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DESIGN AND DEVELOPMENT OF A HIGHLY SENSITIVE PIEZOFILM SENSOR

J. Jagannath Bhat, P.P. Thomson and P.R. Saseendran Pillai

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ABSTRACT. The piezofilm made of polyvinylidene fluoride is being used as an efficient transduction material for the construction of microphones and hydrophones nowadays. An innovative new transducer design for generating comparatively higher voltage output by concentrating the acoustic force to a small cross sectional area is proposed in this paper. In this design, the film is made to vibrate in the (3,1) mode by a modified structural assembly, utilising a perspex diaphragm and a driver pin. Calculations show that, the voltage generated in the (3,1) mode transducer will be approximately 500 times that in the (3,3) mode of construction for the same level of applied force input. Experimentally the receiving sensitivity of the (3,1) mode piezofilm sensor in air is found to be approximately -153 dB re 1V/4 Pa, at around 1.5kHz.

INTRODUCTION

Piezoelectric polymer films have become commercially available and it is widely used in air and underwater applications (1), (2), as an active material for the construction of transducers. The advantageous and meritorious features of piezofilms like, toughness, light weight, flexibility to adhere to irregular and complex structures etc. facilitate the widespread use of this material for the design of transducer systems. Besides, it has got impedance closer to that of water and this along with other attractive features like wide frequency coverage and broad dynamic response offer several potential applications for the piezofilm transducers.

Almost all the transducer designs reported in open literature using piezofilms are operating in the (3,3) mode of vibration. In this mode, the area of the film exposed to the incoming acoustic pressure is relatively large, hence the stress experienced by the film will be less and therefore the voltage generated will also be less. This will reduce the sensitivity of the transducer. On the other hand, if the area of the film that is exposed to the incoming pressure can be reduced, the voltage generated will be large. This is the basic principle that is made use of in the design of transducers operating in the (3,1) mode. The main difference between the (3,3) and (3,1) modes is that, in the former the film is made to vibrate in thickness mode whereas in the latter the film vibrates in length mode.

The piezo stress constant g(3,1) is relatively high and piezo strain constant d(3,1) is relatively low compared to ceramics and other piezoelectric materials. Hence piezofilm hydrophones exhibit high voltage sensitivity and low charge sensitivity.

To illustrate the superiority of the (3,1) mode transducer design over the conventional (3,3) mode of construction, consider a piezofilm of thickness t,
subjected to an applied compressive stress of \( X \) newtons per square metre distributed over its metallised surface. The voltage generated can be shown to be:

\[
V(3,3) = g(3,3) X(3) \cdot t
\]

If the film is pulled to and fro in the length (stretching) direction with the same force by a modified structural assembly, the voltage generated becomes:

\[
V(3,1) = g(3,1) X(1) \cdot t
\]

Calculations show that the voltage generated in the (3,1) mode of construction will be about 500 times greater than that in the (3,3) mode. This sharp increase in the voltage for the same level of force input is the result of the concentration of the applied force to a smaller cross sectional area.

**DESIGN**

The constructional details and structural assembly of the piezofilm transducer operating in the (3,1) mode of vibration is shown in Figure 1. The film was made to vibrate in the (3,1) mode by a special structural assembly, consisting of the diaphragm D and the driver pin P. The vibrations which impinge on a perspex diaphragm of diameter 5 cms and thickness 1mm, which was adhered to the main enclosure were transferred to the film through the driver pin. A film of length 5 cm, breadth 1.5 cm and thickness 28 micron was suitably pre-stretched by properly adjusting the two spring loaded screws S, which were provided at the other end of the film. The whole system was enclosed in a

![Diagram](image-url)
cylindrical chamber.

EXPERIMENTAL SET-UP AND MEASUREMENTS

The experimental set-up for measuring the sensitivity of the transducer is as shown in Figure 2. The gated sinusoidal waves from the gating system are amplified by a power amplifier and these signals were used to generate acoustic waves of desired amplitude and frequency using a Philips high Q speaker.

For computing the sensitivity of the piezofilm transducer in air, it was placed along with a standard B&K 8100 transducer. The standard transducer has a sensitivity that is almost constant from low frequency to about 2 kHz in air and then decreases linearly with frequency. The experimental as well as the standard transducers were placed at equal distances from the speaker. The frequency was swept from 500 Hz to 5 kHz and the voltage generated in both the receiving transducers were measured. For calculating the sensitivity, comparison method was adopted, which is convenient and accurate within the limits of the experimental error. In this method, the output voltages obtained for both the experimental and standard transducers are compared and the sensitivity is calculated using (4).

\[ S_2 = S_1 - 20 \log(V_V/V_S) \text{ dB re } 1V/\mu \text{ Pa} \]

where

- \( S_s \) is the sensitivity of the standard transducer
- \( S_2 \) is the sensitivity of the experimental transducer
- \( V_V \) is the output voltage of the standard transducer
- \( V_S \) is the output voltage of the experimental transducer.
The frequency response of the experimental transducer is shown in Figure 3. From the graph, it is seen that the maximum receiving sensitivity of the piezofilm transducer in air is approximately -153 dB re 1V/µ Pa, at around 1.5 kHz and is almost flat on either side of the resonance peak.

CONCLUSIONS

The frequency response of piezofilm sensor clearly reveals that there is a considerable improvement in its sensitivity over conventional microphones. This enhancement in the receiving sensitivity can be seen to be the direct result of concentration of the force to a much smaller cross sectional area. The smaller cross sectional areas result in correspondingly larger stresses and hence larger voltages.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial support from the Department of Electronics, Government of India.

REFERENCES


4. Bruel & Kjaer Application Notes on Hydrophones—their characteristics and applications
Development of (3,1) drive low-frequency piezofilm hydrophones with improved sensitivity

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Piezopolymers are becoming popular as the active material for the design of probes for sensing ultrasonic fields and quantitative determination of acoustic field parameters in water and biological media. A new innovative transducer design proposed here utilizes a poled piezofilm which is made to vibrate in (3,1) drive by a modified structural assembly. The voltage generated in this design is found to be greater compared to that in the conventional design, due to the concentration of acoustic pressure to a very small cross-sectional area. The prototype design consists of a prestretched piezofilm fixed to a phosphor bronze diaphragm through a driver pin. The proposed design yielded sensitivities to the extent of \(-170\) dB re: 1 V/\(\mu\)Pa in water at around 1.5 kHz.

PACS numbers: 43.88.Ar, 43.88.Fx, 43.30.Yj

INTRODUCTION

Since the discovery of piezopolymer films, they are widely used for transducer applications, particularly for underwater detection purposes. In 1969 Kawai\(^1\) discovered that certain polymers can be poled to a level of activity not previously achieved with any other polymeric material.

Piezopolymers offer several potential advantages\(^2\) such as high chemical resistance, high breakdown field strength, low density, low acoustic impedance, high sensitivity for vibration detection, low wear, high flexibility, easily obtainable film shape, and low cost over the conventional ceramic materials, which are difficult to produce in large size and impractical to machine in complex shapes. Since ceramics are brittle and stiff, they require bases with flat surfaces for mounting. One of the outstanding features of the piezofilm is its low acoustic impedance relative to ceramics, which aids in sorting out the impedance matching problems to water when used in an underwater transducer assembly. The high piezoelectric stress constant and low piezoelectric strain constant make the piezofilm highly voltage sensitive. The product of stress and strain constants is a measure of the figure of merit of hydrophones, which for piezofilms is approximately 2.5 times greater than ceramics.

I. DESIGN PHILOSOPHY

Most of the conventional transducers reported in the open literature\(^3\)\(^-\)\(^5\) utilize the (3,3) drive of vibrations, which makes use of the flexure and thickness modes of vibration. Of all the varieties of flexure mode designs, the simplest is the unimorph, which consists of a single piezoelectric layer bonded to a nonpiezoelectric substrate. The working principle of the flexure mode devices relies on the fact that the external applied force causes it to flex and which, in turn, produces inward and outward excursions in the planes of the active material, and these fluctuating strains will induce a corresponding potential difference proportional to the stress, across the surface of the active material. A multimorph has many layers of active material bonded between backing and radiating faces. In sandwich-type constructions a single disc or paired discs of piezoelectric materials will be packed between metal plates and placed under compression by means of stress bolts.

Due to the anisotropic nature of the piezofilms, the voltage generated for a particular acoustic pressure depends greatly on the mode in which it vibrates. It has been found that the voltage generated across the piezofilm can be increased by concentrating the acoustic pressure field to a much smaller cross-sectional area with the help of a modified structural assembly, resulting in the so-called (3,1) drive transducer.

The superiority of the (3,1) drive design over the conventional (3,3) drive can be further illustrated\(^6\) by considering the mode of vibration as a parameter of the piezofilm for a given acoustic pressure input.

The voltage generated in a piezofilm of length \(l\), width \(w\), and thickness \(t\), subjected to a compressive stress of \(T\) Newton per square meter distributed over its metallized surface is

\[ V_3 = g_{33} T l. \]

In the (3,1) drive of vibration the voltage output produced by the same input acoustic pressure can be computed as

\[ V_1 = g_{31} F / w. \]

<table>
<thead>
<tr>
<th>Film dimensions</th>
<th>Voltage computed in (3,1) drive</th>
<th>Voltage computed in (3,3) drive</th>
<th>The ratio of computed stress developed in the (3,1) drive to that in the (3,3) drive</th>
</tr>
</thead>
<tbody>
<tr>
<td>(5 \text{ cm} \times 1 \text{ cm} \times 28 \mu\text{m})</td>
<td>1.08 V</td>
<td>0.95 mV</td>
<td>1785</td>
</tr>
<tr>
<td>(4 \text{ cm} \times 2 \text{ cm} \times 28 \mu\text{m})</td>
<td>0.86 V</td>
<td>0.95 mV</td>
<td>1428</td>
</tr>
<tr>
<td>(3 \text{ cm} \times 3 \text{ cm} \times 28 \mu\text{m})</td>
<td>0.65 V</td>
<td>0.95 mV</td>
<td>1071</td>
</tr>
</tbody>
</table>

where $F$ is the force acting over the given metallized area, and $g_{31}$ and $g_{33}$ are the piezoelectric voltage constants for the piezofilm. Calculations reveal that the voltage generated in the $(3,1)$ drive will be much greater than that generated in the $(3,3)$ drive for a given force input. This sharp increase can be explained as due to the concentration of the applied force to a smaller cross-sectional area. Typical voltages computed for $(3,3)$ and $(3,1)$ drives for a given stress input of 100 N/m$^2$ are shown in Table I, along with the ratio of stress developed.

II. FORMULATION OF A TEST MODEL

By extracting some of the meritorious features offered by the $(3,1)$ drive of operation, a transducer was designed and fabricated with the help of a modified structural assembly which pulls the piezofilm in the direction of stretching. The cross-sectional view of the $(3,1)$ drive transducer showing the structural components of the system is shown in Fig. 1. The first practical sensor evolved for validating the performance of the $(3,1)$ drive system basically consisted of a perspex diaphragm of diameter 5 cm and of thickness 1 mm, which is firmly adhered to the main enclosure. The diaphragm vibrates in accordance with the incoming acoustic pressure field, and these vibrations are transferred to a prestretched film of length 5 cm, breadth 1.5 cm, and thickness 28 $\mu$m through a driver pin, which is rigidly fixed to the center of the diaphragm. The whole assembly is enclosed in a cylindrical chamber. The film is stretched by adhering one of its ends to the driver pin and the other to two spring-loaded screws. The film can be properly stretched by suitably adjusting these screws.

Perspex is a very light material and has a low spring constant; hence, it is not suitable for underwater applications such as a diaphragm material. Therefore, phosphor bronze, a material with a high spring constant, has been used as a diaphragm material for evolving the $(3,1)$ drive piezofilm underwater transducer.
A prototype version of the (3,1) drive transducer with the phosphor bronze diaphragm of diameter 5 cm and thickness of 1.8 mm has been constructed. Any acoustic pressure variations on the diaphragm is directly transferred to the film through a driver pin of length 1.5 cm. The piezofilm is prestretched by the spring-loaded screws, and the whole assembly is enclosed in a water-tight enclosure.

To facilitate the performance evaluation of the transducer at greater depths in water and also to reduce the attenuation of the signal due to high capacitance of the signal cable, a unity gain MOSFET buffer has been used with a cable length of 30 m.

III. EXPERIMENTAL SETUP AND MEASUREMENTS

To validate the performance in air, the sinusoidal signals from the signal generator are gated and are amplified by a power amplifier and fed to a loudspeaker, which acts as the transmitter. A standard B&K 8100 transducer is placed along with the experimental transducer at about 5 m away from the transmitter. The frequency was swept from 300 Hz to 3 kHz and the voltages generated in both the transducers were measured.

A comparison method has been used for computing the sensitivity of the experimental transducer. It utilizes the method of comparing the voltage generated in both the standard and the experimental transducers for a particular acoustic pressure, and the sensitivity has been calculated using

\[ S_e = S_s - 20 \log \left( \frac{V_s}{V_e} \right) \text{ dB re: } 1 \text{ V/μPa}, \]

where \( S_e \) is the sensitivity of the experimental transducer, \( S_s \) is the sensitivity of the standard transducer, \( V_s \) is the voltage output of the standard transducer, and \( V_e \) is the voltage output of the experimental transducer. Figure 2 shows the frequency response of the (3,1) drive transducer with the phosphor bronze diaphragm in air.

The water measurements were carried out at a dam site, with a floating platform, which can be anchored anywhere in the dam. The experimental transducer was dipped along with the standard B&K 8100 transducer at about 3-m depth. The underwater speaker UW-60 was used as the low-frequency projector, and it was placed at about 10 m away from the receivers at the same depth. The experimental setup was the same as that used for air measurements. The frequency was swept from 400 Hz to 2.5 kHz, and the sensitivity of the experimental transducer was computed by the comparison method. Figure 3 shows the frequency response of the transducer in water.

IV. RESULTS AND DISCUSSIONS

The frequency responses of the (3,1) drive piezofilm transducer shown in Figs. 2 and 3 clearly reveal that there is a considerable improvement in the receiving sensitivity at certain range of frequencies compared to the conventional ones. This improvement in sensitivity can be explained as due to the concentration of the force to a much smaller cross-sectional area.

The leak testing of the transducer has been performed by constantly immersing the transducer at 5-m depth in the dam for 3 days and revalidating its frequency response to a better level of accuracy within the tolerable limit of repeatability.

V. CONCLUSIONS

Low-frequency piezofilm transducers with improved performance have been evolved by utilizing the concept of concentrating the given force input to a much smaller cross-sectional area with the help of a modified structural assembly. Such types of (3,1) drive transducers can be effectively utilized for sonobuoy or other similar applications.

Attempts are being made to miniaturize the design so that the product will be more handy and compact.

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Correspondence

Development of a (3,1) Drive Multifilm Piezopolymer Hydrophone

J. Jagannath Bhat and P. R. Saseendran Pillai

Abstract—A modified (3,1) drive hydrophone design described here utilizes polarized piezopolymer films taut in the stretch direction by a reformed structural construction. It mainly consists of two opposed polymer films attached to a phosphor bronze diaphragm through a perspex structure. Enhancement in sensitivity is achieved, by connecting the films electrically in series thereby adding up the voltages developed across them due to a given acoustic pressure. The response of the hydrophone for individual films and for their series combination, are measured from 300 Hz to 4 kHz.

I. INTRODUCTION

Low frequency hydrophones are finding several potential applications, particularly for long range detection measurements and in sonobuoys. It was shown by many authors [1], [2] that polarized piezopolymers can be effectively employed as the transduction materials for the construction of transducers. The superiority of the polymers can be inferred from their high chemical resistance, high breakdown field strength, low density, low acoustic impedance, high sensitivity for vibration detection, low wear, high flexibility, easily obtainable film shape and low cost over its counterparts like ceramics. The piezoelectric stress constant is very high for piezopolymers compared to ceramics, which make the polymers suitable for hydrophone applications. The anisotropic nature of the piezofilm restrains the possible modes in which the piezofilm can be put to vibrate for better outputs. Of the different modes in which the piezofilm can be made to vibrate, most prominent one is the (3, 3) drive, which makes use of thickness or flexure mode of vibration. In the thickness mode the film is made to vibrate normal to its surface, whereas in flexure mode it is made to flex in accordance with the applied force, in both the cases the output is taken across the film surface. From the calculations it has been shown [3], [4] that the stretch mode vibration called (3, 1) drive will bring forth a higher output voltage than any other mode for a given acoustic input. A relatively higher output obtained in the stretch mode of vibration is the result of the increased stress the film experiences due to the concentration of the given force input to a much smaller cross-sectional area. Utilizing these properties, the hydrophone [4] designed to operate in the low frequency range was found to exhibit better sensitivity compared to the conventional ones.

II. DESCRIPTION OF THE IMPROVED DESIGN

A cross-sectional view of the improved design is shown in Fig. 1. A circular phosphor bronze sheet of diameter 5.5 cm and thickness 1 mm serves as the diaphragm for transferring the impinging acoustic energy to the active element. A perspex annular ring with sides threaded and a groove at the top for an 'O'ring, is fixed over a cylindrical enclosure. A perspex cap is made with its insideside threaded and a groove at the bottom for a second 'O'ring. The diaphragm is placed over the perspex ring with 'O' rings on both sides, and is tightened properly with the cap, so that the diaphragm is pressed uniformly. An opening of approximately 5 cm is provided at the centre of the cap for exposing the diaphragm to the external pressure field. A brass driver pin of length 2 cm and thickness 1 mm is fixed at the centre of the diaphragm. At the other end of the pin a 'T' shaped structure as shown in the figure is attached. This structure is made of perspex sheet of breadth 1 cm and thickness 1.5 mm, and is terminated with a rectangular perspex sheet of 1.5 cm x 1 cm, to which two polarized piezopolymer films of 5 cm x 1 cm x 52 μm are glued as shown. The films are stretched independently and the output is taken across them separately. When the diaphragm vibrates due to the incident acoustic pressure, the perspex structure will also vibrate. This will make one of the films to expand and the other to contract. Corresponding to these strains in the films, voltages will be developed across them simultaneously. The outputs can be suitably extracted with the terminal electrodes.

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A differential amplifier is also connected with the test transducer for reducing the attenuation of the signal due to high capacitance of the signal cable.

III. MEASUREMENTS AND RESULTS

The response of the hydrophone was measured in air and water for the individual films and for their series combination. To validate its performance in air, the sinusoidal signals from the signal generator were gated, amplified and then fed to a loud speaker. These signals were picked up by the test transducer along with a standard B&K 8100 transducer, which were kept about 5 m away from the transmitter. Comparison method [5] was adopted for computing the sensitivity of the test model. Fig. 2 illustrates the response of the hydrophone for individual films and for their series combination in the frequency range 300 Hz to 4 kHz.

Evaluation of performance of the hydrophone in water was carried out in a hydroelectric reservoir. ITT 1042 was used as the standard receiver and UW 15 as the transmitter. The frequency was swept from 300 Hz to 4 kHz, and the corresponding outputs of both the experimental and standard transducer were compared and the sensitivity was calculated. Fig. 3 depicts the response of the hydrophone for individual films and for their series combination.

IV. CONCLUSIONS

An improvement in sensitivity is observed when the films are electrically connected in series. This owed to the adding up of the voltages developed in the films due to the same acoustic input. It may be possible to increase the sensitivity further by connecting more films together. But it is to be quite noted that, when the number of films increases, the effective electrical impedance will also increase, which will eventually dampen the resultant output, if necessary precautions are not taken. This effect will be prominent particularly in the low frequency region.

REFERENCES


AIU: PLEASE PROVIDE PUBLICATION INFORMATION FOR REF. [5].
Design and development of refined (3,1) drive low-frequency piezofilm hydrophones

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A hydrophone design using polarized polyvinylidene fluoride film held taut and made to vibrate in the stretch direction by a modified structural assembly is described in this paper. In this refined design, the diaphragm which is the active face of the hydrophone is uniformly mounted on the enclosure using two rubber O-rings, thereby ensuring smooth transfer of energy from the diaphragm to the polymer film. An acceptable level of reproducibility is also achieved with this approach. A mathematical model for determining the resonance frequency of the (3,1) drive design is also proposed by considering it as an assembly of a circular plate loaded with a point mass at the center and having uniformly clamped contour. Experimental and theoretical results are in good agreement.

PACS numbers: 43.38.Ar, 43.38.Fx

INTRODUCTION

Polarized piezopolymers are getting wide acceptance as transduction materials in audio and ultrasonic applications. The appealing factors that led to the popularity of polymers include their high chemical resistance, high breakdown field strength, low density, low specific acoustic impedance, high sensitivity for vibration detection, low wear, high flexibility, easily obtainable film shape, and low cost over their counterparts such as piezoceramics and quartz materials. For piezopolymers the piezoelectric stress constant is high and piezoelectric strain constant is low which account for a higher voltage sensitivity. The product of piezoelectric stress and strain constants known as the figure merit of hydrophones is 2.5 times greater for piezopolymers than for ceramics. But the piezoelectric coupling factor is comparatively low for piezofilm and hence not usually recommended for projector applications.

The piezofilm is highly anisotropic and hence its electromechanical properties depend largely on the stretching direction and the mode of vibration. Most of the transducers using piezopolymers reported so far in literature are driven to utilize either a thickness or flexure mode of vibration. In the thickness drive the piezofilm is made to vibrate perpendicularly to its surface in accordance with the acoustic pressure variations, whereas in flexure drive the film flexes with the impinging pressure. The simplicity of these designs makes them most prevalent ones. But it has been found that the voltage generated across the piezofilm for a given pressure input can be increased by concentrating it to a much smaller cross-sectional area of the film, with the help of a modified structural design called (3,1) drive of vibration.

This paper is an extension of an earlier work in which the authors developed a (3,1) drive piezofilm hydrophone with improved sensitivity, making use of some of the advantageous features offered by the piezofilm when it vibrates in the (3,1) drive. This design basically consisted of a phosphor bronze diaphragm which was glued at the top of a cylindrical enclosure. One end of a small driver pin was rigidly fixed at the center of the diaphragm and a PVDF film of dimensions 5 cm x 1 cm x 28 μm was adhered to the other end. The film was fixed to the assembly with two spring-loaded screws and prestretched by properly adjusting these screws.

In this paper an attempt has been made to improve the reproducibility of the hydrophone by modifying the design, particularly the mounting of the active face of the hydrophone. As can be seen explicitly from the (3,1) drive design, one of the probable components which is likely to influence the overall performance of this transducer is the diaphragm, which is the only element exposed to acoustic pressure. A study is also undertaken for experimentally verifying the effect of diaphragm and film dimensions on the resonance frequency of the hydrophone. Mathematical support is also attempted in this paper by considering the hydrophone as having a diaphragm with clumped edges and a point mass at the center.

I. DESIGN

The principle of working of the hydrophone model described above is that acoustic pressure variations on the diaphragm are transferred to the taut film, resulting in the production of corresponding strains which develop charges on the surface of the film, and due to the metallic coating on its surface, the charges can be tapped through the terminal electrodes. Hence the active face contributes much to the transfer of vibrations from the medium to the active element. Therefore response of the hydrophone largely depends on the way in which the diaphragm vibrates, and for the consistent transfer of energy to the film, the diaphragm should have a uniform mounting. As the diaphragm was fixed with adhesives, it was very difficult to ensure a uniform mounting as well as a perfect sealing. Nonuniform diaphragm mountings lead to drastic variations in the hydrophone characteristics from piece to piece. Moreover, this type of mounting is not reliable because its stiffness and rigidity will dwindle due to aging and will result in the formation of cracks and flaws at the mounting surface. A uniform mounting along with a good water sealing is achieved by pressing the diaphragm between two rubber O-rings.
Figure 1 shows the cross-sectional view of the modified design. It basically consists of an enclosure over which a threaded Perspex annular ring is attached. The width of the Perspex ring is chosen to be approximately 1 cm, and a groove is provided at the top of this for the proper seating of an O-ring. A cap of Perspex with its inner side threaded and having an opening of approximately 5 cm at its center to expose the diaphragm to the external pressure is used to make the head assembly watertight. A groove is also provided at the bottom of this cap for the seating of second O-ring. The diaphragm is placed over the O-ring loaded Perspex ring and is tightened with the second O-ring on the threaded cap. One end of the driver pin is fixed to the center of the diaphragm and to the other end the polarized polyvinylidene fluoride (PVDF) film, as described in Ref. 5. The film is properly stretched, and the output is taken across the film through the terminal electrodes.

To ascertain the level of reproducibility that can be achieved with the refined design, and to investigate the effect of the diaphragm dimensions on the resonance frequency, three different sets of hydrophones with three similar pieces in each set were constructed. Table 1 shows their film, diaphragm, and O-ring dimensions in detail. Of the A, B, and C series hydrophones, in A and B the diaphragm dimensions are kept the same while the length of the film is varied, whereas in A and C the film lengths are same while the diaphragm dimensions are varied. To minimize the cable loss, a high input impedance MOSFET buffer amplifier is also connected very near to the hydrophone.

II. MEASUREMENTS AND RESULTS

The performance of these hydrophones was evaluated in water. The experimental hydrophone and a standard hydrophone were immersed to a depth of about 10 m in water and a low-frequency transmitter was kept about 10 m away from them at the same depth. The frequency response of the experimental transducer was studied using a comparison method by varying the frequency and comparing the outputs of both the standard and experimental hydrophones. Figure 2(a)–(c) depicts the frequency response for the A, B, and C series hydrophones.

All the three of A series behaved similarly in the region below resonance and had slight variations in their sensitivities thereafter, whereas in B series all but one responded similarly. The difference in its response can be explained as due to some structural inhomogeneities. It may be noted that for the C series there is no clear resonance, and also all the three behaved almost similarly. The reduction in sensitivity of the C series may be due to reduced exposed area of the diaphragm. However, the operating frequency range of the C series has been found to be enhanced.

III. ANALYSIS

For computing the resonance frequency of the design described, it is assumed that the compliance of the diaphragm is small compared to that of the other vibrating components in the model, so that the resonance frequency of the hydrophone is solely determined by the vibrational modes of the diaphragm. As the diaphragm is fixed over the enclosure with the edges clamped, and the driver pin attached at the center of the diaphragm, the whole assembly can be considered to be a circular plate with clamped edges and a point mass loaded at the center.

The frequency of vibration for different modes of a circular plate with free boundary was solved by G. R. Kirchhoff using Poisson–Kirchhoff theory and for the clamped edges by Rayleigh and Timoshenko using an energy method. The exact solution for the problem of vibration of a circular plate involves the use of Bessel functions. The Ritz method can be

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**TABLE 1.** Film, diaphragm and O-ring dimensions of the hydrophones.

<table>
<thead>
<tr>
<th>Transducer type</th>
<th>Film dimensions</th>
<th>Diaphragm dimensions</th>
<th>O-rings dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length x Width x Thickness</strong></td>
<td><strong>Diameter x Thickness</strong></td>
<td><strong>Diameter x Thickness</strong></td>
<td></td>
</tr>
<tr>
<td>A series</td>
<td>4.5 cm x 1 cm x 28 μm</td>
<td>6.0 cm x 1.2 mm</td>
<td>6.0 cm x 4 mm</td>
</tr>
<tr>
<td>B series</td>
<td>6.0 cm x 1 cm x 28 μm</td>
<td>6.0 cm x 1.2 mm</td>
<td>6.0 cm x 4 mm</td>
</tr>
<tr>
<td>C series</td>
<td>4.5 cm x 1 cm x 28 μm</td>
<td>3.0 cm x 1.2 mm</td>
<td>3.0 cm x 3 mm</td>
</tr>
</tbody>
</table>
TABLE II. Mass of the plate, the center mass, and corresponding values for \( \lambda^2 \) for a circular plate vibrating in the fundamental mode, with edges clamped and point mass at the center.

<table>
<thead>
<tr>
<th>Transducer type</th>
<th>Plate mass</th>
<th>Center mass</th>
<th>( \lambda^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A series</td>
<td>30 g</td>
<td>3.0 g</td>
<td>8.1</td>
</tr>
<tr>
<td>B series</td>
<td>30 g</td>
<td>3.0 g</td>
<td>8.1</td>
</tr>
<tr>
<td>C series</td>
<td>7.5 g</td>
<td>2.6 g</td>
<td>5.4</td>
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</tbody>
</table>

where \( \lambda_{ij} \) is a dimensionless parameter, which is a function of the mode indices \((i,j)\). \( D = Eh^3/12(1-\nu^2) \) is the flexural rigidity of the plate, \( E \) its Young's modulus, \( \rho \) the density, and \( \nu \) the Poisson ratio.

For the fundamental mode of vibration, \( i=0 \) and \( j=0 \). Hence the natural frequency of the circular plate with clamped edges is

\[
f = \frac{\lambda^2}{2 \pi a^2} \sqrt{\frac{D}{\rho h}},
\]

where

\[
f_{\text{water}} = \frac{f_{\text{air}}}{1 + (A_p/m_p)^{1/2}},
\]

\[
f_{\text{water}} = \frac{f_{\text{air}}}{(1 + 0.6689(\rho_w a/\rho h))^{1/2}},
\]

where \( m_p \) is the mass of the plate and \( A_p \) the plate added mass, which is a function of the plate geometry, boundary conditions, and mode number. The above equation can be simplified as

\[
E = 11 \times 10^3 \text{ N/m}^2.
\]

III. COMPARISON BETWEEN EXPERIMENTAL AND THEORETICAL RESULTS

The proposed \((3,1)\) drive transducer assembly can be assumed to be a vibrational system having a centrally loaded circular plate with clamped edges. In the case of a plate loaded at the center, the center mass will also contribute to the fundamental frequency, and the extent of influence can be taken into account by considering corresponding values of \( \lambda^2 \) knowing the ratio of the sum of the masses of the driver pin and the film to the mass of the diaphragm. Table II describes the mass of the diaphragm, the center, mass and the corresponding values of \( \lambda^2 \) for all the three series of the experimental transducers.

When the hydrophone is immersed in water, the water surrounding it will act as a load and hence there will be considerable variation in the fundamental resonance frequency of the hydrophone compared to that in air. By knowing the frequency in air \( (f_{\text{air}}) \), that in water \( (f_{\text{water}}) \) can be computed using

\[
\frac{f_{\text{water}}}{f_{\text{air}}} = \left(1 + \frac{A_p/m_p}\right)^{1/2},
\]

\[
\frac{f_{\text{water}}}{f_{\text{air}}} = \frac{1}{1 + 0.6689(\rho_w a/\rho h)}^{1/2},
\]

where \( \rho_w \) is the density of water.

Using the following values for the physical constants of phosphor bronze in Eq. (4), the resonance frequency in water for all the three series of hydrophones are determined by taking the mass of the plate along with that of the driver pin and film assembly, which is acting as the center mass:

\[
E = 11 \times 10^3 \text{ N/m}^2.
\]
TABLE III. Comparative study of the experimental and theoretical resonance frequencies.

<table>
<thead>
<tr>
<th>Transducer type</th>
<th>Experimental</th>
<th>Theoretical</th>
</tr>
</thead>
<tbody>
<tr>
<td>A series</td>
<td>1.00</td>
<td>1.11</td>
</tr>
<tr>
<td>B series</td>
<td>1.00</td>
<td>1.11</td>
</tr>
<tr>
<td>C series</td>
<td>3.50</td>
<td>3.614</td>
</tr>
</tbody>
</table>

\( \rho = 8.85 \times 10^3 \text{ kg/m}^3 \),
\( \nu = 0.38 \).

Table III is a collation of the experimental and theoretical results.

V. CONCLUSIONS

The hydrophones described above exhibit better levels of reproducibility and sensitivity, which enhances the adaptability of this design. Ease and simplicity are some of the prime features offered by this model, particularly for the low-frequency transducer applications. The dimensions of the film have little impact on the resonance frequency as can be inferred by comparing the responses of the A and B series. As can be seen from the response of the C series, the sensitivity of the (3,1) drive design depends on the effective exposed area of the diaphragm.

The resonance frequency of hydrophone is determined theoretically and compared with the experimental results. In order to check its validity, this was extended to diaphragms of 10-cm diameter and also for hydrophones having diaphragms of a different materials like stainless steel, aluminum, etc. It is also evident from this design that along with the mass of the diaphragm and central point mass, which is constituted by the driver pin and film, another probable component that may influence the resonance frequency is the stretching of the film, which may restrict the flexing of the diaphragm. In order to study its influence, the film was fully released and stretched in steps of smaller intervals. For each interval of stretching the resonance frequency is noted, and no marked difference is observed. Hence it can also be inferred that the compliance of the diaphragm is small compared to those of PVDF film and the tensioning spring.

ACKNOWLEDGMENTS

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6. Bruel & Kjaer, “Application notes on hydrophones—Their characteristics and applications.”