April 6, 1965 C. E. GREEN 3,177,382
MOSAIC CONSTRUCTION FOR ELECTROACOUSTICAL
CYLINDRICAL TRANSDUCERS
Filed Jan. 25, 1961 2 Sheets-Sheet 1

Fig. 1

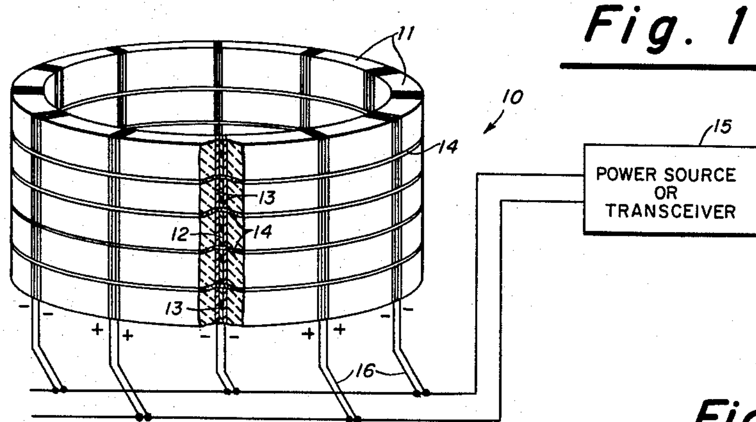


Fig. 1b

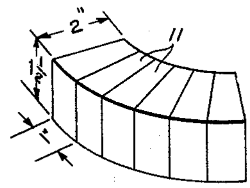


Fig. 1a

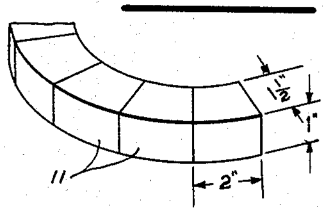


Fig. 1c

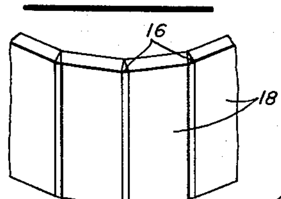


Fig. 1d

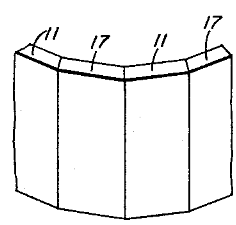
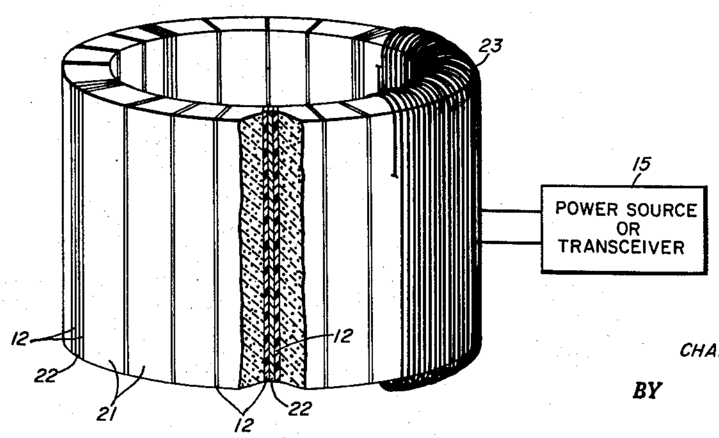


Fig. 2



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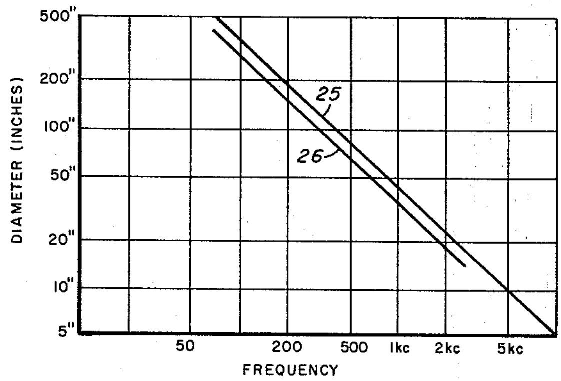


Fig. 3

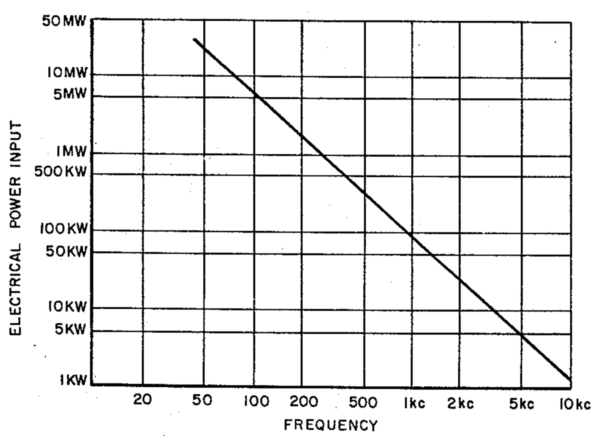


Fig. 4

Fig. 5a

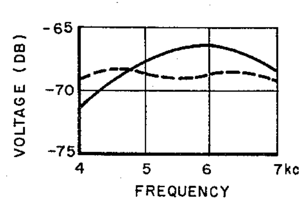
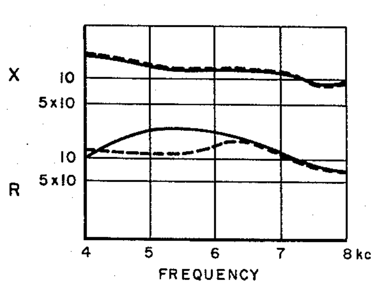


Fig. 5b



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3,177,382
MOSAIC CONSTRUCTION FOR ELECTROACOUSTICAL CYLINDRICAL TRANSDUCERS
Charles E. Green, 3427 Florida St., San Diego 4, Calif.
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5 Claims. (Cl. 310—8.7)
(Granted under Title 35, U.S. Code (1952), sec. 266)

The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

This invention relates to transducers and to methods of making the same, and more particularly, relates to transducers and to a method of making said transducers of magnetostrictive and piezoelectric materials.

These piezoelectric and magnetostrictive materials deform physically in response to electrical potential applied thereto and vice versa, and they have the great advantage over natural piezoelectric crystals in that they are not so limited as to shape or size, are very rugged, and are relatively efficient converters of energy from electrical to mechanical form and vice versa.

The development of electroacoustic projectors capable of operation into the lower frequencies has been facilitated by the entrance of the ferroelectric ceramics and magnetostrictive ferrites in the role of piezoelectric elements for sonar transducers along with the development of large active pieces of the piezoelectric and magnetostrictive materials. One method of achieving low frequency operation is to utilize the radial mode of resonance of a cylinder, i.e., constructing the transducer in the form of a cylinder. Prior heretofore, cylinders were constructed from a single piece of a ceramic such as barium titanate, however, there is a limit to the size of the cylinder that may be made from a single piece in that as a cylinder becomes larger it becomes economically unfeasible to utilize a single cylinder. In addition, it is difficult to achieve a solid cylinder of such a size as would be needed for low frequency application. For example, it has been found that a practical upper limit to a transducer composed of a single cylinder is approximately 13 inches in diameter by 10 inches long. Such a cylinder would have a resonant frequency in water of approximately 3 kilocycles. However, in the range below 3 kilocycles, say from 3 kc. down to and below 100 cycles it takes a much larger cylinder to perform properly in the medium, i.e., at a resonant frequency of 500 cycles it would require a cylinder, properly loaded, of approximately 80 inches in diameter and 53 inches long, which would be completely impossible to fabricate from a single part.

Therefore, an object of the invention is to provide an efficient low frequency transducer.

Another object of the invention is to provide a transducer capable of extremely low frequency operation which is substantially more economical to manufacture.

Another object of the invention is to provide a transducer capable of extremely low frequency operation having large power capabilities.

Another object of the invention is to provide a transducer capable of supplying large signal strength into a given medium.

Another object of the invention is to provide a cylindrical transducer capable of withstanding extremely high pressures.

Another object of the invention is to provide a method of manufacturing a transducer capable of extremely low frequency operation.

Another object of the invention is to provide a method of manufacturing a ceramic transducer capable of extremely low frequency operation.

Another object of the present invention is to provide a method of manufacturing a low frequency transducer comprising a piezoelectric material.

Another object of the invention is to provide a method of manufacturing a low frequency transducer comprising a magnetostrictive material.

Other objects and advantages of the invention will become apparent after reading the following detailed description.

The objects and purposes of the present invention are attained through the utilization of a mosaic construction for electroacoustic transducers suitable for extremely low frequency high power application.

The invention will be described in detail in connection with the following figures wherein like numerals indicate like parts.

FIG. 1 is an elevational view partly in section of an assembled piezoelectric transducer.

FIG. 1(*a*) is a detailed showing of one method of orienting individual segments comprising a ring of the transducer.

FIG. 1(*b*) is a detailed showing of another method of orienting the individual segments comprising a ring of the transducer.

FIG. 1(*c*) is a descriptive view of a further modification of the construction.

FIG. 1(*d*) is a descriptive view of a modification wherein metal segments are interposed between ceramic bars.

FIG. 2 is a descriptive view of a magnetostrictive transducer.

FIG. 3 is a plot of cylinder diameter vs. resonance in water.

FIG. 4 is a plot of power required to cavitate a cylinder vs. frequency near the surface in water.

FIGS. 5(*a*) and 5(*b*) are plots of frequency vs. free field voltage response (db) and R and X respectively obtained in the calibration of an 8 inch diameter cylinder.

The present invention is directed not to any particular compositions of material, but to a method of utilizing materials to obtain extremely efficient low frequency transducers. Various compositions have been developed, and are being developed, but for the purpose of the invention it is merely necessary that the material used be electromechanically responsive and be capable of being formed into the desired shapes. Such shaping may be done by molding or extruding the material in plastic form prior to firing or by cutting or machining after firing.

The materials utilized in the present invention comprise the ceramics consisting of the piezoelectric materials such as, for example barium titanate, and the magnetostrictive materials such as, for example, the ferrites and are presently known.

Various piezoelectric or ferroelectric materials may be used, among which is barium titanate, but the present invention is in no sense limited to the particular compositions in that barium titanate is merely set forth for the purposes of illustrating the invention. The ferrites are relatively new materials and as yet have not found widespread application in the field of underwater transducers however, the only requirement is that the ferrite used in the mosaic construction be one which has magnetostrictive properties, for example, nickel-iron-oxide; zinc-nickel-iron-oxide; aluminum-nickel-iron-oxide; or nickel-copper-manganese-cobalt-aluminum-iron-oxide. As with the ceramics, the ferrites enumerated are only illustrative and are not limiting in the sense that the present invention is not directed to compositions but rather the way in which the compositions are utilized.

The transducers herein disclosed are particularly adapted for the transmission or reception of sonic vibrations in water for use in depth sounding, underwater ranging, etc. but since they are not limited to any particular frequency range the vibrations will be referred to, for convenience, as sound, which term as used herein includes both the sonic and supersonic range frequencies.

The invention will be first described with reference to the use of piezoelectric materials in the construction of the transducers, of which barium titanate is a well known example. The entrance of barium titanate in the role of piezoelectric elements for sonar transducers along with the development of large active pieces of the ceramic has assisted in the development of electroacoustic projectors capable of operation into the lower frequencies. A normal approach to the problem of radiating sound into a given medium such as water is the employment of the radial mode of resonance of a cylinder. At first, cylinders were constructed from a single piece of barium titanate, and cylinders up to 13 inches in diameter by 10 inches long have been built. However, the resonant frequency of such a cylinder in water is about 3 kilocycles and when lower frequencies are desired it is necessary to construct larger and larger cylinders. However, there is a limit or a limitation on the size of cylinder that can be developed due to the fact that a single ceramic element is being utilized. This arises from the fact that as larger and larger individual ceramic elements are utilized such single pieces cannot be manufactured due to the inclusion of defects in the manufacture and due to the extremely high cost of manufacturing such large single parts. In addition, as the cylinders become larger and larger the relative wall thickness and height of the completed cylinders becomes so small that the entire piece is fragile, even assuming that those defects which appear in the manfacture or the formation of the piece do not render the transducer inoperative.

With a requirement for lower and lower frequencies and extremely deep submergence a new approach is taken to the problem as exemplified in FIG. 1. In FIG. 1 there is shown a transducer **10** composed of piezoelectric material, for example, barium titanate in the instant case, made up of a plurality of individual segments which are joined together to form a cylinder. A plurality of individual wedge-shaped segments **11** are formed by molding or extruding the barium titanate or by cutting or machining after molding and then forming the segments into rings which comprise the finished transducer. For example, to construct a cylinder 30 inches in diameter by 10 inches high, rings would be built up wherein individual segments comprising the rings are wedge-shaped and have the dimensions of 1 inch high by 2 inches wide on a taper 1½ inches deep. Upon formation of the individual bars, the tapered width is foiled as at **13** and polarized. It is to be realized that any opposite pair of sides may be foiled and suitably polarized, however, it has been found that foiling the tapered width gives the highest efficiency in the finished cylinder due to the fact that the radial mode of resonance of the cylinder is utilized in projecting the signal into the medium. In order to fabricate the individual rings a cement must be used which is very rigid and approximates the characteristics of the individual bars. In the example chosen an epoxy resin such as Epon Adhesive VI manufactured by the Shell Chemical Corporation was used. Epon Adhesive VI is an adhesive particularly suited for metal bonding as between the silver foil surfaces of the bars, curing at moderate temperatures and requiring only contact pressure. It has a two-component system consisting of a thick, dark gray paste, and a curing agent which is a clear, colorless liquid. The final adhesive used actually comprises approximately 100 parts of the resonant portion of Epon Adhesive VI mixed with 6 parts of curing agent A. After the completed cylinder is formed a curing is necessary to set the adhesives, and in order to cure Epon Adhesive VI a temperature of 165° F. is necessary and at 165° F. the cure cycle would be approximately two hours. As temperature is raised the cure cycle is reduced in time. Properties of the adhesive

are set forth in Shell Chemical Corporation Technical Bulletin SC:51–20, published June 1951.

In order to join together the individual rings an adhesive **14** is used which must be compliant and rubbery and of good adhesive and electrical properties. The adhesive used between the rings must be compliant and rubbery due to the fact that the individual rings, when vibrating, may not have the same characteristic movement, therefore, there must be a compliance between individual rings to allow for differences in such movement between rings. In neither case may the material used as the adhesive between segments or between rings be acoustically lossy. In the 30 inch diameter cylinder a non-lossy compliant adhesive such as Acme Mixture #2001 made by the Acme Wire Company, of New Haven, Conn. was used. The specifications of the Acme compound are contained in Bulletin No. 585, distributed by the Acme Wire Company. The components used in the adhesive mixture #2001 between rings are: XK–262 Base, AL–15 Activator, AL–76 Filler, AL–77 Hardener. Other mixtures disclosed in the Acme bulletin may be used if desired. The Acme compounds are organic; thermosetting materials, either polyester modified epoxies or epoxy modified polyesters, containing no styrene monomer. They are noncorrosive and proximity to, or contact with rubber, copper, or other materials will not inhibit their cure. Curing can be accomplished by application of heat, or at room temperature, depending on mixing, pre-drying, treatment, etc., reference is made to Acme Bulletin #585.

Upon completion of the transducer and when the transducer is being operated a transceiver or power source **15** is coupled to the foils **13** through conductors **16**. In the example shown all bars are wired in parallel. As can be seen, versatility in the choice of electrical impedance is enhanced when cylinders are assembled especially with regard to the piezoelectric cylinders which follows from the fact that the elements or bars comprising the cylinder can be connected in parallel, series, or series-parallel combinations.

In utilizing the method of forming a transducer as illustrated in the present invention the bars used to form the rings can be oriented in any one of three dimensions to form the wall thickness; likewise, the length of the cylinder is not limited to the longest dimension of the bar. FIGS. 1(*a*) and 1(*b*) show two different embodiments utilizing a different orientation of the bars. Assume that the bars **11** shown in FIGS. 1(*a*) and 1(*b*) have the dimensions of 1 inch by 2 inch on a taper by 1½ inches deep. In FIG. 1(*a*) the bars are shown oriented in such a manner that the 1 inch dimension is the height dimension and the 2 inch dimension is in the tangential direction and the thickness of the cylinder is 1½ inches. Should a thicker wall ring be desired the embodiment of FIG. 1(*b*) may be used wherein the 2 inch dimension becomes the wall thickness of the ring and the 1 inch dimension is in the tangential direction. The vertical dimension of the ring would be 1½ inches. By this method the maximum wall thickness of the cylinder is limited only to the longest bar as shown in FIGS. 1(*a*) and 1(*b*). FIG. 1(*a*) might be called a thin ring construction, while FIG. 1(*b*) would correspond to a thick ring construction.

FIG. 1(*c*) shows an alternate construction of the transducers wherein rectangular segments **18** are used and wedge-shaped metallic segments **16** are inserted between segments to fill the wedge-shaped spaces between segments arising from the use of rectangular segments in the construction of a substantially circular element. The segments may be made of any desired metal and in the instant invention iron was used. This construction may be used either with the piezoelectric materials or the magnetostrictive materials.

FIG. 1(*d*) illustrates a mode of construction wherein various of the ceramic segments **11** have metal segments **7** substituted therefor. By utilizing this mode of construction the resonant frequency of a particular size of transducer cylinder may be either raised or lowered. If it is desired to lower the frequency a dense material such as lead is substituted for the ceramic segments removed. If, on the other hand it is desired to raise the resonant frequency of the cylinder a less dense material such as aluminum is substituted for the ceramic segments. Whether the resonant frequency is raised or lowered depends upon the velocity of sound in the material and the density of the material used as the substitute for the ceramic segments.

In the construction of the electroacoustic cylinders there is a practical upper and lower limit to the ratio of wall thickness to diameter. In general, a 1 inch wall to a $1/16$ inch diameter, i.e., 1 to 16 ratio is a heavy wall construction and a 1 to 45 ratio a thin wall construction. A 1 to 20 ratio gives a good workable transducer with an optimum mechanical Q of about 2.

At the present time commercially available bars will permit wall thicknesses up to 12 inches from a 12 by 4 by 2 bar. Utilizing these bars in a 1 to 20 ratio, i.e., wall to diameter, provides a cylinder some 20 feet in diameter. Such a cylinder composed of 1 row of these bars would be impractical; hence, these thin rings are stacked and bonded to construct a height compatible with the diameter. A satisfactory ratio is to make the height $1/2$ to $2/3$ the diameter of the finished cylinder.

In the fabrication of the electroacoustic cylinder the individual segments or bars are extruded or otherwise formed into the desired shape. The silver foil is applied thereto and the bars are then polarized or after the cylinder is completely formed are then polarized. After the silver foil is applied to the opposite surfaces of the bars the rigid adhesive is applied to the foiled surfaces of adjacent bars and the individual bars are formed into rings. In that a cylinder comprising one ring would be impractical under most circumstances the individual rings are then formed into a complete cylinder by applying the compliant rubbery adhesive to adjacent top and bottom surfaces of adjacent rings. The final step in the manufacture is the application of sufficient heat to set the resin glues, yet one should be careful not to apply so much heat in the curing process that the ceramics are depolarized, this assumes that the ceramics have been polarized previous to the curing step. However, as stated before, the polarization may occur after the cylinder is completely manufactured. After the cylinder is formed and the curing step has been accomplished leads **16** may be attached to the foils **13** and a source of power or transceiver **15** attached to the leads.

For extremely large cylinders, it is recommended that the construction be made directly on the transducer case by assembling a ring with a brittle adhesive, then tightening up the ring with a metal band over the outside of the ring, applying a rubbery adhesive on the top surface of the ring, laying on a second row of bars with a brittle adhesive between the individual bars, and clamping this later formed ring with another band, and continuing on with this series of steps until the complete assembly is accomplished.

The metal cylinder referred to forms part of the casement to prevent electrical shorting in the water and comprises a metal cylinder that fits inside the ceramic and which in turn attaches to metal rings to form an air cavity against the inner wall of the ceramic. In that the complete assembly does not form part of the present invention and in that the use of the metal cylinders is old the details of such are not shown.

To complete the assembly or to make the assembly suitable for use in a water medium a rubber sleeve is fitted over the outside of the ceramic and seals against the metal and rings. The ceramic cylinder is then coupled to the water through the rubber sleeve.

FIG. 2 illustrates another embodiment of the invention wherein electromagnetostrictive material such as the ferrites is used in the manufacture of the large electroacoustic transducers. In this embodiment the individual bars are shown as being in the form of a barrel stave, however, should the cylinder become of such a size that it is difficult to form individual bars from the ferrite material it is possible to use the same type of construction as described with respect to FIG. 1, i.e., the formation of smaller bars. In FIG. 2 there is shown a series of individual bars **21** cemented together with a rigid adhesive such as Epon Adhesive VI. In order to provide a polarization for the cylinder the groups of individual bars **21** are separated by a series of permanent magnets **22** which provide a magnetic polarization analogous to the electrical polarization of the barium titanate. Should it be desired to use a plurality of smaller bars composed of ferrite instead of the barrel staves it will be necessary to form the rings and to use a compliant rubbery adhesive between the rings at set forth in connection with the embodiment of FIG. 1, i.e., the resin such as Acme Mixture #2001. In order to drive the electroacoustic cylinder comprised of the ferrite bars the completed cylinder is wrapped with a copper ribbon **23** in the manner of a toroid and a power source or transceiver **24** connected thereto.

As stated previously one of the objects of the invention is to provide a cylinder which is adapted for extremely low frequency use. FIG. 3 shows the diameter of a cylinder vs. resonant frequency in the fundamental radial resonance mode, which is based on information derived from transducers that have been constructed. On the chart are shown two lines, a top line **25** corresponding to proper loading and a bottom line **26** corresponding to a condition of poor loading. Line **25** corresponds to a cylinder wherein the length is greater than one-half the diameter thereby producing a condition corresponding to a well loaded cylinder or stack of cylinders. Lower line **26** corresponds to a cylinder wherein the length is less than one-third the diameter and corresponds to a poorly loaded cylinder. From the chart it is evident that as the lower frequencies are utilized the diameter of the cylinder becomes phenomenally large and without the mosaic construction it would be impossible to construct a cylinder which could be utilized or which would produce the desired low frequencies.

FIG. 4 is a plot of the power required to cavitate a cylinder in a water medium vs. frequency. When one talks of utilizing larger cylinders one not only implies low frequencies but extremely large power capabilities. Power densities of 20 watts per square inch on the surface of the cylinders have been achieved many times and if one used this as a criteria along with 70–80% electroacoustical efficiency then FIG. 4 shows the power input required for cylinders wherein the length is $2/3$ the diameter of the cylinder. As can be seen from an examination of the plot it is apparent that the cylinders constructed by utilizing the method of the instant invention are capable of supply extremely large signal strengths into a water medium. For example, a 150 inch cylinder 100 inches high will resonate at approximately 300 c.p.s. and can accept the power from a one megawatt driver.

Under present day operating conditions it becomes necessary to provide electroacoustic transducers which have depth capabilities and introduces a factor of providing cylinders without pressure compensation. Smaller barium titanate cylinders have been operated to pressures of 40,000 p.s.i. successfully so that by utilizing the 1 to 20 ratio wall to diameter one could operate to approximately 8000 feet in the water without pressure compensation and by beefing up the wall to a 1 to 16 ratio, depths of 10,000 feet are obtainable.

However, an alternative method of operating these cylinders is possible, at extremely deep depths. This is accomplished by assembling the cylinders so that there is no compliant or air chamber on the inner wall for pressure release. In other words they are free flooding and can go to phenomenal pressures. The entire unit or the inner wall of the cylinder is merely insulated from the water with a protective coating and the entire unit allowed to flood, thereby providing no pressure differential between the inner and outer walls of the cylinder. When utilizing such a technique the response at resonance drops approximately 2½ db but the resistive component of the impedance has dropped correspondingly, thereby providing a net result of no effective loss. The electrical Q rises and the mechanical Q drops as would be anticipated from a stable coupling coefficient. This is shown in FIGS. 5(*a*) and 5(*b*) wherein the solid lines depict air backed and the dotted lines the free flooding cylinders.

By utilizing the ceramics comprising the ferrites which correspond to the electromagnetostrictive materials and the barium titanate which corresponds to the piezoelectric material cylinders having capacitive reactance or inductive reactance may be assembled. This is due to the fact that the titanates are a capacity reactance device of not too low an impedance by some standards whereas the ferrites provide an inductive device of a low impedance.

It should be understood, of course, that the foregoing disclosure relates only to preferred embodiments of the invention and that it is intended to cover all changes and modifications of the examples of the invention herein chosen for the purposes of the disclosure, which do not constitute departures from the spirit and scope of the invention.

What is claimed is:

1. A transducer comprising; a plurality of layers of closed loops, each loop being formed of a plurality of electromechanically-responsive means, conducting means joined to opposite faces of said electromechanically-responsive means; rigid adhesive means between said conducting means and joining said electromechanically-responsive means together in a tangential direction to form said closed loops; and compliant non-dissipative adhesive means joining said loops together in an axial direction to form an axially extending cylinder.

2. The transducer of claim 1 wherein said electromechanically-responsive means is a piezoelectric material.

3. An electroacoustic radiator comprising; a plurality of longitudinally extending electromechanically-responsive means having a first density; a plurality of longitudinally extending means having a second density interspersed between various of said electromechanically-responsive means so constructed and arranged that said electromechanically-responsive means and said second means form a closed loop, and adhesive means rigidly joining together said responsive means and said second means so that said closed loop is self supporting.

4. An electroacoustic radiator comprising; a plurality of electromechanically-responsive magnetostrictive means having a first density; a plurality of longitudinally extending means having a second density interspersed between various of said electromechanically-responsive magnetostrictive means so constructed and arranged that said electromechanically-responsive magnetostrictive means and said second means form substantially a cylinder, and adhesive means rigidly joining together said responsive means and said second means.

5. A transducer of the character described comprising;
- a plurality of electro-mechanically responsive polarized piezoelectric means abutting together in a longitudinal direction;
- conducting means bonded to the faces of the polarized piezoelectric means which are in abutting relationship;
- adhesive means rigidly bonding together said piezoelectric means so as to form a self-supporting closed loop in the absence of any exterior clamping and supporting means;
- said adhesive means having vibrational properties approximating the vibrational properties of the piezoelectric means so that when said transducer is energized the transducer vibrates as an integral unit;
- means for applying signal voltage to said transducer so as to induce radial vibration of said transducer.

References Cited by the Examiner

UNITED STATES PATENTS

2,490,273	12/49	Kean	310—26
2,791,990	5/57	Grieb	310—8.2
2,795,709	6/57	Camp	310—9.6
2,834,943	5/58	Grisdale et al.	310—26
2,838,696	6/58	Thurston	310—9.5
2,861,247	11/58	McSkimin	310—8.3
2,961,635	11/60	Trott	310—8.7
3,007,063	10/61	Harris	310—26
3,043,967	7/62	Clearwaters	310—9.8

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