May 12, 1953 W. T. HARRIS 2,638,577

TRANSDUCER

Filed Nov. 15, 1949 2 Sheets-Sheet 1

FIG. 1.

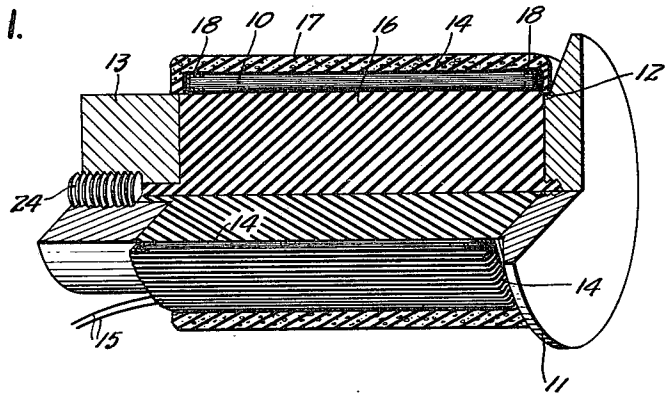


FIG. 2.

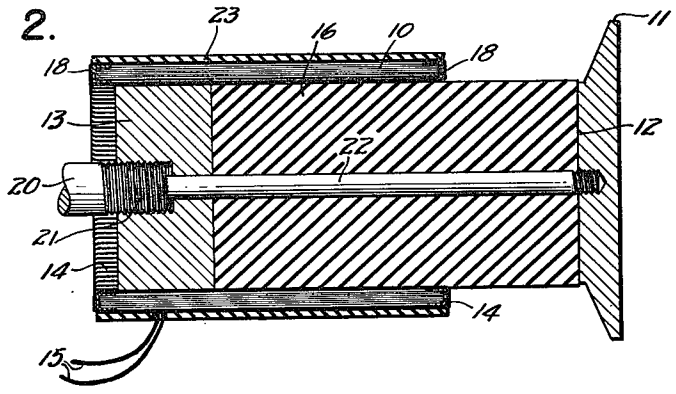
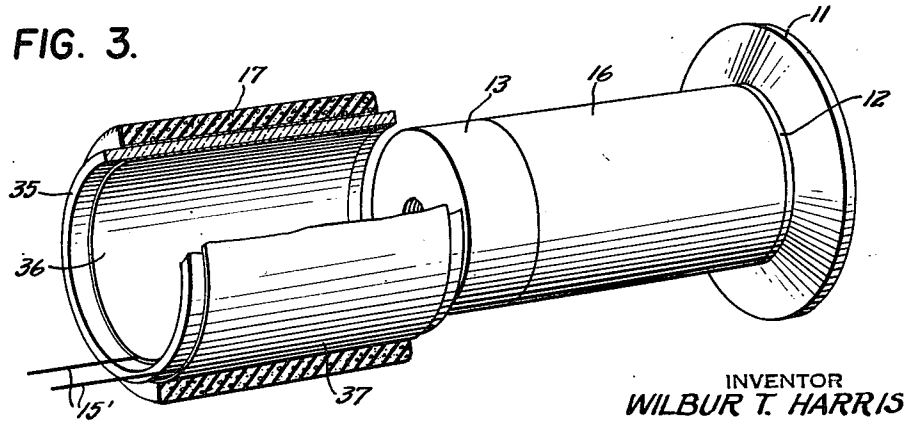


FIG. 3.



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FIG. 4.

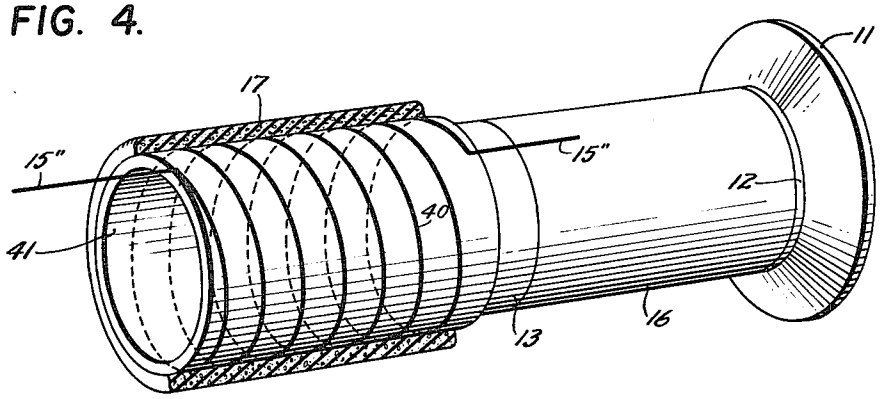


FIG. 5.

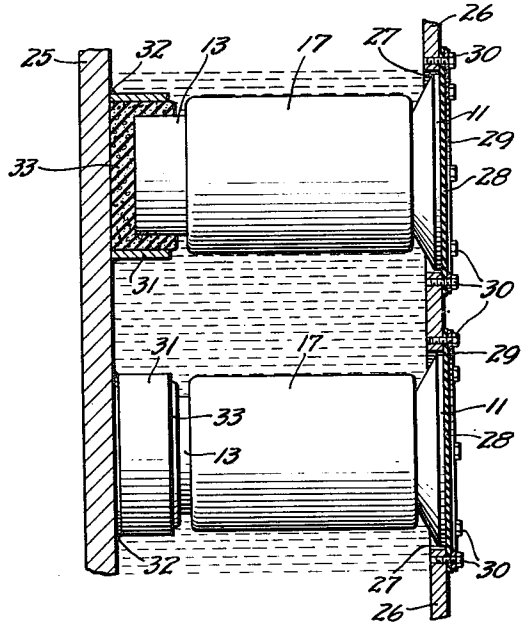
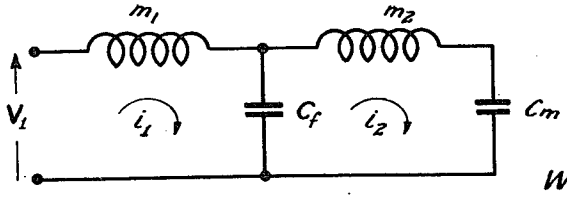


FIG. 6.



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UNITED STATES PATENT OFFICE

2,638,577

TRANSDUCER

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Application November 15, 1949, Serial No. 127,437

19 Claims. (Cl. 340—10)

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My invention relates to transducer means, as for translating mechanical wave energy, sonic or supersonic, into electrical energy, or vice versa.

It is an object of the invention to provide an improved means of the character indicated.

It is another object to provide an improved transducer for converting underwater sound into electrical energy and vice versa.

It is also an object to provide a more efficient transducer construction of the character indicated.

It is a further object to provide an improved unitary transducer construction having particular adaptability for the construction of multiple-unit arrays, as when a more sharply defined directional response is desired.

It is a general object to provide a relatively inexpensive transducer-element construction having high efficiency and capable of substantial abuse without impairment of response.

Other objects and various further features of novelty and invention will be pointed out or will become apparent to those skilled in the art from a reading of the following specification in conjunction with the accompanying drawings. In said drawings, which show, for illustrative purposes only, preferred forms of the invention:

Fig. 1 is a more-or-less perspective view in partial section of a transducer unit incorporating features of the invention;

Fig. 2 is a longitudinal sectional view of a transducer such as that of Fig. 1 during the process of assembly;

Fig. 3 is a perspective view, partly broken-away and partly in section, of principal elements of a transducer of modified construction, the elements being shown in partly separated relation, as during a step in the assembly of the transducer;

Fig. 4 is another partly broken-away perspective view, showing a further modified construction with certain elements partly removed as during a step of assembly;

Fig. 5 is a fragmentary view in partial section of an array of transducer units of the above-identified embodiments, the transducer units being shown in side elevation; and

Fig. 6 is an electric circuit diagram representing an electrical analogy of electro-mechanical relationships within a transducer of the invention.

Briefly stated, my invention contemplates a transducer construction in which a generally axially or longitudinally travelling pressure wave may be caused, through a suitable transforming medium, to produce radial deformations or stresses in a cylindrical member, and electrical means are provided to respond to such deformations or stresses. The efficiency of transformation from longitudinal excitation to radial excitation may be enhanced by employment of suitable counterweight or backing means longitudinally spaced from the end of the cylinder from which the pressure wave originated. In transducers for underwater-sound applications, the cylinder may be freely flooded with water or other fluid, but in the present arrangements I employ a relatively non-compressible effectively-fluid medium within the cylinder and in contact with the counterweight or backing member. The counterweight and, if desired, a diaphragm may effectively close off the longitudinal ends of the cylindrical member; and the natural resonance characterizing the coupling between the counterweight (and diaphragm, if used) and the medium within the cylindrical member is preferably at a different frequency than that of the natural radial-flex resonance of the cylindrical member, so that a broad-band response may be achieved.

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In the forms to be described, the electrically-responsive means is supported upon an open-ended generally cylindrical member, which member is in effective pressure-responsive relation with the effectively fluid material. In one form, the cylinder is of magnetostrictive material, and the electrical means is a toroidal winding about the cylinder as a core. In another form, the cylinder is of electrostrictive material, and the electrical means includes radially opposed spaced plates or electrodes on the inner and outer surfaces of the electrostrictive material. In a third form, a circumferential length of a material electrically sensitive to strain is applied to the outer surface of the cylinder.

Referring to Fig. 1 of the drawings, my invention is shown in application to a transducer having particular utility in underwater-sound applications. The transducer may comprise a generally cylindrical member 10 having open ends and to be subjected to radial stresses or deformations or strictions. One end of the cylinder 10 may be effectively open to the sound-transmitting medium, but in the form shown I employ relatively thin, low-mass diaphragm means 11 which may include a piston portion 12 mechanically isolated from the cylinder 10 and covering substantially the entire internal cross-section of the cylinder 10. At an axially spaced location away from the piston 12 the cylinder 10 may be effectively closed off by a counterweight or backing member 13 which is preferably of high mass and stiffness; in the arrangement shown, the counterweight member 13 effectively closes off the opposite end of cylinder 10.

In order to derive an electric output reflecting transient radial stressing of the cylinder member 10, I have in the form shown in Fig. 1, employed magnetostrictive material in the construction of the cylinder 10, and a toroidal winding 14 of insulated wire terminating in leads 15 may be applied about the cylinder 10 as a core. The winding 14 may serve for magnetically polarizing the core 10. The magnetostrictive material of the core 10 may be of laminar construction, as will be explained.

The interior of the cylinder 10 is preferably filled with a relatively non-compressible sound-transmitting medium. If desired, this interior may be flooded with oil or with water so as to obtain an intimate pressure-transmitting relation between the medium 16 and the diaphragm 11, counterweight 13, and cylinder 10. In the form shown, however, and in order to achieve a unit-handling relation for the entire transducer unit, I have employed so-called rho-c rubber as the filler medium 16. Such rubber will be understood to have the sound-transmitting characteristics of water, which will be assumed to be the medium in which sound is to be detected or projected via the transducer.

In order to render the transducer responsive substantially only to diaphragm displacements, the outer circumference of the wound core 10 may be enveloped by sound-absorbing or attenuating means, and in the form shown I have employed an air-filled rubber or rubber-like blanket 17 substantially enveloping the cylinder. In the event that rubber or rubber-like material is employed as the filling means 16, I prefer that such means 16 shall fill the cylinder homogeneously (as to sound-transmitting characteristics) with an integral bond to the parts 11—13—10, so as to permit good pressure-transmitting relationships between these members via the medium 16.

In the preferred form shown in Fig. 1, the magnetized magnetostrictive cylinder is preferably composed of thin concentric cylinders of magnetostrictive material. These separate cylindrical laminations may be bonded together into a mechanically unified mass; nickel, and alloys of nickel and iron and cobalt possesses the desired properties. Alternatively, the laminated cylinder can be produced by winding a suitably coated magnetostrictive sheet on a mandrel until the desired wall thickness is produced, and this step may be followed by a baking or firing process in order to produce solid bonding. Lamination is desirable for high efficiency because eddy currents within the magnetostrictive material are thereby reduced.

In the construction of transducer units such as shown in Fig. 1, one may separately produce the cylindrical core 10 by one of the methods outlined above, and the toroidal winding 14 may then be applied. In toroidally winding the core 10, I prefer to employ annularly cupped pieces 18 of insulating material fitting over the ends of the lamination assembly, in order to prevent insulation failures in the winding turns at the sharpest corners of the turns.

As a separate assembly, and referring to Fig. 2, the piston or diaphragm means 11 may first be assembled to the counterweight means 13, as by employment of tie-rod means 20. In the form shown, the tie-rod 20 is threaded against a shoulder 21 at the bottom of a counterbore in the counterweight 13, and a longitudinally projecting extension 22 of reduced section is centrally threaded into the diaphragm means 11.

Both threaded engagements are preferably of the same pitch, so that if later disassembly is desired, the rod 20 (including its extension 22) may be removed without upsetting the spaced relation of the diaphragm means 11 and of the counterweight means 13.

In one form of the invention, it may be useful to have the diaphragm and counterweight mechanically linked to each other, as by means of the tie-rod 22; and in such event the fit of tie-rod 22 to the members 11—13 may be made tight and permanent, as by welding, swaging, or other means (not specifically shown). If the tie-rod 22 is to remain a permanent part of the finished transducer, then the tie-rod 22 is preferably coated with a cement so that the rubber for the medium 16 may be intimately bonded thereto; if, on the other hand, the rod 22 is to be removed so as to produce the transducer of Fig. 1, then the rod 22 is preferably coated with parting means rather than with a cement. Such parting means may include an application of stearic acid, followed by a wrapping of cellophane over the rod.

Having suitably coated or otherwise treated the surface to be bonded to the rubber-like medium 16, the volume to be rubber-filled may be built up, as by spirally winding the tie-rod 22 with calendered sheets of tacky raw-rubber compound. The raw rubber may be built up to an excessive thickness and tightly bandaged with cloth tape. The assembly may then be placed in an autoclave and subjected to high gas pressure as the temperature is raised, in order to consolidate the rubber (eliminate porosity and bubbles) and to bring about vulcanization. When vulcanization is complete, the autoclave is gradually cooled and the gas pressure lowered. When cool, the assembly may be mounted in a lathe, utilizing the rod 20 for centering purposes, and the cylindrical rubber surface may be ground to such size that the wound magnetostrictive element 10—14 may be put in place as illustrated in Fig. 2. A rubber sleeve 23 may then be applied over the winding 14, and such sleeve may have provision for bringing out the leads 15. A polymerizable liquid, such as a styrene compound, may then be run in and degassed, and polymerization may be allowed to take place in order to establish an intimate integral bond between the elastic filler 16 and the sleeve 23. The rubber cover 23 may then be removed and the air-filled rubber-like blanket 17 applied and cemented in place.

Clearly, alternative methods of applying the rubber filler, as by injection molding may be evolved.

The interior of the transducer must be solidly filled, so that forces applied to the diaphragm (or to the open end, if no diaphragm is employed) can produce radial application of pressure on the cylinder essentially without loss. Therefore, if the rod 22 is to be removed, the hole left by the rod should be filled solidly with a rubber or rubber-like material. Theoretical analysis has shown, as noted below, that, by use of the rod 22 in a transducer of the character indicated, efficient response is essentially limited to the higher frequencies and that for maximum efficiency over a broad frequency range the rod 22 should be removed. After removal of the rod 22, the hole left by the rod 22 may be filled with a polymerizable synsthetic rubbery "potting compound," and a plug 24 may be screwed into the counterbore of the counterweight 13. By momentarily passing a large electric current

through the winding 14, the magnetostrictive element 10 may be magnetized; then, with suitable mounting and amplifying equipment, the complete transducer is ready for use.

With certain simplifying assumptions (e. g. that the length of the sensitive hollow cylinder be a fraction of the wave length), mechanical characteristics for a transducer of the character indicated may be computed, and its performance predicted. For example, consider a transducer of the following dimensions: a diaphragm diameter of 10 in.; a piston diameter of 8 in. approximately; an inside diameter of 8 in. for the magnetostrictive cylinder; a cylinder-wall thickness of 0.2 in.; Young's modulus for the cylinder material, 16×10^{11} dynes/cm.^{2}; length of cylinder, 6 in.; a counterweight piston of 8 in. diameter by 3 in. thick steel; a diaphragm-piston assembly of mass 1000 g.; stiffness presented to the diaphragm due to radial expansion of the magnetostrictive cylinder is 3.33×10^9 dynes/cm.; compressibility of rubber filling 80×10^{-12} of volume per dyne/cm.^{2}.

In making a theoretical analysis of my transducer, an electrical analogy may be helpful, and Fig. 6 is a simplified representation. In Fig. 6, V_1 represents the alternating pressure on the diaphragm, m_1, the diaphragm and piston mass, i_1 the diaphragram velocity, C_f the reciprocal of the stiffness presented to the diaphragm by the filling material, C_m the reciprocal of the stiffness presented to the filling due to the elasticity of the cylinder, m_2 the effective mass of the magnetostrictive-cylinder element in radial motion, and i_2 the radial velocity of the magnetostrictive cylinder.

Computations have been carried out with and without the mechanical and electrical resistances, and it appears that these need not be significant in practical structures except as they may limit the magnitude of resonant peaks. Making use of Fig. 6, the following equations apply:

$$V_1=j\omega m_1 i_1-\frac{j(i_1-i_2)}{\omega c_f}$$

and

$$0=\frac{-j(i_2-i_1)}{\omega c_f}+j\omega m_2 i_2-\frac{ji_2}{\omega c_m}$$

From these equations a relationship between the frequency

$$\left(f=\frac{\omega}{2\pi}\right)$$

and the velocity (i_2) of the sensitive element may be derived, assuming a constant amplitude of the alternating sound pressure (V_1) on the diaphragm. Making use of this relationship, an approximate frequency response may be deduced, as follows:

f, cycles/sec.	i_2, cm./sec.$\times10^7$
100	$j2.9$
159	$j30$
168	∞
200	$-j8.8$
812	$-j0.96$
1,590	$-j0.36$
6,380	$-j0.57$
6,910	∞
8,000	$j0.2$

Thus, the open-circuit voltage response may be substantially flat or uniform in the region below 7000 cycles/sec., except for a resonant peak near 200 cycles and another near 7000 cycles.

The above-mentioned derived expression for velocity (i_2) of the sensitive element may be useful in predicting the resonant frequencies, and by equating the denominator in said expression to zero, the following approximate relations may be obtained:

$$2\pi f_1=\sqrt{\frac{1}{m_1c_f-m_1c_m}}$$

and

$$2\pi f_2=\sqrt{\frac{1-c_m/c_f}{m_2c_m}}$$

where f_1 and f_2 are respectively the frequencies where the low frequency and high frequency resonances occur.

If an axial steel rod of 0.5 in. diameter rigidly connects the diaphragm and counterweight (e. g. rod 22), the diaphragm stiffness is increased more than 50-fold, and the efficiency of the transducer is impaired at frequencies below 800 cycles per sec.

The described transducer unit may find application as a single unit as in seismic applications, but in underwater-sound applications the unit is particularly useful in multiple-unit arrays, so as to achieve directionally responsive characteristics. For sake of illustration, I have shown in Fig. 5 two adjacent units of such an array. In the form shown, the entire array is included within a suitable tank or vessel having a back wall 25 and a front wall 26, either of which walls may form part of a ship's outer hull structure. The front wall 26 may be pierced with a plurality of windows 27 through which the open ends or diaphragms 11 of the various transducer units may be permitted effective contact with the outside fluid medium. In the form shown, I have employed rubber-like window means 28 bonded to the diaphragms 11 and mounted, as by clamping rings 29 and mounting bolts 30, to the rims of the windows 27. Back support for the transducer units may be provided by cradling the counterweight means 13 within annular flanges 31 which may be secured by welds 32 to the back plate 25. I prefer that the relation between the counterweight means 13 and the back plate 25 shall involve as poor a sound-transmitting character as possible, and in the form shown I have employed a cup 33 of sound-attenuating means such as air-filled rubber to provide the necessary spacing support for the counterweight 13. The assembled array may be completed either by free-flooding the interior of the tank with the fluid (e. g. water) into which the array is to be immersed or by filling the tank with castor-oil or the like.

I have described my invention in considerable detail in connection with a magnetostrictive embodiment, but it will be understood that the principles of the invention are of equal application for constructions employing other means of electro-mechanical energy transformation. In Fig. 3, for example, I have shown a transducer construction in which the diaphragm 11, piston 12, counterweight 13, and elastic medium 16 may be of the same general form as that previously described, but in which electrostrictive phenonema are employed for electro-mechanical energy transformation. Thus, the core of the electrical part of the transducer may comprise a cylindrical member 35 of an electrostrictive material, such as barium titanate. The cylindrical mem-

ber 35 may be included in an electric circuit by employing radially opposed spaced electrodes 36—37. In each case, the electrodes may be cylindrical sheets applied intimately to the inner and outer walls of the electrostrictive member 35, with separate terminal leads 15'. In constructing a transducer according to Fig. 3, essentially the same methods may be employed as described for the magnetostrictive case, that is, the two separate assemblies (shown in Fig. 3 prior to mutual assembly) may be potted together with a polymerizable material upon assembly, as will be clear.

As a still further variation of the invention, I may employ means electrically responsive to strain in order to detect radial stress in the medium 16 as a result of transient radial pressure excitation of the diaphragm 11. Such a construction is shown in Fig. 4, in which I have employed a circumferential spiral of conducting material 40 having a conductivity that is highly sensitive to strain. The spiral 40 may be applied directly to the elastic medium 16, but in the form shown I have employed a cylindrical mounting member 41 of non-conducting material over which the spiral 40 is laid. The completed transducer may be finally assembled in the manner described above for the other transducers, and a permanently rigid unit may be assured by employment of suitable polymerizable compounds, as will be understood.

It will be clear that I have described novel and improved transducers of rugged construction. My transducer construction is more adaptable than others to mounting in arrays and is considered more flexible as to the response and other properties obtainable. For example, it may be shown, with simplifying assumptions, that the following simple approximate relationship exists between diaphragm stiffness ($1/c_m$) and sensitive-cylinder elasticity:

$$1/c_m = \frac{A_2^2 E t}{A_1 r^3 l} \text{ dynes/cm.}$$

where A_1 is the diaphrgam area, A_2 is the piston area, E is Young's modulus for the cylinder material, t the wall thickness of the cylinder, r is the mean radius of the cylinder, and l is the length of the cylinder; this expression suggests that the basic design is versatile, in that it permits the selection of design parameters to obtain desired properties. Smaller transducer elements have desirable characteristics in the higher frequency ranges.

The efficiency of my transducer at low frequencies is greater than that of previous transducers because the diaphragm may be made to give better impedance-matching to the desired medium, e. g. water, especially when baffled by mounting flush in a steel wall, as at 26 in Fig. 5, thus eliminating end effects which would otherwise neutralize the effectiveness of portions of previous types at low frequencies. The improved efficiency of my transducer is evident as long as dimensions (e. g. cylinder length and diaphragm diameter) are of the order of less than a wave length. It will be appreciated that my improved transducer construction has advantages over crystal transducers, in that there will be less expense in construction and in that my transducers may be relatively insensitive to temperature and to thermal damage.

While I have described my invention in detail for the preferred forms shown, it will be understood that modifications may be made within the scope of the invention as defined in the appended claims.

I claim:

1. In a transducer of the character indicated, a hollow generally cylindrical member to be filled with a material having substantially the sound-transmitting characteristics of the sound-transmitting medium in which said transducer is to be immersed, diaphragm means susbtantially closing one end of said cylinder, counterweight means effectively closing the other end of said cylinder, the natural resonance characterizing the coupling between said diaphragm means and said counterweight means and the natural radial-flex resonance of said cylindrical member being at different frequencies, and means electrically responsive to transient generally radial stressing of said cylinder, whereby upon a sound-generated displacement of said diaphragm the walls of said cylinder may be subjected to generally radial stress with substantially uniform response between said frequencies, so that there may be broad-band electrical output from said electrically responsive means.

2. In a transducer of the character indicated, a relatively thin walled radially strictive generally hollow cylindrical member, relatively high-mass longitudinally freely suspended counterweight means effectively closing off one end of said cylinder, a relatively non-compressible fluid-pressure transmitting medium within said cylinder and in intimate pressure-transmitting relation with said counterweight means and said cylinder, the natural resonance determined by the compliance of said medium and the mass of said counterweight means and the natural radial-flex resonance of said cylindrical member being at different frequencies, and means electrically responsive to general radial strictive excitation of said cylinder.

3. In a transducer of the character indicated, a hollow cylindrical member, counterweight means substantially closing off the interior of said cylinder at a location removed from one end of said cylinder, diaphragm means substantially closing off the interior of said cylinder at a second axial location removed from said first-mentioned location, and means electrically responsive to a generally radially directed stressing of said cylinder, whereby when immersed in a relatively incompressible fluid medium said transducer may have a broad-band response.

4. A transducer according to claim 2, in which said cylindrical member is of a magnetostrictive material.

5. A transducer according to claim 2, in which said electric means includes a toroidal winding, with said cylindrical member as the core.

6. A device according to claim 2, in which said electrically responsive means includes a circumferential wrapping of strain-responsive resistance material about said cylindrical member.

7. A transducer according to claim 3, in which said cylindrical member is of electrostrictive material.

8. A transducer according to claim 7, in which said electrically-responsive means includes an electrode on the inner wall of said cylindrical member and an electrode on the outer wall of said cylindrical member.

9. A transducer according to claim 1, in which said cylindrical member is of magnetostrictive material, and in which said electrically responsive means includes a toroidal winding about said member as a core.

10. In a transducer of the character indicated, a hollow open-ended generally cylindrical member, a counterweight member of relatively high mass and stiffness effectively closing one end of said cylinder and mechanically isolated therefrom, effectively fluid means having relatively good sound-transmitting characteristics within said cylindrical member and in intimate pressure-transmitting relation with said counterweight member and with the inner wall of said cylindrical member, the resonant frequency characterizing longitudinal coupling between said counterweight member and said fluid means being substantially different from the natural radial-resonance frequency of said cylindrical member, means electrically responsive to radial strictive displacement of said cylindrical member, and sound-attenuating means surrounding said cylindrical member.

11. A transducer according to claim 10, in which sound-attenuating means is applied in back of said counterweight member, whereby except for the end opposite said counterweight member said transducer may be effectively enveloped by sound-attenuating means so that the difference in compliance between mediums on opposite sides of said counterweight member and of said cylindrical member may enhance the broad-band response of said transducer.

12. A transducer according to claim 2, in which said cylindrical member is of generally cylindrically laminated magnetostrictive material.

13. A transducer according to claim 12, in which said laminations are concentric cylinders.

14. A transducer according to claim 12, in which said laminations comprise a helical winding of sheet material to effectively form a plurality of cylindrical laminations.

15. In a transducer of the character indicated, a relatively thin-walled generally cylindrical hollow member, electric means responsive to radially stressed deflections of said member, a diaphragm longitudinally freely suspended and effectively closing one end of said member and mechanically isolated therefrom, and a longitudinally freely suspended counterweight member mechanically isolated from the other end of said cylinder and effectively closing said other end, said diaphragm member and said counterweight member being mechanically interconnected.

16. In a transducer of the character indicated, a relatively thin-walled hollow open-ended cylindrical member of electrostrictive material, an electrode on the outer surface of said cylindrical member, a second electrode generally radially opposed to said first electrode and on the inner surface of said cylindrical member, counterweight means substantially closing one end of said cylindrical member, and sound-transmitting effectively fluid means associated with said counterweight means and with the inner wall of said cylindrical member.

17. A transducer according to claim 2, in which said last-mentioned means includes a circumferentially extending length of a conducting material whose conductivity is sensitive to strain.

18. In a transducer of the character indicated, an open ended generally cylindrical thin-walled member, counterweight means effectively closing one end of said cylindrical member and mechanically isolated therefrom, diaphragm means effectively closing the other end of said cylindrical member and mechanically isolated therefrom, electric means responsive to radial strictive deformations of said cylindrical member, and a relatively incompressible rubber-like medium in sound-transmitting relation with said diaphragm and with said counterweight means and with the inner wall of said cylindrical member, the natural longitudinal and radial resonance frequencies of said parts in conjunction with said medium being substantially different, whereby broad-band response may be achieved.

19. In a transducer of the character indicated, two mechanical oscillators of substantially different resonant frequencies, elastic coupling means between said oscillators, whereby each oscillator may exhibit both resonant frequencies, and electrical means responsive to oscillations of one of said oscillators, said one oscillator comprising an elongated cylindrical member filled with and in intimate relation with sound-transmitting material, and the other of said oscillators comprising a counterweight longitudinally freely suspended at one end of said cylindrical member and in intimate relation with said sound-transmitting material.

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