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REVIEW PAPER

Polymeric Piezoelectric Transducers for Hydrophone Applications

D.K. Kharat[1], Sandhya Mitra[2], Sania Akhtar[2] and Vijai Kumar[2]

[1]Armament Research and Development Establishment, Pune-411 021
[2]Central Institute of Plastics Engineering and Technology, Lucknow-226 008

ABSTRACT

Conventional ceramic piezoelectric materials have been used in hydrophones for sonar applications since 1940's. In the last few years since the discovery of polymeric piezoelectric hydrophones, the technology has matured, applications have emerged in extraordinary number of cases such as underwater navigation, biomedical applications, biomimetics, etc. Hydrophones are used underwater at high hydrostatic pressures. In the presence of hydrostatic pressures, the anisotropic piezoelectric response of ceramic materials is such that it has poor hydrophone performance characteristics whereas polymeric piezoelectric materials show enough hydrostatic piezoelectric coefficients. Moreover, piezoelectric polymers have low acoustic impedance, which is only 2-6 time that of water, whereas in piezoelectric ceramics, it is typically 11-time greater than that of water. A close impedance match permits efficient transduction of acoustic signals in water and tissues. Newly developed hydrostatic-mode polyvinylidene flouride (PVDF) hydrophones use a pressure-release system to achieve improved sensitivity. Recently, voided PVDF materials have been used for making hydrophones having higher sensitivity and figure of merit than unvoided PVDF materials.

Keywords: Piezoelectric materials, polymeric materials, PVDF, hydrophones, acoustic signal, pressure-release system, ceramics, voided PVDF, sonar, piezoelectric polymers, transducers

NOMENCLATURE

FOM_m	Figure of merit for the raw piezoelectric material
FOM_h	Figure of merit for the finished piezoelectric hydrophones
m_0	Open circuit voltage sensitivity (volts per unit pressure)
t	Thickness
g_{31}	Piezoelectric stress constant for the 31 coupling mode
g_{33}	Piezoelectric stress constant for the 33 coupling mode
g_h	Hydrostatic mode piezoelectric stress constant (is the sum of the uniaxial stress constants)
h_{33}	Piezoelectric stress constant in the thickness mode
c_{33}	Stiffness constant is the stress-to-strain ratio in the thickness direction when the sides are clamped
$\tan\delta_m$	Mechanical loss tangent
$\tan\delta_e$	Dielectric loss tangent
k_t	Electromechanical coupling factor
Q_m	Mechanical quality factor
g_h	Hydrostatic coefficient
Z	Acoustic impedance

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1. INTRODUCTION

A transducer is an electronic device that converts energy from one form to another for measurement of a physical quantity or for information transfer in sensing applications. The tremendous growth in the use of microprocessors has propelled the demand for sensors in diverse applications. Common examples include microphones, hydrophones, loudspeakers, thermometers, position and pressure sensors, and antenna[1].

A hydrophone is a microphone for acoustic measurements in fluids. It is the marine equivalent of the microphone, transforming underwater sound signals (pressure waves) into electrical signals. Hydrophones are commonly used to receive seismic echoes from explosive devices or other low-frequency acoustic signals. Hydrophones return a voltage that is proportional to the spatial average of acoustic pressure experienced at the active element. These are used in sonar apparatus and in certain underwater weapons. The same device may also be used to generate sounds, converting electrical energy to motional mechanical energy; in this capacity it is called a projector.

Piezoelectric materials are widely used in transducers, e.g., phonograph cartridges, microphones, and strain gauges, which produce an electrical output from a mechanical input, and in earphones and ultrasonic radiators, produce a mechanical output from an electrical input. Piezoelectric solids typically resonate within narrowly defined frequency ranges, when suitably mounted, these can be used in electric circuits as components of highly selective filters or as frequency-control devices for stable oscillators. The first practical application of piezoelectric ceramics for piezoelectric devices was sonar, for underwater navigation by submarines developed during world war I and in particular, after the Titanic sank in 1912.

2. HYDROPHONE DESIGN CONSIDERATIONS

2.1 Basic Design

Consider a rectangular solid with length, width, and thickness defined as 1-, 2-, and 3-axes respectively. Material is polarized along the 3-axis and electrodes are on the faces perpendicular to this axis. A stress applied along one or more axes will generate a voltage and many combinations of stress are possible, most hydrophone designs available are four stress combinations which are referred to as piezoelectric coupling modes.

These four piezoelectric coupling modes are 31 mode, 33 mode, hydrostatic (volume) mode, and thickness mode.

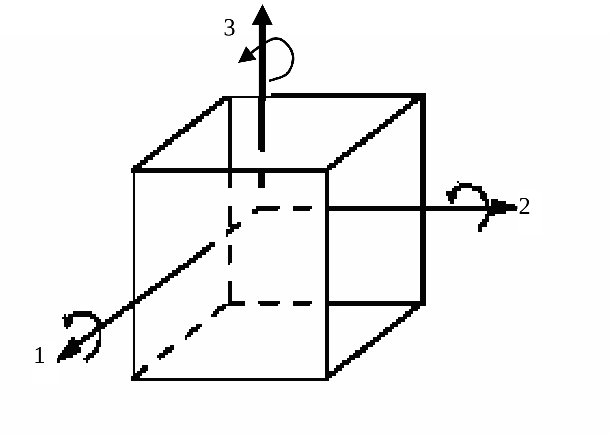

Figure. 1. Reference diagram.

31 Mode

Stress is applied only along the 1-axis. The 2- and 3-axes are free to move and no stress is applied on these. This requires a pressure-release system, which converts 3-D acoustic pressure into a 1-D stress, applied only along 1-axis, and keeps the pressure off the 2- and 3-axes. Bhat[1], *et al.* showed good sensitivity at a particular frequency suggested a 31 mode hydrophone. This is the simplest case mode where acoustic pressure acts directly on the 1-axis and the open circuit voltage sensitivity can be given by

$$m_0 = g_{31} \; t \;\; \text{(V/Pa)}$$

33 Mode

Stress is applied only along the 3-axis. The 1- and 2-axes are free to move and no stress is applied on these. This requires a pressure-release system which converts 3-D acoustic pressure into a 1-D stress applied only along 3-axis, and keeps the pressure off the 1- and 2-axes. This is the simplest case mode where acoustic pressure acts directly on the 3-axis and the open circuit voltage sensitivity can be given by

$$m_0 = g_{33}\ t\ \text{(V/Pa)}$$

Hydrostatic Mode

The hydrostatic (volume) mode uses no pressure-release system. It consists of a solid piece of piezoelectric material with attached electrical leads, encapsulated in a water-proofing elastomer. At lower frequency, where the hydrophone is small compared to a wavelength, the acoustic pressure creates equal stress simultaneously on all the three axes. From superposition, it can be shown that the hydrostatic mode piezoelectric stress constant (g_h) is the sum of the uniaxial stress constants.

$$g_h = g_{31} + g_{32} + g_{33}$$

The voltage sensitivity is given by

$$m_0 = g_h\ t\ \text{(V/Pa)}$$

In PZT ceramics, the g_{31} and g_{32} are of opposite sign to g_{33} resulting in an unusually low value of g_h and sensitivity. A few piezoelectric crystals have a higher g_h than PZT and are occasionally used in the hydrostatic mode as calibration standard hydrophones. Such hydrophones are stable with pressure and temperature because no pressure-release system is used. However hydrostatic mode crystal hydrophones are typically of small size, expensive, and have low sensitivity and capacitance compared to ceramic, and so these are not commonly used in sonar applications.

An outstanding advantage of polyvinylidene flouride (PVDF) is its relatively high hydrostatic mode response, with reasonably high sensitivity and capacitance, as well as simple hydrophone designs of large size and unusual geometry.

Thickness Mode

Thickness mode hydrophones are commonly used in ultrasonic transducers. The acoustic pressure is applied to all the three axes (as in the hydrostatic mode), but at high frequencies, only the 3-axis (the thin dimension) gets squeezed and generates a voltage. Along the 1- and 2-axes (the larger radial dimensions), the alternating acoustic pressure changes sign before it has a chance to propagate very far into the material radially. In effect, the disk becomes radially clamped, the boundary condition defines the thickness mode, in contrast to the free edge (pressure-released) 33 mode. If the frequency were lowered, the wavelength would become long even compared to the radial dimensions, and the disk would changeover to the hydrostatic mode, causing a change in sensitivity.

PVDF is generally laminated to a thin stiff plate, thereby laterally clamping the PVDF and causing it to operate in the thickness mode at low frequencies. Since the thickness mode requires a zero strain (clamped) rather than zero stress (free) boundary condition, the appropriate piezoelectric constant is the h_{33} stress constant.

The voltage sensitivity is given by

$$m_0 = h_{33}\ t/c_{33}\ \text{(V/Pa)}$$

Recently, the work done on design and sensitivity analysis[2] on PVDF-based hydrophones shows that the pressure capability and dynamic range of a clamped end-plate hydrophone are found to be higher than the simply supported plate hydrophone for the same pressure. The relative advantage found for clamped plate end is lost in considerable reduction in sensitivity for the same pressure. Desensitisation of a simply supported end hydrophone was found to takes place at higher depths, which is not a case with clamped end plate[3]. This favours the use of a clamped end-plate hydrophone since the sensitivity remains practically the same for all the depths of operation. The designer has to consider this factor. Further reducing the thickness of the plates at the edges can increase the sensitivity of a hydrophone.

3. DESIRABLE FEATURES OF LOW-FREQUENCY HYDROPHONES

General requirements and desirable features of low-frequency hydrophones are:

- Broad, flat frequency response
- High signal-to-noise ratio

- Low electrical impedance
- Low vibration noise
- Low-flow noise
- High static and dynamic pressure capabilities
- High uniformity (unit to unit)
- Low aging
- Low cost
- High reliability and long life.

3.1 Broad, Flat Frequency Response

The frequency response of a ceramic hydrophone is usually defined as the flat response region below the first resonance frequency. Most stiff ceramic hydrophones have a high resonance frequency, and therefore, easily meet the bandwidth requirement, but PVDF designs have a reduced bandwidth due to low resonance frequencies brought on by the low stiffness of material. New improved PVDF hydrophones whose resonances are highly mechanically damped have been designed, giving a relatively smooth flat response and resulting broad frequency response.

3.2 High Signal-to-noise Ratio

Low frequency hydrophones are frequently required to detect pressure levels at or below sea state zero (SSO), the quietest level in the ocean. Electrical noise in a receiving system includes the hydrophone thermal noise, preamplifier noise, cable microphonic noise, electrical cross noise and electromagnetic interference. Of these noise sources, only the hydrophone thermal noise is to be considered as it is directly affected by the hydrophone design and choice of the material for hydrophone[4-8].

A good measure of detectability of a flaw is its signal-to-noise ratio (S/N). The S/N ratio is a measure of how the signal from the defect compares to other background reflections (categorised as noise). A S/N of 3 to 1 is often required as a minimum. The absolute noise level and the absolute strength of an echo from a small defect depend on the following:

- Probe size and focal properties
- Probe frequency, bandwidth, and efficiency
- Inspection path and distance (water and/or solid)
- Interface (surface curvature and roughness)
- Flaw location wrt the incident beam
- Inherent noisiness of the metal microstructure
- Inherent reflectivity of the flaw (which is dependent on its acoustic impedance, size, shape, and orientation)
- Cracks and volumetric defects can reflect ultrasonic waves quite differently. (Many cracks are invisible from one direction and strong reflectors from another)
- Multifaceted flaws will tend to scatter sound away from the transducer
- Increases with increasing flaw size (scattering amplitude). (The detectability of a defect is directly proportional to its size)
- Increases with a more focused beam. (Flaw detectability is inversely proportional to the transducer beam width)
- Increases with decreasing pulse width (Δ-*t*) (Flaw detectability is inversely proportional to the duration of the pulse produced by an ultrasonic transducer. The shorter the pulse (often higher frequency), the better the detection of the defect. Shorter pulses correspond to broader bandwidth frequency response. Figure 1 shows the waveform of a transducer and its corresponding frequency spectrum.)
- Decreases in materials with high density and/ or a high ultrasonic velocity. (The S/N ratio is inversely proportional to material density and acoustic velocity)
- Generally increases with frequency. (However, in some materials, such as titanium alloys, the FOM terms in the equation change with rate with changing frequency. So, in some cases, the signal-to-noise ratio (S/N) can be somewhat independent of frequency.

3.3 Low Electrical Impedance

Another desirable quality of a piezoelectric hydrophone is its low electrical impedance (high capacitance). High-capacitance hydrophones can drive long lengths of cable with little sensitivity loss due to cable impedance. PVDF are the low-capacitance hydrophones, therefore placing an outboard preamplifier close to the hydrophone to drive the cable modifies it. Subdividing the electrodes and using appropriate series or parallel wiring combinations can further improve capacitance.

3.4 Low Vibration Noise

In addition to acoustic pressure, hydrophones also have an undesirable response to vibration and this energy is transmitted to the hydrophone through the mounting structures. Vibration response can be reduced using acceleration-canceling hydrophone designs, and by careful design of the mount. A typical acceleration-canceling method often used with PZT cylinder hydrophones is the nodal mount design, in which the cylinder is gripped exactly at the middle. An axial acceleration applied at the mount will then generate voltage contributions of opposite sign in the upper and lower halves of the cylinder, resulting in zero net voltage due to acceleration. However the voltage contributions from the acoustic pressure are of the same sign and do not cancel.

It is more difficult to maintain exact mechanical symmetry in the larger extended sensor designs so other methods are needed. PVDF drawn during manufacture has a very low g 32 constant. Therefore, a hydrostatic mode PVDF strip could be mounted so that its 2-axis is aligned with the direction of highest vibration, but unaffected acoustic response. Another example would be a laterally clamped (thickness mode) PVDF sheet with reduced 31-mode and 32-mode response (due to clamping).

3.5 Low-flow Noise

Flow noises are being reduced by moving the hydrophone away from the flow, usually by putting it in a large fluid-filled boot or sonar dome. Recent approach to reduce the flow noise is to use the hydrophones, which are much larger than the conventional sensors. These large hydrophones are also called extended sensors. Polymeric/composite type extended sensors can be made easily and relatively at a lower cost than the ceramic type. This ease of making large sensors have been the major advantage of PVDF over other hydrophones[9-11].

3.6 High Static and Dynamic Pressure Capabilities

Besides waterproofing, the distinguishing feature between a microphone and a hydrophone is that it must operate over a wide range of static and dynamic pressures without changing its sensitivity. Many sonar applications require up to 1000 psi (6.8 MPa) static pressure capability. Occasionally, for great water depth, up to 10,000 psi (68 MPa) static capability is required. Explosive shock requirements typically call out a dynamic pressure capability of 3500 psi (20 MPa) peak[12].

Such requirements frequently limit the design of pressure-released (stress amplified) PZT hydrophones because the static and peak pressures are also amplified and can build up to the fracture limit of the ceramic. Early thin–film PVDF hydrophones used pressure-release systems to achieve adequate sensitivity, and therefore, have lower pressure capabilities. New thick-film PVDF hydrostatic mode designs do not use pressure-release systems; therefore such designs are simpler and have high pressure capability. Voided PVDF are usable to 1000 psi (6.8 MPa) with about a 1 dB (12 %) reversible loss and no irreversible loss in sensitivity. Voided PVDF can withstand higher pressure in short pulses[12-15].

3.7 High Uniformity

Hydrophone sensitivity variations of only a few per cent strongly affect array side-lobe levels. Therefore, it is desirable to have uniform hydrophone elements. In case of ceramic hydrophones, each ceramic piece is individually fabricated and polarised. This individual fabrication and polarisation is subjected to batch-to-batch variation, which is a major problem in the transducer industry. To obtain high uniformity in ceramics, each piece must be measured and sorted. Continuous processing in case of PVDF sheets, rather than individual sheets, promises piece-to-piece uniformity.

3.8 Characteristics of Hydrophones

Hydrophones must be low aging, have long life, and should be strong enough to withstand high storage temperatures, high static pressure, explosive shock, and an underwater environment for as long as 10 to 15 years. Ceramic hydrophone designs basically meet these requirements but at a higher cost. The challenge for new technology including PVDF is to meet the requirements of lower cost than ceramic/PZT hydrophones[16,17].

4. MATERIALS FOR HYDROPHONES

4.1 Piezoelectric Ceramics

The piezoelectric properties were discovered in barium titanate in 1952. A family of ceramics made from lead zirconate and lead titanate are collectively known as PZT. Lead Zirconate Titanate (PZT) has been used in medical ultrasonic transducer design since 1970s. The advantages of PZT are its high electromechanical coupling coefficient in thickness mode ($k_t = 0.50$), high relative dielectric constant (600), and low mechanical loss tangent ($\tan \delta_m = 0.004$), and dielectric loss tangent ($\tan \delta_e = 0.002$).

For medical ultrasound transducers, the electromechanical coupling factor kt is one of the most important factors, which characterises the energy conversion in the thickness mode vibration, resulting in large acoustic power. Since the pulse echo-response amplitude strongly depends on k_t, the larger k_t contributes to the increase in the response amplitude to a great extent. The major disadvantage of PZT is its brittleness. Ceramic transducers have struggled with reproducibility and fabrication difficulties. Because of the high acoustic impedance of piezoceramic (34 MRayls) compared to human tissue (1.7 MRayls), there is an acoustic mismatch. Because of this mismatch, acoustic waves leaving the ceramic and entering the water/tissue are highly reflected, causing reverberations in the ceramic, leading to sharp resonant peak, resulting in narrow bandwidth. It also leads to an impulse response ringing for several cycles, and inefficient power transfer.

To improve these characteristics and increase the efficiency of the transducer, matching layers having intermediate impedances need to be placed between the ceramic and water/tissue, which further limits the bandwidth. The typical bandwidth attainable with PZT is about 60 per cent. PZT cannot be used in imaging transducer above 15 MHz due to difficulties in making and working with the very thin plate, which is very brittle. Furthermore, there are several issues in using single crystals for imaging transducers. There is a practical difficulty in growing the crystal without defects and with consistent properties within a piece, within a batch, and from batch to batch. The other issues are maintaining proper crystal orientation, avoiding chipping and cracking, achieving good electrode and adhesion, problems of depoling and repoling, etc. Although these materials can transmit a large amount of energy, these cannot transmit high bipolar voltage or voltages with incorrect polarity.

Once the above practical problems are resolved, single crystals may dominate the ultrasound industry due to their capability of giving simultaneous broad bandwidth and high sensitivity, which is the prime demand of the ultrasound world. As both the poly- and the single crystals are made of brittle materials, which limits their practical size for high frequency ultrasonic applications where thin wafers are required.

4.2 Piezoelectric Polymers

For many years, the need for flexible and large area piezoelectric materials for ultrasonic transducers was well recognised. The discovery of piezoelectricity in polymers in the early 1920s made this possible. The largest progress in this field was made in the 1960s with the discovery of piezoelectricity in PVDF. After this discovery, numerous applications of this polymer were reported and ultrasonic transducers have emerged as practical nondestructive evaluation (NDE) tasks. The existence of piezoelectric polymers was already known since 1924. Researchers also discovered that rolled films of polypeptides and numerous other polymers induce surface charges when stressed. A major milestone in this field was recorded in 1969 with the Kawai's discovery of the strong piezoelectric effect in (PVDF)[18]. Later, other PVDF co-polymers were also reported, including copolymer polyvinylidene fluoride-trifluoride (P(VDF-TrFE)) and polyvinylidene fluoride-tetrafluoride (P(VDF-TeFE)) and others.

Piezoelectric polymers used in polymeric hydrophone applications are PVDF, P(VDF/TrFE) and weaker effects are found with copolymer P(VDF/TeFE). PVDF is widely used in transducers. PVDF is a semicrystalline polymer. The first commercially available PVDF transducers were audio headphones and loudspeakers, which used thin film PVDF in the 31 mode. Chen and Payne[19] demonstrated the enormous range of applications for piezoelectric polymer materials, particularly for miniature underwater hydrophones[19].

PVDF exhibits non-polarisable form after cooling from the melt. The stretching changes the mechanical properties and density of the material. The dielectric and piezoelectric properties of PVDF are temperature-dependant. While the electromechanical coupling coefficient k_t is independent of temperature, the dielectric properties and mechanical loss tangent are temperature-dependant. When used in an imaging transducer, the centre frequency and bandwidth vary with temperature. The acoustic velocity of PVDF decreases approximately linearly with the temperature. So, the acoustic impedance and the resonance frequency of the imaging transducer made with PVDF decrease similarly with temperature. PVDF is highly flexible and thus allows application on curved structures. It can achieve large strain because of its high depolarisation field and high field strength against electrical breakdown.

PVDF is commercially available as thin films ranging from 4-110 µm thick except in special cases where much thinner/thicker films are made. Owing to poling difficulties, the thickest available film is usually 110 µm except in special cases where higher thickness films are made. The advantages of this material are that it is wideband, flexible, and inexpensive. PVDF (4 MRayls) is close to that of water (1.5 MRayl) and tissue (1.7 MRayl), the reflection at the interface between imaging transducer and the medium of propagation is minimised. Hence, matching layers are not necessary, thus preserving the intrinsic broadband property (mechanical quality factor $Q_m = 1/\tan\delta_m$) of PVDF. The property of large mechanical internal loss (mechanical loss factor $\tan \delta_m = 0.10$) of PVDF decreases the response time considerably and improves the sharpness of the response, thus contributing to widening the frequency bandwidth of the polymer transducers. The short impulse response leads to high spatial resolution capabilities in medical imaging[20,21]. Their low radial/lateral- mode coupling reduces the effects of edge waves and near-field distortions, which is typical of piezoceramic transducers.

Researchers have shown that planar PVDF transducers can produce plane wave performance in the acoustic near- field, which is superior to that of piezoceramics. The copolymer film has maximum operating/storage temperatures as high as 135 °C, while PVDF is not recommended for use or storage above 100 °C. Table 1 lists typical properties of a piezo film. Table 2 provides a comparison of the piezoelectric properties of PVDF polymer and two popular piezoelectric ceramic materials.

5. ADVANTAGES OF PVDF HYDROPHONES OVER COMMODITY HYDROPHONES

- Simplicity of design (no pressure-release system)
- Mechanical flexibility
- Ease of making hydrophones of unusual geometry
- Good acoustic impedance match to water
- Broad bandwidth
- Presumed good explosive shock resistance
- Potentially lower cost.

6. VARIETIES OF PVDF USED IN HYDROPHONE APPLICATIONS

6.1 Homopolymer

6.1.1 Low-draw Unvoided

The first thin film PVDF was low-draw unvoided and was the only PVDF available for several years.

6.1.2 Low-draw Voided

The first thick film introduced was low-draw voided, with higher FOM_m but also some pressure dependence due to voiding. This is currently the

Table 1. Comparison of piezoelectric materials.

Property	Units	PVDF film	PZT	*$BaTiO_3$*
Density	10^3 kg/m^3	1.78	7.5	5.7
Relative permittivity	e/e_0	12	1200	1700
d_{31} constant	(10^{-12}) C/N	23	110	78
g_{31} constant	(10^{-3})Vm/N	216	10	5
k_{31} constant	% at 1 kHz	12	30	21
Acoustic impedance	(10^6) kg/m^2-s	27	30	30

Table 1. Comparison of piezoelectric material parameters

Material property	Piezoceramic (PZT5H)	Piezo polymer (PVDF)
Transmitting constant *d* (10^{-12} C/N)	^{K}583	^{K}15
Receiving constant *g* (10^{-2} Vm/N)	^{K}1.91	^{K}14
Electromechanical coupling coefficient k_t	^{K}0.55	^{f}(0.15 … 0.2)
Free dielectric constant e^T (10^{-II} F/m)	^{K}3010	^{K}9.7
Clamped dielectric constant: e^s (10^{-II} F/m)	^{L}531	^{B}5
Acoustic velocity *c* (m/s)	^{K}3970	^{B}2200… ^{O}2260
Density p (kg/m^3)	^{K}7450	^{O}1780
Acoustic impedance (Z) kg/m^2-s*10^6	^{P}33.7	^{B}2200… ^{O}4.02
Electrical loss tangent tan d_e	^{L}0.002	^{O}0.25
Mechanical loss tangent tan d_m	^{L}0.004	^{O}0.1
Curie temperature (°C)	^{K}190	^{K}100
Typical –6dB fractional bandwidth	^{K}60 %	^{D}>150 %

most widely used homopolymer for low-frequency hydrophones[22].

6.1.3 *High-draw Unvoided*

A promising newer material is high-draw unvoided PVDF. This material has been shown to have improved FOM_m but without the pressure dependence[13].

6.2 Copolymers of PVDF

These materials have the advantage of not requiring drawing, resulting in lower cost processing and allowing hydrophone fabrication methods such as molding or coating unusual shapes. These materials tend to have FOM_m between voided and unvoided homopolymer. Being unvoided, these have little pressure dependence. The first copolymer introduced was VDF-TeFE (tetrafluoroethylene) with a temperature rating on the low side, about 60 °C. More recently, VDF-TrFE (trifluoroethylene) copolymer has been introduced with improved FOM_m and temperature limits in the 80 °C to 90 °C range.

7. TYPES OF PVDF HYDROPHONES

Low frequency hydrophones are divided into the following four major categories:

(a) 31 Mode hydrophones
  i. Membrane hydrophones
  ii. Flexural disk hydrophones
  iii. Flexural plate hydrophones
  iv. Compliant tube hydrophones
  v. Velocity hydrophones
  vi. Cylindrical hydrophones

(b) Hydrostatic mode hydrophones

(c) Thickness mode hydrophones
  i. Backed thin-film hydrophone
  ii. Stiffened thick-film hydrophone
  iii. ρ-c hydrophone
  iv. Shock sensors hydrophone

(d) PVDF hydrophones array

7.1 31 Mode Hydrophones

7.1.1 *Membrane Hydrophones*

The first commercially available PVDF transducers were audio headphones and loudspeakers which used thin film PVDF in the 31 mode.[23] The film was stretched over a frame like a drum head and backed by a compliant air cavity. Such devices are reciprocal and also work as microphones. As a microphone, acoustic pressure drives the membrane in and out, producing alternating stresses in the plane of the membrane. A voltage is generated due to 31 mode coupling. A mechanical bias (a slight concave or convex shape) is required to avoid frequency doubling of the output voltage, which occurs if the membrane passes through a flat geometry during any part of the ac stress cycle. The mechanical bias has typically been provided by filling the compliance chamber with compressed soft open cell foam, which pushed the membrane away from a flat equilibrium condition.

Some researchers introduced PVDF 31 mode membrane consisted of foam rubber pad enclosed by two circular PVDF sheets. The foam kept the sheets mechanically biased. The size was ~ 65 mm in diameter and 15 mm thick. Due to the stress amplification of the membrane mode, the sensitivity was 40 dB higher than a single sheet used in the hydrostatic mode; the capacitance was also very high, about 50 nf. The sensitivity and capacitance resulted in an outstanding high FOM_h.

Another membrane-mode transducer was developed by Sullivan and Powers[24] which consisted of a flat PVDF sheet, 40 mm in diameter, stretched over a cylinder capped metal compliance chamber. To provide mechanical bias, slight vacuum was applied to the air-filled chamber. This also had high sensitivity but was really a microphone because of essentially zero static pressure capability.

Researchers also developed another air-filled membrane transducer. This transducer had two membranes, 24 mm in diameter, one at each end of the cylindrical compliance chamber. An air hose connected to the chamber was used to set the mechanical bias and to change the focal length, presumably for ultrasonic experiments.

7.1.2 Flexural Disk Hydrophones

The fragility and complexity of the oil-filled membrane hydrophone led to the consideration of the more rugged and simpler flexural disk hydrophone, a design commonly used for PZT ceramic[25]. In this design, thin film PVDF sheets were glued to a thick plastic disk that was backed by an air-filled compliance chamber. In a flexural disk hydrophone, the disk compliance, not the chamber compliance, controls the acoustic sensitivity and static pressure limit. Analysis of this design is also given by Ricketts[26], which has two disks, each with four pieces of PVDF electrically connected in series to increase sensitivity. The disk was thick enough to withstand a static pressure of 4 MPa. The PVDF is so thin that it acts as a strain gauge, measuring the strains in the disk generated by flexure. The hydrophone was 40 mm in diameter, and sensitivity changed less than 1.5 dB between ambient and 4 MPa static pressure. This was probably the first PVDF hydrophone, which was rugged, had sea state zero noise performance, and could withstand high static pressure.

The work done by Holden[3], *et al.* studied the PVDF flexural disk, and investigated the sensitivity, change with static pressure caused by changes in the boundary conditions at the edge of the disk. Use of a tapered flexural disk and by making the diameter of the PVDF element smaller than the disk resulted in increased sensitivity.

7.1.3 Flexural Plate Hydrophones

PVDF flexural disk hydrophone was redesigned into a rectangular shape to meet the requirement for a sensitive hydrophone with a long thin shaped hydrophone[27]. Redesigned flexural disk hydrophone was 13 mm wide and 8 cm long. It consisted of two rectangular plastic plates machined such that an air-filled compliance cavity was formed when the plates were glued together around the periphery. The plates were grooved on all four sides to approximate simply supported boundary conditions. Analysis of design was carried out by Ricketts[28,29] and Laura[30]. Further work was done by Arthur Leissa[31].

7.1.4 Compliant Tube Hydrophones

A desire to simplify the design and lower the cost of the flexural plate hydrophone led to the compliant tube hydrophone[32]. Compliant tubes operate in the same manner as flexural plates, but are lower in cost because these are fabricated at a tubing mill in long length rather than individually machined like the flexural plates. The plastic spacer increases sensitivity by moving the thin film PVDF to a region of high strain, away from the neutral plane of the binding beam to where the strain is zero. The hydrophone was 1.5 cm wide and 10 cm long. This design had the advantage of the flexural disk with the rectangular geometry of the flexural plate. The steel compliant tube makes this hydrophone the lowest cost and simplest to build among all the flexural PVDF designs.

7.1.5 Velocity Hydrophones

This type of hydrophone is the dipole, which responds to particle velocity or pressure gradient. One common way to build velocity hydrophone is to use two monopole pressure sensors placed at distance *d* from each other and electrically difference the out voltage (wire them out of phase). Another way is to build a sensitive accelerometer in a large rigid case, the ends of which are distance *d* apart. The third way is the vane type of hydrophone which has the outstanding advantage of not requiring a pressure-release system or air-filled chamber. Compared to mono-poled pressure sensors, all velocity hydrophones have inherently inferior S/N ratio because these must sense the small difference between the two pressures (the pressure gradient) rather than the pressure itself.

Although any of the standard types of velocity hydrophones could be made from PVDF, only one PVDF design has appeared in the literature. It uses a PVDF bimorph strip, rather than the more usual ceramic bimorph, cantilevered from a stationary seismic mass. The advantage of PVDF is that it makes the bimorph strip highly complaint, which in turn increases sensitivity and also allows the seismic mass to be made relatively small[33].

7.1.6 Cylindrical Hydrophones

In this type of 31 mode PVDF cylindrical hydrophones, applied pressure squeezes the cylinder, inducing an amplified tangential strain that is sensed by PVDF wrapped around the circumference. Voltage is produced by 31 mode coupling. Ricketts[28] designed a hydrophone with complete equation, which consists of a thick-walled, end-capped, air-filled plastic cylinder with a layer of thin film PVDF mounted around the inside circumference. Hann and Harrell[34] compared all the four types of low-frequency cylindrical hydrophones. Other scientists such as Kilpatrick[35], Powers,[27] *et al.* and Fox,[36] *et al.* developed a cylindrical hydrophone with increased sensitivity using thick film PVDF.

7.2 Hydrostatic Mode Hydrophones

The strongest point of PVDF is the hydrostatic mode, which is superior to ceramics. PVDF was recognised early as having a relatively high hydrostatic coefficient g_h, a significant advantage but thin film resulted in a very low hydrostatic sensitivity. This problem was solved by Miller[37] in which a large single sheet of PVDF was electroded in parallel strips, the electrodes on one side overlapping neighboring electrodes on the opposite side of the sheet.

The introduction of thick-film PVDF changed the course of PVDF hydrophone development. One sheet of this thick material had the same hydrostatic sensitivity as a 32-layer thin film stack, or a single-layer 31 mode thin-film hydrophone, but without complications of laminating or designing pressure-release systems.

7.3 Thickness Mode Hydrophones

Thickness mode hydrophones have been popular for ultrasonic applications. These operate in the thickness mode even at low frequency due to the lateral clamping of the backing material.

7.3.1 Backed Thin-film Hydrophone

The first hydrophone of this type was a 6 mm x 18 mm backed thin film PVDF rectangle. It had a flat frequency response to 20 MHz. Similar single- layer backed ultrasonic hydrophones are a 15 mm OD disk by Woodward and Chandra[38], a 1.5 mm disk by Wilson[39], *et al.*, a 0.6 mm disk by Lewin[40], and a 0.3 mm needle by Platte[41]. Nakamura and Otani[42] studied surface elastic wave induced on backing material and diffraction field of a piezoelectric polymer film hydrophone. Howie and Gallantre[43] describe an ultrasonic sensor unit with several unusual features. The PVDF element has been made thick by laminating several layers of thin films. In addition, the element is shaped like a concave spherical mirror for ultrasonic focusing. Finally, the backing material is solid PVDF, providing good acoustic impedance match and minimising internal reflections. Koshigoe,[44] *et al.* studied a new technique for controlling noise transmission into a cavity using piezoelectric actuators on an elastic plate.

7.3.2 Stiffened Thickness Mode Hydrophone

As thick-film PVDF became available in 1979, Meyers[45] built a series of large hydrostatic mode thick-film hydrophones by encapsulating a single PVDF sheet in polyurethane. These hydrophones had the expected higher FOM_h due to the increased film thickness but the frequency response was unsatisfactory due to the presence of undesired low frequency resonances. This was overcome by laminating the PVDF sheet between stiffening plates, which flattened the frequency response by raising undesired resonances out of the frequency range of interest.

Ricketts[46] developed stiffened thick- film hydrophones by providing lateral clamping of the stiffening plates. These hydrophones really operate in the thickness mode rather than in the hydrostatic mode. Howie and Gallantree[43] developed the first thickness-mode hydrophone capable of low frequency sonar performance. Tancrell,[22] *et al.* designed stiffened thickness-mode hydrophone, which consists of two sheets of thick-film PVDF laminated to epoxy-glass stiffening plates. Theoretically, the transverse modes of vibration of the above composite polymer plate has been given by Ricketts[46].

Some researchers also described a shock-resistant cylindrical PVDF hydrophone. The frequency was flat and reasonably smooth, further the response was dependent on the acoustic coupling between the compression screw, rubber mandrel, and PVDF cylinder. The hydrophone was exposed to an explosive charge of > 3500 psi peak with no change in performance, which shows the ability of PVDF to withstand explosive shock.

7.3.3 Thickness Mode-ρ-c Hydrophone

Most PVDF hydrophone are not acoustically transparent because of the presence of a pressure-release system or backing material which is not ρ-c. An exception is the stretched membrane ultrasonic probes of DeReggi[7], *et al.* which are transparent at MHz frequencies because of small film thickness and the fact that the acoustic impedance of the (unvoided) PVDF used was only 2.7-time that of water. Mofet[47], *et al.* have reported a ρ-c PVDF hydrophone which was acoustically transparent at lower frequencies. The hydrophone consisted of a thickness mode PVDF element mounted on the end of fibre glass support rod with a nearby preamplifier. The element was a 2.0 cm^2 of PVDF, 0.33 mm thick, specially voided to have an exact ρ-c match to water. The waterproofing urethane and support rod were also carefully chosen to have a closer impedance match to water.

7.3.4 Thickness Mode-shock Sensor Hydrophone

PVDF has been investigated for use as a shock transducer or a blast gauge, to measure high amplitude pressure pulses of short duration. For a shock transducer, amplitude linearity and broad high frequency bandwidth are more important than sensitivity. Berlinsky[12] measured the linearity of thin-film PVDF. Meeks and Ting[14] measured the linearity of both thin and thick-films to pulses of peak amplitude of 80 MPa. Typical values were from 6 per cent to 8 per cent of theoretical, as compared to tourmaline, which was linear to 3.5 per cent. Meeks and Ting[48] built the PVDF shock sensor in which the disk of non-voided thick-film PVDF clamped between the steel retaining rings.

7.4 PVDF Hydrophone Arrays

One of the recognised potential advantages of PVDF was the idea of making large flexible hydrophone arrays from a continuous piece of piezoelectric material, rather than first building discrete hydrophone sub-assemblies. A large sheet of PVDF would be subdivided into hydrophone elements by selectively etching away the electrodes, much like a flexible printed circuit. The PVDF would also carry the wiring and preamplifiers. Although this particular concept was oversimplified, work has since been done towards building arrays from a single piece. Gallantree[49] describes a 360° surveillance sonar receive array, which is the first truly commercial PVDF sonar device made up of 100 element PVDF array mounted on a 300 mm dia ring.

Henriquez and Ting[50] described another example of PVDF hydrophone using large pieces of PVDF for array fabrication. Thick film PVDF strips, each 6 cm x 25 cm long were divided into four squares, and then laminated in a two-layer crosswise configuration, resulting in a 16 element array. Each element therefore consisted of two layers of PVDF with like electrodes facing, and wired in parallel for increased capacitance.

8. PIEZOELECTRIC POLYMER FILM PROPERTIES

Piezoelectric polymer film is a flexible, lightweight, tough engineering plastic available in a wide variety of thicknesses and large areas.

The properties of PVDF film as a hydrophone include:

- Wide frequency range–0.001 Hz to 10^9 Hz
- Wide dynamic range–10^{-8} to 10^6 psi or μ torr to M bar
- Low acoustic impedance–close match to water, human tissue, and adhesive systems
- High elastic compliance
- High voltage output–10-time higher than piezo ceramics for the same force input
- High dielectric strength–withstanding strong fields (75 V/μm) where most piezo ceramics depolarise
- High mechanical strength and impact resistance 10^9–10^{10} Pascal modulus
- High stability-resisting moisture (< 0.02 % moisture absorption), most chemicals, oxidants and intense ultraviolet and nuclear radiation
- Can be fabricated into unusual designs
- Can be glued with commercial adhesives.

9. CONCLUSION

One major advantage of piezoelectric polymer film over piezoelectric ceramic is its low acoustic impedance, which is closer to that of water, human tissue, and other organic materials. For example, the acoustic impedance of piezo polymer film is only 2.6-time that of water, whereas piezo ceramics are typically 11-time greater. A close impedance match permits more efficient transduction of acoustic signals in water and in tissue.

A practical wideband optical fibre hydrophone that offers a realistic prospect of overcoming the shortcomings of piezoelectric PVDF measurement technology has been developed. In terms of acoustic performance, its principal advantage lies in the favorable active element size-sensitivity ratio it offers. In its present form, it can offer a lower directional sensitivity (<10 MHz) than that of a 0.075 mm PVDF needle hydrophone but with detection sensitivity pressure comparable with that of a 0.2 mm PVDF hydrophone. Its potential to self-monitor changes in calibration and to detect temperature changes are also added advantages. An important feature is that it can be fabricated by depositing the polymer film-sensing element directly on to the end of the optical fibre. This enables a rugged sensor head to be batch-fabricated with good repeatability at low cost, thereby offering the prospect of a disposable hydrophone[51]. Much work has been done on wide band hydrophone by many researchers[52]. Piezoelectric polymers are associated with low noise and inherent damping, that makes these very effective receivers as well as broadband transmitters for high frequencies tasks, therefore polymer piezoelectric transducer are widely accepted for ultrasonic NDE applications[53].

The PVDF hydrophones, commonly used to measure the characteristics of ultrasonic transducers, suffer from a number of drawbacks. These disturb the field distribution to be measured and cause spatial averaging effects because of their finite aperture. In addition, these are delicate and susceptible to damage. To overcome some of these problems, many researchers have proposed the use of an optical fibre-based probe to measure the ultrasonic fields[54-59]. Fibreoptic ultrasonic sensor has been used to measure the characteristics of six transducers. Results obtained using the fibreoptic sensors are compared with those obtained using a calibrated PVDF needle hydrophone with an effective diameter of 0.5 mm. The response of the fibreoptic sensor shows excellent agreement with the results obtained using the PVDF needle hydrophone[60].

Researchers are continuously improving the capability of piezoelectric polymers, thus making these more attractive for commercial applications, including ultrasonic NDE. These applications span over industrial and medical applications. Piezoelectric polymers are associated with a low noise and inherent damping for receivers as well as broadband transmitters. Since the discovery of PVDF as a piezoelectric polymer, it is still the leading effective material and is being used to produce various types of hydrophones, including, array, focus, single pulser/receiver, etc.

REFERENCES

1. Bhat, J.J.; Thomson, P.P. & Saseendaran Pillai, P.R. Development of 3, 1 drive low-frequency piezofilm hydrophones with improved sensitivity. *J. Acoust. Soc. Am.*, 1993, **94**(6), 3053-056.
2. Raj, R.V.; Nagapranay, T.; Ravindra, V.; Lakshmana Rao, C.; Sivakumar, S.M. & Padmanabhan, C. PVDF-based hydrophone: Design and sensitivity analysis. *In* Proceedings of ISSS 2005 International Conference on Smart Materials Structures and Systems, 28-30 July 2005, Bangalore. pp. SB 45-52.
3. Holden, A.J.; Parsons, A.D. & Wilson, A.E.J. Flexural disk hydrophone using PVDF piezoelectric film: Desensitisation with increasing pressure. *J. Acoust. Soc. Am.*, 1983, **73**(5), 1858-862.
4. Lerch, R. Electroacoustic properties of piezopolymer microphones. *J. Acoust. Soc. Am.* 1981, **69**(6), 1809-814.
5. Young, J.W. Optimisation of acoustic receiver noise performance. *J. Acoust. Soc. Am.*, 1977 **61**(6), 1471-476.
6. Woollett, R.S. Procedures for comparing hydrophone noise with minimum water noise, *J. Acoust. Soc. Am.*,1973 **54**(5), 1376-379.
7. DeReggi, A.S.; Roth, S.C.; Kenny, J.M.; Edelman, S. & Harris, G.R. Piezoelectric polymer probe for ultrasonic applications. *J. Acoust. Soc. Am.*, 1981, **69**(3), 853-59.
8. Harris, G.R. Sensitivity considerations for PVDF hydrophones using the spot-poled membrane design. *IEEE Trans. Sonics Ultrasonics*, 1982, **SU-29**(6), 370-77.
9. Ko, S.H. & Schloemer, H.H. Flow noise reduction techniques for a planar array of hydrophones. *J. Acoust. Soc. Am.*, 1992, **92**(6), 3409-424.
10. Corcos, G.M. Resolution of pressure in turbulence. *J. Acoust. Soc. Am.*, 1963, **35**(2), 192-99.
11. Gilchrist, R.B. & Strawderman, W.A. Experimental hydrophone-size correction factor for boundary-layer pressure fluctuations. *J. Acoust. Soc. Am.*, 1965, **38**(2), 298-302.
12. Berlinsky, Y. Transduction with PVF2 in the ocean environment. Naval Research Laboratory, Washington D.C. 1980. iv, 32 p. : ill. ; 27 cm., NRL Report 8365, D 210.8:8365
13. JMcGrath, J.C.; Holt, L.; Jones, D.M. & Ward, I.M. Recent measurements on improved thick-film piezoelectric PVDF polymer material of hydrophone applications. *Ferroelectric*, 1983, **50**, 13-20.
14. Meeks, S.W. & Ting, R.Y. Effects of static and dynamic stress on the piezoelectric and dielectric properties of PVDF. *J. Acoust. Soc. Am.*, 1983, **74**(6), 1681-686.
15. Newman, B.A.; Chung, K.T. & DPae, K. Piezoelectric and pyroelectric properties of poly(vinylidene fluoride) films at high hydrostatic pressure. *Ferroelectrics*, 1981, **32,** p.135.
16. Wang, T.T. Aging behavior of piezoelectric poly(vinylidene fluoride) films irradiated byγ rays. *J. Polym. Sci.: Polym. Lett. Ed.*, 1981, **19**(6), 289-93.
17. Kolbeck, A.G. Aging of piezoelectricity in poly(vinylidene fluoride). *J. Polym. Sci., Polym. Phy.*, 1982, **20**(11), 1987-2001.
18. Kawai, H. The piezoelectricity of poly(vinylidene fluoride). Jpn. *J. Appl. Phys.*, 1969, **8**, 975-76.
19. Chen, Q.X. & Payne, P.A. Industrial applications of piezoelectric polymer transducers. *Measurement Sci. Technol.*, 1995, **6**, 249-67.
20. Wen, H.; Wiesler, D.G.; Tveten, A.; Danver, B. & Dandridge, A. High sensitivity fiber optic

ultrasound sensors for medical imaging applications. *Ultrason. Imag.*, 1998, **20,** 102-12.

21. Coleman, J.; Draguioti, E.; Tiptaf, R.; Shotri, N. & Sauders, J.E. Acoustic performance and clinical use of a fiberoptic hydrophone. *Ultrason. Med. Biol.*, 1998, **24**(1), 143-51.
22. Trancrell, R.H.; Wilson, D.T. & Rickets, D. Properties of PVDF polymer for Sonar. *In* Proceeding IEEE ultrasonics symposium, 16-18 October 1985, San Francisco. 624-29.
23. Tamura, M.; Yamaguchi, T.; Obaya, T. & Yoshimi, T. Electroacoustic transducers with piezoelectric high polymer films. *J. Audio Eng. Soc.*, 1975, **23**(1), 21-26.
24. Sullivan, T.D. & Powers, J.M. Piezoelectric polymer flexure disk hydrophones. *J. Acoust. Soc. Am.*, 1978, **63**(5), 1396-401.
25. Powers, J.M. & Sullivan, T.D. Flexural disk peizoelectric polymer hydrophones. *J. Acoust. Soc. Am.*, 1976, **60**. (SI), S47.
26. Ricketts, D. Performance prediction models for piezoelectric polymer hydrophones. *J. Acoust. Soc. Am.*, 1978, **64**(S1), S55.
27. Powers, J.M.; Corcella, A.T. & Crooks, R.E. Lightweight piezoelectric polymer hydrophones. *J. Acoust. Soc. Am.*, 1978, **64** (S1), S56.
28. Ricketts, D. Model for a piezoelectric polymer flexural plate hydrophone. *J. Acoust. Soc. Am.*, 1981, **70**(4), 929-35.
29. Ricketts, D. Electroacoustic sensitivity of composite piezoelectric polymer cylinders. *J. Acoust. Soc. Am.*, 1980, **68**(4), 1025-029.
30. Laura, P.A. & Avalos, D. Variational analysis of a model for a piezoelectric polymer flexural plate hydrophone. *J. Acoust. Soc. Am.*, 1983, **73**(4), 1378-383.
31. Leissa, Arthur. Vibration of plates. Acoustical Society of America, USA. 1993.
32. Powers, J.M. Multi-layered polymer hydrophone array. IEEE Electronics and Aerospace Systems Convention, Arlington, VA, United States Patent 4805157, 25-27 September, 1978, pp. 517-23.
33. Josserand M.A. & Maerfeld, C. PVF2 velocity hydrophones. *J. Acoust. Soc. Am.*, 1985, **78**(3), 861-67.
34. Hann, J. & Harrell, R. Analytical comparisions of four types of low frequency, cylindrical hydrophones. *Oceans*, 1973, **5**, 861-67.
35. Kilpatrick, J.F. Piezoelectric polymer cylindrical hydrophone. *J. Acoust. Soc. Am.*, 1978, **64**(S1), p. S56.
36. Fox, D.R.; Atkinson, E.B. & Penneck, R.J. An extruded acoustic sensor utilising a new piezoelectric cable. Paper presented at IEEE Ultrasonics Symposium, Williamsburg, VA, November 1986, pp. 603-06.
37. Miller, H.B. Piezoelectric polymer hydrophone. Abstract in *J. Acoust. Soc. Am.* 1983, **74**(4). pp.1320. U.S. Patent #4 376 302.
38. Woodward & Chandra, R. Underwater acoustic measurements on polyvinylidene fluroide transducers. *Electrocomp. Sci. Tech.*, 1978, **5**, 149.
39. Wilson, D.; Trancell, R.E. & Callerame, J. PVF2 polymer microprobe. *Ultra Symp Proc IEEE*, 1979, Cat No. 79CH1482-9SU pp.506-10.
40. Lewin, P. Minitaure piezoelectric polymer ultrasonic hydrophone probes. *Ultrasonics*, 1981, **19**(5), 213-16.
41. Platte, M. A polyvinylidene fluoride reedle hydrophone for ultrasonic applications. *Ultrasonics*, 1985, **23**(3), 113-18.
42. Nakamura Y. & Otani, T. Study of surface elastic wave induced on backing material and diffraction field of a piezoelectric polymer film hydrophone. *J. Acoust. Soc. Am.*, 1993, **94**(3), 1191-199.
43. Howie, P.A. & Gallantree, H.R. Transducer applications of PVDF. Ultrasonics Symposium 1983, 566-69.

44. Koshigoe, S.; Gillis, J.T. & Falangas, E.T. A new approach for active control of sound transmission through an elastic plate backed by a rectangular cavity. *J. Acoust. Soc. Am.*, 1993, **94**(2), 900-07.

45. Jones, S.M.; Carson, P.L.; Banjavic, R.A. & Meyer, C.R. Simplified technique for the calibration and use of a miniature hydrophone in intensity measurements of pulsed ultrasound fields. *J. Acoust. Soc. Am.*, 1981, **70**(5), 1220-228.

46. Ricketts, D. Transverse vibrations of composite piezoelectric polymer plates. *J. Acoust. Soc. Am.*, 1985, **77**(5), 1939-945.

47. Moffett, M.B.; Powers, J.M. & McGrath, J.C. A ρ c hydrophone. *J. Acoust. Soc. Am.*, 1986, **80**(2), 375-81.

48. Meeks, S.W. & Ting, R.Y. The evaluation of PVF2 for underwater shock-wave sensor application. *J. Acoust. Soc. Am.*, 1984, **75**(3), 1010-012.

49. Gallantree, H.R. A PMF array for a 360° scanning sonar. *In* Proceeding Ultrasonics Symposium IEEE, 0090-5607/83/0000-0757. 1983, 757-759.

50. Henriquez, T.A. & Ting, R.Y. Application of PVDF thick films in large-area hydrophone arrays. *In* Proceedings of 6th International Meeting on Ferroelectricity, Kobe. Japan *J. Appl. Phys.*, 1985, **24**(24-2), 876-77.

51. Beard, P.C.; Hurrell, Andrew M. & Mills, Tim N. Characterisation of a polymer film optical fiber hydrophone for use in the range 1 to 20 MHz: A comparison with PVDF needle and membrane hydrophones. *IEEE Trans. Ultrasonics, Ferroel. & Freq. Contr.*, 2000, **47**(1), 256-64.

52. Beard, P.C.; Perennes, F. & Mills, T.N. Transduction mechanisms of the Fabry-Perot polymer film sensing concept for wideband ultrasound detection. *IEEE Trans. Ultrason. Ferroelect. Freq. Contr.* 1999, **46**(6), 1575-582.

53. Bar-Cohen, Yoseph; Xeu, Tianji & Shyh-Shiuh. Polymer piezoelectric transducers for ultrasonic NDE. NDT Net 1996, **1**(9), 1-8.

54. Lewin, P.A.;Umchid, S.; Sutin A. & Sarvazyan, A. Beyond 40 MHz frontier: The future technology for calibration and sensing of acoustic fields. *J. Phy.: Conference Series I*, 2004, 38-43.

55. Staudenraus, J. & Eisenmenger, W. Fibre-optic probe hydrophone for ultrasonic and shock-wave measurements in water. *Ultrasonics*, 1993, **31**(4), 267-73.

56. Koch, C. Measurement of ultrasonic pressure by heterodyne interferometry with a fiber-tip sensor. *Appl. Optics*, 1999, **38**(13), 2812-819.

57. Wilkens, V. & Koch, C. Fiber-optic multilayer hydrophone for ultrasonic measurement. *Ultrasonics*, 1999, **37**(1), 45-49.

58. Uno, Y. & Nakamura, K. Pressure sensitivity of a fiber-optic microprobe for high-frequency ultrasonic field. Jpn. *J. Appl. Phys.*, 1999, **38**(1), No. 5B, 3120-123.

59. Beardand, P.C. & Mills T.N. Miniature optical fibre ultrasonic hydrophone using a Fabry-Perot polymer film interferometer. *Electronics Letter.*, 1997, **33**(9), 801-03.

60. Wu, Y.Q.; Shanker, P.M. & Lewin, P.A. Characterisation of ultrasonic transducers using a Fibroptic Sensor. *Ultrasound: Medicine & Biology*, 1994, **20**(7), 645-53.

Contributors

Dr D.K. Kharat is Scientist F at the Armament Research and Development Establishment (ARDE), Pune. He obtained his PhD (Materials Science) from the University of Pune. He has substantially contributed for the development of gun propulsion technologies, advanced composites, ultrasonic and acoustic emission, nondestructive techniques, and piezoceramic materials. He has published more than 70 research papers in national/international journals. He is a life member of the Materials Research Society of India, Aeronautical Society of India, Ultrasonic Society of India, High Energy Materials Society of India, and Indian Society for nondestructive testing. Presently, he is involved in setting up DRDO Centre for Piezoceramics and Devices at ARDE for newer electroceramics and devices for defence and civil applications.

Dr Vijai Kumar, Dy Dir and Head, Central Institute of Plastics Engineering and Technology, (CIPET), Lucknow, obtained his PhD (Polymer Science). He has been with CIPET since 1982. His research interests include: Biodegradable polymers, polymer blends and alloys, piezoelectric polymers, nano composites, and testing and characterisation of polymers.

Dr Sania Akhtar currently Chief Manager at CIPET, Lucknow, obtained her PhD (Rubber Technology) from the IIT, Kharagpur. Her research interest includes: Polymer blends and alloys, polymer nanocomposites, and characterisation of plastics.

Ms Sandhya Mitra obtained her MSc (Plastic Processing Technology. Presently, she is working as Technician in CIPET, Lucknow. She is involved in research on polymers and plastics.