

Oct. 16, 1956

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2,767,387

CYLINDRICAL ELECTRO-MECHANICAL TRANSDUCER

Filed April 5, 1950

2 Sheets-Sheet 1

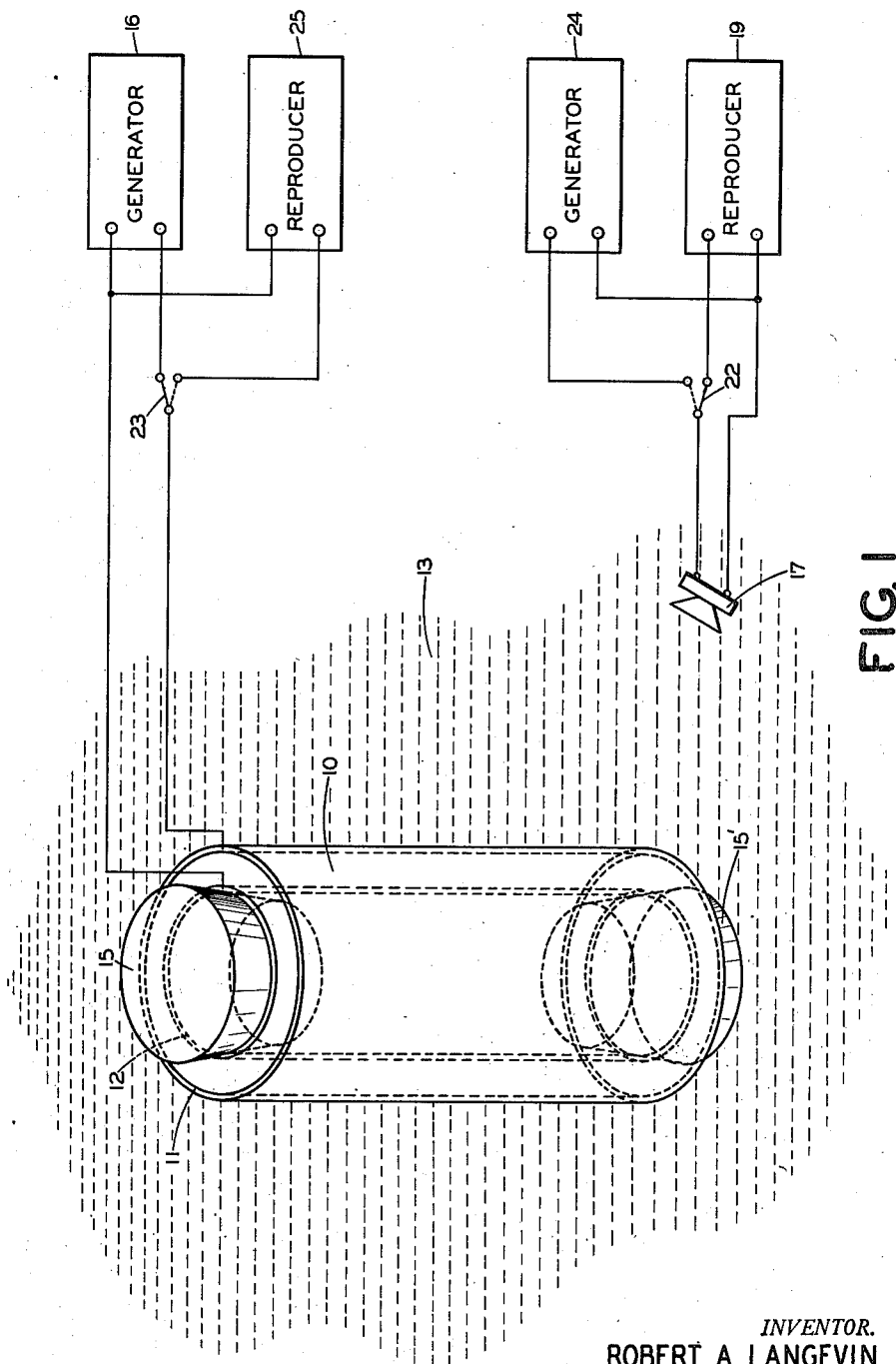


FIG. 1

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2 Sheets-Sheet 2

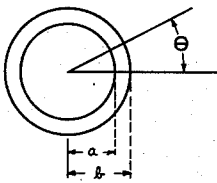


FIG. 2

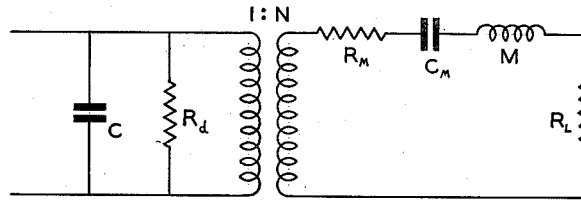


FIG. 3

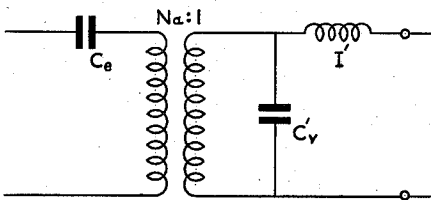


FIG. 4

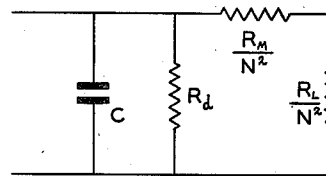


FIG. 5

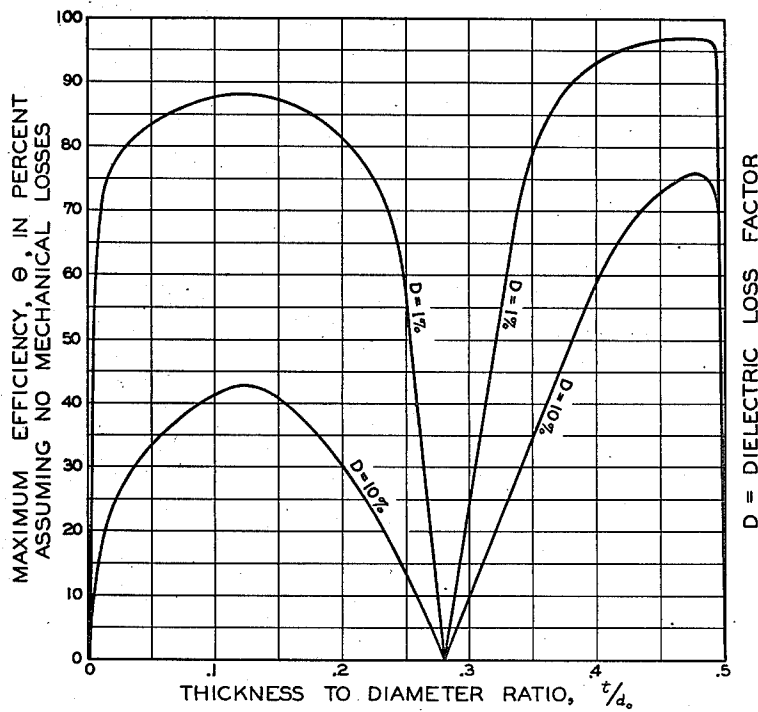


FIG. 6

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CYLINDRICAL ELECTRO-MECHANICAL TRANSDUCER

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Application April 5, 1950, Serial No. 154,037

7 Claims. (Cl. 340—10)

This invention relates to a transducer for operation in a medium such as water and for transducing therein between electrical and mechanical types of energy. Specifically, the transducer is useful for translating electrical energy into mechanical energy or for translating mechanical energy to electrical energy.

Transducers of the type mentioned above are widely used for translating electrical energy to mechanical energy or vice versa. Specifically, piezoelectric materials and magnetostrictive materials have been used for this purpose. More recently barium titanate, when treated in a particular manner, has been found to have transducing properties which are quite beneficial in certain applications.

Also, it has been known for some time that a cylinder has desirable transducing characteristics for certain applications. It is difficult, however, to provide a cylindrical transducer with the piezoelectric crystals of the prior art for the reason that, due to their characteristics of growth, it is impossible to provide a cylindrical transducer which moves radially at all points. Such a device can be approximated by the use of single crystals if a large mosaic of crystals is used, but this provides a very expensive structure. The use of magnetostrictive materials for the same purpose also has certain inherent disadvantages. On the other hand, it is known that polycrystalline barium titanate, which has been vitrified and treated in a manner to provide transducing properties, can be made to have a radial action at all points of the surface when in a cylindrical form. The use of a cylindrical transducer in a liquid such as water, for example, can provide a directional characteristic which is symmetrical for all points around the axis of the cylinder. It, therefore, becomes very desirable in many applications to utilize a tube of electro-mechanically sensitive dielectric material of the nature of barium titanate to provide a transducing action in a liquid, either for changing electrical energy to mechanical or acoustical energy in the liquid or for changing such acoustical energy in the liquid into an electrical form.

Applicant has discovered that, for transducers of the type here under consideration, decided advantages can be obtained when a hollow cylindrical transducer element is used if the ratio of the wall thickness of the cylinder to its diameter is chosen to be within a particular range or preferably to have substantially a given value for the particular material and under the conditions in which it is used. Specifically, it has been found that the maximum efficiency which such a transducer can have is provided if the ratio of thickness to outside diameter is chosen in a manner which will be set forth in detail hereinafter.

It is an object of the invention to provide an improved transducer for use in changing electrical energy to mechanical energy, or vice versa.

It is still another object of the invention to provide a transducer in the form of a hollow cylinder and which

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has substantially the maximum possible efficiency for the transducing material utilized.

It is a specific object of the invention to provide a hollow cylindrical transducer for operation within a liquid with the outside surface of the cylinder acoustically exposed to the liquid and with the inside surface of the cylinder substantially acoustically shielded from the liquid and in which the wall thickness is so chosen with reference to the diameter of the cylinder as to provide the best efficiency in operation.

In accordance with the invention, a transducer for operation in a medium and for transducing therein between electrical and mechanical types of energy comprises a hollow cylinder of electro-mechanically sensitive dielectric material having a radial and tangential activity of opposite sign. In accordance with a preferred embodiment of the invention, the cylinder comprises a major portion of vitrified barium titanate material which has approximately the characteristics of substantially pure barium titanate which has been fired to a temperature within the range of 1300° C. to 1400° C. The transducer of the invention also includes means, including a provision for causing the outer surface of the cylinder to be exposed to the above-mentioned medium and the inner surface to be acoustically shielded from the medium when the cylinder is immersed in the medium and electrodes on the material, for applying one of the above-mentioned types of energy to the cylinder and for deriving the other of the above-mentioned types of energy therefrom. The cylinder is proportioned to have a ratio of thickness to outside diameter which provides substantially maximum efficiency for the material used and for the conditions under which it is operating.

For a better understanding of the present invention, together with other and further objects thereof, reference is had to the following description taken in connection with the accompanying drawings and its scope will be pointed out in the appended claims.

Fig. 1 of the accompanying drawings illustrates a transducer in accordance with the invention which can be utilized either for translating electrical energy to mechanical energy or for translating mechanical energy to electric energy; Fig. 2 represents a section through the transducer 10 of Fig. 1; Figs. 3, 4, and 5 are circuits used in a mathematical description of the proportioning and operating characteristics of the transducer of Fig. 1; while Fig. 6 comprises curves showing certain of the operating characteristics of the transducer of Fig. 1.

Fig. 1 of the drawings illustrates a preferred embodiment of the invention. Here a transducer 10 is illustrated in the form of a hollow cylinder of electro-mechanically sensitive di-electric material which may be barium titanate. This cylinder has an electrode 11 on the outside surface and an electrode 12 on the inside surface thereof and, when in operation is adapted to be immersed in a liquid such as water 13. The arrangement includes means for causing the outer surface of the cylinder to be acoustically exposed to the water 13 and for causing the inner surface of the cylinder to be acoustically shielded from the water when the cylinder is immersed in the water. Specifically, plugs 15 and 15' are provided for the cylinder and these plugs may be comprised of cork, rubber, or any other suitable material. An electrical generator 16 is shown for applying electrical energy to the electrodes 11 and 12. Also, a microphone 17 is included in the liquid 13 in order to generate electrical currents corresponding to the mechanical energy introduced into the liquid by the operation of the cylinder 10 as a transducer for converting the electrical energy of generator 16 to mechanical energy, or specifically to sound energy, in the water 13.

This sound energy, of course, may be of any frequency depending upon the frequency of the input signal provided by generator 16 and the resonant characteristics of the transducer 10 and may, of course, be very much above any audible frequency. A reproducer 19 is illustrated for reproducing or utilizing the energy from microphone 17. The reproducer 19 could, for example, be a cathode-ray tube or a loud-speaker or any other reproducing device depending upon the purpose for which the apparatus is to be used.

In considering the operation of the device of Fig. 1 as so far described, it will be seen that electrical energy, generated by the generator 16, is applied to the electrodes 11 and 12 thereby causing, under the conditions to be described in more detail hereinafter, a mechanical action within the cylinder 10 which in turn causes sound waves to be propagated into the water 13. These sound waves are picked up by the microphone 17 and reproduced on the reproducer 19 in any desired manner. As described, therefore, the arrangement of Fig. 1 is one for changing an electrical input to transducer 10 into a mechanical output which comprises the sound energy propagated into the water 13.

Alternatively, the arrangement of Fig. 1 can be used in the reverse manner. In order to illustrate this use of the arrangement, switches 22 and 23 are shown. When these switches are in their dotted position, the microphone or transducer 17 is connected to a generator 24 and the electrodes 11 and 12 are connected to a reproducer 25. Under these conditions, the generator 24 is effective to excite the device 17 and produce sound energy in the liquid 13. This sound energy impinging upon the cylinder 10 is transformed by the cylinder 10 into electrical energy and means, including electrodes 11 and 12, are provided for deriving and utilizing this electrical energy. Specifically, the electrical energy is reproduced by reproducer 25 which again may be an oscillograph or any other device which can be actuated by the electrical energy.

In order to explain in detail applicant's novel method of proportioning the transducer 10, it is deemed desirable to set forth in a mathematical manner the steps which must be followed and the conditions which must be met. Fig. 2, therefore, illustrates a section through the transducer 10 and certain parameters utilized in the following mathematical analysis are indicated thereon. The electrodes and other portions of the Fig. 1 arrangement have been omitted for sake of simplicity.

If the transducer of Fig. 1 is operated with the switches 22 and 23 in the positions illustrated in the drawing, electrical energy is supplied to the transducer 10 from the generator 16 and mechanical energy is derived from the transducer 10 through the medium of the water 13. Under these conditions, the electro-mechanical behavior of such a cylindrical tube transducer can be described up through the radial resonance of the tube by an equivalent circuit of the type illustrated in Fig. 3. The symbols used in Fig. 3 have the following significance:

C—Blocked capacity in farads.

R_a—Resistance taking account of dielectric loss. Specifically if D is the dielectric loss factor at a frequency, f ,

$$D = \frac{X_c}{R_a} \text{ where } X_c = \frac{1}{\omega C} \text{ and } \omega = 2\pi f$$

N—Transducer ratio in Newton/volt.

C_m—Volume compliance in meters³/Newton/meter² (electrically short circuited).

M—Inertance in kilograms/meter⁴.

R_m—Resistance in m. k. s. acoustical ohms taking account of mechanical losses.

R_L—Resistance in m. k. s. acoustical ohms representing effect of water load on the outside lateral surface of the tube.

In order to calculate the equivalent circuit constants of the subject transducer, it is convenient to neglect the losses and transform the circuit of Fig. 3 into that of Fig. 4. The circuit of Fig. 4 is the equivalent at all frequencies of that of Fig. 3 (neglecting the losses) provided certain relations are satisfied between the constants of the two circuits. These relations are:

$$C = \frac{C_e C'}{N_a^2 C_e + C'} \quad (1)$$

$$N = \frac{N_a C_e}{N_a^2 C_e + C'} \quad (2)$$

$$C_M = N_a^2 C_e + C' \quad (3)$$

$$M = I' \quad (4)$$

Utilizing Equations 1, 2, 3 and 4, the constants of the circuit of Fig. 3 are easily calculated providing certain properties of the transducing material used in cylinder 10 are known. Cylinder 10 is comprised, in a preferred form, substantially solely of barium titanate which has been vitrified by firing to a temperature within the range of 1300° C. to 1500° C., and which has thereafter been polarized by the application of a high unidirectional potential between the electrodes 11 and 12 in a manner which is generally understood by those skilled in the art. It will be understood that some impurities in addition to barium titanate are frequently included in the material as a practical necessity, but, in general, if the composition is at least 95% barium titanate the material will generally have the following properties within the percentage variations designated:

Density, ρ -----	5.6×10 ³ ±2% kilograms/meter ³ .
Open circuit compliance, S ^D ---	10.2×10 ⁻¹² ±3% meters ² /Newton.
Piezoelectric moduli, g_{31} -----	-5.2×10 ⁻³ ±20% meter volts/Newton.
g_{33} -----	12.6×10 ⁻³ ±20% meter volts/Newton.
Dielectric constant, K-----	1700±20%.
Poisson ratio, σ -----	.31±10%.

All above values taken at 25° centigrade.

Utilizing the above constants, therefore, it is now possible to obtain an evaluation of the right-hand portions of Equations 1 to 4.

Specifically, the electrical capacity C_e of a cylindrical tube fully electroded on its inside and outside surface is given by the formula for coaxial cylindrical conductors separated by a medium of dielectric constant K. This equation is as follows:

$$C_e = \frac{0.6128K}{\log_{10} d_o/d_i} \mu\text{farad/inch of length} \quad (5)$$

where d_i and d_o are the inside and outside diameters of the tube respectively. If t is the thickness of the tube and noting that $d_i/d_o = 1 - 2t/d_o$, it is clear that the capacity per inch of length can be represented solely as a function of the ratio t/d_o which is the thickness of tube 10 divided by the outside diameter of the tube.

The following relates to the evaluation of the transducer ratio N_a . If the tube of Fig. 1 is subjected to increments of hydrostatic pressure P_o Newtons/meter² on the outside there are set up in the material radial and tangential stresses T_r and T_θ which by virtue of the symmetry of the structure can depend only on r and not on θ . Observing that the piezoelectric modulus in the radial direction is everywhere equal to g_{33} and, normal to the radius, to g_{31} , it follows that the open circuit voltages developed by the stresses T_r and T_θ are given respectively by:

$$V_r = \int_a^b g_{33} T_r dr \quad (6)$$

$$V_\theta = \int_a^b g_{31} T_\theta dr \quad (7)$$

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Expressions for T_r and T_θ in terms of the radius, r , of the tube and P_0 are readily obtained from elementary elastic theory. (Cf. Timoshenko, Theory of Elasticity, p. 56; McGraw-Hill, 1934.) They are

$$T_r = \frac{b^2 P_0}{b^2 - a^2} \left\{ \frac{a^2}{r^2} - 1 \right\}$$

$$T_\theta = -\frac{b^2 P_0}{b^2 - a^2} \left\{ \frac{a^2}{r^2} + 1 \right\}$$

Carrying out the indicated integrations there results:

$$N_a = \frac{V}{P_0} = \frac{V_r + V_\theta}{P_0} = g_{33} b \frac{a-b}{a+b} - g_{31} b \quad (8)$$

It should be observed that because of the opposite signs of g_{33} and g_{31} and because $|g_{33}| > |2g_{31}|$ for some critical ratio of inside to outside diameter the ratio N_a for such cylindrical transducers will be 0.

The following relates to the evaluation of the volume compliance C_v .

If e_r is the radial strain and if u is the displacement of the tube in the radial direction as a result of the stresses set up by the increment of hydrostatic force, P_0 , we have

$$\frac{\partial u}{\partial r} = e_r$$

and $e_\theta = S^D(T_r - \sigma T_\theta)$. In addition let v and e_θ be the tangential components of displacement and strain respectively. Then

$$\frac{\partial v}{\partial \theta} = r e_\theta - u \quad (9)$$

But

$$\frac{\partial v}{\partial \theta}$$

must be identically zero for all θ and r which can only be true if $r e_\theta = u$. Since $e_\theta = S^D(T_r - \sigma T_\theta)$ a direct calculation using the previous values of T_r and T_θ gives

$$u = r e_\theta = \frac{S^D b^2 P_0}{b^2 - a^2} \left\{ (\sigma - 1) r - \frac{a^2}{r} (\sigma + 1) \right\} \quad (10)$$

Then the displacement of the outer radius of the cylinder is given by substituting $r = b$ in Equation 10 to give

$$u_b = S^D b P_0 \left\{ \sigma - \frac{b^2 + a^2}{b^2 - a^2} \right\} \quad (11)$$

Now the change in the volume of the cylinder (neglecting end effects) produced by the increment of pressure P_0 is $dV = 2\pi b l dr$, if l is the length of the cylinder and dr is the change in the radius as a result of the pressure. But $dr = u_b$ so that the volume compliance of the cylinder is given by

$$C'_v = \frac{dV}{P_0} = \frac{2\pi b l u_b}{P_0} = 2\pi l b^2 S^D \left\{ \sigma - \frac{b^2 + a^2}{b^2 - a^2} \right\} \quad (12)$$

where $| \quad |$ indicates that the absolute value is taken.

Having now calculated C_e , N_a , and C'_v (Equations 5, 8, and 12, respectively) as functions of the fundamental constants of the material and the dimensions of the structure, the constants C , N , and C_m of Fig. 3 are known by an application of Equations 1, 2, 3, 4.

It is now possible to turn to the circuit of Fig. 3 and derive an equation for the efficiency of the transducer 10 driving a water load and with its inner surface shielded from the water. For resonant operation, the reactance of C_m and M exactly cancel and by transferring R_m and R_L to the electrical side of the transducer there results the equivalent circuit of Fig. 5.

Throughout this discussion it is supposed that all the elements in the equivalent circuit Fig. 5 are linear. Now, if a voltage V , be applied to the terminals of the transducer as represented by the equivalent circuit of Fig. 3 real power will be dissipated as follows:

$$\text{Dielectric loss} = \frac{V^2}{R_D} \quad (13)$$

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$$\text{Mechanical loss} = \frac{N^2 R_m V^2}{(R_m + R_L)^2} \quad (14)$$

$$\text{Radiation loss} = \frac{N^2 R_L V^2}{(R_m + R_L)^2} \quad (15)$$

If now we define, as is usual, the efficiency, θ , of the transducer as the ratio of the power radiated to the real power supplied, then

$$\theta = \frac{\frac{N^2 R_L}{(R_m + R_L)^2}}{\frac{N^2 R_L}{(R_m + R_L)^2} + \frac{N^2 R_m}{(R_m + R_L)^2} + \frac{1}{R_D}} \quad (16)$$

It is now desirable to re-express this equation for the efficiency, θ , in terms of more familiar parameters. One simple approach to this problem is the following:

The dissipation factor, D , of the dielectric is given by the relation

$$D = \frac{X_c}{R_D}$$

so that

$$R_D = \frac{1}{D \omega_r C}$$

where ω_r is 2π times the resonant frequency of the transducer.

N is, as has been shown, calculable in terms of constants of the material and dimensions of the transducer structure.

If Q_0 is the unloaded ($R_L = 0$) mechanical Q of the transducer represented in Fig. 1, then

$$R_m = \frac{\omega_r M}{Q_0}$$

If Q_L is the loaded ($Q(R_L \neq 0)$) of the transducer of Fig. 1

$$R_m + R_L = \frac{\omega_r M}{Q_L} \quad (17)$$

and

$$R_L = \omega_r M \left(\frac{1}{Q_L} - \frac{1}{Q_0} \right) \quad (18)$$

Using these expressions for R_D , R_m , R_L , and the relation

$$M = \frac{1}{\omega_r^2 C_m}$$

Equation 16 can be put in the form:

$$\theta = \frac{1 - \frac{Q_L}{Q_0}}{1 + \frac{C}{N^2 C_m} \frac{D}{Q_L}} \quad (19)$$

Now referring to the equivalent circuit of the transducer the coupling coefficient, k , is given by the relation

$$k^2 = \frac{N^2 C_m}{N^2 C_m + C} \quad (20)$$

from which we find that

$$\frac{C}{N^2 C_m} = \frac{1 - k^2}{k^2} \quad (21)$$

and the efficiency, θ , can finally be expressed in the form:

$$\theta = \frac{1 - \frac{Q_L}{Q_0}}{1 + \left(\frac{1 - k^2}{k^2} \right) \frac{D}{Q_L}} \quad (22)$$

The ratio

$$\frac{Q_L}{Q_0}$$

is not calculable from theoretical considerations since the unloaded Q , Q_0 , necessarily includes mounting losses,

cement losses, etc. On this basis Q_L/Q_0 should properly be considered a kind of figure of merit of a given transducer design.

Rewriting Equation 22 in the form,

$$\frac{\theta}{1 - \frac{Q_L}{Q_0}} = \frac{1}{1 + \left(\frac{1-k^2}{k^2} \right) \frac{D}{Q_L}} \quad (23)$$

it is clear that if in the right-hand side of this equation we replace Q_L by, say, Q'_L which is the loaded Q assuming no mechanical losses; it will always be true that $Q'_L \geq Q_L$ so that

$$\frac{\theta}{1 - \frac{Q_L}{Q_0}} = \frac{1}{1 + \left(\frac{1-k^2}{k^2} \right) \frac{D}{Q_L}} \leq \frac{1}{1 + \left(\frac{1-k^2}{k^2} \right) \frac{D}{Q'_L}} \quad (24)$$

Hence the replacement in the right-hand side of Equation 23 of Q_L by Q'_L can only result in an efficiency θ which is too high. Noting, though, that the left-hand term of Equation 24 is free of the dielectric loss factor, D ; it is evident that the expression

$$\frac{1}{1 + \left(\frac{1-k^2}{k^2} \right) \frac{D}{Q'_L}} \quad (25)$$

gives an upper bound to the efficiency of such a transducer in the presence of a dielectric loss factor, D .

In order to obtain numerical values for the maximum efficiency figure given in the last expression it is necessary to know the values of the coupling coefficient, k , and the loaded Q , Q'_L (assuming no mechanical losses). These can be obtained in the following way.

The coupling coefficient, k , is also expressible in terms of the constants of the circuit of Fig. 4 as can be shown by a direct application of the transformation equations. It is, in fact, given by the expression

$$k^2 = \frac{N_a^2 C_e}{N_a^2 C_e + C'_v} \quad (26)$$

Now, expressions for all of the constants of the right-hand side of this equation have already been obtained (Equations 5, 8, and 12, respectively). Inserting them into this equation for the coupling coefficient, there results

$$k^2 = \frac{\left\{ g_{33} \frac{1-r}{1+r} - g_{31} \right\} \times \frac{0.6128K \times 10^{-12}}{\log_{10} 1/r}}{2\pi S^D \left\{ \frac{1+r^2}{1-r^2} - \sigma \right\}} \quad (27)$$

where

$$r = di/do = \frac{\text{inside diameter}}{\text{outside diameter}} = \frac{2a}{2b}$$

Noting that

$$\frac{di}{do} = 1 - 2 \frac{t}{do}$$

it is clear that the coupling is a function solely of the ratio t/do .

To calculate the loaded Q , Q'_L , we note that a cylindrical tube represented by the numeral 10 of Fig. 1 radiating into water with a specific acoustic resistance $\rho_w V_w$ will, in the absence of mechanical losses, have a mechanical Q at its radial resonance given very nearly (since the coupling squared is much less than one) by the expression

$$Q'_L = \frac{1}{\omega_r C_M \frac{\rho_w V_w}{A}} \frac{\text{reactance of compliance at resonance}}{\text{load resistance}} \quad (28)$$

where ω_r is 2π times the radial resonant frequency and A is the lateral area of the tube (end effects are neglected). For purposes of calculating Q it is feasible to neglect the

effect of the elastic coupling to the length mode on the radial frequency constant so that it is permissible to write

$$\omega_r = \frac{B}{d_m}$$

where B is a constant and d_m is the mean diameter.

A suitable value of B can be obtained from the elastic constants of the material by the relation

$$B = \sqrt{\frac{4E}{1-\sigma^2}} \cdot \frac{1}{\rho} \quad (E = S^D)$$

(cf.: Rayleigh, "Theory of Sound," vols. I and II, 1945). With these assumptions and using the equation already developed for the volume compliance there results

$$Q'_L = \frac{1-r}{B S^D \rho_w V_w \left\{ \frac{1+r^2}{1-r^2} - \sigma \right\}} \quad (29)$$

$$r = t/do$$

which it is clear is a function only of the ratio t/do .

Finally, now, inserting values of the constants of the material into the expressions obtained above for k^2 and Q'_L , and using these results in the previously obtained expression for maximum efficiency

$$\frac{1}{1 + \left(\frac{1-k^2}{k^2} \right) \frac{D}{Q'_L}} \quad (30)$$

there result curves of the form shown in Fig. 6. Here, for the sake of illustrating the principles, curves have been drawn for dielectric loss factors of 1 and 10 percent. Several points are at once evident:

1. Loss factors greater than say 1 percent seriously impair the efficiency of ceramic cylindrical tube transducers.

2. Irrespective of the loss factor there exist two critical thickness to diameter ratios, of the order of .125 and .48 (corresponding to a "thin" and "thick" walled case respectively) at which the efficiency of the tubes is a maximum.

3. For any given loss factor, higher efficiencies can be realized with the thick-walled tubes, the relative superiority of the "thick"-walled tube increasing as the loss factor increases.

It will thus be seen that by substituting for the value of Q'_L found in Equation 28 in the last term of the denominator in Equation 30 the following expression is obtained:

$$\frac{1-k^2}{k^2} \frac{\omega_r C_M}{A} \quad (31)$$

It will be seen that the value of the Expression 30 which represents the maximum efficiency of a cylindrical tube transducer will be a maximum when the expression of 31 is a minimum. Therefore, in accordance with the teachings of the invention, the tube 10 of Fig. 1 is proportioned in such a manner as to provide a minimum in the Expression 31. It will be seen by reference to the curves of Fig. 6 that two different conditions are represented, namely one in which the dielectric losses are 1% and one in which the dielectric losses are 10%. Curves for the conditions in which the dielectric losses lie between 1% and 10% have generally the same form and lie between two curves which are actually shown in Fig. 6. From an inspection of the curves of Fig. 6, it will be seen that the maximum efficiency is a maximum or is optimum if the ratio of thickness to diameter is substantially 0.48 and that another maximum is provided if this ratio is substantially 0.125. Also, from an inspection of the curves of Fig. 6, this maximum is seen to occur at the same point regardless of the value of the dielectric loss for the two conditions shown and it has been determined that the ratio is substantially the same for all intermediate values of the dielectric loss factor D . Furthermore, it will be seen that the efficiency of the transducer is maintained safely at a high value if the ratio of thickness to outer diameter is within

the range of 0.03 and 0.2 or if it is within the range of 0.4 and 0.49. It is furthermore apparent that the efficiency is zero for the transducer under consideration for all values of dielectric loss factor D if the ratio of thickness to outer diameter is substantially 0.28. From the above, it will be seen that, regardless of the dielectric loss factor of the material, substantially the highest possible operating efficiency will be obtained from the transducer of Fig. 1 if either ratio of thickness to outer diameter is selected to provide optimum efficiency as taught by the above description of the invention.

While there have been described what are at present considered to be the preferred embodiments of the invention, it will be obvious to those skilled in the art that various changes and modifications may be made therein without departing from the invention and it is, therefore, aimed to cover all such modifications and changes as fall within the true spirit and scope of the invention.

What is claimed is:

1. A transducer for operation in a medium and for transducing therein between electrical and mechanical types of energy comprising: a hollow cylinder of electromechanically sensitive dielectric material having a radial and a tangential activity of opposite sign; means, including provisions for causing the outer surface of said cylinder to be acoustically exposed to said medium and the inner surface to be acoustically shielded from said medium when said cylinder is immersed in said medium and electrodes on said material, for applying one of said types of energy to said cylinder and for deriving the other of said types of energy therefrom; said cylinder having a ratio of thickness to outside diameter which substantially provides a minimum of the expression,

$$\frac{1-k^2}{k^2} \frac{\omega_r C_M}{A}$$

wherein:

k denotes the electromechanical coupling coefficient of said material;

ω_r is equal to 2 times the radial resonant frequency of the transducer;

C_M denotes the volume compliance of said cylinder in meters³/Newton/meter²; and

A is the lateral area of said cylinder in meters².

2. A transducer for operation in a medium and for transducing therein between electrical and mechanical types of energy comprising: a hollow cylinder having a ratio of thickness to outer diameter within the range of 0.03 and 0.2 and of material containing a major portion of vitrified barium titanate with a density of substantially 5.6×10^3 kilograms per cubic meter, an open-circuit compliance of substantially 10×10^{-12} meters squared per Newton, a radial modulus of substantially 12.6×10^{-3} meter volts per Newton, a tangential modulus of substantially -5.2×10^{-3} meter volts per Newton, a dielectric constant of substantially 1700 and a Poisson ratio of substantially 0.31; and means, including provisions for causing the outer surface of said cylinder to be acoustically exposed to said medium and the inner surface of said cylinder to be acoustically shielded from the surface of said medium when said cylinder is immersed in said material and electrodes on said material, for applying one of said types of energy to said cylinder and for deriving the other of said types of energy therefrom.

3. A transducer for operation in a medium and for transducing therein between electrical and mechanical types of energy comprising: a hollow cylinder having a ratio of thickness to outer diameter of substantially 0.125 and of material containing a major portion of vitrified barium titanate with a density of substantially 5.6×10^3 kilograms per cubic meter, an open-circuit compliance of substantially 10×10^{-12} meters squared per Newton, a radial modulus of substantially 12.6×10^{-3} meter volts per Newton, a tangential modulus of substantially -5.2

$\times 10^{-3}$ meter volts per Newton, a dielectric constant of substantially 1700 and a Poisson ratio of substantially 0.31; and means, including provisions for causing the outer surface of said cylinder to be acoustically exposed to said medium and the inner surface of said cylinder to be acoustically shielded from the surface of said medium when said cylinder is immersed in said material and electrodes on said material, for applying one of said types of energy to said cylinder and for deriving the other of said types of energy therefrom.

4. A transducer for operation in a medium and for transducing therein between electrical and mechanical types of energy comprising: a hollow cylinder having a ratio of thickness to outer diameter within the range of 0.4 to 0.49 and of material containing a major portion of vitrified barium titanate with a density of substantially 5.6×10^3 kilograms per cubic meter, an open-circuit compliance of substantially 10×10^{-12} meters squared per Newton, a radial modulus of substantially 12.6×10^{-3} meter volts per Newton, a tangential modulus of substantially -5.2×10^{-3} meter volts per Newton, a dielectric constant of substantially 1700, and a Poisson ratio of substantially 0.31; and means, including provisions for causing the outer surface of said cylinder to be acoustically exposed to said medium and the inner surface of said cylinder to be acoustically shielded from the surface of said medium when said cylinder is immersed in said medium and electrodes on said material, for applying one of said types of energy to said cylinder and for deriving the other of said types of energy therefrom.

5. A transducer for operation in a medium and for transducing mechanical energy to electrical energy comprising: a hollow cylinder having a ratio of thickness to outer diameter of substantially 0.48 and of material containing a major portion of vitrified barium titanate with a density of substantially 5.6×10^3 kilograms per cubic meter, an open-circuit compliance of substantially 10×10^{-12} meters squared per Newton, a radial modulus of substantially 12.0×10^{-3} meter volts per Newton, a tangential modulus of substantially -5.2×10^{-3} meter volts per Newton, a dielectric constant of substantially 1700 and a Poisson ratio of substantially 0.31; means, including provisions for causing the outer surface of said cylinder to be acoustically exposed to said medium and the inner surface of said cylinder to be acoustically shielded from the surface of said medium when said cylinder is immersed in said medium, for applying mechanical energy to said cylinder; and means, including electrodes on said material, for deriving electrical energy from said cylinder.

6. A transducer for operation in a medium and for transducing therein between electrical and mechanical types of energy comprising: a hollow cylinder having a ratio of thickness to outer diameter within the range of 0.03 and 0.2 and composed substantially only of barium titanate which has been vitrified by firing to a temperature within the range of 1300° C. to 1400° C.; and means, including provisions for causing the outer surface of said cylinder to be acoustically exposed to said medium and the inner surface of said cylinder to be acoustically shielded from the surface of said medium when said cylinder is immersed in said material and electrodes on said material, for applying one of said types of energy to said cylinder and for deriving the other of said types of energy therefrom.

7. A transducer for operation in a medium and for transducing therein between electrical and mechanical types of energy comprising: a hollow cylinder having a ratio of thickness to outer diameter within the range of 0.4 and 0.49 and of material composed substantially solely of barium titanate which has been vitrified by being fired to a temperature within the range of 1300° C. to 1400° C.; and means, including provisions for causing the outer surface of said cylinder to be acoustically exposed to said medium and the inner surface of said cylinder to be acoustically shielded from the surface of said medium

when said cylinder is immersed in said medium and electrodes on said material, for applying one of said types of energy to said cylinder and for deriving the other of said types of energy therefrom.

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