PROC. INST. ACOUSTICS VOL 6 PT 3 1984

RECENT DEVELOPMENTS IN THE USA IN THE APPLICATION OF PVF_2 POLYMER IN UNDERWATER TRANSDUCERS

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Piezoelectric polymers,[1,2] particularly polyvinylidene fluoride (PVF_2), show considerable promise for hydrophone applications. PVF_2 offers the advantages of a characteristic impedance that closely matches water, low mass density, mechanical flexibility, and it can be manufactured in large dimensions as a single piece. The development of thick film PVF_2 with large values for the hydrostatic piezoelectric constant makes it suitable for hydrostatic drive hydrophones, with their associated simplicity of fabrication and virtually unlimited depth capability. These advantages and the unique properties of polymer, with applications to novel hydrophone designs, are reviewed in this paper.

Presently piezoelectric polymers are commercially available in experimental quantities from at least three sources: Thorn EMI Central Research Laboratories, Pennwalt Corporation, and Raychem. Because of difficulties in polarizing the material, the maximum thickness is limited to about one millimeter.

Current interest in the U.S. is focused on thick film PVF_2, particularly for use in large area passive arrays. Considerable effort is underway in the development of large area hydrostatic-drive hydrophones. Strictly speaking, we mean a hydrophone devoid of any form of pressure release; for clearly, as we shall see, polymer hydrophones of this genre are not adequately described by the simple hydrostatic model. Nevertheless the advantages of simplicity of construction and virtually unlimited depth capability are retained by hydrostatically operated polymer hydrophones. Manufacturing processes are now being developed for very large area polymer hydrophones. All of this is being made possible by the development of thick film piezoelectric polymers, and the high figure-of-merit of these materials, particulary for the hydrostatic case.

First, we shall review some applications of thin film PVF_2. Later we shall discuss applications of thick film polymer in both hydrophones and arrays and show some design concepts that use the unique properties of piezoelectric polymers.

THIN FILM POLYMER HYDROPHONES

Thin-film polymer hydrophone designs usually employ a substrate for mechanical strength. The PVF_2 is attached to the substrate, which is air-loaded on one side. Because the polymer has negligible stiffness compared to the substrate, the mechanical behavior of the hydrophone is governed by the substrate. During operation of the hydrophone, the incident acoustic pressure causes the substrate to deflect. The resulting strains are sensed by the polymer, and a voltage proportional to strain is developed. The sensitivity is governed by the piezoelectric coefficients g_{31} and g_{32}.

The geometrical configuration of thin film polymer hydrophones is established by the substrate. Since thin-film PVF_2 is mechanically flexible, the choice of shapes is virtually unlimited. In order to maximize the product of hydrophone sensitivity and maximum operating pressure, a selection criterion for the substrate is its strength-to-elastic modulus ratio.[3] Examples of hydrophones employ ing thin-film polymer are shown in Figs. 1-6 along with their theoretical low-frequency sensitivies.

Our first example of a hydrophone employing thin-film polymer, a cyclindrical hydrophone, is shown in Fig. 1. The PVF_2 film is attached to the inside surface of the tube with its stretch direction (1-axis) along the circumference of the tube. Experimental hydrophones of this configuration have been constructed to test the theoretical results on composite cylinders.[4] An acrylic tube with the dimensions 3.81cm o.d., 3.75cm i.d., and 3.81cm length, 0.635cm - thick phenolic end caps, and Kureha Piezofilm #30 were used in the experimental hydrophones. Waterproofing was provided by the silicone (RTV) encapsulant. The measured low-frequency sensitivity was -211dB re 1V/μPa compared to a computed value of -210.7

Expressions for the sensitivity below resonance have been developed from elastic theory for several boundary conditions.[4] In particular, the sensitivity versus substrate thickness-to-outside diameter ratio is plotted in Fig.1 for the illustrated case (acrylic tube and Kureha Piezofilm #30). It has been assumed that the elastic modulus of the PVF_2 in the 1 and 2-directions are equal, an approximation supported by published data on the Kureha material. Numerical results show that maximum sensitivity is obtained with the PVF_2 film attached to the inside surface of the cylindrical substrate.[4] (Cylindrical polymer hydrophones are also reported in references 3, 4, and 5).

The next example of thin film polymer hydrophone is the dual bender disk illustrated in Fig. 2 along with a graph of its theoretical sensitivity and maximum operating depth.[8,9,10] As shown in Fig. 2, the two substrate disks are glued to the radially compliant mounting ring, an arrangement which approximates the simply-supported edge boundary condition. In this case, the polymer film, in the form of a circular disk, is attached to both sides of the two substrate disks, which are separated by a sealed air cavity. The entire assembly is encapsulated within the housing. Since the polymer is oppositely stressed on opposing sides of the substrate, the PVF_2 layers are electrically interconnected so that their voltages are brought in-phase.

The theoretical low-frequency sensitivity[8,9] for the flexual disk (Fig. 2) is for the case of $\sigma^D = -s^D_{12}/s^D_{11} = \nu$, $Y^D_{11} = Y^D_{22} = E$, where ν and E are Poissons's ratio and Young's modulus. Otherwise the anisotropy of the uniaxially oriented PVF_2 has been accounted for. In addition, the maximum operating depth[9] (Fig. 2) is for a substrate tensile strength of 65.6MPa (~9500psi). Recall that the substrate material should have a high strength-to-modulus ratio to maximize hydrophone sensitivity for a specified operating pressure. Composite flexural disk polymer hydrophones are characterized by high sensitivity but limited depth capability.

Long, narrow, thin and lightweight polymer hydrophones, with potential application to towed arrays, have been realized in flexural plate designs.[11] A cross-section of this type of polymer hydrophone is shown in Fig. 3. The thin film polymer is attached to the two rectangular substrate-plates which are separated by an air space. The groove in each plate serves as a hinge for the purpose of approximating the simply-supported edge condition at each of the four plate edges. For analytical purposes, an edge is located at the center of the groove. The expansion axis of the PVF_2 is along the width of the plate. Expressions have been developed for the electroacoustic sensitivity of flexural plate polymer hydrophones.[3,12] Plots of the low-frequency sensitivity are shown in Fig. 4 for Kureha Piezofilm #30 on acrylic substrate-plates.[3] The indicated ratios b/a and h/a are the effective length-to-width and thickness-to-width ratios of the acrylic plastic plate. In applications where the hydrophone is under long term static loading, a glass fiber reinforced plastic offers the advantage of creep resistance.

We conclude our review of thin film PVF_2 hydrophones with the compliant tube polymer hydrophone, which is shown in Fig. 5.[5,13] This hydrophone also operates in a bending mode. It consists of an air-filled tube (closed at each end) of flattened oval cross section, a plastic spacer plate attached to the flattened surface of the tube, and the piezoelectric polymer film bonded to the spacer plate. The stretch axis of the PVF_2 is in the width direction. The use of the spacer, as opposed to bonding the PVF_2 directly to the tube, results in a significant increase in sensitivity. The spacer serves to move the PVF_2 film farther away from the neutral plane of bending. This sensitivity enhancement, as well as other performance parameters, is predicted by the theoretical model.[13] Compliant tube polymer hydrophones employing high strength steel compliant tubes have withstood maximum pressures of 2.1MPa(300psi) and provided sensitivities of -200dB re 1V/μPa. These values are compared to the predicted values of 2.1MPa and -200.1dB re 1V/μPa. By designing the hydrophone so the tube walls touch at just above the maximum operating pressure, the hydrophone can be given an over pressure capability. The theoretical stiffness-controlled sensitivity is plotted in Fig. 6 for a ratio of spacer plate-to-steel tube thickness (h_s/h_m) of 1.65. This ratio maximizes the sensitivity for $E_s/E_m = 0.0116$, where E_s and E_m are the elastic modulii, and the subscripts s and m refer to the spacer plate and metal tube.

HYDROSTATIC HYDROPHONES AND ARRAYS

We have already noted the advantages of hydrostatic polymer (thick film) hydrophones with regard to simplicity of construction and operating depth capability. The basic action is illustrated in Fig. 7, where we see that the acoustic pressure acts equally in all the three coordinate directions 1, 2, and 3, resulting in a uniform stress distribution $T_1 = T_2 = T_3 = T_h$. For this simple volume expander plate, it is well-known that the low-frequency free-field voltage sensitivity (M_0) is given by the product of the piezoelectric coefficient g_h and the thickness t between electrodes. Experimental verification of this simple model has been obtained in nonresonant modes. However, as suggested earlier, the hydrostatic model is generally inadequate.

The simplest practical form of polymer hydrostatic hydrophone is the encapsulated bilaminar plate. Fig. 8 shows the electrical interconnection of the polymer plates. This arrangement provides voltage cancellation in flexural modes, self-shielding and minimizes coupling losses caused by extraneous capacitance. An experimental implementation of this configuration has been realized using square polymer plates, each measuring 100mm in length and 0.6mm - thick. The plates were rigidly bonded to each other with their expansion axes oriented in the same direction. A plot of the free-field voltage sensitivity is shown in Fig. 9,[14] where the inadequacy of the simple hydrostatic model[15] is revealed, particularly by the anomalous behavior in the vicinity of 1.5kHz. However, the low frequency sensitivity, when corrected for cable losses, is about -201dB re 1V/μPa, which is in close agreement with the predicted value. The observed anomaly in the response at about 1.5kHz was attributed to a flexural resonance. Thus, more mechanical stiffness appeared to be necessary.

Fig. 10 is a plot of the free-field voltage sensitivity of a "stiffened" hydrostatic polymer hydrophone, the successful result of an effort to improve the hydrophone response.[16,21] This experimental hydrophone is shown in Fig. 11. The added mechanical stiffness was provided by glass fiber reinforced plastic plates, which were bonded to the outer surface of the polymer. Also shown in Fig. 10, for comparison, is the measured free-field voltage sensitivity of a piezoceramic bilaminar plate (100mm X 100mm) hydrostatic drive hydrophone. It should be noted that the thickness of each of the lead zirconate titanate plates was 3.2mm or about 5.4 times the thickness of the polymer plates; hence the sensitivity of the ceramic hydrophone should be reduced by 14.7dB before comparing the two sensitivities. Clearly, polymer hydrostatic hydrophones are superior to their piezoelectric ceramic counterparts. Moreover, the temperature and hydrostatic stability of the experimental polymer hydrophone (Fig. 11) are notable. Plots of the free-field voltage sensitivity at 3°C are shown in Fig. 12 for hydrostatic pressures of 69, 3450, and 6900 kPa.[17] The 25°C plots overlay these results.[17]

Using the approximate method of Rayleigh, closed formulas have been obtained for the frequencies of flexural vibration for the completely free composite piezoelectric plate.[18] These results facilitate the design of stiffened, multilayered hydrostatic drive polymer hydrophones.

The stiffening plates also raise the frequency of contour-extensional modes,[19] particularly the low frequency longitudinal modes, which can reduce the bandwidth of the flat region of the receiving response. Moreover, the use of mechanical stiffening layers results in directivity patterns that more closely approximate the sin x/x function.

The importance of realizing the sin x/x directivity function relates to the use of these hydrophones in large hull-mounted arrays of closely spaced elements and their performance in the presence of high wave number noise fields. For example, a line array comprised of N elements of length ℓ and spacing d whose element function is sin x/x $[x = (\pi\ell/\lambda)\sin\theta]$ has the array pattern function of sin Nx/Nsin x, provided $d = \ell$, i.e., the gap between elements is negligibly small. This array pattern function exhibits diminishing side lobe levels for increasing values of Nx. Thus, the realization of the idealized sin x/x element pattern would eliminate grating lobes for the case $(d \to \ell)$ of closely spaced elements.

Note that the nulls occur at endfire ($\theta = \pm 90°$) for the ideal element pattern at frequencies corresponding to $\ell = K\lambda$ $(K = 1,2,3,\ldots)$, i.e., when the length ℓ is equal to an integral number of wavelengths. As previously indicated, hydrophones employing stiffening layers have better beam patterns referred to the sin x/x pattern function, as well as more uniform receiving response. In addition, it has been found beneficial to use materials for the mechanical stiffeners that have relatively high elastic modulus-to-density ratios.

At this point, it should be noted that the observed directivity patterns of hydrostatic drive square plate polymer hydrophones in the planes containing and perpendicular to the stretch axis differ. This difference is more pronounced for hydrophones without stiffening layers, and it is caused by the anisotropy of uniaxially oriented PVF_2. PVF_2 plates stretched in a single direction are orthotropic, with very weak electromechanical coupling in the 2-(unstretched) direction. This property could be of practical importance; for example, in the case of unidirectional noise sources, orientation of the 2-direction of the hydrophone toward the source might prove beneficial. In the case of bilaminar PVF_2 plates, the relative orientation of their stretch directions has a measurable effect on receiving response. It was found, for example, that the anomaly in the response (Fig. 9) is moved from 1.5kHz to about 3.0kHz when the expansion axes of the two polymer plates are orthogonal to each other. In the frequency region of this anomalous behavior, the hydrophone exhibits increased directionality. For sonar array applications the hydrophones of this type should be omnidirectional in a free-field over the operating frequency band.

Fig. 13 shows a plot of the free-field voltage sensitivity of a multilayered polymer hydrophone.[20,21] The more uniform response of this hydrophone, compared to the plots of Figs 10 and 12, is attributed to better bonding of the hydrophone laminations and also to the use of thicker (38μm) copper electrodes on the PVF_2.

In hull-mounted applications, a hydrophone of this type could be sandwiched between an inner and outer decoupler in order to minimize the effects of propulsor, machinery, and flow-induced noise at the array.

33-DRIVEN POLYMER HYDROPHONE

The stiffness controlled sensitivity of this type of hydrophone is governed by the piezoelectric coefficient g_{33}. The edges of the PVF_2 are shielded from the acoustic field; hence the stress components $T_1 = T_2 = 0$ and the electric field $E_3 = g_{33}T_3$. A 33-driven polymer hydrophone design concept is shown in Fig. 14. The gap provides the acoustic shielding in coordinate directions x_1 and x_2 while the end plates couple the sound pressure (P_0) and PVF_2. If these plates are stiff in a flexural sense, then the polymer stress (T_3) is simply equal to $(A_p/A)P_0$. Hence, the low frequency sensitivity $M = (A_p/A)g_{33}t$, where t and A are the polymer thickness and major surface area, and A_p is the area of the two coupling plates. Since $|g_{33}|>|g_h|$ and $A_p/A>1$, the 33-drive hydrophone is more sensitive than its hydrostatically driven counterpart. Experimental 33-drive polymer hydrophones have provided a measured 2-3dB improvement over the theoretical sensitivity of equivalent hydrostatic polymer hydrophones. Moreover, the stability of the free-field voltage sensitivity of these hydrophones has been demonstrated over the hydrostatic pressure range from 69kPa to 6900kPa.[21]

COMPOSITE TRANSDUCER

Our final example of the application of thick film PVF_2 in underwater acoustic transducers is made possible by the acoustic transparency of polymer. It is a composite transducer with separate transmit and receiver elements. The PVF_2 hydrophone is attached to the radiating head of the projector. During transmission the polymer hydrophone is short-circuited; likewise the projector element is short-circuited or terminated when receiving. The terminating impedance is selected to provide a uniform hydrophone receiving response. The experimental composite transducer employs a longitudinal vibrator-type projector element. Its piston radiating head assembly with the polymer hydrophone attached to the aluminum head mass is shown in Fig. 15. The hydrophone itself is comprised of two square PVF_2 plates (100mm X 100mm X 0.6mm) which are bonded together and electrically interconnected as shown in Fig. 8. A thin fiberglass electrical insulator separates the polymer and radiating head.

The experimental composite transducer has extended receiving response to 200kHz and excellent directivity patterns at this frequency and below. The results of high power projector tests indicate that exposure to high intensity sound fields has no measurable effect on the polymer hydrophone performance properties.

SUMMARY

PVF_2 shows considerable promise for hydrophone applications. Thin film polymers are normally used with a substrate for mechanical strength. Potential uses for thin film polymer hydrophones include sensors for sonobuoys and towed thin line arrays. Current attention is focused on thick film polymers and their applications to large area hydrostatic hydrophones for use in large conformal sonar arrays. An array of closely packed, large area hydrophones, with associated noise reduction through spatial averaging, is expected to result in significant improvements in array performance. All of this is made possible because PVF_2 can be fabricated in large sheets, and it can be used effectively in the hydrostatic drive. Future improvements in the temperature stability of PVF_2

can be expected.[22] These improvements will make it even easier to manufacture polymer hydrophones. Already hydrostatic PVF_2 hydrophones have exhibited excellent operational temperature stability, as well as hydrostatic pressure stability.

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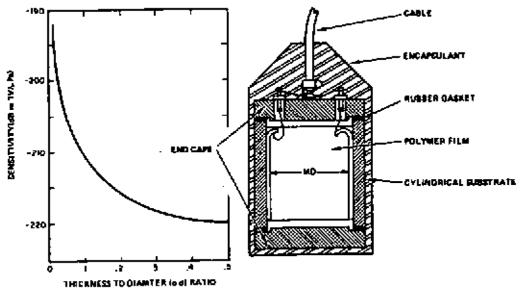

Figure 1 Cylindrical Polymer Hydrophone

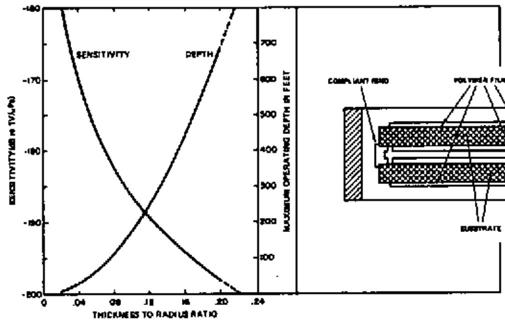

Figure 2 Flexural Disk Polymer Hydrophone

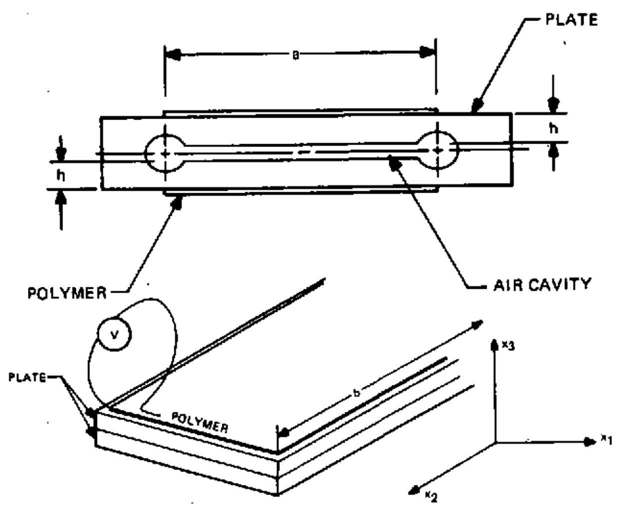

Figure 3 Flexural Plate Polymer Hydrophone

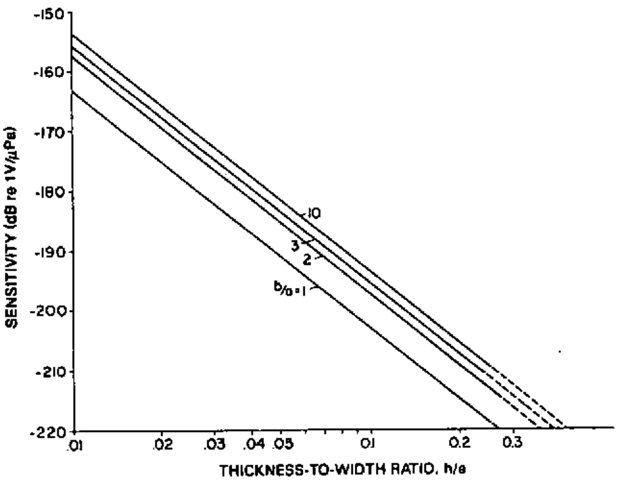

Figure 4 Theoretical Sensitivity of Flexural Plate Polymer Hydrophone

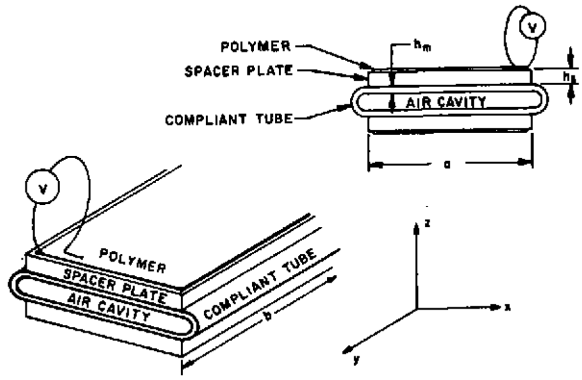

Figure 5 Compliant Tube Polymer Hydrophone

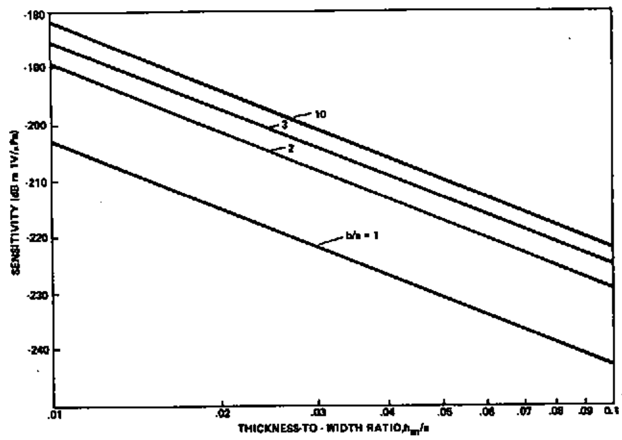

Figure 6 Theoretical Sensitivity of Compliant Tube Polymer Hydrophone

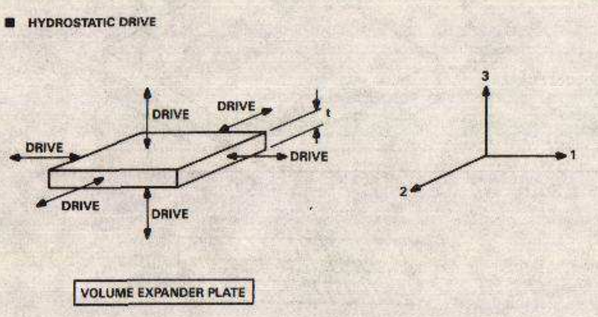

Figure 7 Hydrostatic Operation

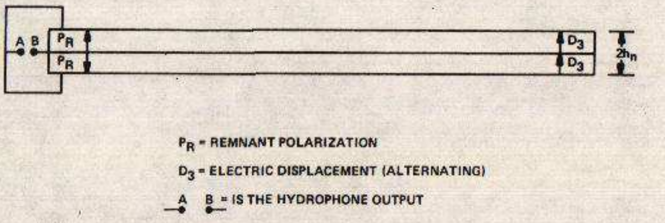

Figure 8 Bilaminar Polymer Plate

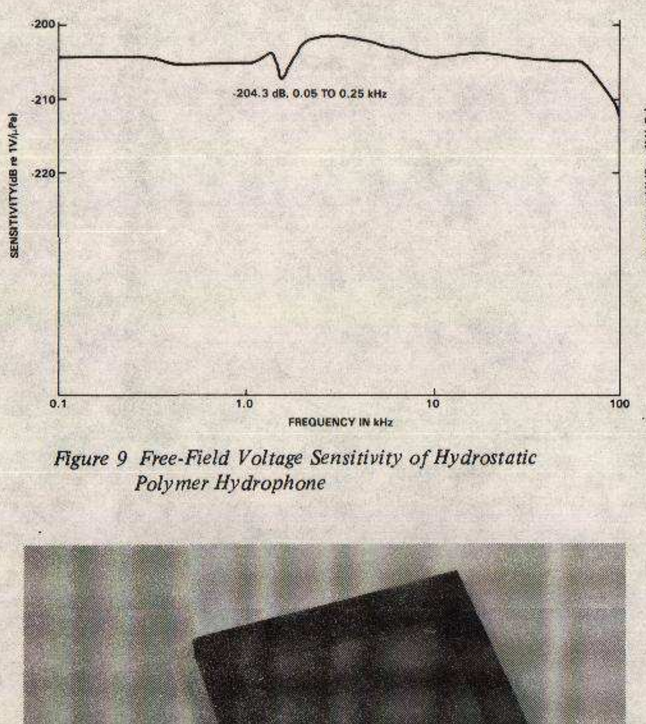

Figure 9 Free-Field Voltage Sensitivity of Hydrostatic Polymer Hydrophone

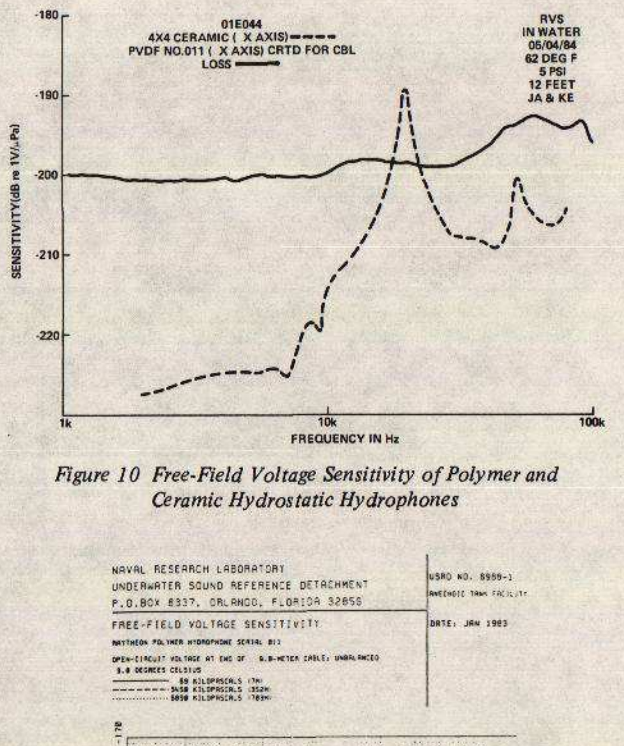

Figure 10 Free-Field Voltage Sensitivity of Polymer and Ceramic Hydrostatic Hydrophones

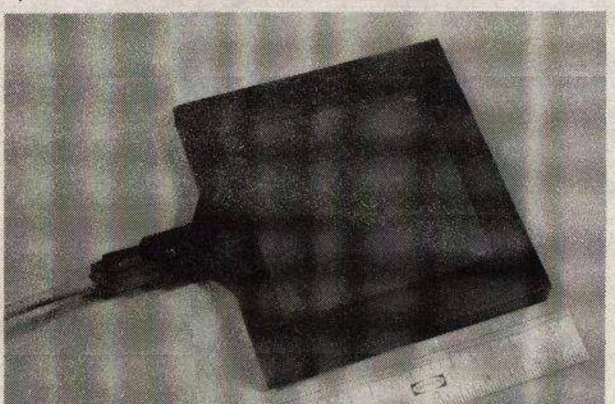

Figure 11 Experimental Hydrostatic Polymer Hydrophone

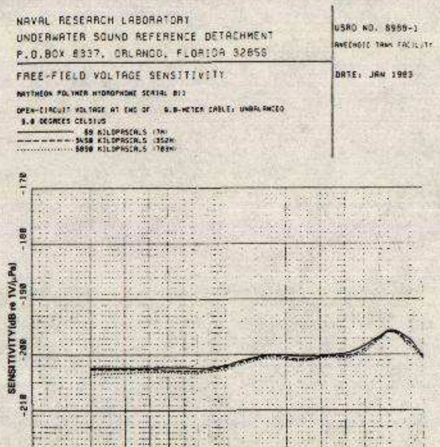

Figure 12 Free-Field Voltage Sensitivity of Hydrostatic Polymer Hydrophone at 3°C For Various Pressures

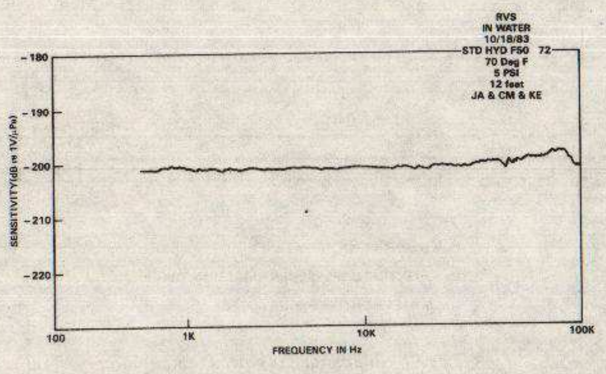

Figure 13 Free-Field Voltage Sensitivity of Multilayer Polymer Hydrophone

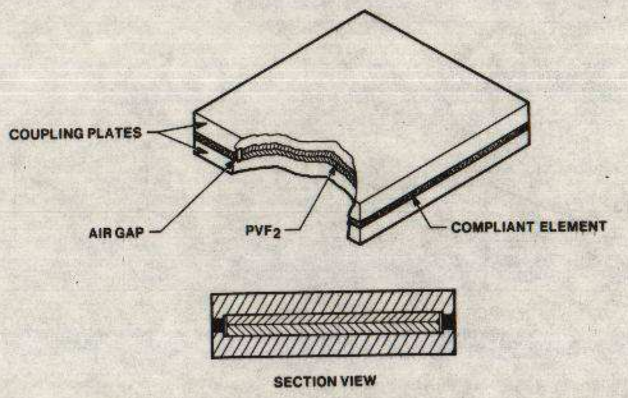

Figure 14 33-Driven Polymer Hydrophone

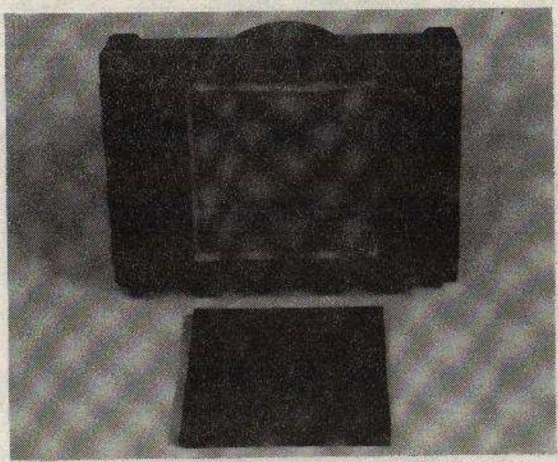

Figure 15 Polymer Attached To Radiating Head of Composite Transducer