A porous capacitance transducer for producing electrical output signals in response to dynamic pressure fluctuations in a surrounding liquid medium substantially comprises an electrically conductive membrane in parallel spaced relation with a collimated hole structure (CHS) plate, which is a porous metal structure containing a controlled number and distribution of discrete parallel capillaries. An inertia and depth-compensated a.c. biased hydrophone incorporating the basic porous capacitance transducer substantially comprises first and second membranes respectively associated with first and second pairs of CHS plates and first and second pairs of oil-filled reservoirs. Such a hydrophone exhibits improved sensitivity, acoustic bandwidth response, dynamic pressure response, and noise immunity.

13 Claims, 3 Drawing Figures
INERTIA-COMPENSATED A.C. BIASED HYDROPHONE INCORPORATING A POROUS CAPACITANCE TRANSDUCER

GOVERNMENT CONTRACT

The invention herein claimed was made in the course of or under a contract with the Department of the Navy.

FIELD OF THE INVENTION

This invention relates to hydrophones and in particular to an inertia and depth-compensated a.c. biased hydrophone incorporating a porous capacitance transducer.

BACKGROUND OF THE INVENTION

Several prior art hydrophones employ an elongated cylindrical transducer element of the radically strictive variety in combination with pressure release materials, such as cork and air-filled rubber, within the cylindrical transducer element. However, it has been observed that at extreme depths the high ambient pressure damages or crushes the pressure release material or otherwise impairs transducer performance.

Improved radically strictive transducers include an automatic depth-compensation feature which does away with use of such pressure release materials.

A second feature, other than automatic depth-compensation, which is desirable in a hydrophone is that of inertia-compensation in which case the hydrophone output signals result from dynamic pressure fluctuations and not from longitudinal hydrophone acceleration. Up to now compensation for signal interferences, such as longitudinal hydrophone acceleration, has been found impracticable in many cases.

It is therefore an object of this invention to provide a depth-compensated hydrophone incorporating a porous capacitance transducer.

It is another object of this invention to provide an inertia-compensated hydrophone incorporating a porous capacitance transducer.

SUMMARY OF THE INVENTION

According to the present invention, a porous capacitance transducer for producing electrical output signals in response to dynamic pressure fluctuations in a surrounding liquid medium substantially comprises an electrically conductive membrane in parallel spaced relation with a collimated hole structure (CHS) plate, which is a porous metal structure containing a controlled number and distribution of discrete parallel capillaries.

According to the present invention, an inertia and depth-compensated a.c. biased hydrophone incorporating the porous capacitance transducer substantially comprises first and second membranes respectively associated with first and second pairs of CHS plates and first and second pairs of oil-filled reservoirs.

It is an advantage of this invention that the hydrophone is inexpensive to manufacture, easy to assemble and disassemble, and physically small.

It is another advantage of this invention that the hydrophone exhibits improved sensitivity, acoustic bandwidth response, dynamic pressure response, and noise immunity.

It is a feature of this invention that the CHS plate has mechanical strength substantially equal to that of a solid plate.

It is another feature of this invention that the CHS plate provides a flow area approximately equal to 41 percent of the total area of a solid plate.

It is a further feature of this invention that the CHS plate provides a capacitance substantially equal (i.e., 92 percent) to that of a solid plate of the same external dimensions.

It is a still further feature of this invention that in the proposed hydrophone no net forces due to electric fields are imparted to the membranes.

It is a still further feature of this invention that in the proposed hydrophone substantially no thermal noise results since purely reactive elements are utilized.

DESCRIPTION OF THE DRAWING

The above and other objects, advantages, and features of this invention will be better appreciated by a consideration of the following detailed description and the drawing in which:

FIG. 1 is a cross section through a diameter of a porous capacitance transducer according to the present invention;

FIG. 2 is a longitudinal sectional view of a hydrophone incorporating the porous capacitance transducer of the present invention; and

FIG. 3 is a circuit diagram showing four variable capacitance membrane-CHS plate pairs in a normally balanced bridge circuit which is driven by an alternating current source.

DETAILED DESCRIPTION

Referring to FIG. 1, porous capacitance transducer 10 comprises electrically conductive circular membrane 11 in parallel spaced relation with collimated hole structure (CHS) plate 12, which is a porous metal structure, of the type manufactured, for example, by the Brunswick Corporation of Chicago, Illinois, containing a controlled number and distribution of discrete parallel capillaries 13. Collimated hole structure plates are described in a “Development Report” of the Technical Products Division (Form 4-001), Brunswick Corporation, copyright 1968. Membrane 11 and plate 12 which are electrically insulated from each other, form the elements of a variable capacitor. Surface 14 of plate 12, is spherically concave in order to improve the sensitivity and noise immunity of transducer 10. Further, transducer 10 is surrounded by liquid medium 15, part of which fills gap 16 located between membrane 11 and plate 12. Membrane 11 can advantageously be made of aluminum or be a sandwich of metalized mylar.

A desirable feature of a hydrophone is automatic depth compensation. This, of course, allows ambient or static pressure equalization within the hydrophone structure without simultaneous dynamic pressure equalization. In such a case, acoustic sensitivity is assured and static equilibrium maintained. It is apparent that transducer 10, to some extent, has the automatic depth-compensation feature since parallel capillaries 13 allow for ambient pressure equalization within gap 16. However, any sudden or dynamic pressure fluctuations in liquid medium 15 are attenuated before
reaching membrane 11 via the capillary route. In other words, parallel capillaries 13 act as restrictive orifices which block any dynamic pressure fluctuations from being applied to membrane 11 from the right. Therefore, a dynamic pressure fluctuation in surrounding liquid 15 causes a deflection of membrane 11 relative to plate 12 thereby effecting a detectable change of capacitance.

It has been determined that CHS plate 12 has mechanical strength substantially equal to that of a solid plate, provides a flow area approximately equal to 41 percent of the total area of a solid plate, and provides a capacitance substantially equal (i.e., 92 percent) to that of a solid plate.

FIG. 2 is a longitudinal sectional view of an inertia and depth-compensated hydrophone incorporating porous capacitance transducer 10 of FIG. 1. Hydrophone 20 comprises hollow cylindrical steel housing 21 further including threaded hole 22 to which eye bolt 80 is fastened. Attached to eye bolt 80 is an undersized towing cable, not shown, which contains a plurality of electrical conductors. Housing 21 also includes wall 23 which divides the housing into two separate but similar chambers.

Hydrophone 20 further comprises transducer structure 35 which includes CHS plates 36 and 37, membrane 38, and membrane mounting ring 39, and transducer structure 45 which includes CHS plates 46 and 47, membrane 48, and membrane mounting ring 49. Circular membranes 38 and 48 are supported at their periphery by membrane mounting rings 39 and 49, respectively. The CHS plate pairs form double capacitors with their associated membranes acting as common elements. The housing, the CHS plates, and the membranes are electrically insulated from each other, by means not shown.

Advantageously, the membrane mounting rings are made of steel while the membranes are made of aluminum. Fastening of a membrane to its associated ring is done at a slightly elevated temperature, such as 100°F. Upon cooling of the members, differential thermal contraction produces the desired nominal membrane tension.

Housing 21 further includes annular shoulders 24a and 24b and threaded portions 25a and 25b. Thus, transducer structures 35 and 45 are secured to housing 21 by threading annular retaining rings 31a and 31b onto portions 25a and 25b, respectively, whereupon the transducer structures are caused to bear against their respective shoulders.

Hydrophone 20 further comprises boot structures 30a and 30b of yieldable sound transmitting material which cover the open ends of housing 21. The bonding or sealing of boots 30a and 30b relative to housing 21 is done using well-known techniques. Boot 30a and membrane 38 define depth-compensating reservoir 50 while membrane 38 and wall 23 define pressure-release reservoir 51. In a similar manner, boot 30b and membrane 48 define depth-compensating reservoir 52 while membrane 48 and wall 23 define pressure-release reservoir 53. It should be noted that reservoirs 50 and 51 are respectively similar to reservoirs 52 and 53.

Reservoirs 50, 51, 52 and 53 contain a liquid, such as oil, having a compressibility exceeding that of the surrounding liquid medium, water in this case, in which the hydrophone is to be immersed.

Automatic depth-compensation of hydrophone 20 is effected by flow-communicating means such as restricted orifice 85 in membrane 38 and capillary hole 86 in housing 21. It is apparent that orifice 85 allows limited flow between reservoirs 50 and 51 while hole 86 allows limited flow between reservoirs 52 and 53. Hole 86 may be machined on housing 21 using well-known techniques such as by longitudinal as well as radial drilling and by utilizing threaded plug 87. The method of depth-compensation used is determined by the particular application.

Boots 30a and 30b, which are exposed to the surrounding liquid medium, expand and contract in order to equalize the oil pressure within reservoirs 50, 51, 52, and 53 with the ambient hydrostatic pressure. Such static pressure equalization between reservoirs 50 and 51 and between reservoirs 52 and 53 is effected by means of restrictive orifice 85 and capillary hole 86, respectively. It should be noted that the oil volume within the depth-compensating reservoirs must be sufficient to enable ample fluid flow to their associated pressure-release reservoirs for the full range of ambient hydrostatic pressures expected. However, dynamic pressure fluctuations, which are transmitted by boots 30a and 30b to their respective depth-compensating reservoirs, do not reach the pressure-release reservoirs, since such fluctuations are attenuated by restrictive orifice 85 and capillary hole 86.

Therefore, the oil in reservoirs 50, 51, 52, and 53, together with restrictive orifice 85 and capillary hole 86, decouple membranes 38 and 48 from the high ambient hydrostatic pressure while simultaneously allowing them to sense dynamic pressure fluctuations. In addition to compensating for such high ambient hydrostatic pressure, the oil within pressure-release reservoirs 51 and 53 places an equivalent spring stiffness in parallel with the effective membrane stiffness. While the oil is relatively compressible, the stiffness of the oil within reservoirs 51 and 53 may be much greater than the effective membrane stiffness thereby substantially influencing the sensitivity, acoustic bandwidth response, and dynamic range of hydrophone 20. The dynamic range is given when there is contact between the membrane and the CHS plate. Therefore, the desired nominal membrane tension can be relatively low since such an effect stabilizes the membrane’s null position. The low membrane tension requirement greatly simplifies the fabrication and mounting of membranes 38 and 48 on mounting rings 39 and 49, respectively.

Housing 21 can be characterized as comprising left and right back-to-back cup-shaped structures whose respective open ends are oppositely directed and whose respective closed ends are formed by common wall 23. As mentioned above, the open ends of these left and right cup-shaped structures are respectively covered by boots 30a and 30b. Depth-compensating and pressure-release reservoirs, as defined above, are respectively associated with these left and right cup-shaped portions of housing 21. In light of the above, it is apparent that those components of hydrophone 20 to the left and right of wall 23 respectively form first and second depth-compensated hydrophone structures. The combination of these two hydrophone structures yields the inertia and depth-compensated hydrophone, as will become more apparent hereinafter.
Referring back to FIG. 2, the output of a.c. source 60 is applied to membranes 38 and 48 by leads 61 and 62, respectively. Leads 61 and 62 are attached to their respective membranes by braizing or other suitable method. In addition, CHS plates 36, 37, 46, and 47 are connected electrically to the input terminals of detector means 70 by leads 71, 72, 73, and 74, respectively. It should be recalled that the two pairs of CHS plates form two double capacitances with their associated membranes acting as common elements. It should also be noted that leads 61, 62, 71, 72, 73 and 74 are part of the undersea towing cable, not shown, which is attached to eye bolt 80.

FIG. 3 is a circuit diagram showing four variable capacitances $C_1, C_2, C_3, \text{ and } C_4$ in a normally balanced bridge 90 which is driven by a.c. source 60 via leads 61 and 62. Capacitance $C_1$, which is located between bridge terminals 75 and 78, comprises membrane 48 and CHS plate 46; capacitance $C_2$, which is located between bridge terminals 75 and 76, comprises membrane 48 and CHS plate 47; capacitance $C_3$, which is located between bridge terminals 76 and 77, comprises membrane 38 and CHS plate 36; and capacitance $C_4$, which is located between bridge terminals 77 and 78, comprises membrane 38 and CHS plate 37. With the capacitances arranged in the bridge as shown, no net forces due to electric fields are imparted to the membranes in which case the electrical circuit does not influence the mechanical response of the membranes. Output $e_o$ of bridge 90 is detected across terminals 76 and 78 by detection means 70. It is assumed that detection means 70 has infinite input impedance.

In light of the above, the voltage across capacitance $C_i$ can be written as:

$$e_i = \frac{Z_1}{Z_1 + Z_4} e_o = -\frac{1}{j \omega C_2 + \frac{1}{j \omega C_4}} e_o = \frac{C_4}{C_1 + C_4} e_o,$$

(1)

where $Z_1$ and $Z_4$ are the impedances across capacitors $C_1$ and $C_4$, respectively, and $e_o$ is the input a.c. voltage from source 60. Similarly, the voltage across capacitance $C_2$ can be written as:

$$e_o = C_2/(C_2 + C_4) e_o.$$

(2)

Therefore, the voltage at terminal 78 is given by:

$$e_{78} = e_i - (C_2)/(C_2 + C_4) e_o,$$

(3)

while the voltage at terminal 76 is given by:

$$e_{76} = e_i - (C_4)/(C_4 + C_2) e_o.$$  

(4)

Taking the difference of $e_{78}$ and $e_{76}$ yields the output voltage $e_o$, which is given by:

$$e_o = \frac{(C_2/(C_2 + C_4) - (C_4/(C_4 + C_2)) e_o.}$$

(5)

Recalling that hydrophone 20 has the depth-compensation feature, a change in the ambient hydrostatic pressure yields no output $e_o$, since in such a case $C_1 = C_2 = C_3 = C_4$.

Now, in order to show that hydrophone 20 is inertia compensated, i.e., that the bridge output $e_o$ is not affected by acceleration of hydrophone 20 along its longitudinal axis, it is assumed that capacitances $C_1, C_2, C_3, \text{ and } C_4$ have the nominal value $C_2$ and that they change by the amount $\epsilon$. Therefore, if hydrophone 20 is accelerated to the right, $C_1$ becomes $C_2 - \epsilon, C_2$ becomes $C_2 + \epsilon, C_3$ becomes $C_2 - \epsilon, \text{ and } C_4$ becomes $C_2 + \epsilon$ as a result of the inertia of the oil in depth-compensating reservoir 52 and pressure-release reservoir 51. Substituting these values into equation (5) yields:

$$e_o = [(C_2 - \epsilon)/(2(C_2 + \epsilon)) - (C_2 - \epsilon)/(2(C_2 - \epsilon))] e_i,$$

(6)

or

$$e_o = [\frac{1}{2} - \frac{\epsilon}{2C_2}] e_i = 0.$$  

(7)

A similar result is gotten when hydrophone 20 is accelerated to the left. However, if hydrophone 20 is subjected to a dynamic pressure fluctuation, $C_1$ becomes $C_2 - \epsilon, C_2$ becomes $C_2 + \epsilon, C_3$ becomes $C_2 - \epsilon, \text{ and } C_4$ becomes $C_2 + \epsilon$. Substituting these values into equation (5) yields:

$$e_o = [(C_2 + \epsilon)/(2C_2) - (C_2 - \epsilon)/(2C_2)] e_i,$$

(8)

or

$$e_o = [-2\epsilon/(2C_2)] e_i = (-\epsilon/C_2) e_i.$$  

(9)

Therefore, hydrophone 20 is sensitive to dynamic pressure fluctuations but insensitive to longitudinal acceleration. In the above cases, it is assumed that the distance between membranes 38 and 48 is small compared to the wavelength of the acoustic signal to be detected.

In summary, transducer 10 of FIG. 1 is particularly useful in hydrophone 20 since the diameter of membrane 11 and CHS plate 12 is substantially equal to the inner diameter of housing 21. This, of course, lends itself to a compact hydrophone structure. Since hydrophone 20 comprises relatively few parts, it is inexpensive to manufacture and easy to assemble and disassemble. Also, very little thermal noise results since purely reactive elements are utilized. Additional advantages accrue in the area of signal processing since the carrier is modulated directly thereby reducing multiplexing requirements. Also, the IF noise contribution is greatly reduced and simpler, more compact a.c. amplifiers can be employed.

It will be recalled that CHS plate 12 of FIG. 1 has spherically concave surface 14. It is shown by H. V. P. Neubert in “Instrument Transducers,” Oxford, 1963, that when the moving element in a capacitance transducer is a thin membrane, the change in capacitance $\epsilon$, divided by the nominal capacitance $C_n$, i.e., $\epsilon/C_n$, is only half that obtained when a rigid plate is moved an amount equal to the maximum membrane displacement. However, it can also be shown that $\epsilon/C_n$, for the case where a rigid plate is displaced a certain fraction of its quiescent gap, is the same as $\epsilon/C_n$ for the case where a membrane is displaced the same fraction of its quiescent gap relative to a concave surface. This is true if the shape of the backing plate’s surface is similar to the deflection profile of the membrane and the curvature of the backing plate’s surface is relatively small. It can also be shown that for thin membranes deflected a small amount by a uniform pressure difference, the membrane assumes a spherical shape. Since spherical
surfaces can be ground with utmost precision, very small gaps between the diaphragm and the CHS plate are possible. Therefore, $\varepsilon/C_d$ for the membrane with the spherically concave CHS plate is comparable to that of a flat plate of equal area. In addition, for the spherically concave CHS plate, $C_d$ is much greater for equal surface area since smaller quiescent gaps are possible. The nominal capacitance $C_d$ should be large to minimize the effect of stray capacitance on sensitivity. Therefore, the effective $\varepsilon/C_d$ for the membrane with the spherically concave CHS plate results in higher sensitivity and greater noise immunity since both $\varepsilon/C_d$ and $C_d$ are increased.

While the arrangement according to this invention for detecting dynamic pressure fluctuations in a surrounding liquid medium has been described in terms of a specific embodiment, it will be apparent to one skilled in the art that many modifications are possible within the spirit and scope of the disclosed principle.

What is claimed is:

1. A porous capacitance transducer responsive to dynamic pressure fluctuations and substantially non-responsive to static pressure fluctuations in a surrounding liquid medium comprising
   an electrically conductive membrane subjected to mechanical excitation by said dynamic pressure fluctuations, and
   a collimated hole structure plate immersed in said surrounding liquid medium and in parallel spaced relation with said membrane,
   said membrane, surrounding liquid medium, and plate having a capacitance substantially equal to that of an uncollimated hole structure plate of the same overall area, and
   said plate impeding the transfer of said surrounding liquid medium therethrough when said transducer is subjected to dynamic pressure fluctuations and providing substantially unimpeded transfer of said surrounding liquid medium therethrough when said transducer is subjected to static pressure fluctuations.

2. The porous capacitance transducer of claim 1 wherein the plate surface adjacent said membrane is concave.

3. The porous capacitance transducer of claim 2 wherein said concave surface is spherical.

4. A depth-compensated hydrophone responsive to dynamic pressure fluctuations and substantially non-responsive to static pressure fluctuations in a surrounding liquid medium, said hydrophone comprising:
   a cylindrical housing, said housing further including a cup-shaped structure having one open end and one closed end;
   a boot structure of yieldable sound transmitting material covering said open end and intimately attached to said housing;
   a porous capacitance transducer including an electrically conductive membrane and first and second collimated hole structure plates, said first and second plates respectively being located on opposite sides of said membrane and in parallel spaced relation therewith;
   means for securing said transducer within said housing, said boot structure and said transducer defining a depth-compensating reservoir and said transducer and said closed end defining a pressure-release reservoir;
   a pressure transmitting liquid filling said reservoir and having a compressibility exceeding that of said surrounding liquid medium; and
   flow-communicating means joining said reservoirs for impeding the transfer of said pressure transmitting liquid between said reservoirs when said hydrophone is subjected to dynamic pressure fluctuations and for providing substantially unimpeded transfer of said pressure transmitting liquid between said reservoirs when said hydrophone is subjected to static pressure fluctuations.

5. The hydrophone of claim 4 wherein said plate surfaces adjacent said membrane are concave.

6. The hydrophone of claim 5 wherein said concave surfaces are spherical.

7. The hydrophone of claim 4 wherein said flow-communicating means is a restrictive orifice in said membrane.

8. The hydrophone of claim 4 wherein said flow-communicating means is a relatively small diameter orifice in said housing.

9. An inertia and depth-compensated hydrophone responsive to dynamic pressure fluctuations in a surrounding liquid medium and substantially non-responsive to both hydrostatic pressure fluctuations in said medium and to longitudinal hydrophone acceleration comprising
   a cylindrical housing including a wall which divides said housing into first and second open-end chambers,
   first and second boot structures of yieldable sound transmitting material respectively covering said first and second open-end chambers and intimately attached to said housing,
   first and second porous capacitance transducers each including an electrically conductive membrane and two collimated hole structure plates one on each side of said membrane and in parallel spaced relation therewith,
   first and second means for respectively mounting said first and second transducers within said first and second chambers whereby said first boot structure and said first transducer define a first depth-compensating reservoir, said transducer and said wall define a first pressure-release reservoir, said second boot structure and said second transducer define a second depth-compensating reservoir, and said second transducer and said wall define a second pressure-release reservoir,
   a pressure transmitting liquid having a compressibility exceeding that of said surrounding liquid medium filling said reservoirs, and
   first and second flow-communicating means respectively joining the depth-compensating reservoirs with their associated pressure-release reservoirs for impeding the transfer of said pressure transmitting liquid between said associated reservoirs when said hydrophone is subjected to dynamic pressure fluctuations and for providing substantially unimpeded transfer of said pressure transmitting liquid between said associated reservoirs when said hydrophone is subjected to static pressure fluctuations.
10. The hydrophone of claim 9 wherein the plate surfaces adjacent their associated membranes are concave.

11. The hydrophone of claim 10 wherein said concave surfaces are spherical.

12. The hydrophone of claim 9 wherein said first and second flow-communicating means are restrictive orifices in their respective membranes.

13. The hydrophone of claim 9 wherein said first and second flow-communicating means are relatively small diameter orifices in said housing.