong and flexible sheet of material similar to the diaphragm. The free ends of each tab 124 are adhered to the magnet pole plates. The tabs have sufficient thickness that the diaphragm slits 122 do not shift or slide along the tabs during normal use. A deliberate force may be used to adjust the alignment during assembly.

FIG. 19 shows an alternative alignment approach using similar tabs 124 as in the embodiment of FIG. 18. Instead of retaining the tabs 124 in slits 122, however, the diaphragm defines tab holes 126 corresponding with the slit 122 positions of FIG. 18. The tab holes 126 are sized slightly smaller than the width of the tabs 124 so that the tabs resist sliding through the holes 126. The tabs 124 may thus need to be curved to pass through the holes when inserted during assembly. The tab holes 126 are shown as circular, but any shape, such as an ellipse or diamond, that snugly retains the tab 124 in a vertical plane is suitable.

It will be appreciated that while the use of alignment tangs, central mass reduction perforations, and hinge flexibility perforations is preferred, the principles of the present invention can be applied with fewer than all of the above features, or with only one of the selected features.

Having illustrated and described the principles of my invention by what is presently a preferred embodiment, it should be apparent to those persons skilled in the art that the illustrated embodiment may be modified without departing from such principles. I claim as my invention not only the illustrated embodiment, but all such modifications, variations and equivalents thereof, as within the true spirit and scope of the following claims.

I claim:

1. An audio transducer comprising:

first and second magnet assemblies, each having opposed side surfaces;

support means affixed to the side surfaces of the first and second magnet assemblies for supporting the magnet assemblies in a rigid aligned relationship with a gap therebetween, the support means defining a pair of opposed diaphragm openings aligned with the gap;

a diaphragm assembly comprising a pair of flexible first and second webs having central portions joined together to form a movable expanse, each web having opposite end portions which are supportively affixed to the support means, a portion of the diaphragm being received within the diaphragm openings;

the support means supporting the diaphragm such that the movable expanse is located centrally within the gap; and

coil means attached to the expanse of the diaphragm.

2. The transducer of claim 1 further including connecting means for conducting electrical impulses to the coil means.

3. The transducer of claim 1 wherein the support means includes a pair of parallel, laterally spaced support plates, each of which defines one of the diaphragm openings.

4. The transducer of claim 3 wherein each support plate has a pair of opposed end surfaces to which one of the end portions of one web is affixed such that the webs are supported in a substantially figure eight configuration.

5. The transducer of claim 4 wherein the end portion of each web is adhered to the end surface of one of the support plates.

6. The transducer of claim 1 wherein the coil means is adhered directly to both webs.

7. The transducer of claim 1 further including centering means for centering the expanse in the gap between the first and second magnet assemblies.

8. The transducer of claim 7 wherein the centering means includes tab means integrally formed from at least one of the webs for connecting the web to one of the magnet assemblies so as to constrain the expanse from moving toward or away from the magnet assemblies while permitting the expanse to move laterally.

9. The transducer of claim 8 wherein the tab means includes plural tabs integrally formed from the first web and plural tabs integrally formed from the second web, the first web having at least one tab affixed to one of the side surfaces of the first magnet assembly and at least one tab affixed to the other side surface of the first magnet assembly, the second web having at least one tab affixed to one of the side surfaces of the second magnet assembly and at least one tab affixed to the other side surface of the second magnet assembly.

10. The transducer of claim 8 wherein the tab means includes plural tabs formed by bending slit portions of the diaphragm substantially perpendicularly along a hinge line proximate to the expanse.

11. An audio transducer comprising:

a pair of first and second magnet assemblies

first and second support plates affixed to the first and second magnet assemblies, the support plates supporting the magnet assemblies such that the magnet assemblies are disposed between the support plates and in an aligned spaced apart relationship to one another to define a magnet gap therebetween, each support plate defining a central diaphragm opening aligned in registration with the magnet gap;

a diaphragm comprising a pair of elongate flexible webs having central portions joined together to form a movable expanse located between the first and second magnet assemblies, each web having opposite end portions, one end portion of which is affixed to the first support plate and the other end portion of which is affixed to the second support plate, the webs being supported such that they extend through both central diaphragm openings and define curved surfaces which are mere images of one another; and

coil means attached to the expanse of the diaphragm.

12. An audio transducer comprising:

a pair of first and second magnet assemblies spaced apart by a magnet gap therebetween, each magnet assembly having a magnetic core and a pair of first and second magnetic pole plates of opposite magnetic polarity affixed to opposite sides of the magnetic core;

a pair of first and second parallel plates affixed to the pole plates such that the first and second magnet assemblies are disposed therebetween, the first and second plates each defining a central opening aligned with the magnet gap;

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a diaphragm comprising a pair of elongate curved webs having central portions joined together to form a movable expanse supported within the magnet gap, each web extending through the central openings in the first and second plates and having opposite end portions, one of which is affixed to an end of the first plate and the other of which is affixed to an end of the second plate, whereby the webs are supported such that they form a substantially figure eight pattern; and

coil means attached to the expanse.

13. The transducer of claim 12 wherein the webs are each made of NOMEX® fiber paper.

14. An audio transducer comprising:

a pair of first and second magnet assemblies;

a frame for supporting the magnet assemblies adjacent to one another with a gap therebetween;

a diaphragm comprising a pair of first and second elongate flexible webs having central portions joined together to form a movable expanse located in the gap, the webs each having opposite end portions;

web supporting means for supporting the end portions of the webs such that the webs form curved surfaces which are mirror images of one another;

centering means for centering the expanse in the gap, the centering means including tab means integrally formed from at least one of the webs; and

tab securing means for securing the tab means against at least one of the magnet assemblies.

15. The transducer of claim 14 wherein the tab means includes at least one tab projecting from the first web and at least one tab projecting from the second web, the tab securing means securing the tab projecting from the first web against the first magnet assembly and securing

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the tab projecting from the second web against the second magnet assembly.

16. The transducer of claim 14 wherein each web has plural tabs formed from slit web portions which are bent substantially perpendicularly along a hinge line adjacent the expanse, the tabs of the first web being secured against the first magnet assembly and the tabs of the second web being secured against the second magnet assembly.

17. The transducer of claim 14 wherein the tab securing means includes glue for adhering the tab means against the magnet assemblies.

18. The transducer of claim 14 wherein the tab securing means includes at least one securing bar affixed to the magnet assembly and overlying the tab means so as to sandwich the tab means therebetween.

19. An audio transducer comprising:

a frame;

a diaphragm comprising a pair of elongate webs having portions joined to each other to form a movable substantially planar expanse, the webs each having flexible end portions extending from the expanse in an arc to a remote frame location;

coil means attached to the expanse of the diaphragm;

magnetic means adjacent to and on opposite sides of the expanse for producing opposing magnetic fields extending normal to the expanse;

centering means for centering the expanse within the magnetic field, the centering means including at least one tab extending from the first web away from the expanse in one direction and at least one additional tab extending from the second web away from the expanse in the opposite direction; and

tab securing means for securing the tabs against the magnetic means.

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US005230021A

## United States Patent [19]

## Paddock

**[11] Patent Number: 5,230,021**

[45] **Date of Patent:** Jul. 20, 1993

## [54] AUDIO TRANSDUCER IMPROVEMENTS

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[73] Assignee: **Linnaeum Corporation, Portland, Oreg.**

[21] Appl. No.: 730,172

[22] Filed: Jul. 12, 1991

### Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 708,924, May 31, 1991.

**[51] Int. Cl.<sup>5</sup> ..... H04R 25/00**

[52] U.S. Cl. .... 381/202; 381/194;  
381/199

[58] **Field of Search** ..... 381/202, 204, 194, 195,  
381/199, 196, 197

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*Primary Examiner—Jin F. Ng*

*Assistant Examiner—Huyen D. Le*

**Attorney, Agent, or Firm—Klarquist, Sparkman,  
Campbell, Leigh & Winston**

[57] **ABSTRACT**

An audio transducer having a pair of magnets supported to provide a magnet gap within which a flexible diaphragm supporting an electrical coil is received. The diaphragm is formed of a pair of flexible cylindrical webs joined at their centers to support the coil within the magnet gap. The diaphragm is provided with a row of perforations on either side of the gap to provide flexibility and is aligned centrally within the gap by flexible foam strips attaching the magnets to the diaphragm.

**20 Claims, 8 Drawing Sheets**

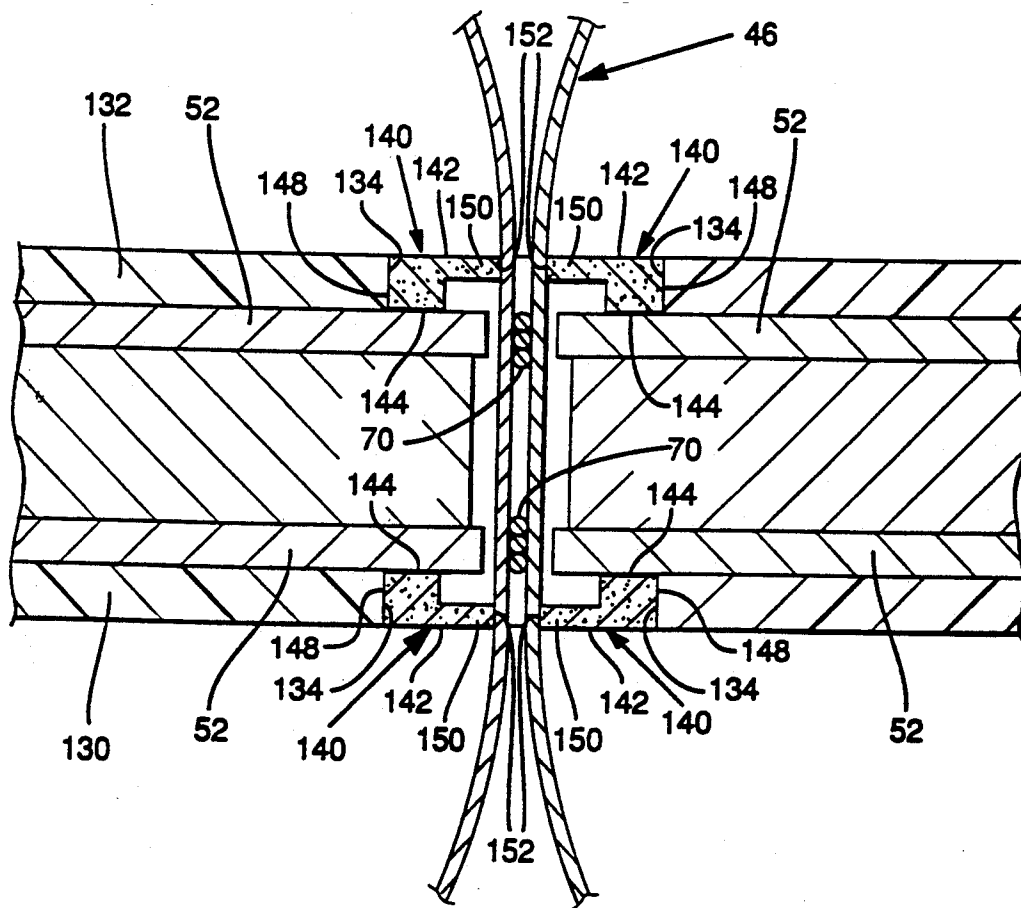


FIG. 1

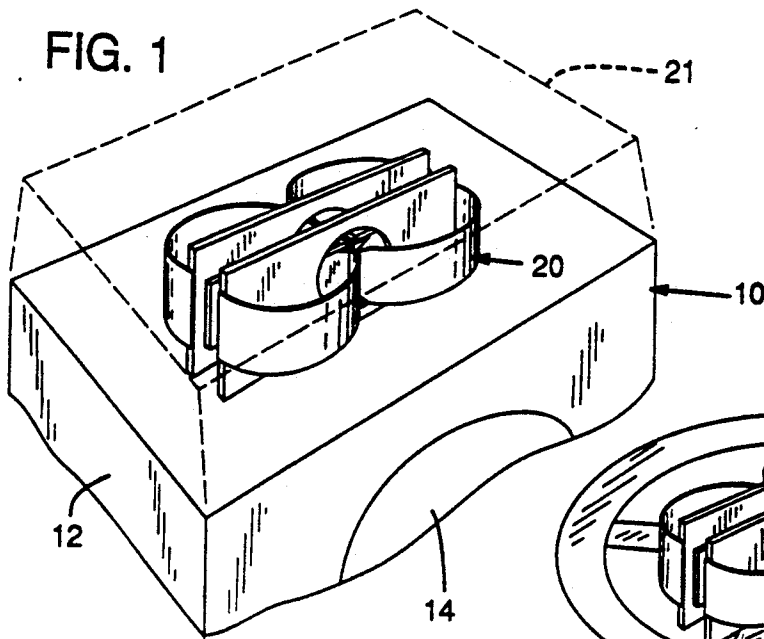


FIG. 2

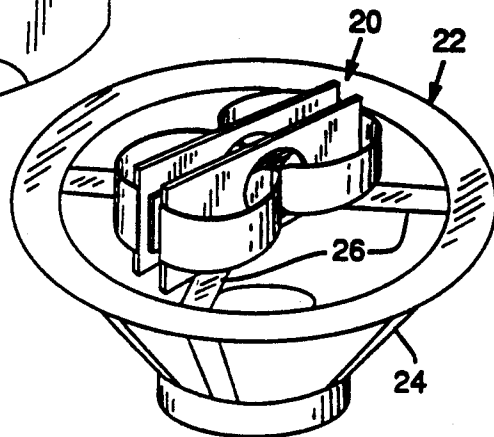


FIG. 3

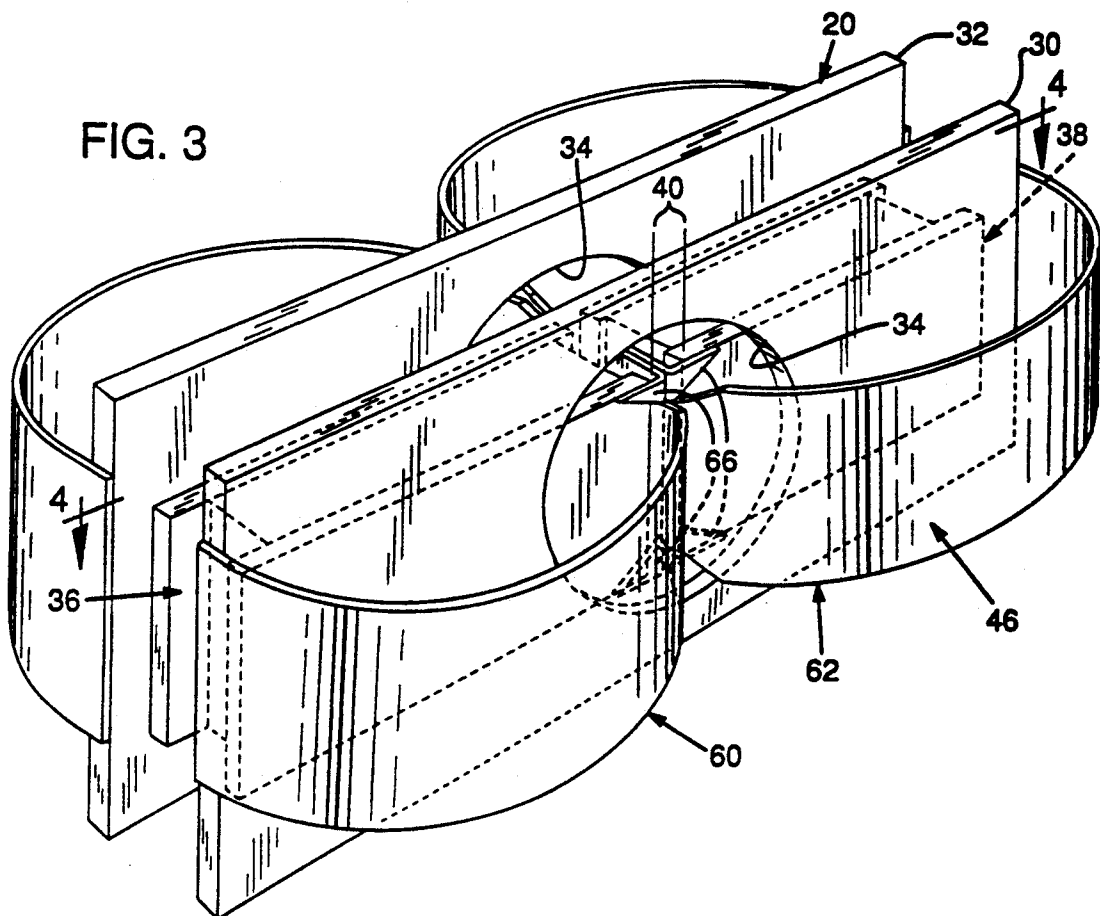


FIG. 4

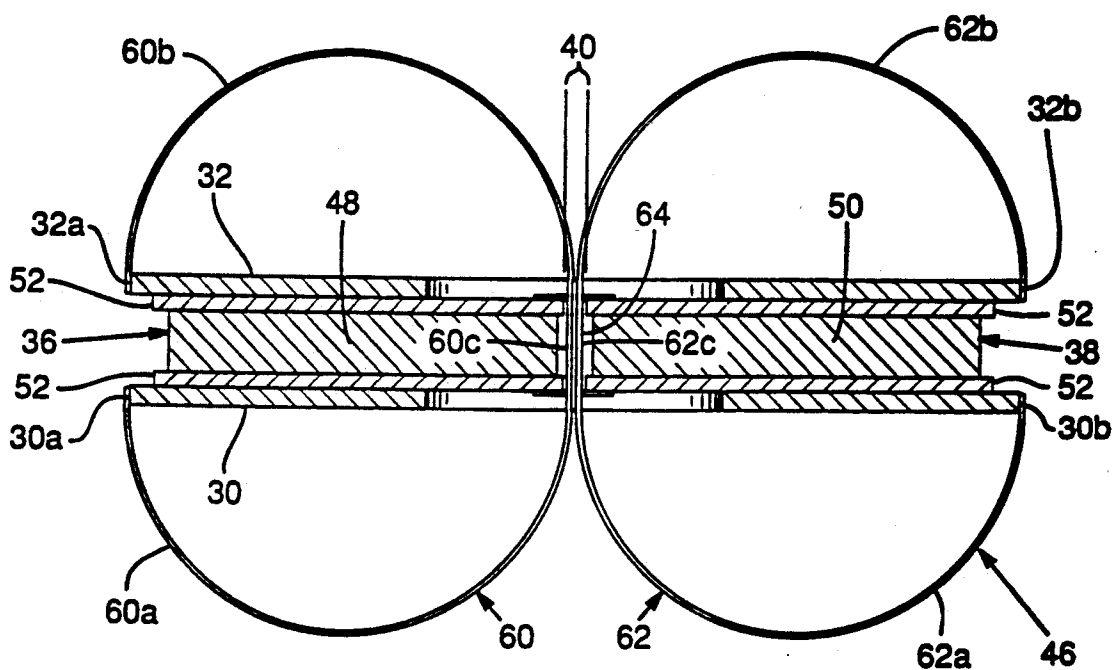


FIG. 5

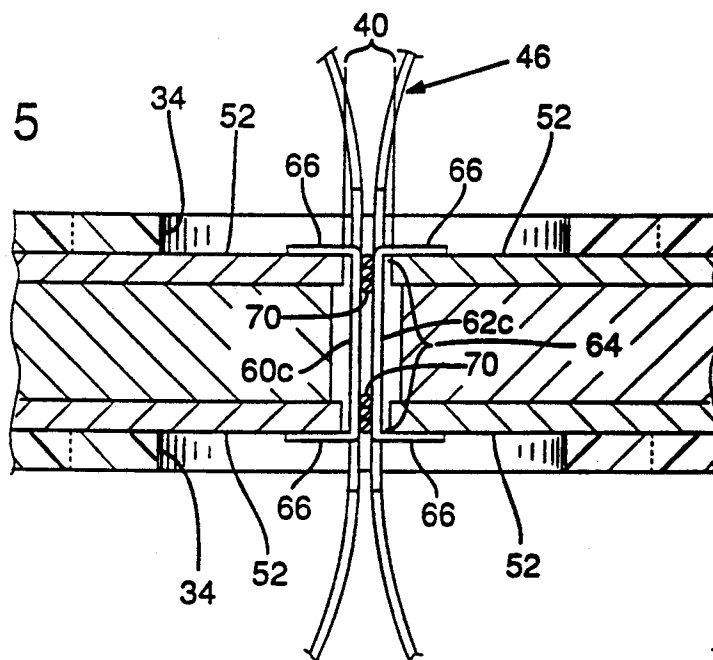


FIG. 6

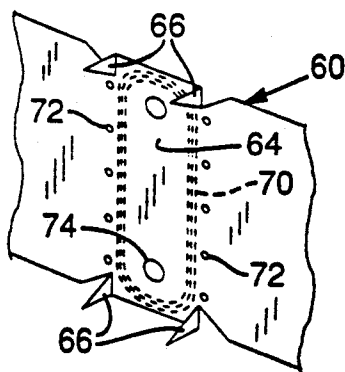


FIG. 14

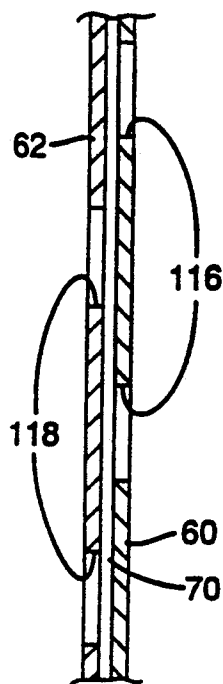


FIG. 7

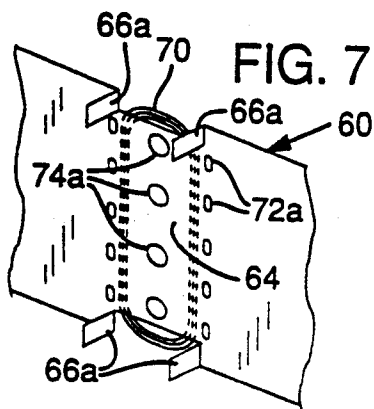


FIG. 12

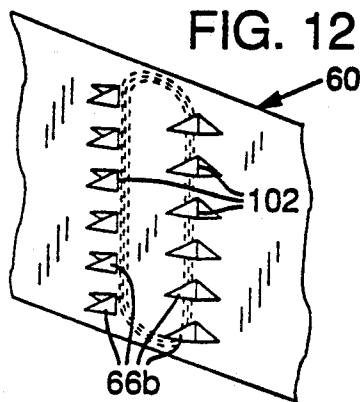


FIG. 13

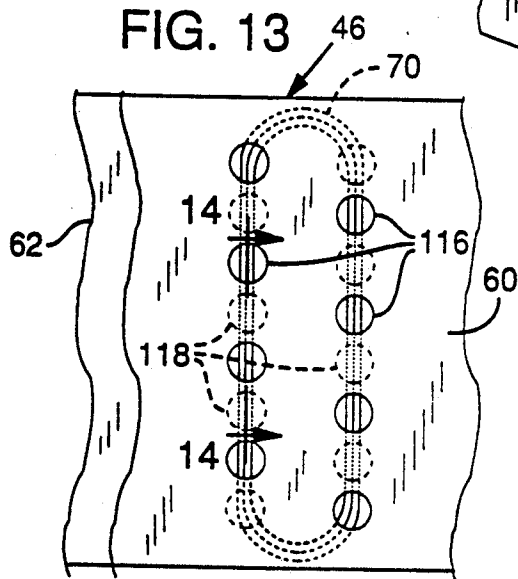


FIG. 15

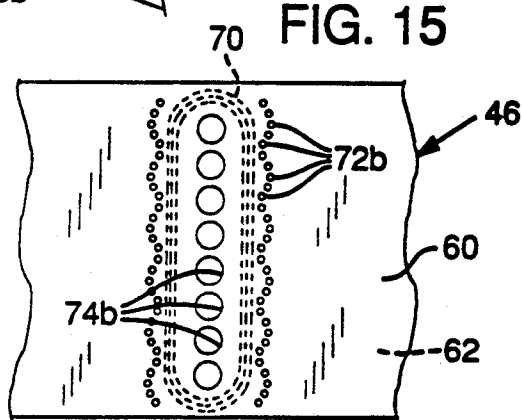


FIG. 16

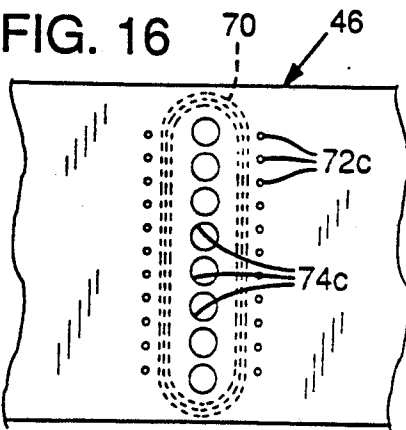


FIG. 17

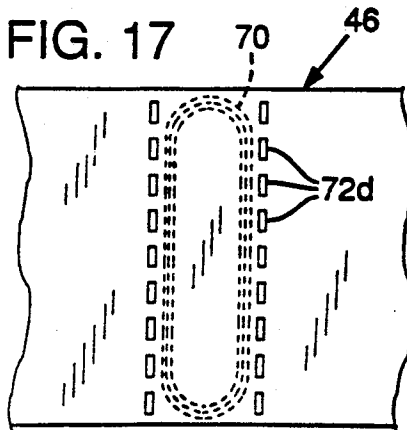


FIG. 8

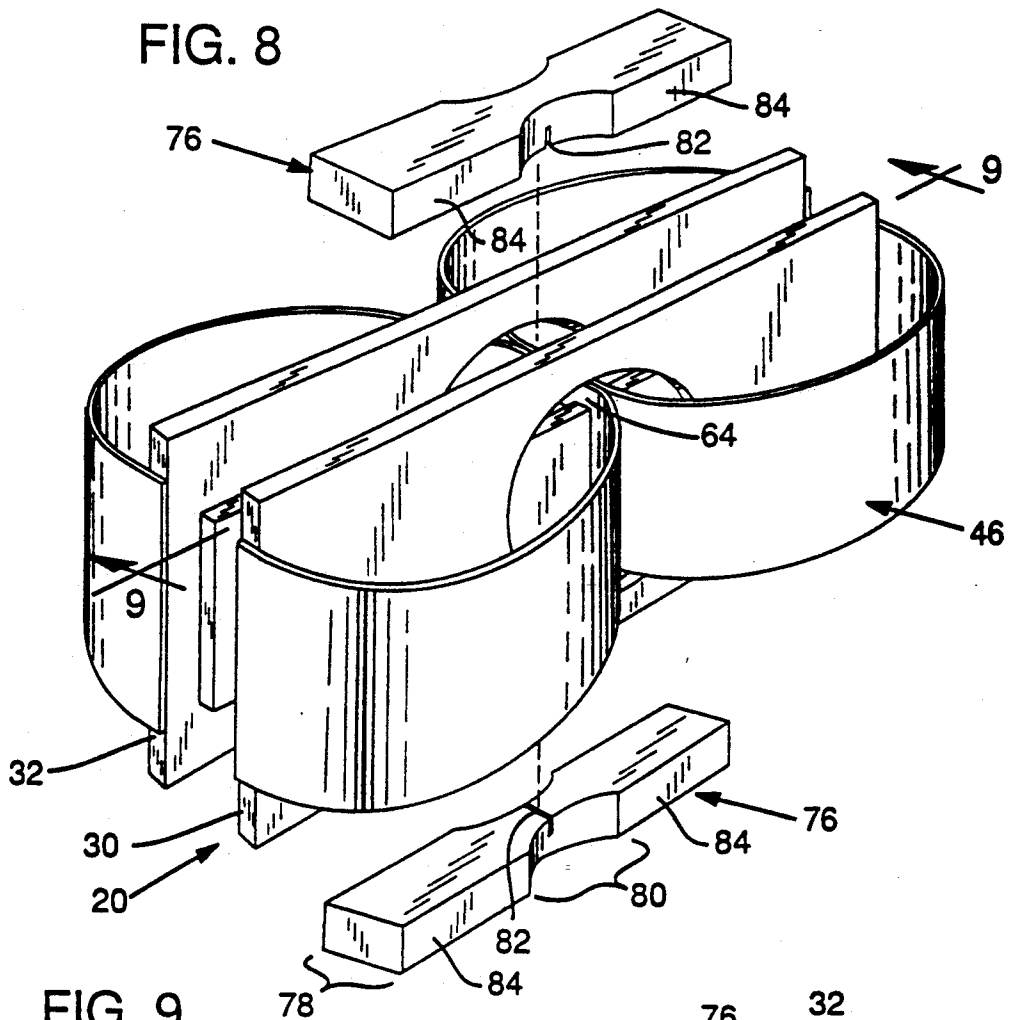


FIG. 9

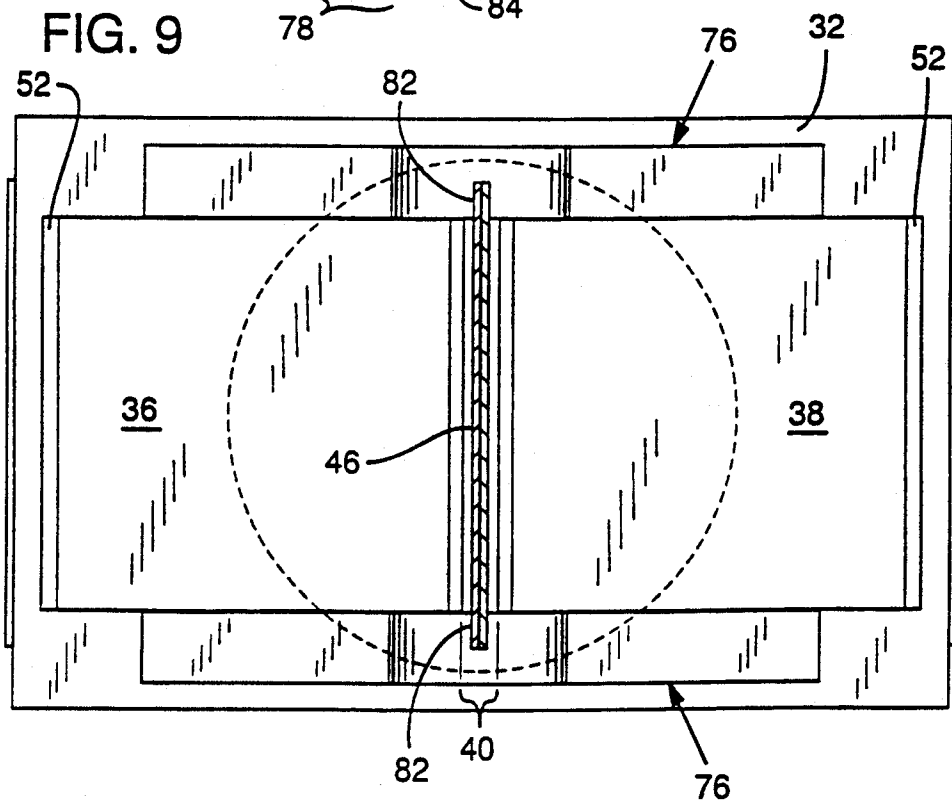


FIG. 10

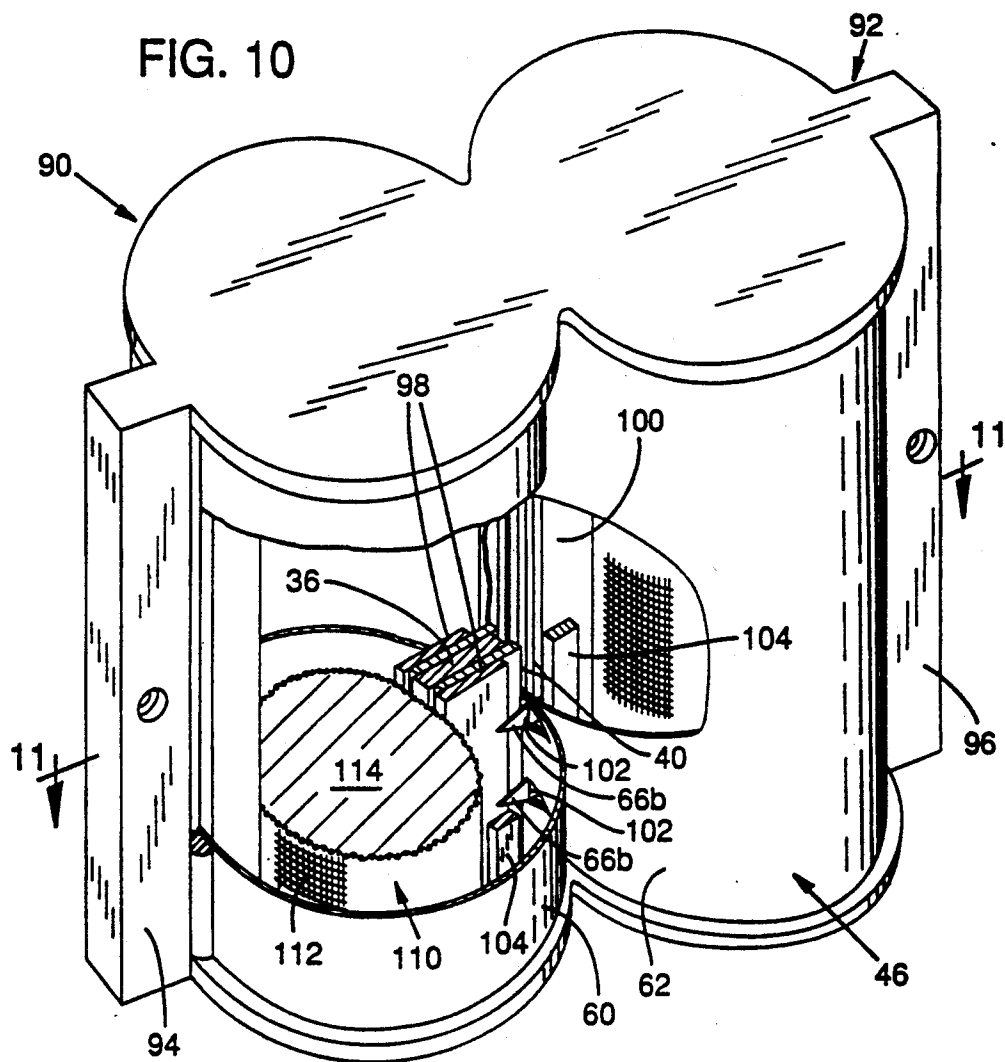
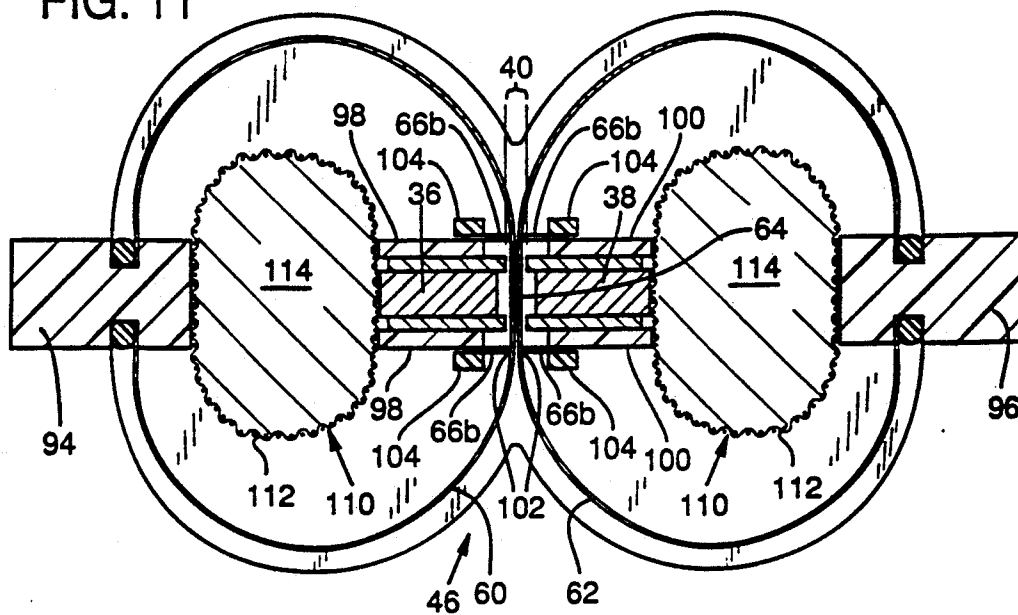
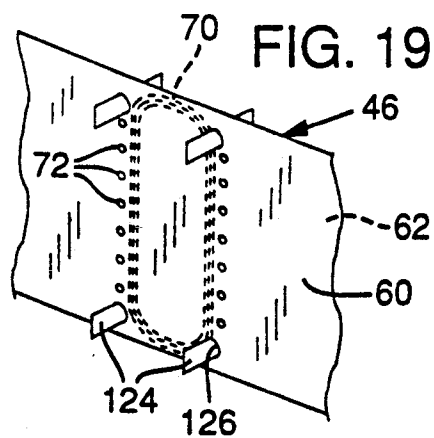
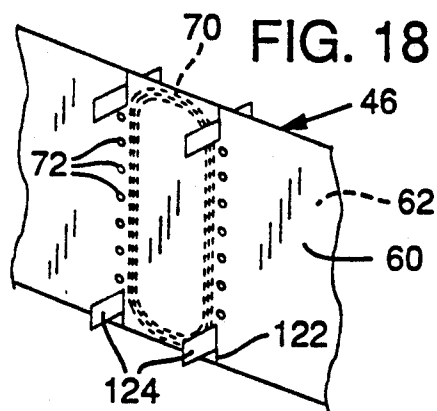


FIG. 11





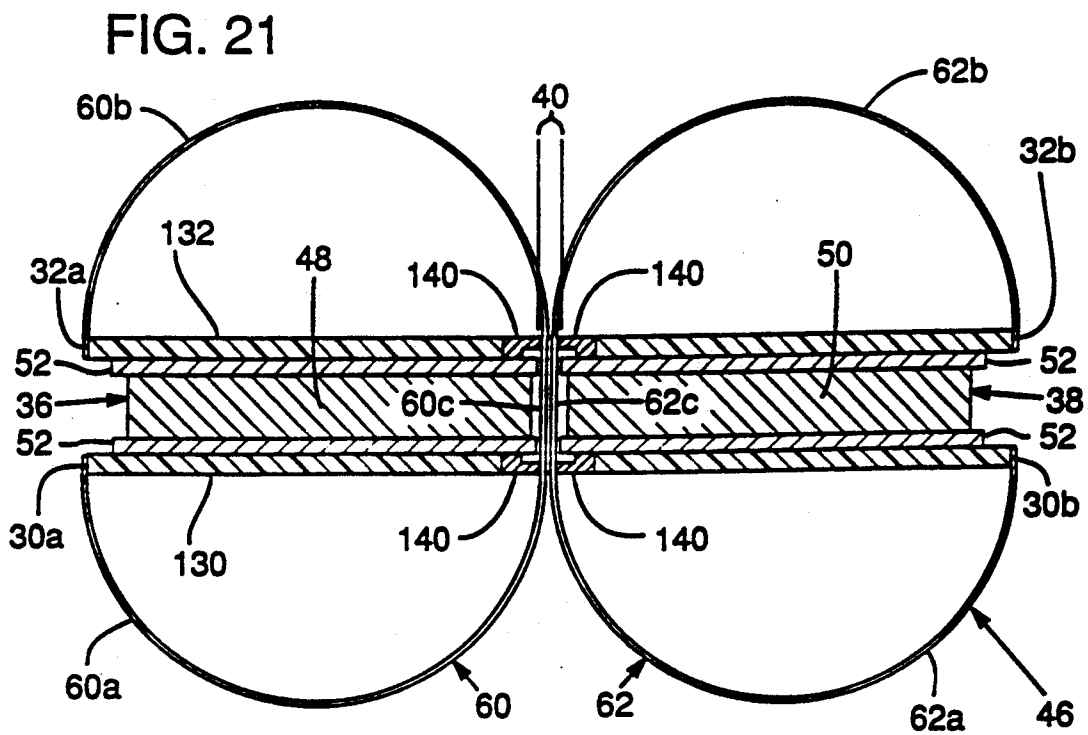
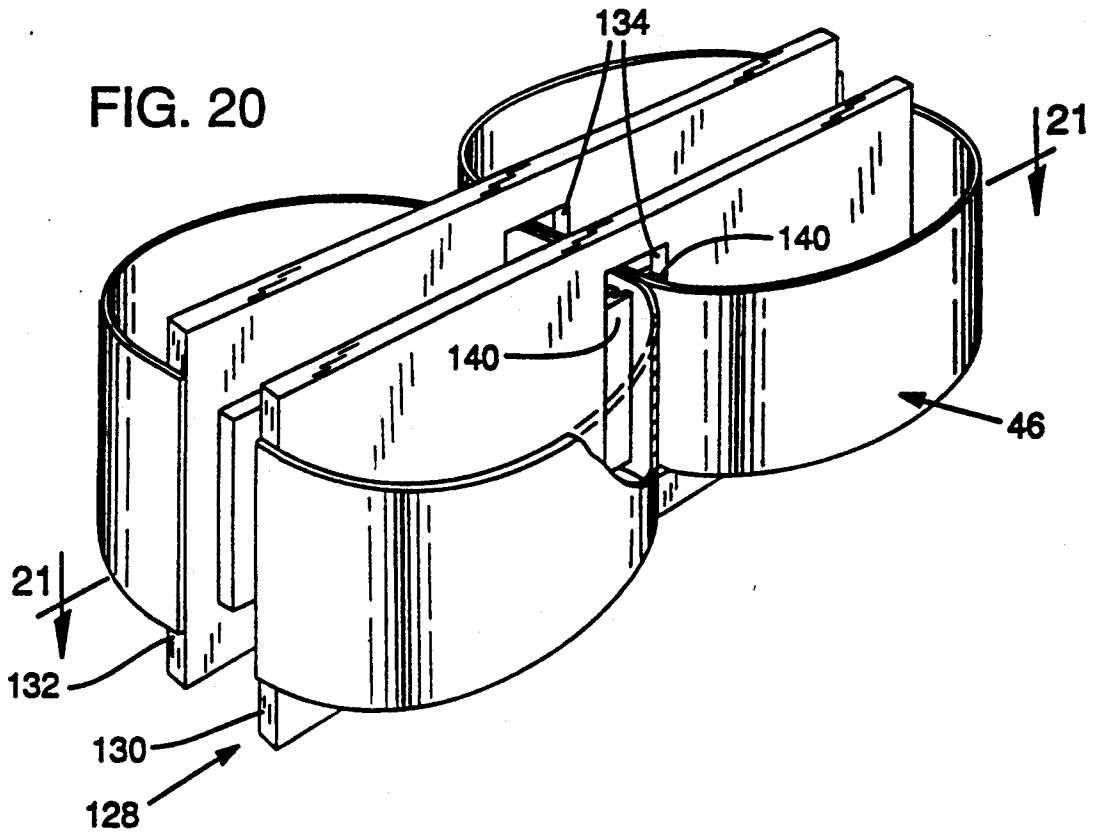




FIG. 22

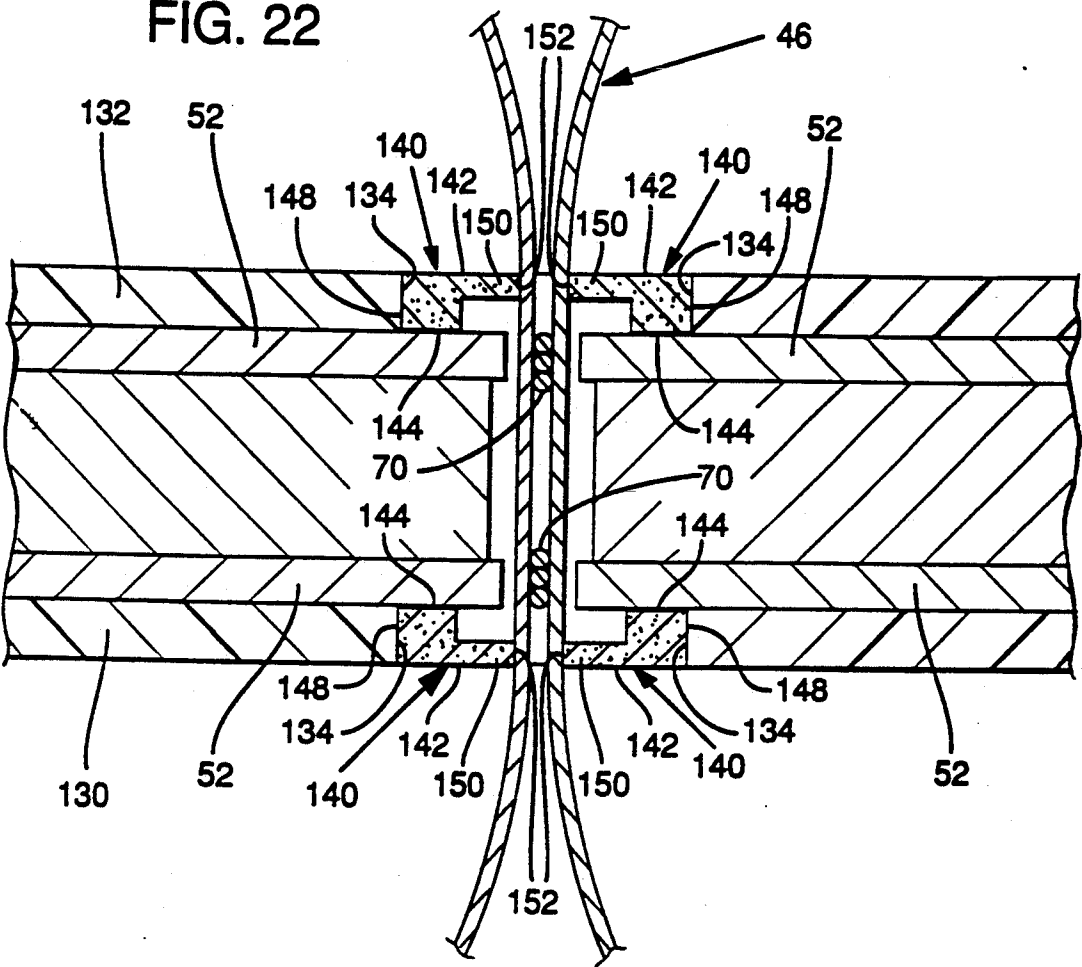
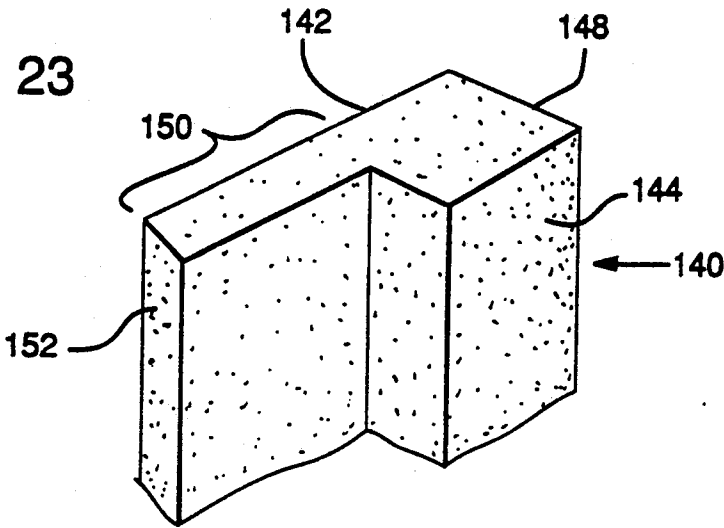


FIG. 23



## AUDIO TRANSDUCER IMPROVEMENTS

### CROSS-REFERENCE TO RELATED APPLICATION

This is a continuation-in-part of co-pending application Ser. No. 07/708,924, filed May 31, 1991.

### TECHNICAL FIELD

This invention generally relates to audio transducers. More particularly, the invention relates to improvements in the design of a transducer with at least one arcuate diaphragm.

### BACKGROUND OF THE ART

U.S. Pat. No. 4,903,308, which is incorporated herein by reference, discloses an audio transducer used for producing mid-range to high range frequencies. This transducer has a pair of elongated resilient webs whose intermediate portions are joined together forming an expanse that extends generally in a plane, with the expanse supported for movement in the direction of the plane. This transducer is particularly well suited for high end consumer audio markets in which cost is not a substantial concern. Therefore, the complexity of the assembly and the precise manufacturing processes required do not prevent this transducer from being highly effective and marketable. In addition, overall efficiency of the existing transducer need not be maximized due to the generally adequate power capabilities of typical home audio amplifiers.

The foregoing transducer design is not as well suited for applications in which the manufacturing cost is critical and power is limited, as in portable stereo and car stereo applications. This is true of many other prior transducer designs as well. It is always desirable to reduce manufacturing cost and to increase efficiency for any application, particularly without sacrificing performance. Also, any transducer may be improved by widening its frequency range, especially by improving its high frequency efficiency.

A fundamental problem in extending the range of frequencies in any transducer is the seemingly unavoidable trade-off between the high and low frequency performance of the transducer. Measures to improve high frequency response, such as the use of lighter diaphragm materials, have the effect of diminishing output efficiency at the lower range of the transducer. Measures to improve low frequency response, such as the use of stiffer diaphragm materials, cause high frequency losses.

All prior art devices can benefit by reducing manufacturing costs. High performance transducers generally have numerous complex parts which must be carefully aligned in a labor- and skill-intensive manufacturing process that requires many assembly steps.

A further disadvantage of many prior transducers is that the speaker coil does not easily dissipate the heat that is generated when the transducer is driven under high load conditions. The coil is typically covered by material that thermally insulates the coil.

A further drawback in many prior transducers is the less than optimum high frequency efficiency due to the moving mass of the rigid portion of the diaphragm.

A further disadvantage in the prior art is the efficiency limitation caused by the lack of precision of alignment of the diaphragm relative to the magnet structure. To provide maximum efficiency, the magnets

should be closely spaced adjacent the coil. This is especially critical with small, high frequency drivers, which typically use fewer coil turns and, thus, require a high strength magnetic field. The limitation of the prior art, however, is that imprecise positioning of the diaphragm and coil relative to the magnet creates a risk of the diaphragm contacting the magnet structure as the diaphragm vibrates or as misalignment occurs over time and use. Thus, a wide gap is required to tolerate imprecise alignment of the diaphragm and to prevent the unacceptably distorted output that occurs when the diaphragm contacts the magnet.

In the above-referenced prior art transducer, the diaphragms are aligned centrally in the magnet gap by a set of elastic cords, each spanning from one magnet to the other and passing through a small hole defined in the diaphragm. Although the elastic cords are sized to tightly fit the holes defined in the diaphragm, the diaphragm may slightly shift over time. This shift is tolerated by using a wider magnet gap, which results in a lower efficiency transducer unsuitable for applications such as automotive and portable stereos. An additional characteristic of this suspension approach is that the added mass of the elastic cords tends to slightly diminish the high frequency performance of the transducer.

A further characteristic of the prior art transducer making it less than ideal for portable applications, is the further reduced efficiency caused by the larger magnet pole plates, which must extend beyond the magnets to provide a rigid position for the magnets to be secured to each other across the magnet gap above and below the diaphragm, and without interfering with the diaphragm. The securing bars used for this purpose tend to limit the width of the diaphragm, resulting in limited efficiency.

A further disadvantage of all prior art audio transducers is that the diaphragm material has a less than desirable strength-to-weight ratio. In addition, the flexible materials such as the plastics and papers that are commonly used for such applications have a low resistance to solvents and acids and are highly susceptible to degradation in various types of radiation, particularly ultraviolet light as is found in outdoor applications, such as automotive installations.

A further disadvantage of the diaphragm materials used in the prior art is that the plastics and plastic coated papers commonly used have a surface that is generally incompatible with many adhesives, making manufacturing difficult by limiting adhesive choices to those adhesives with other undesirable properties.

### SUMMARY OF INVENTION

An object of this invention, therefore, is to provide an improved transducer featuring a construction which overcomes the difficulties and shortcomings indicated.

More specifically, an object of the invention is to provide a transducer with an improved high frequency response without a loss of efficiency or performance at the low end of the transducer frequency range.

Another object of the invention is to provide a high performance transducer that may be inexpensively manufactured, having a small number of parts and requiring few complex manufacturing processes.

Still another object of the invention is provide a transducer wherein the speaker coil may easily dissipate accumulated heat.

A further object of the invention is to provide a transducer having a rigid moving mass of reduced weight.

Yet another object of the invention is provide a transducer wherein the diaphragm may be easily and precisely aligned within the magnet gap to safely permit a narrowed magnet gap such that the alignment remains fixed over use and time.

It is a further object of the invention to provide a transducer with a diaphragm alignment system that does not add appreciable mass to the transducer and which is sufficiently lightweight to avoid damping the vibration of the diaphragm.

A further object of the invention is to provide a transducer having a diaphragm alignment system that distributes suspension forces equally along the length of the diaphragm.

It is a further object of the invention to provide a transducer having a rigid magnet alignment structure that does not limit the width of the diaphragm employed.

A further object of the invention is provide a transducer with a diaphragm constructed from a material that has a high strength-to-weight ratio, is resistant to solvents and acids, which resists degradation on exposure to ultraviolet radiation, which has a surface that is compatible with a wide variety of standard adhesives, and which is highly thermally transmissive without warpage at high temperatures and temperature differentials.

These and other objects and advantages of the invention will become more fully apparent as the description which follows is read in conjunction with the accompanying drawings.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of a transducer according to the present invention used in one application as a high frequency transducer attached to a standard low-frequency speaker with a cone driver.

FIG. 2 is a perspective view of the transducer of FIG. 1 as mounted to an automobile low frequency cone driver.

FIG. 3 is a perspective view of the transducer of FIG. 1.

FIG. 4 is a cross-sectional view taken along line 4—4 of FIG. 3.

FIG. 5 is an enlarged cross-sectional view taken along line 4—4 of FIG. 3 showing the structure in the vicinity of the electrical coil.

FIG. 6 is a fragmentary perspective view of an alternate diaphragm embodiment of the apparatus of FIG. 3 in preassembled form with triangular tangs extended.

FIG. 7 shows a fragmentary perspective view of an alternate diaphragm embodiment in preassembled form with rectangular tangs extended.

FIG. 8 is a partially exploded perspective view of the transducer of FIG. 3 with an alternative diaphragm centering arrangement.

FIG. 9 is a cross-sectional view taken along line 9—9 of FIG. 8.

FIG. 10 is a fragmentary perspective view of a mid- and high-frequency transducer constructed in accordance with another embodiment of the invention.

FIG. 11 is a cross-sectional view taken along line 11—11 of FIG. 10.

FIG. 12 is a fragmentary perspective view of an alternate diaphragm embodiment of the apparatus of FIG. 10 in preassembled form with alignment tangs extended.

FIG. 13 is fragmentary side view of an alternative diaphragm embodiment of the apparatus of FIG. 10.

FIG. 14 is an enlarged cross-sectional view of the diaphragm of FIG. 13 taken along line 14—14 of FIG. 13.

FIG. 15 is a fragmentary side view of an alternate diaphragm embodiment of the apparatus of FIG. 10.

FIG. 16 is a fragmentary side view of a further alternate diaphragm embodiment of the apparatus of FIG. 10.

FIG. 17 is a fragmentary side view of a further alternate diaphragm embodiment of the apparatus of FIG. 10.

FIG. 18 is a fragmentary perspective view of an alternate diaphragm alignment arrangement of the apparatus of FIG. 3.

FIG. 19 is a fragmentary perspective view of a further alternative diaphragm alignment arrangement of the apparatus of FIG. 3.

FIG. 20 is a perspective view of a high frequency transducer constructed in accordance with another embodiment of the invention.

FIG. 21 is a cross-sectional view taken along 21—21 of FIG. 20.

FIG. 22 is an enlarged cross-sectional view taken along line 21—21 of FIG. 20 showing the structure in the vicinity of the electrical coil.

FIG. 23 is an enlarged perspective view of the suspension strip of the transducer of FIG. 20.

#### DETAILED DESCRIPTION OF THE INVENTION

FIG. 1 shows a book shelf speaker 10 embodying the present invention in the application. The speaker includes a standard box-type enclosure 12 with a cone driver 14 for producing low- and mid range frequencies. A high frequency transducer 20 in accordance with the present invention is mounted to the top of the enclosure 12. The driver 14 and high frequency transducer 20 are electrically connected to a standard cross-over network (not shown) so that the high frequency transducer 20 receives frequencies over 2,000 Hz and the driver 14 receives frequencies below 2,000 Hz. This cross-over point may be varied to suit the needs of the particular application. An acoustically transparent grille 21 (shown in dashed lines) may be provided to protect the speaker from dust and damage, and to provide an aesthetic appearance.

As a second exemplary application of the present invention, FIG. 2 shows an automotive speaker 22 for mounting in a typical rear deck position of an automobile interior. A standard upward facing cone-type low- or mid-range driver 24, such as a typical 6"×9" woofer, is oriented horizontally with its diaphragm facing upward. The high frequency transducer 20 is rigidly suspended above the diaphragm of the driver 24 by horizontal brackets 26 that allow substantial open space for the sound emitted by the driver 24 to be upwardly projected. The high frequency transducer 20 thereby protrudes above the rear deck (not shown) and transmits sound directly forward toward the automobile passengers. The high frequency transducer 20 and driver 24 are interconnected by a cross-over network (not shown) as discussed above with reference to speaker 10 of FIG. 1. A protective grille (not shown) may be used to shroud the speaker 22.

As shown in FIG. 3, the high frequency transducer 20 is generally of a rigid, layered construction. This

construction includes a chassis or frame having a front chassis plate 30 and a rear chassis plate 32. Plates 30, 32 are vertically oriented rectangular plates made preferably of a rigid plastic material. The plates are identical to one another and oriented in a parallel, laterally spaced relationship. Each plate defines a circular central aperture 34 having a diameter that is a substantial fraction of the height of the chassis plates 30, 32, to permit passage of large items without sacrificing rigidity. The apertures of the plates are in registration with one another. A first magnet assembly 36 and a second magnet assembly 38 are supportively sandwiched between the chassis plates 30, 32 with the chassis plates adhesively affixed thereto to provide a rigid chassis structure. The magnet assemblies 36, 38 thereby provide a fixed magnetic field suitable for interaction with a coil carrying an electrical current as will be discussed below. The magnet assemblies 36, 38 are rigid rectangular structures arranged symmetrically and orthogonally between the chassis plates 30, 32 to define a magnet gap 40 of constant width therebetween. The magnet gap 40 extends vertically the full height of the magnet assemblies and if extended laterally, would bisect the central apertures 34. Thus, the centers of the apertures are aligned with the magnet gap.

To maximize speaker efficiency, the magnet gap should be as narrow as possible while allowing sufficient clearance to permit passage of a planar diaphragm 46 as will be discussed below. The ideal gap width varies depending on the size of the transducer and application being fulfilled. The magnet gap 40 may range between 0.020 and 0.062 inch, with a spacing of inch being preferred in the particular high frequency transducer 20 illustrated.

As shown in FIG. 4, each magnet assembly 36, 38 comprises a magnetic core 48, 50, respectively, with a pair of rigid, ferro-magnetic metal pole plates 52 affixed to the opposite sides of each magnetic core. The pole plates 52 are generally coextensive with the magnetic cores 48, 50, extending slightly beyond the magnetic cores in the direction of the magnet gap 40 so that the separation between opposed pole plates 52 defines the magnet gap. The magnetic cores 52 are magnetically oriented so that each pole plate is of opposite magnetic polarity from the other pole plate attached to the same magnetic core and so that each pole plate 52 is also magnetically opposite from its counterpart across the magnet gap 40.

It will be apparent from the foregoing that each chassis plate is adhered to one of the pole plates of each magnet assembly to provide a sandwich construction which is perfectly symmetrical.

The diaphragm 46 is formed of a pair of elongate resilient webs 60, 62. The paired structure provides a symmetrical structure, but a single diaphragm may be used where this characteristic is unnecessary. Each web includes flexible curved portions forming the end of each web, joined to and extending from an intermediate, generally planar central portion 64 also indicated in FIG. 5. Web 60 includes a front curved portion 60a, a rear curved portion 60b and a central expanse 60c. Web 62 includes a front curved portion 62a, a rear curved portion 62b and a central expanse 62c. The central expanses 60c, 62c of the two webs are joined together, as with an adhesive, to form the central portion 64. The central portion 64 is an essentially rigid unit functioning as a narrow beam, and is movable generally in the plane occupied by the expanse. That is, it moves perpendicu-

larly to the plane of the chassis plates 30, 32. Thus, the central portion is movable laterally relative to the transducer as a whole.

The diaphragm 46 is preferably constructed of an aramid fiber paper sheet such as Nomex®, produced by duPont, but other flexible, lightweight, high-strength, environmentally stable materials may be used.

The central portion 64 of the diaphragm 46 is suspended centrally within the magnet gap 40 by the flexible curved portions 60a, 60b, 62a, 62b. The end of each flexible curved portion is attached adhesively to a respective end portion 30a, 30b, 32a, 32b of each chassis plate 30, 32 so that each flexible portion forms a semi-circular shape, giving the diaphragm the general shape of a figure-eight when viewed from above or below. The curved portions of each web define curved surfaces which extend through respective central apertures 34 to meet at the expanse. The curved portions 60a, 60b, 62a, 62b primarily act as flexible suspension members and not as sound radiating surfaces. This is particularly true at high frequencies, at which only the portions of the diaphragm 46 closest to the center portion 64 are actively radiating sound. Thus, alternate suspension devices may be used without impairing the function of the invention, particularly at high frequencies.

FIG. 5 shows the central portion 64 of the diaphragm 46 that resides within the magnetic gap 40. As will be discussed below with reference to FIG. 6, a set of tab portions or tangs 66 are partially cut from the diaphragm 46 and folded perpendicular to the central portion 64 of the diaphragm so that they extend in planes substantially coincident with the exterior surfaces of the pole plates 52, to which the free ends of the tangs 66 are adhesively attached. The central apertures 34 are large enough to expose a sufficiently large area of the exterior surfaces of the pole plates 52 to permit the tangs to be attached thereto. As a result, the central portion 64 is maintained in the central location between the magnets while being free to move laterally within its own plane by a sufficient amount to produce high audio frequencies. The tangs 66 prevent longitudinal movement of the central portion 64 of the diaphragm 46, while permitting unimpaired lateral movement in the plane of the central portion 64.

FIG. 5 further illustrates an electromagnetic coil 70 laminated between the central expanses 60c, 62c of the web 60, 62 to become a rigid portion of the central portion 64. The vertical portions (shown in cross-section) of the coil 70 are positioned in the regions immediately between the pairs of opposed pole plates 52.

FIG. 6 shows web 60 in a straightened, partially preassembled condition with triangular tangs 66 cut and folded in position for attachment to the magnet pole pieces 52. In this embodiment, one edge of each tang is an extension of either the upper or lower portion of the web, depending on whether the tang is the upper or lower tang. The coil 70 (shown in dashed lines) is an elongate looped coil of wire forming a vertically oriented generally oblong or rectangular shape, with a pair of opposed straight, vertically oriented wire segment portions being spaced apart to align with the magnet pole pieces 52. Similar tangs are cut in web 62 (not shown) and folded in the opposite direction as those shown, providing a symmetrical diaphragm.

As further shown in FIG. 6, the diaphragm 46 is provided with a vertical row of hinge perforations 72 on each side of the coil 70. The perforations are preferably aligned with the folded tangs 66 and are positioned

within about  $\frac{1}{4}$  inch of the coil 70 and hence within about  $\frac{1}{4}$  inch of the joined expanse portion. The tangs are integral extensions of the web formed by folding pre-slitted tab-like portions of the web. Positioning the perforations 72 close to the coil 70 effectively reduces the mass of the rigid center portion 64 of the diaphragm 46. The perforations 72 may be circular as shown or, alternatively, may be any other shape including oblong, square or elliptical and may alternatively be sheared line segments with no diaphragm material removed. FIG. 6 further shows the center portion 64 defining mass reduction holes 74, the advantages of which are discussed below with reference to FIG. 7.

Each row of perforations acts like a hinge to permit a less constrained, more responsive movement of the central diaphragm expanse portion 64. The size of the perforations is not critical, only the proportion of material removed affects the key property of hinge-like flexibility at the edges of the center portion 64. Along the hinge center line of each row of hinge perforations 72, the sum of the linear dimensions of the perforations is preferably between about 10% and 50% of the full linear dimension of the web 60 along the same vertical line. With current materials used, the perforations define a pair of hinge lines at which the web material is preferably about 80% connected and 20% perforated. Thus, it is apparent that the web shown in FIG. 6 is less than 20% perforated and thus less than optimum. The foregoing parameters likely will become better defined with further experimentation.

The added hinge-like flexibility provided by the perforations 72, permits the efficiency of the transducer at very high frequencies to be substantially increased as the rigid central portion 64 of the diaphragm 46 is able to move more independently of the mass of the web curved portions 60a, 60b, 62a, 62b. In addition, the reduced mass resulting from the removal of the diaphragm material is the close vicinity of the central portion may also contribute to this effect. Experimental analysis has shown a 3 to 6 db increase in output over the 12 to 24 kHz high frequency range, with no sacrifice in efficiency at the low end of the transducer's output. Previous attempts to provide an improved high frequency efficiency, such as using a lighter and more flexible diaphragm material, have resulted in an undesirable drop off in low frequency performance.

FIG. 7 shows a web 60 having an alternative arrangement of tangs 66a and perforations 72a. In this embodiment, the tangs are rectangular and folded perpendicularly outward from their original pre-folded positions in the center portion 64 of the diaphragm 46 covering the end portions of the coil 70. While it is generally desirable that the coil be supported by and rigidly affixed to the webs 60 and 62, this is only important along the vertical portions of the coil (shown in dashed lines), which magnetically interact with the magnets shown in FIGS. 3 and 4. The exposed end portions of the coil 70 need not be supported. A further advantage of the FIG. 7 web construction is that the exposed end portions of coil 70 dissipate accumulated heat more effectively, as they are directly exposed to the environment.

The perforations 72 are shown in FIG. 7 as oblongs aligned axially in a vertical row, but any shape may be used as discussed above with reference to FIG. 6. As in FIG. 6, FIG. 7 shows only a single web 60. A similar web 62 would be adhered at the central portion 64 to create a sandwich, with the coil 70 between the webs. FIG. 7 also shows central mass reduction perforations

74 defined in the central portion 64 of the diaphragm, and centered entirely within the coil 70 to reduce the mass of the central portion 64. The central portion 64 is rigid and functions essentially as a planar beam translating in its own plane. The mass reduction provided decreases the inertia of the central portion 64 and results in a slight improvement in high frequency efficiency, with a subjectively perceptible increase in the quality of sound perceived as quickness.

FIGS. 8 and 9 show the high frequency transducer 20 with an alternative diaphragm centering mechanism. Instead of the tangs 66 formed of the diaphragm 46 to align the diaphragm within the magnet gap 40, as shown in FIGS. 3-7, the embodiment of FIG. 8 uses a pair of elongated foam members 76 to retain the central portion 64 of the diaphragm centrally within the magnet gap 40. Each foam member has a width 78 sized to closely fit between the front and rear chassis plates 30, 32. Each foam member 76 has a slitted central neck portion 80 with a reduced width. A slit 82 is cut across the width of the neck portion to a depth of about one-half the thickness of the foam member. The foam members 76 are attached to the high frequency transducer 20 by mating the slits 82 with the corresponding top and bottom edges of the central portion 64 of the diaphragm 46 and adhesively securing the sides 84 of the foam member 76 to the inner surfaces of the chassis plates 30, 32. In addition, the slits 82 are adhesively secured to corresponding edges of center portion 64 of the diaphragm 46.

The diaphragm 46 is thereby retained perfectly centered within the magnet gap 40 by the slits 82 provided in the elongated foam members 76. Because the foam members 76 are formed of a lightweight open cell foam having a low resistance to small displacements, they have a negligible damping effect on high frequency vibrations of the diaphragm 46, yet they preserve a central alignment of the diaphragm 46 that is not susceptible to shifting over time.

FIGS. 10 and 11 show a wide range, mid- to high-frequency transducer 90 embodying the invention as an essentially improved version of the audio transducer disclosed in U.S. Pat. No. 4,903,308. Transducer 90 operates on the same general principal as the high frequency transducer 20, with a diaphragm 46 formed by webs 60, 62, as a figure-eight shape. The central portion 64 of the diaphragm 46 passes through the magnet gap 40 (FIG. 11) with a coil 70 (not shown) sandwiched between the webs 60, 62 and residing within the magnet gap in the manner precisely described. In this larger embodiment of the transducer 90, a larger chassis 92 retains the diaphragm 46 and the magnet assemblies 36, 38. The chassis 92 is formed generally of spaced apart vertical diaphragm retaining members 94, 96 and two opposed pairs of central opposed vertical magnet retaining members 98, 100 located between the diaphragm retaining members 94, 96. The magnet retaining members 98 comprise a pair of rigid vertical planar members spaced apart sufficiently so that magnet assembly 36 may be rigidly affixed therebetween to define the magnet gap 40 with the opposite magnet assembly 38, which is similarly affixed between the opposing pair of magnet retaining members 100.

FIGS. 10 and 11 further show a diaphragm centering means including triangular alignment tangs 66b formed by V-shaped cuts in each web 60, 62. The apex of each

"V" forms a free end that points horizontally away from the central portion 64 of the diaphragm 46. The base of each "V," that is, the portion closest to the central portion 64 of the diaphragm 46 and integrally attached to the diaphragm at a fold line 102, extends substantially perpendicularly from the web in a plane parallel to the exposed exterior surface of the adjacent magnet retaining pair member 98, 100 so that the tang 66b may be adhered to or secured against the adjacent retaining member. With the diaphragm 46 suitably centered in the magnet gap 40, the free end tips of the tangs are adhered or clamped to the exposed surfaces of the magnet retaining pair members 98, 100 and covered by rigid elongated tang retaining members 104, which are adhesively affixed to the magnet retaining pair members 98, 100 so that the tips of the tang 66 are sandwiched therebetween. The cuts forming the tangs 66 have the additional advantage of providing a flexible hinge line as discussed above with respect to the hinge perforations 72 and 72a of FIGS. 6 and 7. Additional perforations (not shown) between tangs 66b may be provided to increase the diaphragm's flexibility still further.

FIGS. 10 and 11 also show a pair of cylindrical acoustic dampers 110 oriented vertically and positioned between the respective diaphragm retaining member 94, 96 and magnet retaining pair 98, 100 in each chamber defined by the respective circular web 60, 62. Each damper 110 is formed by a cylindrical tube of perforated webbing, such as a flexible plastic mesh 112, which is filled with a core of lightweight fibrous stuffing 114. The stuffing 114 may be any suitable material, such as wool, felt, cellulose fiber or fiberglass. The dampers prevent internal acoustic reflections and vibrations from degrading the output sound.

FIG. 12 shows preassembled web 60 of the embodiment of FIGS. 10 and 11 with the tangs 66b shown as "V" cuts and folded along fold lines 102. Tangs 66 are arranged in two vertically aligned rows, one row on each side and located about  $\frac{1}{4}$  inch from coil 70. Like tangs 66, tangs 66b are formed as integral folded extensions of the diaphragm.

FIGS. 13 and 14 show an alternative configuration of the diaphragm 46 for use on the mid- to high-frequency range transducer 90 of FIGS. 10 and 11. Web 60 is provided with a plurality of circular holes 116 arranged in vertical rows registered with the linear vertical portions of the coil 70. The holes 116 are spaced apart in each row by a center-to-center distance greater than twice the diameter of the holes. The holes are staggered in each row so that the holes in one row are aligned with the mid points between centers of adjacent holes in the opposite row. The web 62 is provided with an identical set of holes 118, shown in dashed lines. Webs 60, 62 are registered with the holes 116, 118 aligned in reverse registration so that each hole 116 overlies a solid unbroken portion of adjacent web 62 and each hole 118 underlies a solid, unbroken portion of adjacent web 60. Therefore, there are no openings passing entirely through both webs 60, 62. The coil 70 is adhesively laminated between the webs 60, 62 so that its vertical linear sections are generally aligned with the rows of holes 116, 118. Because of the arrangement of holes 116, 118, every point along the entire length of the coil 70 is adhered either to web 60 or web 62 or both. This prevents any undesirable relative motion between the coil 70 and the webs 60, 62. Because the webs 60, 62 are adhered only to the coil, and not to each other in the region beyond the periphery of the coil, the holes 116,

118 provide the hinge-like flexibility discussed above, and produce high frequency efficiency improvements without sacrificing low frequency efficiency. In addition, heat in the coil 70 is readily dissipated by the substantial portions exposed to air through the holes 116, 118, while performance is maintained with a rigidly attached coil.

FIG. 15 shows an alternative diaphragm arrangement for the transducer 90 of FIGS. 10 and 11. An articulated row of perforations 72b is defined entirely through the diaphragm 46, penetrating both webs 60, 62 on both sides of the coil 70. The perforations as shown are circular, but numerous other shapes are contemplated and may be substituted. The holes 72b of this embodiment are separated by at least a minimal distance from the coil 70 to ensure that the coil is entirely adhered to the diaphragm 46. At least a portion of some of the perforations preferably are within at least about  $\frac{1}{4}$  inch of the coil 70 to provide optimal flexibility in the diaphragm 46 for high frequency efficiency. FIG. 15 further shows a centrally aligned row of mass reduction perforations 74b positioned in a vertical row within the coil 70. The perforations 74b may pass entirely through the diaphragm 46 or may each be defined only in a single web 60 or 62 so that through holes are not provided through the diaphragm. In an alternative embodiment, a thin film or sheet of thin material may be provided between the webs 60, 62 to close the perforations 74b while allowing the advantages of substantial weight reduction.

FIG. 16 shows an additional alternative embodiment, with diaphragm 46 having hinge perforations 72c defined in the diaphragm 46 as small diameter circular holes in a linear configuration. In this embodiment shown, about 20% of each row is perforated while about 80% of the diaphragm remains connected at each row. FIG. 16 further shows the optional mass reduction perforations 74c.

FIG. 17 shows a further alternative diaphragm 46 embodiment having elongated rectangular perforations 72d that provide a hinge-line of approximately 50% perforated length and 50% connected length.

It will be appreciated that the perforations 72 located along the outside vertical edges of coil 70 can have a wide variety of shapes and sizes. The perforations 72, for example, have a diameter of about  $\frac{1}{4}$  inch and are spaced apart about  $\frac{1}{4}$  inch. Perforations 72a have a length of about  $\frac{1}{4}$  inch and are spaced apart about  $\frac{1}{4}$  inch. Similarly, perforations 72b have a diameter of about  $\frac{1}{4}$  inch and a spacing of about  $\frac{1}{4}$  inch, and perforations 72c have a diameter of about  $\frac{1}{4}$  inch and a spacing of about  $\frac{1}{4}$  inch.

The increased flexibility and compliance which the perforations 72 provide the diaphragm is, in part, a function of the distance of the perforations from the vertical edge of the coil (which edge also defines the edge of the rigid central portion formed by adhering the two webs together). The perforations preferably eliminate diaphragm material along a hinge line within about  $\frac{1}{4}$  inch and, most preferably, within  $\frac{1}{4}$  inch or less of the vertical edges of the central joined-together portion of the webs. As this distance increases, spacing the perforations further from the coil, the increased flexibility and compliance drops off because the perforations are located farther from "hinge zone" on either side of the rigid beam-like central portion and hence farther from the primary high frequency radiator zone.

As the perforations move toward the coil to the point where they overlap the coil and extend into the rigid

central portion area, the perforations cease to contribute increased flexibility but still improve the diaphragm performance to some extent by reducing the mass of the central portion which oscillates in response to the changing magnetic field.

For balance, it is important that the perforation pattern on both sides of a vertical line bisecting the coil be substantially symmetric. When web 60 in FIG. 13 is considered by itself, the perforations 116 do not provide a perfectly symmetric pattern as just noted. However, the webs 60 and 62 together do provide a balanced symmetry as FIG. 13 illustrates. It is also desirable that the perforation patterns above and below a horizontal line bisecting the coil also be symmetric.

FIG. 18 shows an alternative approach for suspending and aligning the diaphragm 46 in the magnet gap 40. The diaphragm defines a pair of vertical slits 122 at both the upper and lower edges thereof, with the slits being aligned to register with the magnet pole plate surfaces 52 when the diaphragm is installed. An elongated rectangular tab 124 is inserted into each slit 122 so that it extends perpendicularly by an equal amount from each side of the diaphragm. Each tab is preferably formed of a strong and flexible sheet of material similar to the diaphragm. The free ends of each tab 124 are adhered to the magnet pole plates. The tabs have sufficient thickness that the diaphragm slits 122 do not shift or slide along the tabs during normal use. A deliberate force may be used to adjust the alignment during assembly.

FIG. 19 shows an alternative alignment approach using similar tabs 124 as in the embodiment of FIG. 18. Instead of retaining the tabs 124 in slits 122, however, the diaphragm defines tab holes 126 corresponding with the slit 122 positions of FIG. 18. The tab holes 126 are sized slightly smaller than the width of the tabs 124 so that the tabs resist sliding through the holes 126. The tabs 124 may thus need to be curved to pass through the holes when inserted during assembly. The tab holes 126 are shown as circular, but any shape, such as an ellipse or diamond, that snugly retains the tab 124 in a vertical plane is suitable.

FIGS. 20-22 show an alternative approach for suspending and aligning the diaphragm 46 in the magnet gap 40 of an alternative embodiment high frequency transducer 128. The illustrated embodiment is otherwise similar in function and structure to the embodiment of FIG. 3. A pair of parallel, laterally spaced chassis plates 130, 132 each define an elongated rectangular central aperture 134 to permit passage of the diaphragm 46. Each central aperture 134 is vertically oriented. The length of each aperture is greater than the height of the diaphragm 46 so that the diaphragm may pass freely through the aperture. The aperture length is also sufficiently less than the overall height of each chassis plate 130, 132 so that adequate chassis plate material remains above and below the aperture to provide a rigid structure. The width of each aperture 134 is preferably about  $\frac{1}{2}$  inch, but this may be adjusted to suit the size of other suspension components, as will be discussed below. The apertures 134 are centrally positioned on each chassis plate 130, 132, and centrally registered with the magnet gap 40 (shown in FIG. 21) so that the diaphragm 46 passes centrally through each aperture 134.

As shown in FIG. 21, four elongated flexible suspension strips 140 are inserted in the central apertures 134 to align and suspend the joined central expanse of the diaphragm in the desired position. A pair of suspension

strips is positioned within each aperture 134 on opposite sides of the diaphragm 46. The suspension strips 140 are formed of a flexible closed cell foam with a pressure sensitive adhesive backing. The range of foam strip products sold as household weatherstripping provides a suitable selection of foam types and densities, with medium density closed-cell foam being preferred.

In the preferred embodiment, each strip 140 has a length generally corresponding to the height of the diaphragm 46. Alternatively, the length may be extended to the full height of the central aperture to provide a complete mechanical barrier against debris which might otherwise enter the magnet gap and cause interference with the motion of the diaphragm. The width of each strip 140 is preferably about  $\frac{1}{4}$  inch. This permits the strips to entirely fill the width of each central aperture 134, with a slight compression due to the space occupied by the thickness of the diaphragm 46 between each pair of strips 140. Each strip has a thickness approximately equal to the thickness of the chassis plate 130, 132, or about  $\frac{1}{8}$  inch.

As shown in FIGS. 22 and 23, each suspension strip 140 has an L-shaped cross-section formed by removing a rectangular corner section from an original rectangular strip. The removed portion has width and thickness dimensions approximately equal to one-half those of the original rectangular strip, leaving three-quarters of the original material to form the suspension strip 140. Each strip 140 has a face surface 142 running the full width of each strip and an opposite base surface 144 running half the width of the strip due to the removed portion. The base surface 144 includes an adhesive layer, which securely attaches the strip by adhesion to the corresponding magnet pole plate 52.

Each strip includes a butt surface 148 running the full length and thickness of each suspension strip 140 and abutting the respective chassis plate 130, 132 within the central aperture 134. A cantilevered nose 150 extends away from the butt surface 148 and terminates in a nose end 152 which contacts the diaphragm 46. The nose 150 is spaced apart from the respective pole plate 52 and forms, in part, the face surface 142. The nose end 152 is preferably adhesively attached to the diaphragm to prevent accidental mechanical misalignment during shipping or use.

The nose 150 functions as a cantilever that suspends the diaphragm 46 at the free end of the cantilever. The nose flexes in compliance with vibration of the diaphragm, giving negligible resistance to the small amplitude vibrations in the high frequency range, but offering significant resistance to the larger amplitude vibrations at the lowest frequencies. This effectively provides a low frequency cutoff that may be adjusted to the advantage of the application by selecting the material properties and dimensions of the suspension strips 140.

The nose 150 may be made narrower or longer to create a less stiff cantilever, thereby increasing compliance and extending low frequency response. A thicker or shorter nose will diminish low frequency response by acting as a stiffer, less compliant cantilever. In addition, the density and flexibility of the selected suspension strip material may be varied to adjust effective cantilever stiffness, with lightweight open cell foam providing the greatest compliance for low frequency extension and denser foam or rubber material providing a firmer alignment useful for high frequency transducers. It is not necessary that the nose be rectangular; tapered versions are contemplated.



The primary advantage of the suspension strips 140 to align the diaphragm 46 is that all suspension forces are distributed equally along the vertical length of the active acoustical area of the diaphragm 46. This eliminates any distortions and interference that might arise from the focusing of suspension forces on discrete points or zones of the diaphragm. It is contemplated, however, that the suspension strips may be modified to contact the diaphragm at selected limited points. This may be provided by scalloping the nose end or by using spaced-apart segments of suspension strips along the length of the diaphragm.

It will be appreciated that while the use of alignment tangs, central mass reduction perforations, and hinge flexibility perforations works well, the principles of the present invention can be applied with fewer than all of the above features, or with only one of the selected features. In addition, the embodiment employing foam suspension strips has further advantages in manufacturability and sound quality, and may also incorporate the perforations illustrated in alternative embodiments.

Having illustrated and described the principles of my invention by what is presently a preferred embodiment, it should be apparent to those persons skilled in the art that the illustrated embodiment may be modified without departing from such principles. I claim as my invention not only the illustrated embodiment, but all such modifications, variations and equivalents thereof, as within the true spirit and scope of the following claims.

I claim:

1. An audio transducer comprising:
  - a pair of first and second magnet assemblies spaced apart by a magnet gap therebetween, each magnet assembly having a magnetic core and a pair of first and second magnetic pole plates of opposite magnetic polarity affixed to opposite sides of the magnetic core;
  - a chassis for maintaining the magnet assemblies in spaced relation;
  - a diaphragm comprising a pair of elongate curved webs having central portions joined together to form a movable expanse having a first side and an opposed second side and supported within the magnet gap such that the first magnet assembly is positioned on the first side of the expanse and the second magnet assembly is positioned on the second side of the expanse, each web having opposite end portions, each of which is affixed to the chassis, whereby the webs are supported such that they form a substantially figure eight pattern;
  - a pair of first and second distinct flexible diaphragm suspension strips attached in fixed relation to the magnet assemblies, the first strip being positioned entirely on the first side of the movable expanse, the second strip being positioned entirely on the second side of the expanse, the strips being in opposing contact with the movable expanse, such that the movable expanse is maintained centrally within the magnet gap while being free to move otherwise; and
  - a coil attached to the expanse.
2. The transducer of claim 1 wherein the first suspension strip abuts the first side of the movable expanse and the second suspension strip abuts the second side of the movable expanse.
3. The transducer of claim 1 wherein the suspension strips are formed of flexible foam.

4. The transducer of claim 1 wherein the strips are elongated to contact the movable expanse along substantially the entire height dimension of the expanse.

5. The transducer of claim 1 wherein each suspension strip includes a base portion and a nose portion, the base portion being attached to one of the magnets, and the nose portion abutting the movable expanse.

6. The transducer of claim 5 wherein the nose portion extends away from the base portion in a cantilevered manner and has a length dimension which exceeds its thickness dimension.

7. The transducer of claim 1 wherein the suspension strips are biased against the movable expanse.

8. The transducer of claim 1 wherein the first and second suspension strips are in opposed relationship on one side of the magnet assemblies, and the transducer further includes a pair of third and fourth distinct flexible diaphragm suspension strips positioned on an opposite side of the magnet assemblies opposite the first side, the third and fourth suspension strips being positioned on opposite sides of and in abutting contact with the movable expanse.

9. An audio transducer comprising:

a chassis;

drive means attached to the chassis for creating a motive field, the drive means including a first portion and a second portion spaced apart by a drive gap therebetween, the chassis and drive means together comprising a diaphragm support structure;

a cylindrical diaphragm comprising an elongate curved web having a movable central expanse supported within the drive gap, the diaphragm having opposite end portions, each of which is affixed to the chassis;

a motion generating element attached to the central expanse for interacting with the motive field and thereby moving the diaphragm to generate sound; and

a pair of first and second distinct flexible diaphragm suspension strips attached to the diaphragm support structure, each strip being positioned on opposite sides of the central expanse and abutting the central expanse, the central expanse being received between the strips such that the central expanse is maintained centrally within the drive gap while being free to move without contacting the diaphragm support structure.

10. The transducer of claim 9 wherein the strips are formed of flexible foam.

11. The transducer of claim 9 wherein the strips are elongated to contact the central expanse along substantially the entire height dimension of the central expanse.

12. The transducer of claim 9 wherein each strip includes a base portion and a nose portion, the base portion being attached to the diaphragm support structure, and the nose portion abutting the central expanse.

13. The transducer of claim 12 wherein the nose portion extends away from the base portion in a cantilevered manner and has a dimension which exceeds its thickness dimension length.

14. The transducer of claim 12 wherein the nose portion terminates at a nose end in abutting contact with the diaphragm.

15. The transducer of claim 9 wherein each strip is biased against the central expanse.

16. The transducer of claim 9 wherein the first and second strips are positioned in opposed relationship on



15

one side of the drive means, the transducer further comprising a pair of third and fourth distinct flexible diaphragm suspension strips positioned on an opposite side of the drive means, in abutting relationship with the central expanse.

17. An audio transducer comprising:

a chassis;

a magnet assembly supported by the chassis and having first and second magnet elements spaced apart by a magnet gap, the first and second magnet elements creating a magnetic field in the magnet gap;

a sound-generating diaphragm including at least two arcuate web portions joined together at a central coil-carrying expanse located within the magnet gap, each web portion having opposed end portions affixed to the chassis, the central expanse having opposed first and second sides;

a first pair of distinct flexible suspension strips positioned on opposite sides of the first magnet element, each strip of the first pair being in abutting contact with a substantial linear portion of the central expanse;

16

a second pair of distinct flexible suspension strips positioned on opposite sides of the second magnet element, each strip of the second pair being in abutting contact with a substantial linear portion of the central expanse, whereby the first and second pair of strips abut from opposite abutting directions the central expanse to center the central expanse within the magnet gap while permitting the central expanse to move in a direction substantially tangential to the abutting directions.

18. The transducer of claim 17 wherein the first and second pair of suspension strips abuttingly contact the central expanse along respective substantially continuous linear portions of the central expanse.

19. The transducer of claim 17 wherein the first suspension strips each have a substantially "L" shaped cross-section including a cantilevered nose portion, the nose portion of each strip being in abutting contact with the central expanse.

20. The transducer of claim 19 wherein the strips are elongated and have a length substantially equal to the height dimensions of the central expanse.

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