The effect of backing material on the sensitivity of PVDF hydrophones at high frequencies.

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ABSTRACT

PVDF (polyvinylidene difluoride) piezoelectric film has many properties that make it attractive for underwater acoustic applications. In order to utilise these it has been necessary to understand some of the basic mechanisms affecting the performance of this material as an underwater sensor. In order to do this, hydrophones have been constructed using thick film (28 μm) PVDF elements which have been mounted on various substrates and encapsulated in polyurethane. The effect of the substrate shape and material on the sensitivity and directionality of the hydrophones has been measured at frequencies from 40 kHz to 100 kHz and their useability as an underwater sensor discussed.

INTRODUCTION

The piezoelectric effect in polymer Polyvinylidene Difluoride (PVDF) has been known for over forty years (Kawai 1969). Despite this, reports of its use as a low to mid-frequency underwater acoustic sensor is quite limited (Van Ransbeek 1991). Most of the research focuses on using PVDF in ultrasonic applications (Toda 2002, Fiorillo 1992, Bacon 1982).

PVDF has many properties that make it attractive for use as an underwater sensor; its acoustic impedance is close to that of water which minimises any diffraction effects commonly seen in ceramic hydrophones, it has a very flat frequency response over a very wide frequency range (10^{-3} Hz – 10^{9} Hz) (Measurement Specialities 1999) and its flexibility makes it ideal for attaching to various shapes and surfaces. The main drawback of this material as a hydrophone is its susceptibility to noise but provided adequate care is taken during construction this can be overcome.

Our main focus in using PVDF as a hydrophone is in the development of sound intensity sensors. Initial work began by fabricating a 1D vector sensor using two PVDF elements (Killeen 2009). The two PVDF films were attached to opposite sides of thin (2mm) PCB fibreglass board and encapsulated in polyurethane. Characterisation of this sensor showed some promising results however there were some unexplained features that were tentatively attributed to the effect of the PCB backing material. A 2D sensor has also been constructed where the four elements are separated by the polyurethane itself. Characterisation of this sensor is reported by Killeen (Killeen 2012) which again highlights the need to have a better understanding of the directionality of the PVDF elements themselves, the effect of the backing material that the PVDF is mounted on and the effect of the encapsulation material. This paper focuses on these issues by investigating the effect of fibreglass and aluminium backing materials on the sensitivity and directionality of PVDF films. It also makes a comparison of the effect of two different encapsulants on the sensor sensitivity.

METHOD

Sample preparation.

The PVDF films used for this work were purchased from Measurement Specialties Inc. (Measurement Specialties 1999). They supply a number of different films of various sizes and thickness. All results shown in this paper were done using the SDT1028 film. This film has been doubled over so that the silver electrodes provide a shielding effect from external noise. The effective thickness of the film is 56 μm with a length of 30 mm and a width of 13 mm. These films have significantly less noise issues than their DT series counterparts which are not doubled over. The films were co-centrically positioned in plastic moulds 30 mm in diameter. Polyurethane was poured into the moulds to waterproof the films resulting in sensors that were 80 mm long. Two types of polyurethane were used; (a) Robnor (b) Scorpion. The physical characteristics of these are given in Table 1. It was hoped that the acoustic impedance of these resins would be similar to that of water however it was not possible to obtain values for the sound speed in these two materials. From the specification sheets their hardness values appear to be quite similar but the Scorpion resin was considerably more elastic.

Table 1. Details of the two polyurethanes used for encapsulating the PVDF films. Obtaining the compressional sound speeds was not possible.

Polyurethane Resin	**Shore Hardness (A)**	**ρ(kgm^{-3})**
Robnor semi-rigid potting resin EL171C	90	1720
Scorpion two part flexible polyurethane SOL-RES 01	80-90	930

Four different sensors were prepared. These are listed below,

Sensor#1. Plain SDT1028 film, no backing material. Robnor polyurethane.

Sensor#2. Plain SDT1028 film, no backing material. Scorpion polyurethane.

Sensor#3. SDT1028 film on Aluminium backing (39mm x 30mm x 2mm), ρ= 2698 kgm^{-3}, c_p= 6374 ms^{-1}

Sensor#4. SDT1028 film on FR4 PCB Fibreglass (no copper) backing (39mm x 30mm x 2mm), ρ= 1850 kgm^{-3}, c_p= 2740 ms^{-1}(this is a generic value for fibreglass as it was not possible to obtain the actual value for FR4 PCB)

RESULTS

Each of the sensors above were characterised in a tank using a calibrated Reson TC4014-5 hydrophone. An ITC 1042 hydrophone was used to transmit a pulsed pure tone frequency situated equidistant from the PVDF sensor and the Reson hydrophone. The pulse tone consisted of a burst of 10 cycles at certain frequencies separated by a non-transmitting time of 1 sec. This ensured that only the direct path was analysed with no contributions from reflections from the surface and the tank. It was also ensured that the transient effects of the transmitter were minimised. The lowest frequency that could be used in this tank was 30 kHz. The PVDF sensor was rotated around its central axis through 360^o in increments of 10^o. The voltage of the PVDF sensor and Reson hydrophone were recorded at each position. The frequency was then incremented by 10 kHz and the procedure repeated up to f = 100 kHz.

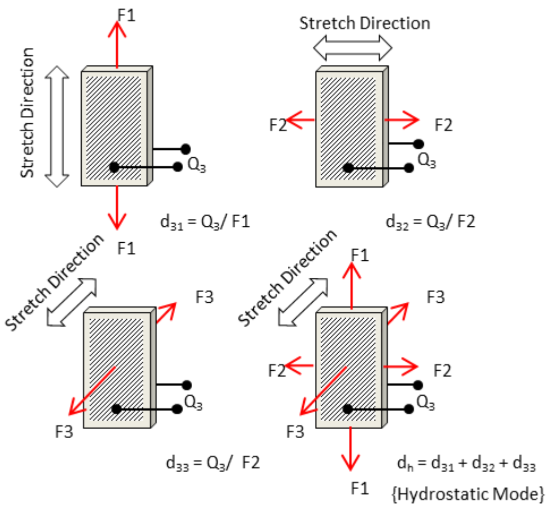

Figure 1. Schematic of the piezoelectric tensors associated with the three orthogonal directions of the film. d_{31} and d_{32} are both positive while d_{33} is negative (original diagram Tancrell 1985).

The open circuit voltage output V_0 of a film of thickness *l* under a stress T_n (in the direction n) with a piezoelectric stress coefficient g_{3n} is given by

$$V_0 = g_{3n} T_n l$$

Where g_{3n} (n=1, 2, 3) corresponds to the piezoelectric stress constant in the 1, 2 and 3 directions. These are shown in figure 1. The g and d (figure (1)) constants are related by the expression, $d_{ij} = \varepsilon\varepsilon_o g_{ij}$ where ε_o is the dielectric constant of free space and ε is the dielectric constant of the material relative to ε_o. Since the g constant is proportional to the hydrophone sensitivity it is more common to use these constants when defining piezoelectric materials used in hydrophone applications.

The piezoelectric stress constant of a film of PVDF subjected to pressure applied to all the surfaces (i.e. operating hydrostatically), is given by the tensor relationship,

$$g_h = g_{31} + g_{32} + g_{33} \qquad (1)$$

PVDF, like some conventional ceramic piezoelectric materialso has a negative g_{33} component with the other two components (g_{31} and g_{32}) being positive. This means that when the film is working in the hydrostatic mode (contributions from all three directions) the net total sensitivity of the film is reduced due to these opposite polarities. For PVDF films g_{33} = -0.330 V.mN^{-1}, g_{31} =0.216 V.mN^{-1} and g_{32} = 0.003 V.mN^{-1}. Since g_{33} and g_{31} are comparable in size this can have a dramatic effect on the overall sensitivity. Compared to g_{33} and g_{31}, g_{32} is so small that its effect can be ignored. It is therefore clear that in order to maximise the sensitivity of the PVDF sensor it is necessary to minimise either the g_{33} or the g_{31} contributions. For the sensors discussed in this paper it is expected that the three tensors in equation (1) will each be affected differently for various potting mixes and backing materials. For a piezoelectric material the open circuit sensitivity is given by (Moffett 1986),

$$M_o = 20\log|m_o| - 120 \qquad \text{(dB re 1V/µPa)} \qquad (2)$$

For frequencies where the dimensions of the film are much smaller than the wavelength (which is our case) the PVDF acts in a volume expansion mode where the volume expansion coefficient g_h is given by equation (1) and

$$m_o = g_h l \qquad (3)$$

In this case *l* = 56 µm. From equations (2) and (3) the smallest expected free field sensitivity (SES) expected for these films will be observed when all three components are contributing to g_h. This is estimated to be -226 dB re 1v/µPa. The case where g_{31} and g_{32} have been suppressed will result in the largest expected free field sensitivity (LES) achievable had has been estimated to be -218 dB re 1v/µPa.

Effect of polyurethane potting mixture

Figure 2 shows the sensitivity (M_o) as a function of frequency for the two films potted in Robnor (a) and Scorpion (b) polyurethane (Sensor#1 and Sensor#2). This is for the sound source at normal incidence to the large face of the film. The calculated smallest expected sensitivity (SES) and the largest expected sensitivity (LES) are shown in dotted lines on the plot.

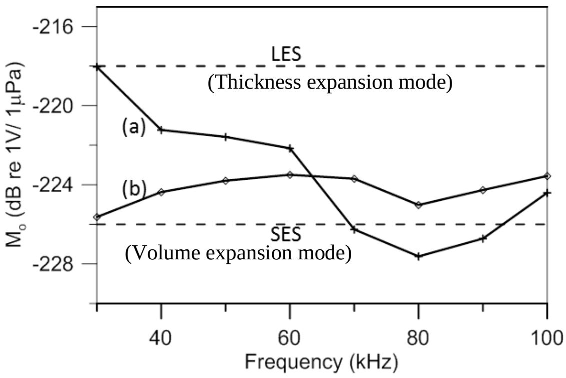

Figure 2. Sensitivity curves as a function of frequency for the two different polyurethane resins (a.Robnor, b.Scorpion) at normal incidence

As can be seen there is a significant difference in M_o for the two polyurethane resins especially at lower frequencies. The Scorpion resin appears to make the sensor respond more in the volume expansion mode (SES) over the entire frequency range. At 30 kHz, the Robnor resin sensor (a) has a sensitivity equal to the LES which suggests that it is responding in a thickness expansion mode (i.e. g_{33}). As the frequency increases its sensitivity decreases and drops below the calculated SES for the frequency range 70 kHz < f < 92 kHz. This is most likely due to the effects of the Robnor polyurethane which is not taken into account when calculating the SES.

Figure 3 shows the directionality plots of sensors #1 and #2 (Scorpion and Robnor resins) for frequencies from 30 kHz to 100 kHz. The sensitivity at the centre and outer radius of the circles is -250 and -210 dB re 1V/μPa respectively. As can be seen both sensors are quite directional even down to 30 kHz. The flat face of the film is facing the source at 0^o and 180^o.

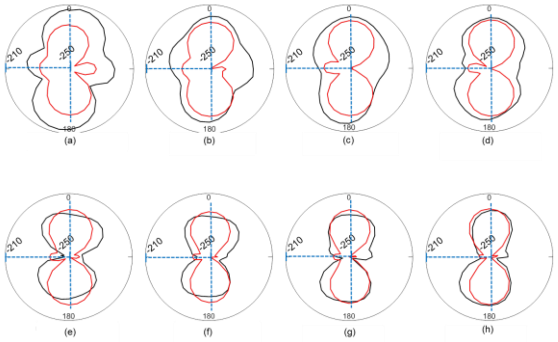

Figure 3. Directionality plots for sensor #1 (Robnor, black) and #2 (Scorpion, red) for f=30 kHz to 100 kHz ((a)→(h) respectively).

The largest differences in the sensitivity are observed for 30 kHz < f < 60 kHz ((a) to (d)). The presence of only one side lobe observed in the Scorpion sensor (red) could be due to slight misalignments in the film during construction but this would not explain the flip of the side lobe to -270^o observed at frequencies greater than 50 kHz.

Table 2 shows the beam widths (BW) $(2\theta_{-3})$ for sensors #1 and #2. As can be seen the BW for sample#2 has little variation with frequency whereas the sample#1 has quite large variations. The asymmetry seen in Figure 3(c) at f= 50 kHz resulted in two different BW shown in Table 2.

Moffett et. al. (Moffett 1986) successfully modelled the directionality of their PVDF sensor as a piston set in a rigid baffle. The total 3dB beamwidth for this can be approximated by (Urban 2002),

$$2\theta_{-3} \approx 52\frac{\lambda}{a} \qquad (4)$$

The beamwidths using equation (4) are shown in Table 2. Large discrepancies can be found at the lower frequencies where the PVDF samples are more directional than that predicted by the rigid baffle model. This could be due to mismatches of the acoustic impedance of the PVDF films (2.7M Nsm^{-3}) and the polyurethane resins with that of water.

Table 2. Total 3dB beam widths for samples #1 and #2 and those predicted from equation (4)

f (kHz)	**Beam Width** $(2\theta_{-3})^o$ **Sample#1 Robnor**	**Beam Width** $(2\theta_{-3})^o$ **Sample#2 Scorpion**	**Beam Width** $(2\theta_{-3})^o$ **eq. (4)**
30	54	55	200
40	50	58	150
50	79/48	57	120
60	76	49	100
70	99	51	86
80	91	53	75
90	78	48	67
100	70	47	60

Effect of backing material

In order to construct multi-element sensors using some form of scaffolding to hold the piezoelectric elements in place is unavoidable. It is very likely that this will have some effect on the sensor performance. To investigate this we attached PVDF to aluminium and fibreglass substrates and measured their sensitivities and directionalities. These correspond to sensors #3 and #4 above. Their sensitivities and directionalities were measured using the same method used for samples #1 and #2.

Figure 4 shows the directionality plots as a function of frequency for sensor #3 (aluminium). The black curves correspond to sensor #3 while the red curves correspond to the free PVDF film (sensor #1) both of which were encapsulated in the Robnor resin. It is clear that the aluminium backing has little effect on the overall sensitivities and directionality of the sensor. The main difference (which is not evident from the plots) is associated with the front to back ratio of the sensor sensitivity. When the aluminium is positioned between the PVDF film and the sound source there is attenuation in the sensitivity that varies as a function of frequency. This is shown in Figure 5. The dotted lines represent the maximum and minimum theoretical sensitivities for a free field film of PVDF as shown in Figure 2.

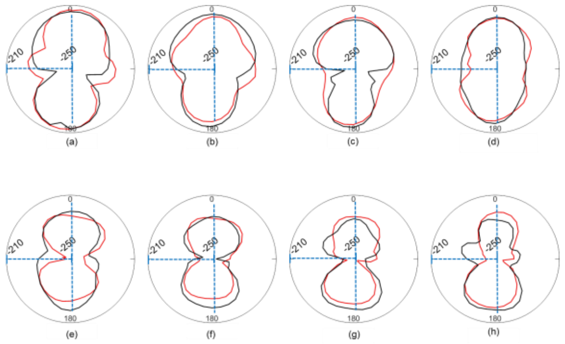

Figure 4. Directionality plots for samples #3 (aluminium, black) for f=30 kHz to 100 kHz ((a)→(h) respectively). The red plots show the directionality plots for sample #1 which is the plain PVDF film potted in the same Robnor polyurethane as sample #3.

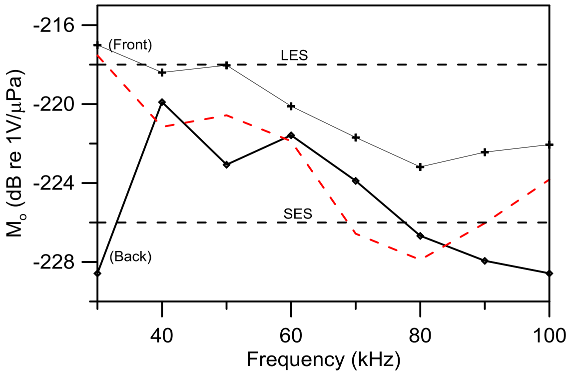

Figure 5. Sensitivity curves as a function of frequency for sample #3 at normal incidence. The top curve is for the sample at θ=0^o (ie directly in front of sound source) and the bottom curve is for θ=180^o (ie Aluminium is between the PVDF and the sound source (back)). The red curve is for sensor #1.

The red line represents the sensitivity curve for sample #1, the plain film potted in Robnor resin (Figure 2a) . This was the same polyurethane used to encapsulate sensor #3. When the sensor is positioned such that the aluminium substrate is between the PVDF film and the sound source the sensitivity of the aluminium backed film is very similar to that of the plain film (neglecting the value at f = 30 kHz). When the sample is rotated such that the PVDF film is in direct line with the sound source the aluminium substrate effectively increases the sensitivity of the sensor by approximately 3 dB for the entire frequency range. Similar effects have been reported by Sheman (Sheman 2007).

Similar measurements were conducted on the fibreglass mounted PVDF sensor (sensor #4). Figure 6 shows the directionality plot for this sensor. In this case the sensor is omnidirectional for frequencies less than 50 kHz and even at the higher frequencies the directionality has been drastically reduced. The cause for this is difficult to understand. One possibility is that it is due to the anisotropic sound speeds in the fibreglass substrate. Such anisotropy in the compressional sound speeds in similar materials has been reported by Sheman (Sheman 2007). Whether this omnidirectionality persists to lower frequencies needs further investigation.

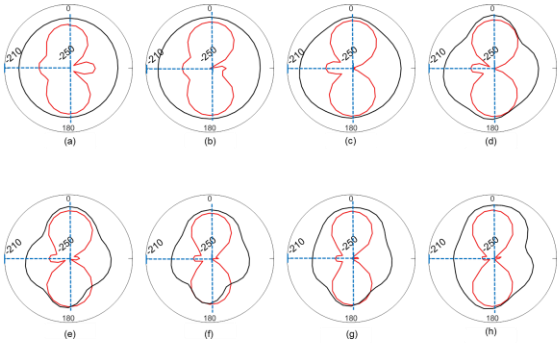

Figure 6 Directionality plots for sensor #4 (Fibreglass, black) for f=30 kHz to 100 kHz ((a)→(h) respectively). The red plots show the directionality plots for sensor #2 which is the plain PVDF film potted in the same Scorpion polyurethane as sample #4.

The front and back sensitivity curves as a function of frequency, for sample #4 are shown in Figure 7. The difference in the sensitivities gradually increases as the frequency increases. The red line represents the sensitivity of the plain PVDF film encapsulated in Scorpion polyurethane (sample #2) (Figure 2b). The smallest and largest expected sensitivities are shown in dotted lines.

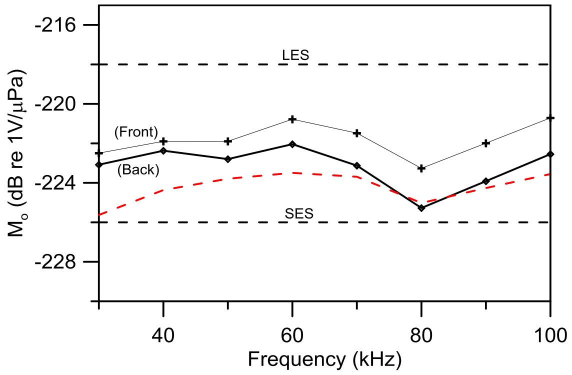

Figure 7. Sensitivity curves as a function of frequency for sample#4 at normal incidence. The top curve is for the sample at θ=0^o (i.e. directly in front of sound source) and the bottom curve is for θ=180^o (i.e. Fibreglass is between the PVDF and the sound source (back)). The red curve is for sensor #2.

CONCLUSION

Polyurethane resins and backing materials can have dramatic effects on the sensitivity and directionality of PVDF hydrophone sensors. Even polyurethane resins with similar hardness can have different effects on the sensor performance. Obtaining information about the acoustic impedance of these encapsulants has proven difficult. Future work will be done to measure these properties to gain a better understanding of the insertion loss mechanism of these materials and their role in the sensor performance.

Mounting PVDF films on thin substrates of aluminium has minimal effect on the directivity of the sensor. Some gain in sensitivity can be obtained from the aluminium provided that the PVDF film is directly facing the sound source.

Fixing PVDF film onto a thin fibreglass PCB backing drastically affects the directionality of the sensor so much so that for frequencies less than 50 kHz the sensor is omnidirectional. Further work needs to be done to investigate if this omnidirectionality persists at lower frequencies.

The piston set in rigid baffle model for modelling the directionality of a PVDF hydrophone, which was successfully used by Moffett (Moffett 1986) for their sensor, could not be used to model the frequency variation of the beam widths observed in our sensors. These discrepancies are probably due to the fact that the impedance of the polyurethanes and the backing materials are different from that of water. In Moffett's work his sensor had the same impedance as water.

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