Nov. 27, 1962 H. B. MILLER 3,066,233

FERRITE TRANSDUCERS

Filed July 25, 1957 2 Sheets-Sheet 1

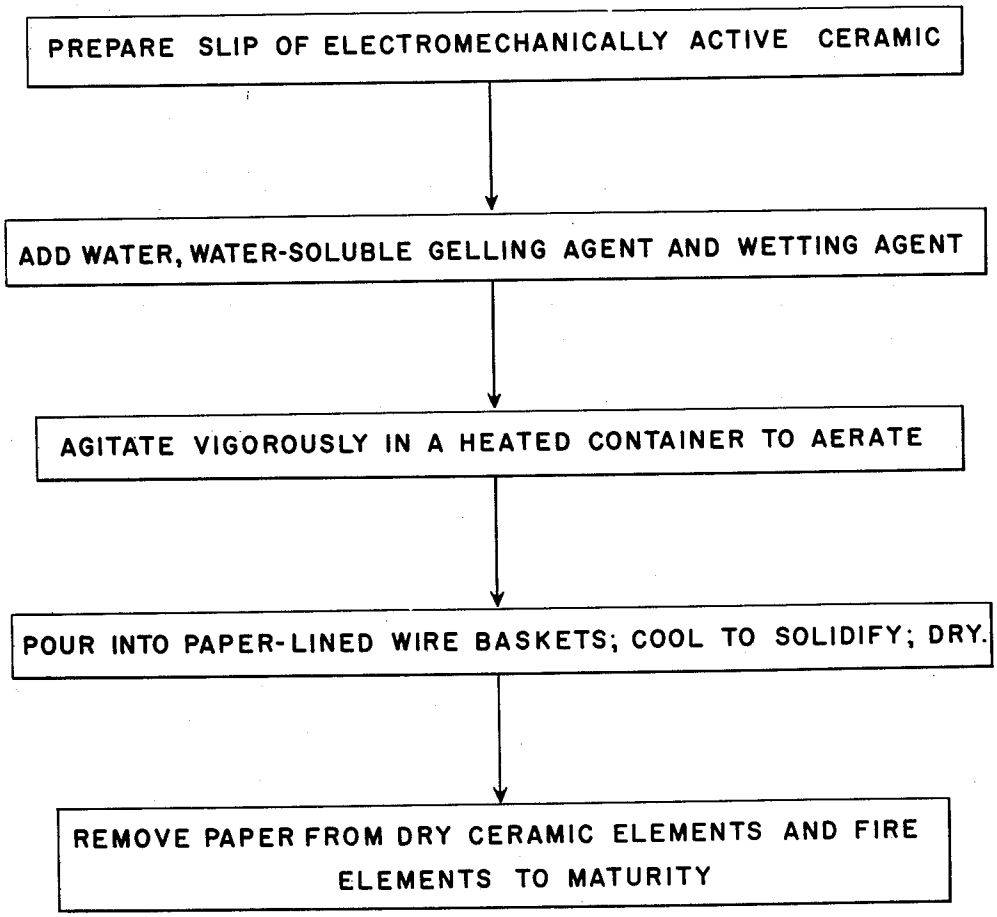


FIG. 1

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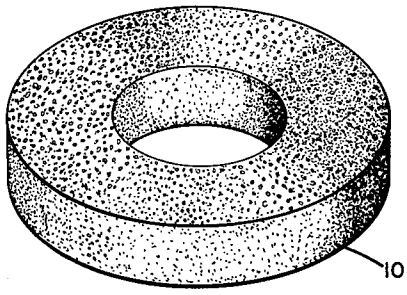


FIG. 2

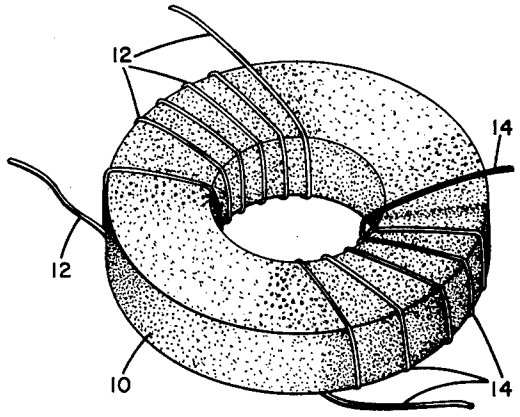


FIG. 3

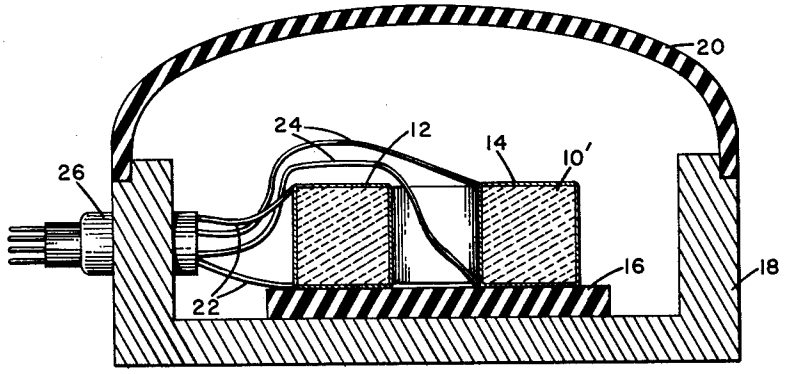


FIG. 4

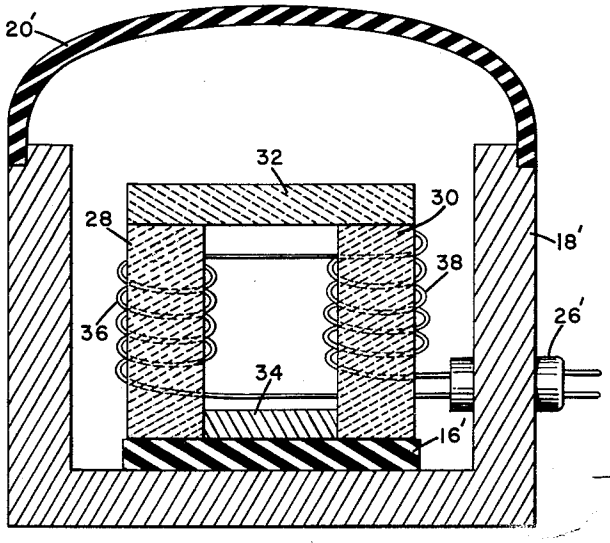


FIG. 5

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FERRITE TRANSDUCERS

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6 Claims. (Cl. 310—26)

This invention relates to magnetostrictive transducers and transducer elements and ferromagnetic transducer materials.

A particularly important aspect of the present invention is in connection with underwater electroacoustic transducers, in which electrical energy applied to the transducer causes it to radiate acoustic energy into the water, or an acoustic signal transmitted through the water actuates the transducer to produce an electrical response.

It is well known that a prime requisite of underwater electroacoustic transducers for good transfer of power or high "conversion efficiency," is a good impedance match of the transducer with water. This applies also to ultrasonic transducers, such as are used for cleaning, sonic irradiation, etc., which operate in fluid transmission media other than water.

The impedance matching of transducers to transmission media has long been a serious problem in the art. Many of the electromechanical transducing materials and elements heretofore available have a fixed density and fixed mechanical compliance—and, therefore, a fixed acoustic characteristic impedance. This acoustic characteristic impedance usually is much higher than that of the water or other transmission fluid involved. This is particularly true of the piezomagnetic metal and ceramic materials as well as the ferroelectric ceramics. For example, the normal specific acoustic impedances of ferroelectric lead zirconate titanate and barium titanate ceramics are in the range from about 20 to 30×10^6 (kg./m.^{3}) (m./sec.) or rayls as compared to 1.5×10^6 rayls for water. The unit of specific acoustic impedance used here is the mks. rayl. Nickel has an acoustic impedance of about 42.3×10^6 rayls and ceramic nickel ferrite about 27×10^6 rayls. Some monocrystalline transducer materials, e.g., ammonium dihydrogen phosphate ($NH_4H_2PO_4$) have relatively low acoustic impedance and are therefore a comparatively good match to water but transducer elements of these materials suffer from other disadvantages: they are limited in size and, therefore, are not suitable for low frequency resonant operation unless mass-loading is resorted to; they are relatively more expensive to produce than ceramic elements and are not susceptible of being formed and shaped by ceramic techniques; and, for generating highly directional signals, large heavy arrays of monocrystalline elements must be used because of their individual size limitations.

Due to the inherent shortcomings of monocrystalline transducer materials and elements, the trend in recent years has been toward polycrystalline materials such as the ferroelectric and ferromagnetic ceramics. Heretofore, the problem of impedance matching thus encountered has been attacked by resort to various impedance transformation means such as horns, plates, etc. Such impedance matching expedients, however, are undesirable in that they add weight, bulk, complexity and cost to the transducer.

These difficulties and problems are overcome by the present invention which contemplates an electromechanical transducer comprising a cellulated body of ferromagnetic ceramic material. Due to the fact that the ceramic material is cellulated, its density is less and its compliance greater than conventional material; thus it has a lower

characteristic impedance which is a much better match to water and most other common transmission media.

It is a general object of the invention to provide piezoelectric or magnetostrictive transducers, transducer elements and ferromagnetic ceramic materials which overcome at least one of the problems of the prior art.

It is another general object of the invention to provide a novel ferromagnetic ceramic element of low density which is capable of a substantial magnetostrictive response.

Still another object of the invention is the provision of a novel transducer element capable of satisfying the practical requirements for underwater transducer operation.

A further object of the invention is the provision of novel magnetostrictive transducer elements of cellulated ceramic material which, because of their porous structure, have a reduced mechanical characteristic impedance, thereby making them capable of an effective electromechanical response over a wider frequency bandwidth.

A further object of the present invention is to provide more readily machinable dielectric ceramic material adapted for use in magnetostrictive transducers.

A still further object of the present invention is to provide a novel transducer element of ceramic material which has reduced elastic cross-coupling between the parallel and lateral modes and, therefore, has improved piezomagnetic activity in its parallel mode, as compared with prior art elements of this general type.

Further objects and advantages of the invention as well as the specific details of construction and mode of operation of the transducer element and the preferred manner of making it will be apparent from the following description taken in conjunction with the subjoined claims and annexed drawings, in which,

FIGURE 1 is a flow diagram of the preferred process of making cellular ceramic transducer materials and elements in accordance with the present invention;

FIGURE 2 is a perspective view of a magnetostrictive cellular ceramic element according to the present invention;

FIGURE 3 is a perspective view of a cellular ceramic element as shown in FIGURE 2, with polarizing and signal windings schematically indicated; and

FIGURES 4 and 5 are longitudinal sections through electroacoustic transducers for underwater operation which incorporate ceramic magnetostrictive elements according to the present invention.

The flow diagram in FIGURE 1 illustrates broadly the steps involved in making magnetostrictive elements and material in accordance with the invention. Thus a slip is prepared of raw materials or precursors of a magnetostrictive ceramic material such as nickel ferrite ($NiFe_2O_4$). To this slip is added water, a gelling agent and a wetting agent. The slip is beaten wtih a food mixer in a heated container to aerate it and then poured into paper-lined molds to cool, solidify and dry. The dry elements are removed from the molds and fired to ceramic maturity.

Before proceeding with an example of the method, it is pointed out that the method employed and further examples of its application to various electromechanically responsive materials are disclosed in detail and claimed in U.S. Letters Patent No. 2,892,107 issued to C. K. Gravley and A. L. W. Williams and assigned to the same assignee as the present invention.

One class of ferromagnetic materials suitable for practicing the present invention are the polycrystalline ceramic ferrites. As is well known, the ferrites have the type formula MFe_2O_4 (or $MO\cdot Fe_2O_3$) where M is a divalent metal, e.g. nickel, cobalt, zinc. The stoichiometric

mol ratio of the metal oxide to the iron oxide is 1:1. In "mixed" ferrites the metal oxide component (MO) is a mixture of two or more divalent metal oxides as, for example, in nickel cobalt ferrite.

For the sake of example, the present invention will be described using nickel ferrite ($NiFe_2O_4$) as a typical ferromagnetic material.

The nickel ferrite is prepared in powder form in any suitable manner and a ceramic slip made of the powder. One suitable slip was made by dispersing dry ferrite powder with about 1% Marasperse (a dispersing agent which is a sodium salt of ligno-sulfonic acid) and 30% water, all percentages being on a weight basis. The mixture was rendered alkaline by the addition of ammonium hydroxide (NH_4OH) solution and wet milled for several hours. Thereafter, a 10% solution of P.V.A. 71–24 (a commercially available polyvinyl alcohol, used as a binder), Congo red (gelling agent) and Igapal (a commercially available wetting agent) were added to the mixture. In this particular example, 30 cc. of the P.V.A. 71–24, 0.3 gram of Congo red and 0.3 cc. of Igapal were used in a batch consisting of about 300 grams of ferrite in 110 ml. of water. Other water-soluble binders, such as gelatin, can be used with or in lieu of the P.V.A.; other water-soluble gelling agents (e.g., ammonium pentaborate) can be used with or in lieu of the Congo red. Similarly, the Marasperse and/or Igapal can be replaced wholly or partly by other suitable dispersing and wetting agents, respectively.

This mixture is a relatively thick gel at this point and is put in a container and heated to a temperature of about 55° C. After heating it converts to a somewhat viscous liquid. The heated liquid mixture then is vigorously agitated to entrain bubbles of air or other ambient gaseous medium. The aeration may be accomplished conveniently by whipping the mixture with a conventional motor-driven food mixer, such as a "Sunbeam Mixmaster." Sufficient aeration usually requires whipping for eight minutes or more. Use of this method of agitation gives satisfactory results with the entrained gas bubbles dispersed more or less uniformly throughout the mixture. It is pointed out that, in most cases, the whipping would be carried out in an ordinary atmosphere; however, this could be done in an enclosure filled with some other gas and it is to be understood that the terms "aerated," "air bubbles," and the like are used loosely throughout this description and the appended claims and are intended to encompass gases other than air.

The density of the finished ceramic ferrite elements produced by the process is determined by the ferrite used, the amount of water in the mixture, the amount of wetting agent therein, and its temperature during the beating operation.

After being aerated in the manner just described, the foamed dispersion is poured into paper-lined, open mesh wire baskets, where it is cooled down to room temperature so that it solidifies. Then it is dried thoroughly, which may take from one to three days at room temperature and ordinary atmospheric conditions. After having been dried, the "green" ceramic elements have interstices or crevices formed by air bubbles throughout. The nickel ferrite elements had a bulk density of the order of one-fourth of the theoretical (or microscopic) density of nickel ferrite (about 5.35 grams/cc.) or the maximum density obtainable as a practical matter in compacted, fired nickel ferrite ceramic which is better than 90% of the theoretical.

The paper is removed from the dried elements and the elements fired to maturity in substantially the standard manner of the conventional dense ceramic elements. In this particular example, the elements were fired at about 1300° C. for one hour. The fired elements had a bulk density of about 1.16 whereas dry-pressed (solid) disks of the same material had a density of about 5.

The magnetostrictive transducer element produced by the foregoing process is of cellular structure throughout formed with separate macroscopic interstices or crevices filled with air (or other gaseous medium). Because of its cellulated, sponge-like construction the transducer element has a bulk density which is much lower than the density of nickel ferrite. Depending upon the amount of water added before stirring and the temperature during stirring, ceramic nickel ferrite sponge may have a density within the range from about 0.5 to 3.0, with 1.1 being a typical value. Because of the lower density of sponge ceramic materials, and because of the higher compliance of the elements due to their cellulated structure, the mechanical (acoustic) characteristic impedance of the sponge ceramic elements is much lower than for dense ceramic elements, this mechanical impedance being equal to $\sqrt{\text{density/compliance}}$. As a result, the sponge elements have a good impedance match with water, which makes them very good transducer elements for underwater operation.

The cellulated transducer elements of the present invention have been found to operate effectively over a much wider frequency band width around resonance than has been possible with transducers employing dense ceramic elements. Consequently, the transducer elements of the present invention are capable of a rapid response to signals which start and end abruptly. Thus, transducers incorporating such elements are particularly well adapted for echo-ranging using pulse techniques, and other applications where a short time constant is vital.

In addition, the cellular ceramic material of the present invention has been found to be considerably easier to machine into a transducer element of the desired configuration, such as by cutting with a hack-saw or sanding, than is the dense piezomagnetic ceramic.

It will be apparent to those skilled in the art to which this invention pertains that the present transducer element has a reduced elastic cross coupling, as a consequence of its cellular structure. For this reason, when the porous ceramic is operated in the parallel mode, radiating acoustic energy from only one electroded face, there is relatively little energy radiated from the element transverse to this direction. Accordingly, the radiated acoustic energy is highly directive and by proper design a substantially single lobe pattern may be obtained, which is particularly desirable in certain underwater applications. In the past, because of the relatively high elastic cross coupling in dense ceramic elements, it was not possible to operate such elements in the parallel mode where directivity was an important consideration, except by providing a number of elements of that type each elongated in the parallel mode direction and each having a relatively small radiating face area and arranged in mosaic arrays which were difficult and expensive to construct for operation in the desired manner. With the cellular ceramic element of the present invention, by proper design good directivity may be obtained with an electroacoustic transducer employing a single ceramic element having a relatively large radiating face area which radiates energy in the 33, or parallel mode. A further important consideration worth noting is that any ceramic element used for electromechanical transducer purposes has the optimum coupling when operated in its 33 mode; that is, for a given electrical energy input maximum conversion to mechanical energy is obtained by operating in this mode. Thus, in the present invention, a ceramic transducer element of simple and inexpensive configuration may be operated in its most effective mode (the 33 mode), without resulting in lack of directivity or substantial interference between the parallel and lateral modes.

FIGURE 2 illustrates a cellular ceramic element **10** according to the present invention produced by the method described in detail above and outlined in FIG. 1. This element is here shown as toroidal in configuration. As indicated in the drawing, the element is of cellular construction, having separated macroscopic air holes or

interstices throughout. This particular element was cut from a fired block of sponge ferrite but it will be appreciated that the aerated mixture may be cast directly into the desired shapes.

FIGURE 3 illustrates this cellular ceramic torus **10** wrapped with a biasing (or polarizing) coil **12** and a signal coil **14**. In operation, biasing coil **12** is connected to a suitable source of D.-C. potential (not shown) which polarizes the element magnetically while a signal applied to coil **14** causes the element to vibrate in the radial mode at the signal frequency. If desired, once polarized, the biasing voltage may be cut off and the element operated on the remanent polarization. Alternatively, a polarizing permanent magnet can be used in place of coil **12** as hereinafter described in another embodiment.

In FIGURE 4, there is shown an underwater transducer employing a transducer element generally similar to that shown in FIG. 3. The ceramic element **10** is similar in all respects to that of FIG. 3, except that its axial dimension is greater thus enabling it to function as a cavity resonator. Element **10** is mounted on a sponge rubber pad **16** which is full of air holes which act effectively to decouple the adjacent face of the ceramic element. The mounting pad **16** is mounted on an open ended housing base **18** across whose open end there extends a rubber cap **20**. The interior of the housing is filled with oil. The lead-in conductors **22** and **24** for the coils **12** and **14**, respectively, on the ceramic element extend into the housing through a fluid-tight seal **26**.

In the operation of the transducer for transmitting acoustic energy a D.-C. biasing voltage is connected across conductors **22** and a voltage of a predetermined frequency is applied across the signal conductors **24** causing acoustic energy to be radiated from the ceramic element. This acoustic energy is transmitted through the oil and the rubber cap **20** into the surrounding water with very little energy loss therein since both the oil and rubber have a very good impedance match with water.

Conversely, if the transducer is operated as a receiver, then acoustic energy transmitted through the water passes through the rubber cap **20** and the oil in the housing and stresses the ceramic element **10**, causing the latter to produce a voltage across the conductor **24** which is representative of the acoustic signal received.

FIGURE 5 illustrates, somewhat schematically, another magnetostrictive underwater transducer embodying the present invention. The transducer is similar to that shown in FIGURE 4, comprising an oil-filled housing **18'**, having one side closed by an acoustically transparent rubber cap **20'**. Mounted on a sponge pad **16'** is a magnetostrictive transducer element made up of a pair of spaced, parallel sponge ferrite blocks **28, 30** and a transverse member **32** cemented to and connecting the adjacent ends of the blocks so as to form three sides of a rectangle. Preferably member **32** is a sponge ceramic material also albeit the material may be electromechanically inert. Alternatively, the members **28, 30** and **32** may be cast of sponge ferrite as an integral piece. Between the ends of blocks **28, 30** remote from member **32** is a permanent magnet **34** which polarizes the ferrite blocks and completes the magnetic circuit.

Each of the ferrite blocks **28, 30** is wound with a respective signal coil **36, 38**. The signal coils are connected in series-aiding relation and are provided with suitable leads which pass through a watertight seal **26'** to the exterior of housing **18'** for connection to the signal source.

In operation the signal field developed by coils **36** and **38** causes corresponding longitudinal vibration of blocks **28** and **30** which drive transverse member **32**. Member **32** radiates acoustic energy through the coupling fluid in the housing and rubber cap **20'** with the surrounding water or other transmission medium. As already explained in conjunction with FIGURE 4, the transducer also may be operated as a receiver in which case acoustic energy transmitted through the water passes through the rubber cap **20'** and the coupling fluid in the housing and stresses blocks **28** and **30**, thus developing a voltage across coils **36, 38** which is representative of the acoustic signal received.

In the foregoing description, the material of which the transducer element is composed has been specified as being nickel ferrite. However, it is to be understood that within the purview of the present invention, there may be employed other ferromagnetic ceramic materials which, when polarized, have a substantial electromechanical response, particularly a piezomagnetic response. By the term "polarized" as used herein is meant either permanently polarized (i.e., having a remanent polarization) or else subjected to a temporary polarizing field the time it is operated so as to render it capable of an electromechanical response, particularly a piezomagnetic response. As examples of other suitable ceramic ferrites, the ceramic may consist of a cobalt ferrite or a mixture of nickel ferrite and cobalt or zinc ferrites.

A discussion of the piezomagnetic behavior of dense ferrite is given in an article by C. M. Van der Burgt entitled "Ceramic Ferrite Resonators" published in the Journal of the Acoustic Society of America, November 1956.

Insofar as the transducer element itself is concerned, without departing from the purview of this invention it may be made by processes other than that described herein, so long as it has the low density, cellular structure which renders it capable of accomplishing the purposes of this invention.

Therefore, while there have been disclosed in the foregoing description a specific presently preferred manner of practicing the process of the present invention and a specific preferred embodiment of the ceramic transducer element itself, it is to be understood that various modifications, omissions and refinements which depart from the disclosed embodiments of the process and product of the present invention may be adopted without departing from the spirit and scope of this invention.

I claim:

1. An electromechanical transducer element comprising a body of cellular structure formed with a multiplicity of macroscopic interstices throughout, each of said interstices being substantially smaller in any direction than the dimension of said body in the same direction, said body consisting essentially of ferromagnetic ceramic material capable of a substantial electromechanical response.

2. An electromechanical transducer element in the form of a fired body consisting of polycrystalline ferromagnetic ceramic capable of a substantial magnetostrictive response, the body having throughout its extent a multiplicity of macroscopic interstices each of which is substantially smaller in any direction than the dimension of the body in the same direction, the body having a substantially lower bulk density than the theoretical density of said material.

3. An electromechanical transducer element comprising a body of polarizable ferromagnetic material of macroscopically cellular structure having a multiplicity of interstices throughout, each of said interstices being substantially smaller in any direction than the dimension of the body in the same direction.

4. An electromechanical transducer element according to claim 3, wherein said material is composed primarily of a ferromagnetic ferrite.

5. An electromechanical transducer element according to claim 3, wherein said material is composed primarily of at least one ferrite selected from the group consisting of nickel ferrite, cobalt ferrite, mixed nickel-cobalt ferrites, and mixed nickel-zinc ferrites.

6. An electromechanical transducer comprising an aerated body formed with a multiplicity of macroscopic air holes throughout and consisting primarily of polycrystalline ferromagnetic ceramic material of cellulated structure throughout, each of said air holes being sub-

stantially smaller in any direction than the dimension of the body in the same direction, the bulk density of said body being substantially lower than the theoretical microscopic density of said ceramic material; means for magnetically polarizing said body; and means for supplying an electromagnetic signal field to said body.

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