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PIEZOELECTRIC POLYMER HYDROPHONES

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Abstract

Three hydrophones are described which use piezoelectric polymer (PVDF) as the active element. These hydrophones are designed to withstand high hydrostatic pressure and to provide good signal to noise ratio at low audio frequencies. Of the three designs, the compliant tube hydrophone has the highest signal to noise ratio and can be used to 4 MPa static pressure. The cylindrical hydrophone has positive buoyancy and can be used to 12 MPa. The hydrostatic mode hydrophone can be used to "unlimited" pressure and is mechanically semi-flexible. Also discussed are expected performance improvements to be obtained by using recently developed thick film polymer.

Introduction

For thirty years piezoelectric ceramic made of lead zirconate titanate (PZT) has proven to be an ideal material for making sonar hydrophones. However, new applications require hydrophones which are lightweight, mechanically flexible, and of large dimensions, requirements which are difficult for ceramic. Since ceramic can only be made in small sizes, a large number of small ceramic elements must be used to fabricate a hydrophone of large dimensions, resulting in high cost. New technologies such as piezoelectric polymer[1], flexible piezoelectric composite[2], and new optical methods[3], are being developed which should allow large area or long length hydrophones to be made relatively easily and inexpensively.

Piezoelectric Polymer

Piezoelectric polymer is made of polyvinylidene flouride (PVDF), a plastic film which has been permanently stretched up to 500% and polarized. Polarization usually consists of applying a high D.C. electric field (up to 1.0 MV/cm) through the thickness of the film while slowly raising the temperature to about 80°C and then cooling. The polymer used in the hydrophones to be described was Kureha KF Piezofilm #30, which came in sheets 10 cm x 20 cm x 30μ. Although Kureha film is no longer commercially available, similar thin film

PVDF is now offered by the Pennwalt Corp. (900 First Ave., King of Prussia, PA 19406, USA) and the 3M Co. (3M Center, St. Paul, MN 55101, USA).

The extreme thinness of 30μ film has been an advantage for certain ultrasonic and audio loudspeaker applications. But in sonar hydrophones the minimum detectable acoustic pressure is inversely proportional to the volume of piezoelectric material used. 30μ film is so thin that it is difficult to get a sufficient volume of polymer into a hydrophone. An important improvement has been the development of thicker polymer (600μ) from EMI Central Research Laboratories (Trevor Road, Hayes, Middlesex, UB31HH, UK).

Table 1 compares polymer with PZT ceramic. The piezoelectric stress coefficient g is proportional to hydrophone voltage sensitivity. The subscripts refer to the piezoelectric coupling modes which describe how stress is applied to the material. The dielectric constant K_{33}^T is proportional to hydrophone capacitance. High capacitance means low impedance which results in low thermal noise voltage. A preferred way to compare piezoelectric material is to combine g and K_{33}^T to form a piezoelectric figure of merit $gd = g^2 K_{33}^T \varepsilon_0$ which is inversely proportional to the minimum detectable acoustic pressure of a hydrophone. If gd is too low, the volume of material must be increased. Fig. 1 shows that polymer and ceramic have a comparable figure of merit in the 31 mode but polymer is 6 times higher than ceramic in the hydrostatic mode. Also shown are lead metaniobate and lithium sulfate, superior hydrostatic mode materials, but they are rigid and brittle like PZT ceramic. Scientists developing improved polymer and flexible composite have estimated up to a factor of 10 future increase in g (100 in gd).

The aging of thin film polymer versus time and temperature is shown in Fig. 2. The 50°C and 90°C data is from a Kureha publication[4]. Beyond 100 days the aging rates are low at all temperatures. However, high temperatures up to 90°C cause an initial loss of a few dB in sensitivity in the first 10 days.

Compliant Tube Hydrophone

The polymer hydrophones to be discussed were all designed to take substantial static pressure and be as long as possible (10 to 20 cm) using commercially available thin film polymer. Several features of their designs are required to make up for the extreme thinness (30μ) of the polymer which is 10 to 100 times too thin for optimum sonar hydrophones. Both the compliant tube and cylindrical hydrophone use the 31 piezoelectric coupling mode. In these designs a compliance element or pressure release system is used to convert the three dimensional acoustic pressure to a one dimensional stress. This compliance element increases hydrophone sensitivity but is highly stressed by static pressure and therefore imposes a depth limitation on the hydrophone.

The compliant tube hydrophone is a rectangular version of a flexural disk hydrophone[5]. As shown in Fig. 3 the compliance element is a steel tube of flattened oval cross section. The tube is air filled and the ends are sealed. The geometry makes the tube acoustically soft, compared to a round tube. The stronger the steel used (requiring carefully heat treated premium alloys) the more compliant the tube can be made without being crushed flat by static pressure. The walls are usually designed to touch at the maximum design pressure thus allowing an overpressure capability (even though the hydrophone is temporarily inoperative). Acoustic and static pressures cause the tube to bend across its width resulting in high strain at the surface of the wall, which can be sensed by an attached piece of polymer, oriented so the sensitive "1" axis is in the width direction. An output voltage results from 31 piezoelectric coupling.

Because the polymer is so thin it is advantageous to use a plastic spacer to move the polymer farther from the neutral plane of the bending beam. The use of an optimum thickness spacer gives this particular hydrophone 10 dB higher sensitivity than if the polymer was glued directly to the tube wall. The use of thick film polymer would give about 20 dB increase in sensitivity and no spacer would be needed. Complete design equations for this hydrophone have been given by Ricketts[6]. The finished hydrophone is shown in Fig. 4 and its properties are given in Table 2. Due to the weight of the steel tube this hydrophone has a specific gravity of 3.5, heavy for polymer but comparable to most ceramic designs. Similar hydrophones built with plastic compliant tubes are neutrally bouyant. But plastic (unlike steel) is subject to creep under long term static loading. The use of glass fiber or carbon fiber reinforced plastic compliant tubes should allow both low density and creep resistance.

The acoustic performance of a piezoelectric hydrophone can be conveniently compared by combining the voltage sensitivity M_o and the capacitance C into the hydrophone figure of merit M_o^2C which is inversely proportional to minimum detectable acoustic pressure. If a high impedance low noise preamplifier can be used adjacent to the hydrophone, a value of M_o^2C 8 x 10^{-18} m^3/Pa is sufficient to detect sea state zero (SSO) pressure levels. From Table 2 it is noted that the compliant tube hydrophone is slightly better than required to detect SSO.

Cylindrical Hydrophone

Cylindrical polymer hydrophones have been reported in references 6-8. Our version is shown in cross section in Figure 5. The round geometry offers less sensitivity than the compliant tube but it is favorable for higher static pressures. Plastic can be used for the cylinder because (unlike compliant tubes) the stresses are purely compressive for improved creep resistance. Acoustic pressure causes an alternating change in tube diameter creating tangential surface strains sensed by polymer whose "1" axis is oriented tangentially around the tube. Since the polymer is so thin the effective thickness is increased by the use of a multiturn winding. In each winding two strips are rolled up together with like poled sides facing each other to prevent a short circuit. As shown in Fig. 6 three windings are used on a single 10 cm plastic tube and connected electrically in series for increased sensitivity. The properties of this hydrophone are included in Table 2. Due to the all plastic construction this hydrophone is positively buoyant. The static pressure capability is three times higher than the compliant tube hydrophone but M_0^2C is 2½ times lower and 20 times more polymer was used.

Both the compliant tube and cylindrical hydrophones are rigid but not brittle. Steel compliant tubes and plastic cylinders are routinely fabricated and handled without damage in lengths up to several meters. If long pieces of polymer were available the techniques just described could be used to make hydrophone elements as long as the tubing stock. For the cylinder, thick film polymer would eliminate the need for the elaborate winding and series connection schemes, one turn of polymer would be sufficient. Even better would be thick walled cylinder stock made entirely of polymer. We have seen extruded tubes of thick film polymer but the sensitive "1" axis is along the length rather than tangentially oriented.

Hydrostatic Mode Hydrophone

In the hydrostatic mode hydrophone the acoustic pressure acts directly on the piezoelectric material, no compliance element is used. However a single piece of thin (30μ) polymer used in the hydrostatic mode has a very low sensitivity (-232 dB re 1V/μPa). To increase the sensitivity by 30 dB we use a 32 layer stack connected in series as shown in Fig. 7. The polymer layers are laid up in castor oil (not glued) which results in a semiflexible hydrophone. The electrical series connections are made by compression from a single insulated clamp. The loose sheets are held together by a tight fitting polyurethane boot which is molded in place. Because no pressure release mechanism is used, this design has practically unlimited pressure capability (verified to 7.0 MPa to date). The penalty is a low M_0^2C, 9 times lower than the compliant tube hydrophone, and 40 times more polymer was used. The specific gravity of this hydrophone is 1.8, essentially that of the raw polymer. Because of flexibility and relatively long length (20 cm) a flexural resonance occurs at about 600 Hz limiting the (flat) bandwidth to 150 Hz. A photograph of the finished hydrophone is shown in Fig. 8.

Unlike the compliant tube and cylindrical hydrophones which could be made in lengths of several meters, the hydrostatic hydrophone (due to flexibility) could be made by a continuous roll process. The multilayer structure is a complication which will not be required with future hydrophones made of thick film polymer.

Fig. 9 shows a future hydrostatic mode hydrophone concept. Here an entire array structure is made from a single roll of thick film polymer. The structure has many characteristics of two sided flexible printed circuits.

Conclusion

The characteristics of three polymer hydrophones which use thin film have been presented. The advantages of these hydrophones and potential advantages of thick film hydrophones are summarized in Fig. 10. Such hydrophones should allow the construction of large elements and receiving arrays without the geometry and weight constraints of ceramic.

Acknowledgments

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TABLE 1. Properties of Polymer and Ceramic

Symbol	Property	Units	Polymer (PVF_2)	Ceramic (PZT-4)
g_{31}	Piezoelectric stress constant	10^{-3}Vm/N	180	11.1
g_{32}			20	11.1
g_{33}			290	26.1
g_h			90	3.6
K_{33}^T	Relative dielectric constant	. . .	13	1300
$(gd)_{31}$	Piezoelectric figure of merit	$10^{-12}m^2/N$	3.7	1.4
$(gd)_{33}$			9.7	7.8
$(gd)_h$			.93	.15
k_{31}	Electromechanical coupling factor	. . .	.12	.33
k_{33}		. . .	.19	.70
s_{11}^D	Elastic compliance	$10^{-11}m^2/N$	33	1.1
tan δ	Electrical dissipation factor	. . .	.02	.004
ρ	Density	$10^3 kg/m^3$	1.8	7.5
ρc	Acoustic impedance	$10^6 kg/m^2 s$	2.5	22
Qm	Mechanical loss factor	. . .	11	500

TABLE 2. Properties of Polymer Hydrophones

Property	Units	Compliant Tube	Cylinder	Hydrostatic
Sensitivity (M_o)	dB re 1V/μPa	-200	-213	-203
Capacitance (C)	nF	1.6	13	.35
Figure of merit (M_o^2C)	$10^{-18}m^3/Pa$	16	6.5	1.7
Density	$10^3 kg/m^3$	3.5	< 1.0	1.8
Size	cm	1.5 x 10	1.3 x 10	1.5 x 20
Maximum pressure	MPa	4.1	12.4	"Unlimited"
Bandwidth (±1.0 dB)	Hz	5-3000	5-20,000	5-150
Stiffness	....	Rigid	Rigid	Semi-flexible
Change in M_o versus:				
Pressure (0-4.8 MPa)	dB	-1.0	0.0	-2.0
Temperature (20^o-0^oC)	dB	-1.0	-1.5	-3.0

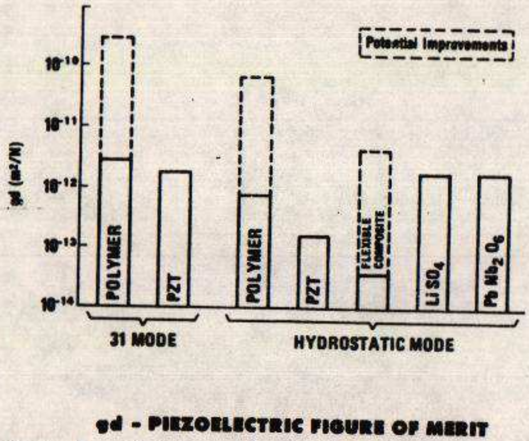

Fig. 1 gd-piezoelectric figure of merit

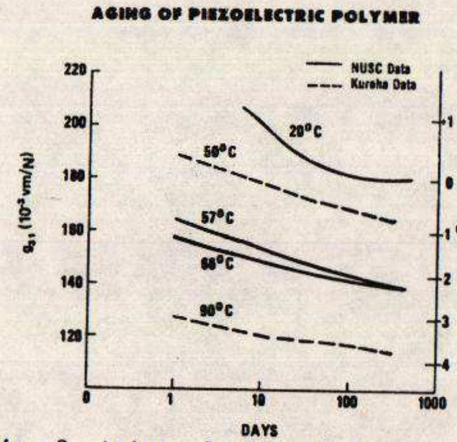

Fig. 2 Aging of piezoelectric polymer

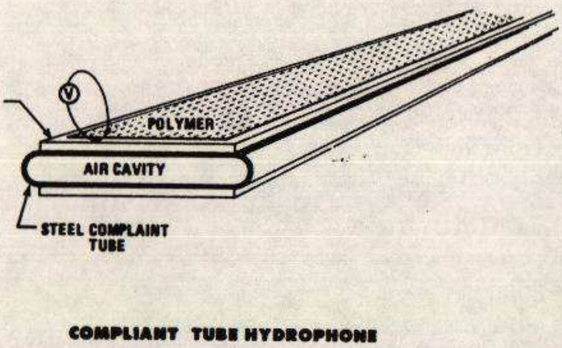

Fig. 3 Compliant tube polymer hydrophone

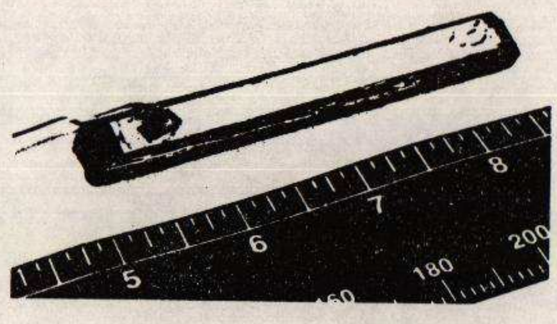

Fig. 4 Compliant tube polymer hydrophone

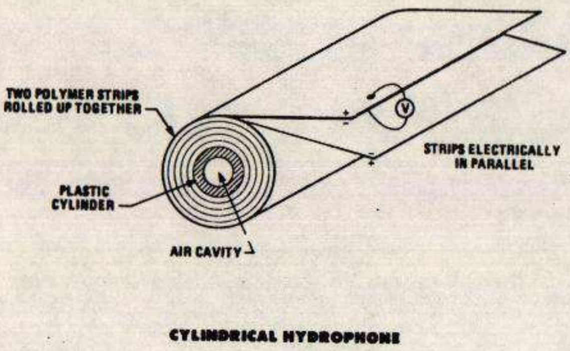

Fig. 5 Cylindrical polymer hydrophone

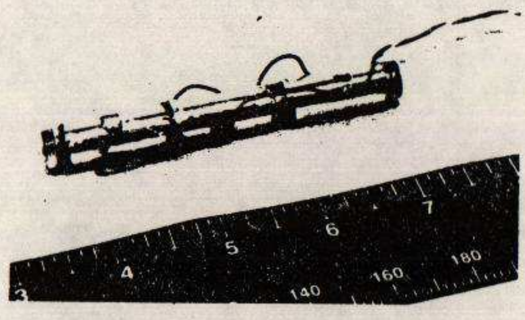

Fig. 6 Cylindrical polymer hydrophone

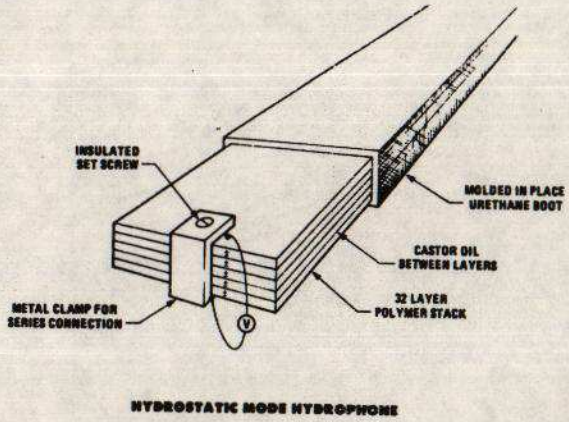

Fig. 7 Hydrostatic mode polymer hydrophone

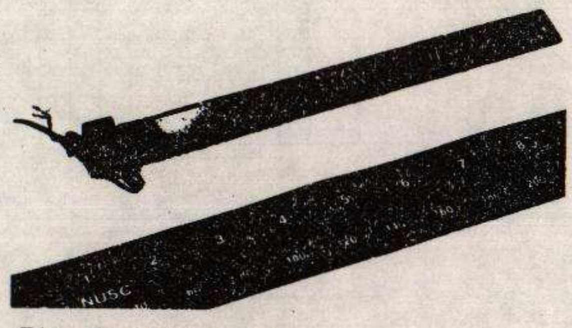

Fig. 8 Hydrostatic mode polymer hydrophone

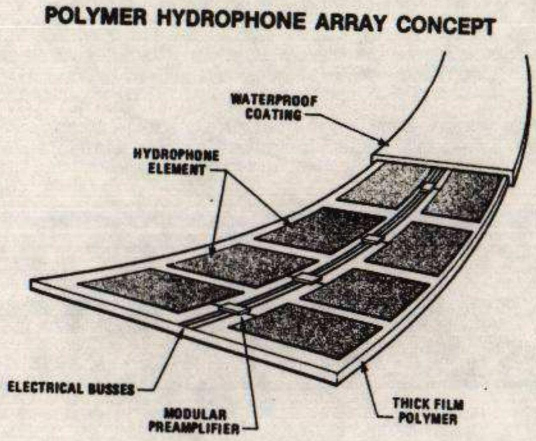

Fig. 9 Polymer hydrophone array concept

PIEZOPOLYMER HYDROPHONES

ADVANTAGES

- LARGE ELEMENT SIZE
- LIGHTWEIGHT
- UNLIMITED DEPTH CAPABILITY (HYDROSTATIC MODE)

POTENTIAL ADVANTAGES

- LOW COST
- RUGGED
- ADJUSTABLE FLEXIBILITY (THICKNESS DEPENDENT)
- VERY LARGE, LONG, OR THIN HYDROPHONE ELEMENTS
- LARGE ARRAYS MADE BY CONTINUOUS ROLL PROCESS

Fig. 10 Advantages of polymer hydrophones