United States Patent

Flint et al.

[15] **3,697,790**

[45] **Oct. 10, 1972**

[54] **TRANSDUCERS HAVING PIEZOELECTRIC STRUTS**

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[52] **U.S. Cl.** **310/8.3,** 310/8.5, 310/8.6, 310/8.7, 310/9.1

[51] **Int. Cl.** **H04r 17/00**

[58] **Field of Search**..............310/8, 8.2, 8.3, 8.5, 8.6, 310/8.9, 9.1, 9.4; 179/110 A

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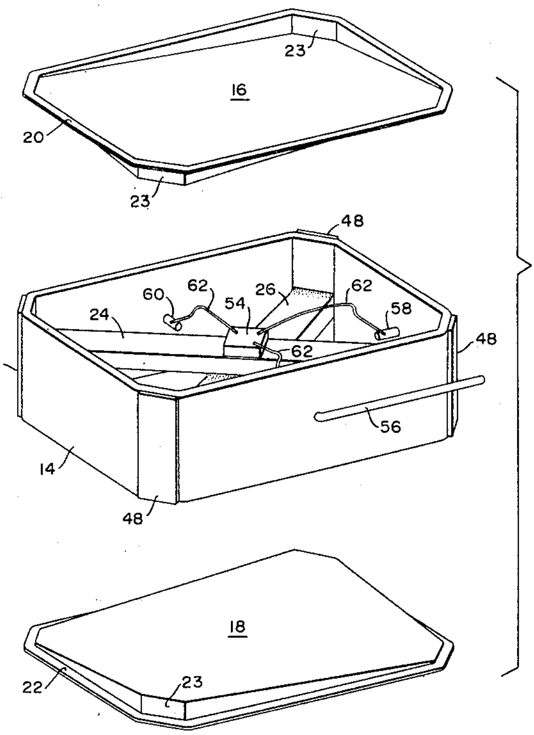
[57] **ABSTRACT**

A transducer of electromechanical or electroacoustic type comprising a piezoelectric strut supported by a frame on a diagonal thereof. The frame is subjected to face shear stress by deflections of a generally saddle shaped diaphragm termed a "diabow," inducing longitudinal stresses in the piezoelectric strut. The strut has electrodes for connection with an electrical circuit.

33 Claims, 10 Drawing Figures



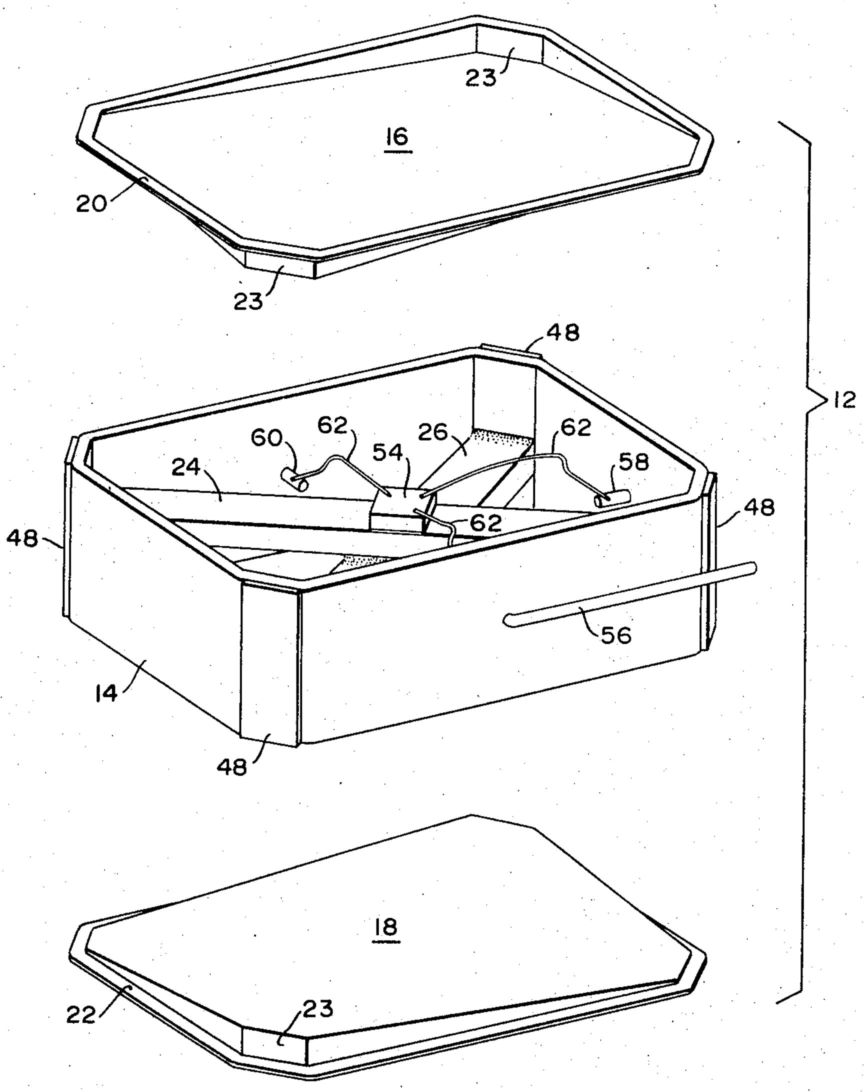


FIG. 1

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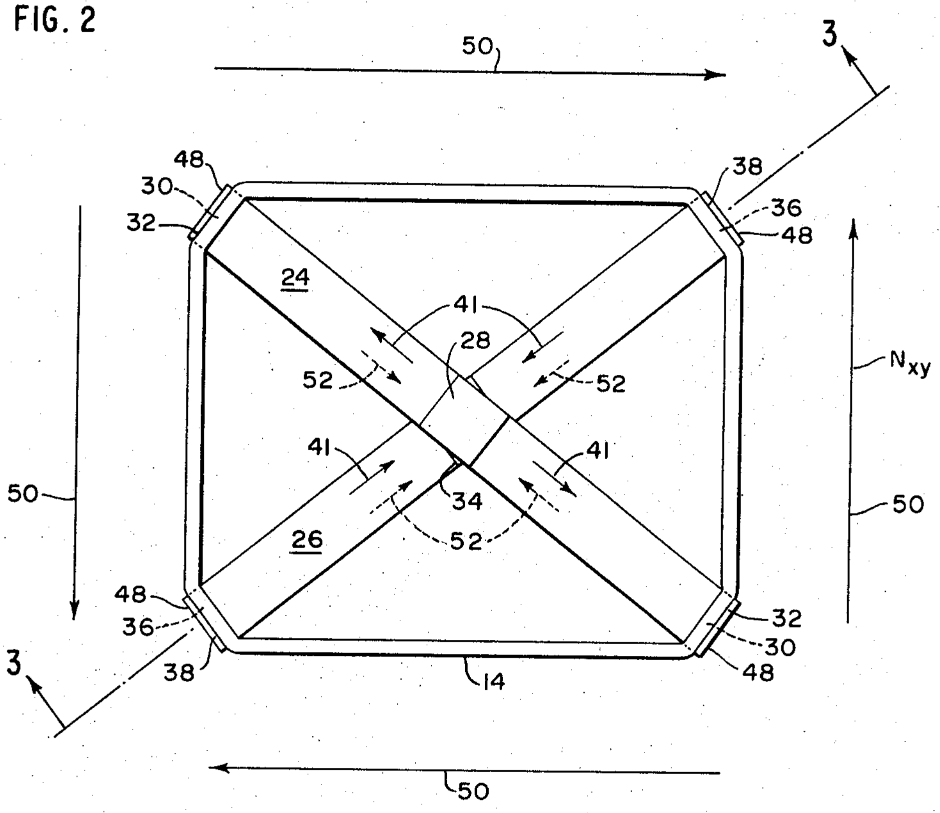
FIG. 2



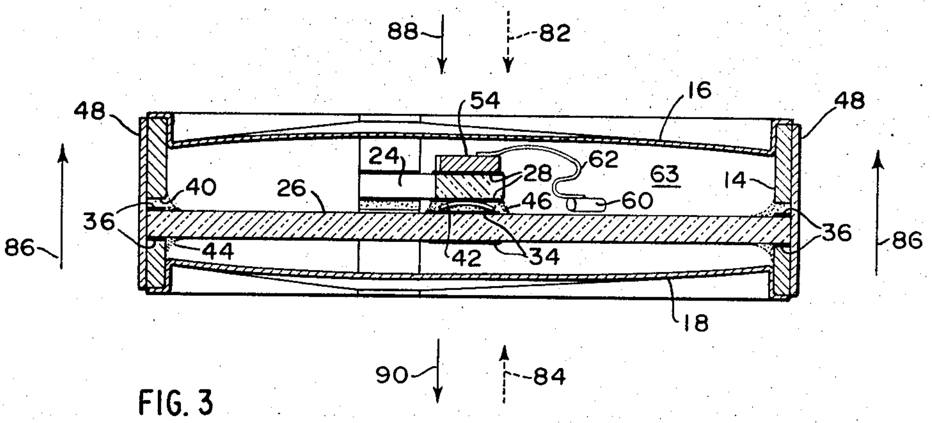


FIG. 3

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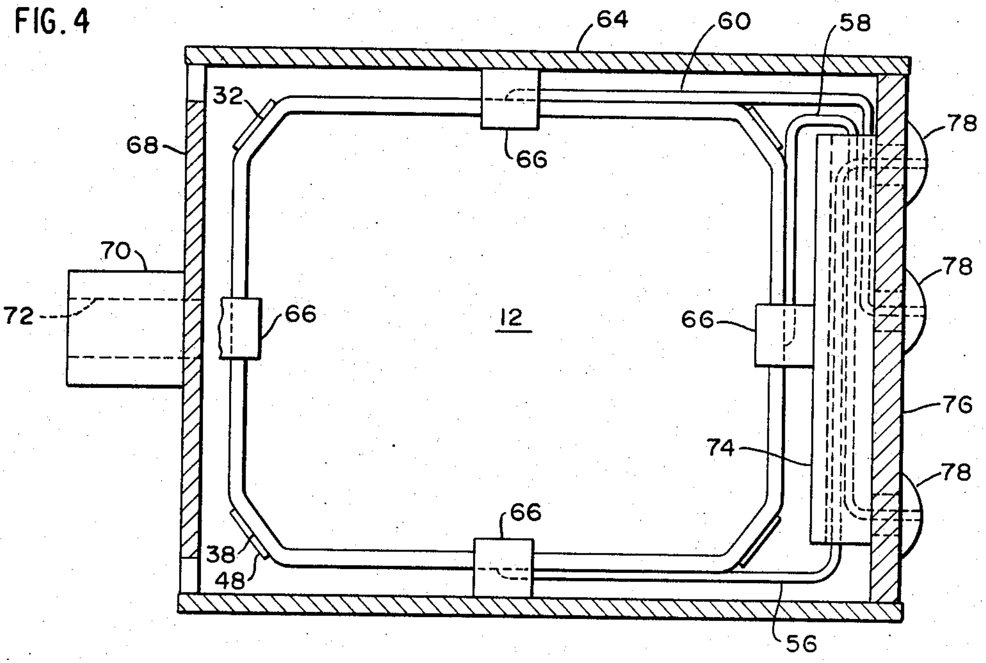
FIG. 4



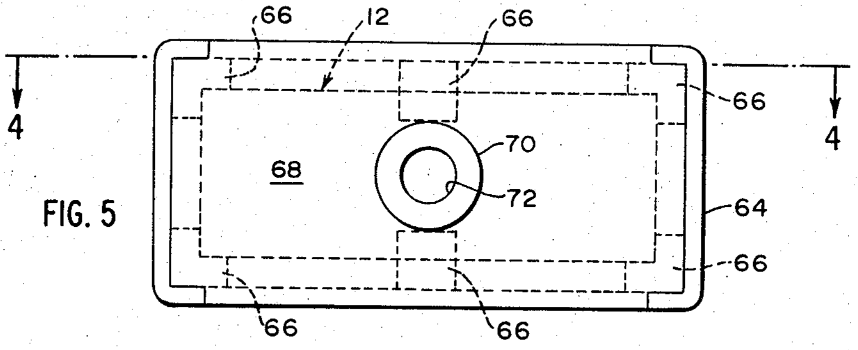


FIG. 5

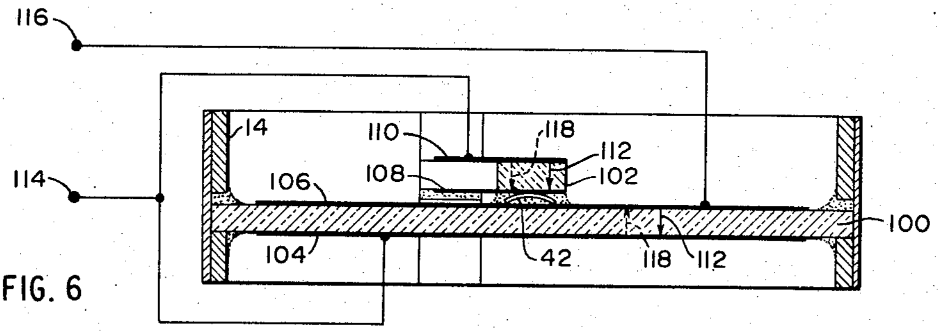


FIG. 6

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FIG. 7a

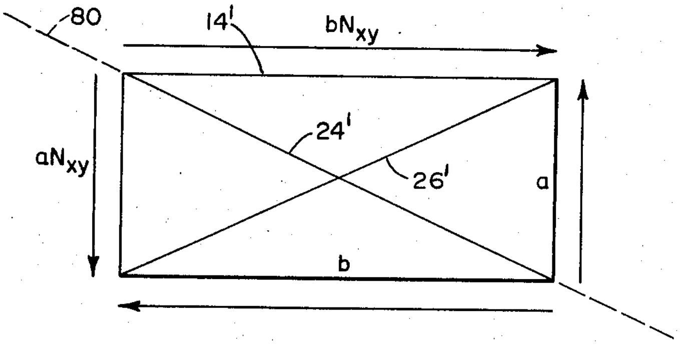


FIG. 7b

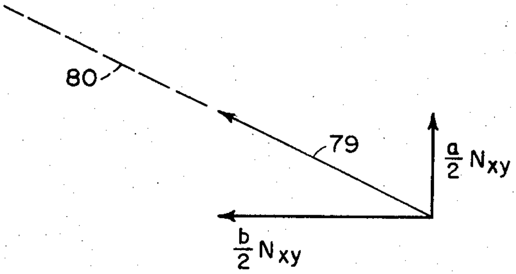


FIG. 8

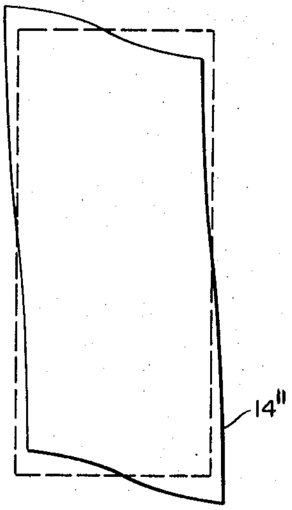
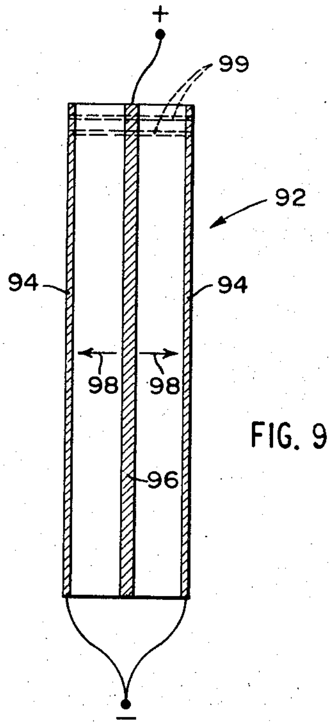


FIG. 9



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TRANSDUCERS HAVING PIEZOELECTRIC STRUTS

BACKGROUND OF THE INVENTION

This invention relates generally to transducers for converting electrical energy to mechanical energy, or mechanical energy to electrical energy, or both. More specifically, it relates to devices for efficiently using the piezoelectric properties of certain known substances.

The piezoelectric properties of single crystals, for example Rochelle salt crystals, have long been known and have been widely used in electromechanical and electroacoustic transducers. Examples are described in U. S. Pat. No. 2,403,692 to George C. Tibbetts, dated July 9, 1946. Various vibrational modes either natural or essentially static may be employed. Each static mode has a corresponding piezoelectric coupling coefficient "*k*" related to the way in which energy is stored in the piezoelectric body.

Comparable properties exist for piezoceramics, which are polycrystalline aggregates of ferroelectric materials, one example of which is a ceramic comprising barium titanate fired to vitrification, as described in U. S. Pat. No. 2,540,412 to Robert Adler, dated Feb. 6, 1951. Contemporary piezoceramics commonly are based on solid solutions of lead zirconate and lead titanate. A piezoceramic material is poled, that is, it has a remanent polarization imparted to it, by subjecting it to a high electric field at room or elevated temperatures. Piezoceramic materials are preferred over single crystal elements in many current applications, such as hearing aid transducers, phonograph pickups, underwater sound transducers, and so forth. The reasons for this preference include greater strength to withstand mechanical shock, thermal and environmental stability, high electromechanical coupling coefficients, ease of fabrication, versatility of the poling techniques and low cost of manufacture.

In the following discussion the "longitudinal piezoelectric coupling coefficient" is that which applies to changes in dimension in the direction of poling when other changes in dimension are unconstrained. The "transverse piezoelectric coupling coefficient" is that which applies to changes in dimension perpendicular to the direction of poling, and is about half the value of the longitudinal coupling coefficient for a typical piezoceramic material. In each of these particular cases the electric signal field is parallel to the direction of poling.

In the design of any practical electromechanical or electroacoustic transducer using a piezoelectric body, it is necessary to provide mechanically vibratable means and electrical circuit means for coupling to the body. Both of these means present practical problems. The electrical circuit means must have an impedance adapted to that of the piezoelectric body. Ideally, in addition to its functions in the transduction of energy, the mechanically vibratable means should also provide mechanical and environmental protection to the piezoelectric body.

A considerable development has occurred in the art with respect to the foregoing means, but hitherto the devices found commercially practical have presented substantial compromises among the various desirable properties. Electromechanical transducers employing piezoceramics for audio frequency applications have nearly always used flexural or torsional effects obtained either in laminated plates or one piece tubes, certain examples being given, for example, in U. S. Pat. No. 3,219,850 to Robert A. Langevin, dated Nov. 23, 1965. Flexural devices are the most common, and for this type the transverse electromechanical coupling coefficient is most commonly employed. One of the problems with flexural piezoelectric devices is fragility, which persists even when the relatively stronger piezoceramic materials are employed rather than single crystal materials. To overcome fragility it has been proposed to use trilaminates having metal substrates, in which reliance is placed on the strength of ceramics in compression. These methods in turn impose their own limitations including permissible directions of poling, usable coupling coefficients and electrical properties.

Other problems associated with prior art devices arise from excessive elastic energy storage in the mechanically vibratable means engaged with the piezoceramic elements. The result is a large reduction in the overall electromechanical coupling coefficient of the devices. Examples are provided by all of the embodiments disclosed in U. S. Pat. No. 2,487,962 to John P. Arndt, Jr., dated Nov. 15, 1949.

Still other problems encountered in prior art devices include limitations of practical materials for the mechanically vibratable means arising from their electrical conductivity and the consequent limitations on permissible signal electrode locations. There are also limitations on methods of fabrication, especially the feasible arrangements of the poling of piezoceramic elements.

Many of the devices also have undesirable properties such as accelerometer sensitivity which is a major source of undesired feedback in such applications as hearing aids and of handling and other mechanically borne noise in microphone applications generally.

SUMMARY OF THE INVENTION

This invention provides improvements in piezoelectric transducers that afford a combination of desirable properties in a unit of simple construction and low cost of fabrication. It permits the utilization of the preferred piezoceramics in simple one-piece shapes such as struts of rectangular cross section, which are easily fabricated and readily poled. Moreover, the other parts are also simple in structure and readily assembled to provide a small, compact, rugged and highly sensitive transducer.

The invention comprises one or more piezoelectric struts having electric signal field directions either longitudinal or transverse with respect to their lengthwise axes, the struts extending along one or both diagonals of a quadrilateral. Means are provided to transform external stress into face shear stress in a plane parallel to this quadrilateral, and means are further provided to transform this face shear stress into longitudinal stress in the struts. By this combination of elements energy may be transformed from the mechanical form to the electrical form, or from the electrical form to the mechanical form, or in both directions. That is, both the stress transforming means and the overall transduction are bilateral in operation.

The preferred means for transforming the face shear stress into longitudinal stress in the struts comprises a peripheral frame, preferably in the general shape of the quadrilateral, the strut or struts being mounted within the outline of the frame in force-transmitting relation to the frame in the regions of the respective corners of the quadrilateral.

The preferred means for transforming external stress into face shear stress comprises one or two "diabows." For purposes of this description, the meaning of the term "diabow" includes a diaphragm lying near a plane and so shaped that face shear stress applied to its periphery in that plane produces displacements of the diaphragm relative to its periphery that have relatively large components normal to the plane. The term also includes any other means, whether in the form of a diaphragm or not, that is capable of transforming such face shear stress into an external stress system. The reverse is also true, namely, that the diabow transforms deflections or forces normal to the plane of its periphery into forces delivered at its periphery that correspond approximately to a uniform face shear stress system in the plane.

The stress within the strut produces, or is produced by, electric signal fields having directions oriented with respect to the strut. These signal field directions may be along any of the three dimensions of the strut, and may also be symmetrically oriented with respect to its midpoint. For example, they may be directed from the midpoint longitudinally toward the respective ends of a strut, and this particular configuration may provide important advantages including that of having the strut ends and the stress transforming means at a common ground potential, with the mid-point of the strut providing a signal electrode with respect to that ground potential. A substantial number of other possible configurations are also provided, as will be evident from the following description from which the various other advantages of the invention will become evident.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an exploded view of an electroacoustic piezoelectric transducer or "cell" embodying a preferred form of this invention.

FIG. 2 is a view in plan showing the transducer of FIG. 1 with the diabows and some electrical parts removed.

FIG. 3 is an elevation in section taken on line 3—3 in FIG. 2 with all parts of FIG. 1 in place.

FIG. 4 is a plan view in section of a hearing aid type microphone incorporating the transducer of FIGS. 1 to 3.

FIG. 5 is an end view of the microphone viewed from the left in FIG. 4.

FIG. 6 is an elevation in section of an alternative form of transducer utilizing a different piezoelecic coupling coefficient preferred for "loudspeaker" type applications.

FIGS. 7*a* and 7*b* are diagrams illustrating forces existing within an idealized transducer of the type embodying the invention.

FIG. 8 is a diagram illustrating in exaggerated degree the flexure of the frame of the transducer associated with face shear deflection.

FIG. 9 is a view illustrating a method of poling and fabricating one embodiment of the piezoelectric struts.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 shows in exploded form the principal parts of an electroacoustic transducer or "cell," designated generally at **12** (also shown in FIGS. **4** and **5**). The cell comprises an enclosure having sides formed by a generally rectangular or square shaped frame **14** preferably fabricated from a material having a low thermal expansion coefficient and a relatively high elastic modulus, such as the nickel-iron alloy containing 36 percent nickel and commonly known as "Invar." For purposes of this description and the appended claims, "rectangular"is intended to include "square" as well as other shapes, as is commonly understood. The frame is gold plated to provide surfaces having good electrical contact with the struts as hereinafter more fully described.

Diabows **16** and **18**, in the form of generally saddle-shaped metal diaphragms having peripheral flanges **20** and **22**, respectively, are assembled with the flanges abutting the side edges of the frame. This forms a closure that protects the parts contained within it.

The structure and configurations of the diabows are well known in the art. The saddle-shaped central regions are preferably smoothly curved, and preferably each diabow is mirror symmetrical with respect to the other. The flanges each lie in a plane to which the central portions are joined by integral skirts **23** of varying height. The skirts **23** are of maximum height at two diagonally opposite corners and of minimum height at the other two diagonally opposite corners. Other suitable forms of diabows are described in the above-mentioned patent to Tibbetts. In all of these forms the diabows have the property that if forces with components normal to their principal surfaces are delivered thereto, such forces are transformed into forces delivered to the frame at their peripheries as face shear stresses, that is, stresses acting to draw two diagonally opposed corners of the frame toward one another while simultaneously forcing apart the other two diagonally opposed corners, and acting in the opposite direction to have the reverse effect. Thus the cell **12** as a whole is characterized by face shear response to acoustic waves impinging upon the diabows. The two diabows are so positioned on the frame that if the central regions of both are forced inwardly toward the enclosure at the same time, the face shear stresses applied to the frame are in the same sense or direction and are additive.

When the diabows **16** and **18** are in place, their major saddle-shaped surfaces are recessed into the frame **14**, while the skirt **23** and flange **20** or **22** of each diabow is bonded to the frame as by epoxy adhesive, soft solder, or the like.

A pair of piezoelectric struts **24** and **26** extend diagonally across and within the frame **14**. These struts are preferably fabricated from a piezoceramic material such as a lead zirconate-titanate polycrystalline body of a commercially available form, or the equivalent. The strut **24** has a pair of center or mid-point electrodes **28** (FIGS. **2** and **3**) and two pairs of end electrodes **30** (FIG. **2**) respectively located within rectangular apertures blanked in chamfers **32** formed in the frame. Similarly, the strut **26** has a pair of center electrodes **34** and two pairs of end electrodes **36** respectively located within rectangular apertures blanked in chamfers **38** formed in the frame. A typical aperture in one of the chamfers is designated **40** in FIG. **3** and preferably provides a clearance vertically for the strut as viewed in FIG. 3. These electrodes are all preferably coatings having precious metal powder bases, glass bonded and fired on the strut material.

In this embodiment the struts are electrically poled in the directions indicated by solid arrows **41** in FIG. **2**. Each strut is poled in directions parallel to its lengthwise dimension. One strut is poled in one direction from its center electrode toward one of its end electrodes and in the opposite direction from its center electrode toward the other of its end electrodes, while the other strut is poled in one direction from one of its end electrodes toward its center electrode and in the opposite direction from the other of its end electrodes toward its center electrode. A suitable method of poling the struts is described below in connection with FIG. **9**.

The struts may be threaded through the apertures such as **40**, or alternatively one end may be tipped through one aperture before insertion of the other end if the vertical clearance in the aperture is sufficient.

Electrical contact between facing center electrodes **28** and **34** is provided by a gold alloy curved leaf spring **42** (FIG. **3**) which also seats each strut outwardly in its respective apertures with sufficient force to provide reliable electrical contact at each end of the strut between one of the electrodes **30** or **36** and the corresponding aperture. At this point of assembly a suitable adhesive such as epoxy adhesive may be flowed into the five sets of joints to provide fillets **44** and **46**. After curing of the adhesive, which may be done at temperatures such that depoling of the struts is negligible, the ends of the struts will, in general, slightly protrude outwardly of the aperture in the frame. These protrusions may be removed, as by a diamond filing operation, to produce ends flush with the outside of the frame chamfers **32** and **38** as shown in the drawings. Corner plates **48**, fabricated from a high elastic modulus material, are then bonded to the outside of the frame chamfers by a similar adhesive. The purpose of the corner plates **48** is to increase the elastic stiffness of the joints between the struts and the frame. The adhesive in the butt joints between the struts and the corner plates, and between the corner plates and the outside chamfers of the frame, is partially confined because the lateral extensions of the joints are much greater than the film thickness of the adhesive. Since in the butt joints the adhesive is essentially under tension or compression, the partial confinement of the adhesive raises the effective elastic modulus of the adhesive to a considerably greater value than the Young's elastic modulus of the adhesive. This in turn is nearly three times greater than the elastic modulus in shear, which is applicable to the adhesive within the apertures **40** during operation of the system as described below.

When assembled, as described below, the structure of FIGS. **1** to **3** has very high resistance to mechanical breakage of the struts when the assembly is subjected to mechanical shock.

In operation of the system shown in FIGS. **1** to **3**, if face shear forces per unit length N_{xy} are applied by the diabows to the periphery of the frame **14** in the directions shown by arrows **50** in FIG. **2**, then the strut **24** is placed under compression and the strut **26** under tension. If the piezoceramic material is of the type that lengthens during poling in the direction of poling, then these stresses in the struts will result in signal polarizations as indicated in FIG. **2** by dotted arrows **52**, parallel to the lengthwise dimensions of the struts. That is, in this particular case the electrical signal polarizations all point inwardly from the frame toward the center electrodes. Since the center electrodes are electrically connected together, and since the frame is a common contact to all the ends of the struts, the system possesses four essentially capacitive generators, each having the same voltage, polarity of voltage and capacitance, which are placed electrically in parallel by the nature of the construction. Because of the equality of the signal voltages, the electrostatic signal energies of the four capacitive generators are additive. In this embodiment, which is preferred for mechanical to electrical transduction as in microphones, an important advantage resides in this efficient provision of an electrical signal voltage at the center of the structure and relative to an equipotential periphery. When the directions of the face shear forces indicated by arrows **50** are reversed, the directions **52** of the signal polarizations are also reversed and thus point outwardly. That is, the operation of the system is essentially linear, and it can be used in linear electromechanical or electroacoustic devices such as microphones, phonograph pickups, and the like.

In the other direction of energy transduction, a voltage difference applied between the common center electrodes and the frame will cause one strut to expand while the other strut contracts. This causes the frame to take on face shear components of motion in a plane (the plane of FIG. 2), and results in movement of the central portions of the diabows, with both diabows moving at the same time either inwardly toward the struts or outwardly from the struts, depending on the polarity of the applied signal voltage.

Each diabow, by the nature of its configuration, possesses a negligible self-stiffness in excess of the flexural stiffness that it would have if formed as a flat plate. By self-stiffness is meant the stiffness of the diabow in the case that motion of its periphery is unconstrained in any direction parallel to the plane of its flange. This fact explains in part why the above described embodiment has a high overall electromechanical coupling coefficient. Of equal importance is the fact that this coefficient is degraded very little by the frame as hereinafter more fully discussed.

It will be noted that in the above-described embodiment the electrical capacitance is low because of the relatively large spacing between the center electrodes and the frame, and the relatively small cross section of the struts. In this case it is a matter of choice whether the pairs of electrodes **28, 30, 34** and **36** on opposite sides of the struts are pair-wise interconnected. The system is operative without such externally applied conductive means because of the relatively high capacitance between such electrode pairs.

As shown in FIGS. **1** and **3**, a transistor amplifier chip **54** is bonded to the strut **24** over an electrode **28**, and one of the electrical connections of the chip is made at the face bonded to this chip. External leads **56, 58** and

60 are fabricated from film insulated wire similar to magnet wire, and pass through holes in the frame **14**. The leads **56** and **60** are secured to the frame but electrically insulated therefrom, and the lead **58** is electrically contacted to the frame, as by spot welding, in order to make electrical connection with the electrodes **30** and **36** at the ends of the struts. Internal wires **62** interconnect the chip **54** with the leads **56, 58** and **60**.

A vent (not shown) may be made in the frame **14** to equalize the atmospheric pressure between the enclosed space **63** (FIG. **3**) and the exterior of the cell. In certain cases it is practical to fabricate the cell without the vent, as a hermetically or substantially hermetically sealed case that provides protection of the transistor amplifier chip against adverse environmental conditions.

A microphone embodiment incorporating the cell **12** of FIGS. **1** to **3** is shown in FIGS. **4** and **5**. The cell is compliantly supported within a tubular metal casing **64** of generally rectangular cross-section, by eight elastomeric mounts **66**. The mounts are L-shaped and are adhesively bonded to the cell **12** before insertion into the casing. The casing is closed at one end by an end plate **68** which carries an acoustic inlet tubulation **70** having an aperture **72** which also extends through the end plate. A U-shaped bulkhead **74** is mounted within the casing to provide support for the adjacent elastomeric mounts and to locate, by its major edges, a terminal plate **76**. The leads **56, 58** and **60** are connected to soldered terminals **78** on the plate **76**. Preferably the terminal plate has a thick film circuit on its inner face which is used in conjunction with the transistor amplifier contained within the cell **12**. Thus the space between the terminal plate **76** and the facing major surface of the bulkhead **74** is used to provide space for the thick film circuitry as well as for the leads **56, 58** and **60**. The leads are disposed in such a way as to obtain maximum elastic compliance between the soldered terminals **78** and the entrance of the leads through the frame of the cell **12**. By reason of this disposition of the leads, the elastic support of the cell within the casing is provided mainly by the elastomeric mounts **66**. The elastomeric mounts are aligned with the centers of the frame sides so that forces exerted on the frame by the mounts as a result of acceleration of the casing **64** in directions parallel to the plane of FIG. **4** are not electromechanically coupled to the signal electrodes of the transducer. The compliance of the mounts reduces such forces to a minimum, and likewise attenuates the acceleration of the cell **12** compared with that of casing **64** when the casing is accelerated normally to the plane of FIG. **4**. The compliance of the mounts also prevents constraint on the motion of the frame in response to electroacoustic transduction. The entire structure is very resistant to mechanical shock and also has substantially no accelerometer sensitivity from the point of view of mechanical vibration, as discussed further below. Both of these features are extremely important in hearing aid and similar applications, in which failure of the electroacoustic transducer components in use has been predominantly the result of destruction by mechanical shock, and in which accelerometer sensitivity of the electroacoustic transducers has been a major source of undesired feedback from the output to the input of the system. Mechanical vibration effects of this type cause feedback oscillations in systems using prior art devices, unless both transducers are extensively cushioned to provide sufficient attenuation of the mechanical feedback path.

The microphone embodied in FIGS. **4** and **5** can be rigidly bonded into the casing of devices such as hearing aids, and with the described structure the in situ mechanical shock resistance and accelerometer insensitivity characteristics will be excellent. The resulting saving of space and complexity in such devices will widen the applicability of transducers constructed in accordance with this disclosure.

FIG. **7***a* is a schematic diagram that indicates the effect of a uniform face shear force per unit length N_{xy} applied to a frame **14'** idealized to have zero wall thickness and connected to struts **24'** and **26'** idealized to have zero width. Because of the symmetry of the structure, the total force applied along any side of the frame divides into two halves delivered at each end of the side. This is shown in FIG. **7***b*, which shows the force components delivered to the strut **24'** at its lower end as viewed in FIG. **7***a*. By reason of the fact that the force components are proportional to the lengths of the corresponding sides of the frame, the total force resultant **79** is directed along and parallel to the axis **80** of the strut **24'**. In an actual structure having struts with width and corresponding chamfers on the frame, the geometry is somewhat altered so that the force resultants are no longer exactly parallel to the axes of the struts. Furthermore, forces are required to flex the frame and these cause an additional deviation of the force resultants from parallelism with the axes of the struts. Equilibrium is achieved by moments and transverse forces in the plane of FIG. **7***a* applied to the ends of the struts, and these are parasitic in the sense that they are not coupled electromechanically to the electrical terminals of the system. However, in actual devices these effects are fairly small, and frames of substantial rectangularity are thoroughly practical.

FIG. **8** is a schematic diagram showing a greatly exaggerated deformation of an idealized unchamfered frame **14''** relative to the undeformed frame indicated by broken lines. Whether in combination with diabows or not, the right angles in the neighborhoods of the frame corners persist under deformation of the frame, and therefore the frame is required to flex as it deforms. In combination with diabows, the flexure of the frame is partially constrained by the diabows. Energy is required to flex the frame, and this energy is least (zero) when the frame wall thickness is zero. However, each frame side also serves to transform the shear forces per unit length applied at its edges, to forces at the strut ends that cause the displacements of the strut ends and the corresponding flexure of the frame. A membrane force system exists in each of the frame sides in order to effect this transformation. This force system also results in the storage of elastic energy, which becomes smaller as the wall thickness of the frame becomes greater. Since both of these energies are subtracted from the total energy delivered to the frame-strut system to give the energy stored in the pair of struts, there exists an optimum for the wall thickness of the frame such that the electromechanical coupling coefficient of the frame-strut system is maximum. The higher the elastic modulus of the frame material, the thinner will be the optimum wall thickness and the greater will be the corresponding electromechanical coupling coefficient of the system as the piezoelectric coupling coefficient of the strut is approached. In this restricted sense the behavior of the frame is analogous to that of a diabow, but at the same time it is obvious that the frame is distinguished from the diabow in many other respects. In combination with a diabow and a strut, the frame ranks in importance with the diabow itself. In combination with a strut, the frame is a novel element essential to the provision of a structure that is face shear responsive over a periphery.

The cell 12 of FIGS. 1 to 3 may employ pin driven diabows as disclosed in said patent to Tibbetts. However, FIG. 3 illustrates some of the advantages that are obtained when the diabows are the only diaphragms of an electroacoustic transducer incorporating the cell of FIGS. 1 to 3. In this case, acoustic pressure differences act directly on the diabows **16** and **18** as described above, and acoustic volume displacements are produced solely by the deflections of the diabows. Dotted arrows **82** and **84** indicate the direction of the forces on the diabows **16** and **18**, respectively, when the external pressure exceeds the pressure in the space **63**. These forces result in face shear forces having the same sign in each diabow, which are applied additively at the top and bottom of the frame **14** to drive the frame-strut system, as described above. On the other hand, if the entire cell **12** were accelerated in the direction indicated by arrows **86**, as by mechanical vibration or shock, the resulting inertial forces due to the mass of the diabows would be in the direction indicated by arrow **88** for diabow **16**, and by arrow **90** for diabow **18**. To the extent that the cell is elastically symmetrical, which it approximates to a high degree, the face shear forces applied by each diabow to the frame **14** cancel one another, and there is no net shear force to cause an electrical signal voltage between the center electrodes and the frame **14**. Although the struts flex slightly due to their own mass under acceleration, the resulting stresses are not electromechanically coupled to the signal electrodes. Hence there is substantially no accelerometer sensitivity of the cell, compared with non-cancelling electroacoustic transducers, and this fact is extremely important in a large number of applications. Another consequence is that mechanical shock acceleration pulses applied in the direction of the arrows **86** cancel in the same way; it is necessary only that the struts be able to support the inertial effects of their own mass under such shock. Since each strut is fixed at both ends in the frame **14**, the flexural strength of the struts under shock is very high and more than adequate for all practical applications.

Thus, although the diabows have low self-stiffness as discussed above, each is bonded to the frame. Under inertial forces the diabows develop membrane forces N_{xy} of opposite sign which are connected together by the frame in such a way that the distortion of the frame is negligible. As a result, the total stiffness of the diabows with respect to inertial forces is even greater than the total stiffness with respect to acoustic pressures, and consequently the diabows deflect only moderately and substantially linearly when very large accelerations are applied by mechanical shock pulses.

As noted above, the embodiment of FIGS. 1 to 3 is preferred for transduction to the electrical form of energy. This is because the piezoelectric coupling coefficient of a piezoceramic is greatest when the direction of poling is in the direction of the tensile-compressive signal forces, and because the path length between the signal electrodes (in this case between the center and the end electrodes) is maximum. As a result, the open-circuit electrical signal voltage is relatively large for the embodiment of FIGS. 1 to 3. A corollary of this, however, is that the electrical capacitance of the transducer is minimized in the embodiment of FIGS. 1 to 3. Thus the high open-circuit signal voltage can be used to advantage only if the impedance of the electrical load on the transducer is at least comparable with that of the transducer itself. For example, a transducer using currently available piezoceramics and constructed according to FIGS. 1 to 3 typically has an electrical capacitance of only a few pico-farads. Therefore it is essential that an electronic amplifier be placed as closely as possible to the set of center electrodes, and this is accomplished by mounting the transistor amplifier chip **54** directly on a center electrode **28** and causing the mounted face of the chip to be the high impedance electrical input terminal of the amplifier, as described above.

Piezoceramic struts such as **24** and **26** may be fabricated conveniently from larger strips as illustrated in FIG. 9. A strip of piezoceramic material **92** carries electrodes **94** surrounding its outer edges, and a pair of central electrode strips **96**, one on each major face. The electroded strip may be poled in the directions indicated by arrows **98** by conventional techniques adapted to the particular piezoceramic body. Such techniques are described, for example, in said patent to Adler. Thereafter, the strip may be mounted on a flat surface by means of a fairly low temperature hot melt adhesive. Struts such as **24** may then be produced by slicing the strip, as by diamond wheel slotting indicated by broken lines **99**, and then removing and cleaning the struts in a solvent for the adhesive. Struts such as **26** can also be produced by reversing the polarity of the D. C. poling voltage and thus the directions of poling in the strip **92**.

Various modifications and variations may be made in the embodiment of FIGS. 1 to 5. For example, although a pair of struts has been illustrated and is preferred, the system is operable with only a single strut in combination with the frame. Similarly, the system is operable with only a single diabow in combination with the frame and either one or two struts, although two diabows are preferred.

FIG. 6 illustrates another variation characterized by a different direction of poling of the struts. The frame **14** is identical with that of FIGS. 1 to 3 but piezoceramic struts **100** and **102** are preferably employed. The strut **100** has electrodes **104** and **106** on its major surfaces and the strut **102** has electrodes **108** and **110** on its major surfaces. Each strut is poled in the direction of its thickness as indicated by solid arrows **112**. The electrodes do not extend to the frame **14**. The leaf spring **42**, which may be identical to that of FIGS. 1 to 3, connects the electrodes **106** and **108**. The two struts are placed electrically in parallel with a common connection **114** being made to the electrodes **104** and **110** and another connection **116** being made to the electrode **106**. The directions of the signal polarizations for the directions of shear stress shown by the arrows **50** in FIG. **2** are indicated by dotted arrows **118** through the thickness of the struts. This embodiment in which the struts are electroded on major surfaces is preferred for electrical to mechanical transduction, even though the transverse piezoelectric coupling coefficient employed in the embodiment of FIG. **6** is only about one-half of the longitudinal piezoelectric coupling coefficient employed in the embodiment of FIGS. **1** to **3**. This is because the electrical voltage required to produce a given mechanical displacement is much smaller for the embodiment of FIG. **6** than that for the embodiment of FIGS. **1** to **3**.

Struts fabricated from single crystal piezoelectric materials, instead of the described piezoceramic materials, may also be employed in the embodiment of FIG. **6**. Further, the embodiment of FIG. **6** may be modified to have electrodes on the side edges rather than the major surfaces of the struts, whether the struts are made of piezoceramic or single crystal piezoelectric material. In this case the central areas of the struts are not electroded to avoid the shorting of electrode pairs on one strut by the other strut. If a piezoceramic is used, the direction of poling is edgewise, that is, at right angles to the arrows **41** in FIG. **2** and in the same plane. Poling may be uniform through out the strut, or it may have opposite directions on each side of the non-electroded central area. The resulting four pairs of electrodes may be connected all in series, all in parallel, or in any suitable series-parallel combination, as desired. Of course, similar variations are applicable to the embodiment of FIG. **6** electroded on major surfaces of the struts if at least two electrode pairs are provided on each strut.

We claim:

1. A face shear responsive transducer having, in combination,

a strut of piezoelectric material,

an elastic peripheral frame, generally in the form of a quadrilateral, supporting the strut near the ends thereof and substantially only at a diagonally opposite pair of corners of the quadrilateral,

and means in stress communicating relation with the major part of an entire periphery of the frame and adapted to transform bilaterally between an external stress system and a face shear stress system acting over all of said major part of said periphery in a plane substantially parallel to said quadrilateral, said frame transforming bilaterally between said face shear stress system and longitudinal stress in the strut, the frame being stiff peripherally relative to the longitudinal stiffness of the strut, and the frame being compliant flexurally relative to the longitudinal compliance of the strut.

2. A transducer according to claim **1**, in which the strut is formed of a piezoceramic material.

3. A transducer according to claim **1**, having a pair of electrodes on the strut and spaced transversely of its lengthwise axis.

4. An electroacoustic transducer having, in combination,

a strut of piezoelectric material,

a pair of diabows spaced from and facing one another, each diabow having a substantially closed periphery,

elastic peripheral frame means supporting the strut near the ends thereof, said frame means extending between and being attached to the major part of the periphery of each of said pair of diabows, said frame means transforming bilaterally between longitudinal stress in the strut and face shear stress in each of the diabows, the frame means being flexurally deformable cooperatively with longitudinal deformation of the strut, said frame means being stiff peripherally and compliant flexurally relative to the longitudinal elasticity of the strut,

a casing having an acoustic connection through a wall thereof,

and means to support the frame means resiliently within the casing.

5. An electroacoustic transducer according to claim **4**, in which the diabows are substantially mirror symmetrical with respect to one another to provide substantial cancellation of accelerometer sensitivity.

6. An electroacoustic transducer according to claim **4**, in which the frame means is generally in the form of a quadrilateral and is supported in the casing substantially at mid points of its sides.

7. A face shear responsive transducer having, in combination,

a strut of piezoceramic material poled in one direction between a mid region thereof and one end thereof along its lengthwise axis and in the opposite direction between the other end thereof and said mid region along said lengthwise axis,

and an elastic peripheral frame generally in the form of a quadrilateral and supporting the strut substantially on a diagonal thereof, said frame transforming bilaterally between longitudinal stress in the strut and face shear stress acting at the frame in a plane substantially parallel to said quadrilateral, said frame being flexurally deformable cooperatively with longitudinal deformation of the strut, and said frame being compliant flexurally relative to the longitudinal compliance of said strut.

8. A transducer according to claim **7**, in which the frame is electrically conductive and electrically connected with the ends of the strut.

9. A face shear responsive transducer having, in combination,

a pair of struts of piezoelectric material,

and elastic means including a peripheral frame, said frame being generally in the form of a quadrilateral and supporting a strut substantially on each diagonal thereof, said elastic means being adapted to transform bilaterally between longitudinal stress in the struts and face shear stress acting at the frame in a plane substantially parallel to said diagonals, said longitudinal stress being of opposite sense in the respective struts.

10. A transducer according to claim **9**, in which the struts are each formed of piezoceramic material, each strut being poled in one direction between a mid region thereof and one end thereof along its lengthwise axis and in the opposite direction between the other end thereof and said mid region along said lengthwise axis.

11. A transducer according to claim **10**, in which one strut is poled outwardly from the mid region thereof and the other strut is poled inwardly toward the mid region thereof, and in which said mid regions are connected together.

12. A transducer according to claim **10**, in which the frame is electrically conductive and electrically connected with the ends of the struts.

13. A transducer between an external stress system and electrical terminals having, in combination,

a pair of electroded piezoelectric struts,

an elastic peripheral frame supporting each strut substantially only near the ends thereof, the struts crossing one another, said frame transforming bilaterally between longitudinal stress in the struts and face shear stress acting at the frame in a plane substantially parallel to the lengthwise axis of each strut, said longitudinal stress being of opposite sense in the respective struts,

and elastic means in contact with said external stress system and with said frame, and transforming bilaterally between said face shear stress and said external stress system.

14. A transducer according to claim **13** in which the elastic means is a diabow having a substantially closed periphery, and in which the frame is attached to said periphery.

15. A transducer according to claim **13**, in which said frame is generally in the form of a quadrilateral supporting said struts substantially on diagonals thereof.

16. A transducer according to claim **13**, in which the struts are each formed of a piezoceramic material.

17. A transducer according to claim **16**, in which each strut is poled in one direction between a mid region thereof and one end thereof along its lengthwise axis and in the opposite direction between the other end thereof and said mid region along said lengthwise axis.

18. A transducer according to claim **17**, in which one strut is poled outwardly from the mid region thereof and the other strut is poled inwardly toward the mid region thereof, and in which said mid regions are connected together.

19. A transducer according to claim **17**, in which the frame is electrically conductive and electrically connected with the ends of the struts.

20. A transducer according to claim **13**, in which each strut has a pair of electrodes thereon spaced transversely of its lengthwise axis.

21. A transducer according to claim **14**, in which the struts are formed of a piezoceramic material.

22. A transducer according to claim **21**, in which each strut is poled in one direction between a mid region thereof and one end thereof along its lengthwise axis and in the opposite direction between the other end thereof and said mid region along said lengthwise axis.

23. A transducer according to claim **22**, in which the frame is electrically conductive and electrically connected with the ends of the struts.

24. A transducer according to claim **14**, having a pair of electrodes on each strut and spaced transversely of its lengthwise axis.

25. A transducer according to claim **22**, in which one strut is poled outwardly from the mid region thereof and the other strut is poled inwardly toward the mid region thereof, and in which said mid regions are connected together.

26. A transducer according to claim **14**, having a second diabow having a substantially closed periphery, said frame being attached to the peripheries of both diabows.

27. A transducer according to claim **26**, in which each of the peripheries of the diabows is substantially rectangular.

28. A transducer according to claim **23**, in which the diabow is electrically conductive and electrically connected with the frame.

29. A transducer according to claim **24**, in which said electrodes extend along said lengthwise axis without electrically contacting the frame.

30. A transducer according to claim **29**, having a plurality of pairs of electrodes on each strut.

31. A transducer according to claim **25**, including electronic amplifier means mounted on and electrically contacting said connected mid regions to minimize the capacitive electrical load on the transducer.

32. A transducer according to claim **26**, in which the diabows and frame substantially enclose the struts.

33. A transducer according to claim **26**, in which the diabows are substantially mirror symmetrical with respect to one another.

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