Performance evaluation of a PVDF hydrophone for deep sea applications

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***Abstract*— The lack of penetration of light and electromagnetic radiation beyond a few meters in the ocean makes acoustics the technique of choice for data transmission, target detection and ocean sensing in general. Acoustic transducers are typically based on piezoelectric materials due to the good response at high frequencies. Depending on the application it can be built using ceramics, polymers and composite materials.**

In the hydrostatic mode PZT ceramics hydrophones have low performance due to the low hydrostatic piezoelectric stress value. On the other hand, PVDF have shown relatively high hydrostatic mode response. This work presents the development of a PVDF hydrophone for deep sea applications. The hydrophone was subjected to a pressure test up to 25 MPa to evaluate the response variation under high hydrostatic pressure. The results show an increase up to 6 dB sensitivity under 15 MPa pressure.

Keywords—deep-sea hydrophone; high pressure; PVDF hydrophone, acoustic transducer.

I. Introduction

Acoustic transducer designs (either projector or hydrophone) are dependent on the frequency band, beam pattern, acoustic power and operation mode. The ultrasonic transducer can be optimized to emit, receive or both, but definition of the operating frequency for a hydrophone or a projector have different meanings. Projectors usually take leverage of the resonance effect, using only drive signals at the resonance frequencies, where the highest acoustic pressure is delivered to the output. Hydrophones, on the other hand, are usually used below resonance frequencies, over a much wider frequency band [1]. There are several piezoelectric materials available for ultrasound transducers. The most common are the Lead Zirconate Titanate (PZT), Lead Titanate (PT), Lead Magnesium Niobate (PMN) and Lead Zinc Niobate (PZN) ceramics (polycrystalline [2] or single crystal [3]) and Polyviylidenefluoride (PVDF) and P(VDFTrFE) polymers [4].

One of the most common hydrophone designs for deep sea is the hydrostatic mode [6], where the hydrostatic piezoelectric stress constant is equal to the sum of the Piezoelectric stress constant for each coupling direction. In PZT ceramics, hydrostatic piezoelectric stress constants are of opposite sign resulting in a low value and sensitivity. This problem can be compensated by using a pressure release system.

On the other hand, some advantages of polymeric based piezoelectric materials are its relatively high hydrostatic mode response, simple hydrophone designs of large size and unusual geometry without the need for a pressure release system. [5] Recently, a new design of PVDF sonar array was presented by Woods Hole Oceanographic Institution for deep sea exploration [6].

This work describes the development and evaluation of a PVDF hydrophone for deep sea applications. The main objective is to evaluate the PVDF performance under high hydrostatic pressure and measure the sensitivity variations as a function of pressure. Ideally, in terms of transducer development such materials should present high piezoelectric modulus, low dielectric constant, low elastic compliance coefficient and low acoustic impedance.

This paper is organized as follows: Section 2 summarizes the hydrophone design considerations. Section 3 describes the pre-amplifier implementation. Section 4 describes the experimental setup and respective results. Finally, in Section 6, are drawn some conclusions.

II. Hydrophone design

The common used piezoelectric materials for acoustic transducers are the ferroelectrics, such as the PZT, PT, PMN and PZN [7], where hydrostatic piezoelectric stress constants are of opposite sign in different coupling directions, resulting in an unusually low value and sensitivity, reducing the operational depth [8]. Therefore, it is necessary to find other piezoelectric materials that meet the special needs of the deep sea. Case study piezoelectric materials are the Polyvinylidene fluoride (PVDF) [9], Poly(vinylidene fluoridetrifluoroethylene) (P(VDFTrFE)) [10], Polytetrafluoroethylene (PTFE) [11] and Polypropylene (PP) [12]. These materials show several advantages over piezoceramics, such as being lead free, low acoustic impedance (close to water), high elastic compliance, high mechanical strength and impact, high stability-resistance to moisture, can be fabricated into unusual flexible designs without the need for a pressure release system [13], high power efficiency [14], high frequency [4], larger bandwidth [15] and high hydrostatic mode response [16]. In terms of piezoelectric coefficients the polymer materials have some disadvantages, but PTFE has demonstrated

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in some publications values up to 2000 pC/N [11] and PP up to 600pC/N [12], PVDF up to 34pC/N and P(VDFTrFE) up to 11pC/N [17]. The PTFE shows the higher piezoelectric coefficient of the 4 materials, but also has a microporous structure which is not suitable for high pressure applications [18], nevertheless PVDF and P(VDFTrFE) has a solid structure with a very high young modulus (up to 10GPa).

The hydrophone dimensions must respect a delicate relation between the desired characteristics. To increase the sensitivity, it is necessary to increase the active element thickness and useful area, however the increase of these characteristics affect other characteristics, such as: increasing the thickness leads to a decrease in operating frequency while increasing the area leads to a decrease in acceptance angle. Another important aspect is the multilayer structure, if all active element layers are placed with the same polarity orientation, the hydrophone will be sensitive to pressure waves and to deformations by bending. But, if the multi-layer structure were assembled with half of the layers oriented with the inverse orientation of the other half, the hydrophone would only be sensitive to pressure waves.

Therefore, considering the main objective of using the PVDF at high hydrostatic pressures, it was decided to use a thin-film hydrophone in the d_{33} mode design with only two layers of 50 µm PVDF with inverted polarities and an acceptance angle of 70°x20° at 76kHz, which resulted in the dimensions 5.7 by 2.1 cm and 100 µm final thickness.

III. PRE-AMPLIFIER

Due to the PVDF low piezoelectric coefficient the electric charge generated by the pressure waves, the electric current generated by the active element will be in the range of tens of nanoamperes, which is not suitable for direct measurement made by a conventional oscilloscope. Therefore, a transimpedance pre-amplifier it was to implement with the specifications presented in figure 1. It was selected an Op Amp LT1169 since has a typical bias current of 4 picoamperes.

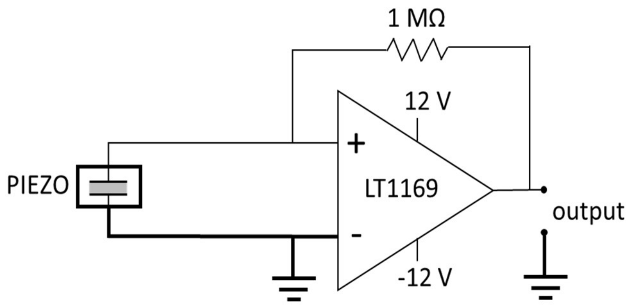


Figure 1:Pre-amplifier circuit based in a transimpedance amplifier with an Op Amp LT1169.

The preamplifier has to be used as close as possible to the PVDF active element in order to reduce signal losses and interference by external noise.

IV. HYDROPHONE IMPLEMENTATION

Being a hydrophone for the deep sea, it was necessary to project the hydrophone so that the final result was a solid block without joints and air gaps. Thus, a skeleton was developed in PLA with 155x60x8 mm dimensions using a 3D printer, as presented in figure 2, to support the PVDF films, preamplifier and the cable in place, then the skeleton is filled with polyurethane UR5041RP.

Figure 2:PLA skeleton to support the hydrophone parts in place until the polyurethane stays solid.

The polyurethane UR5041RP form ELECTROLUBE [19] was selected due to the following characteristics:

- Excellent resistance to sea water; ideal for marine environments;
- Good low temperature performance; suitable for use down to -60°C;
- High toughness and tear resistance; offers good physical protection;
- Excellent oxidation resistance; high performance in a range of challenging environments;
- Relatively low acoustic impedance.

Figure 3 presents the hydrophone prototype final result.

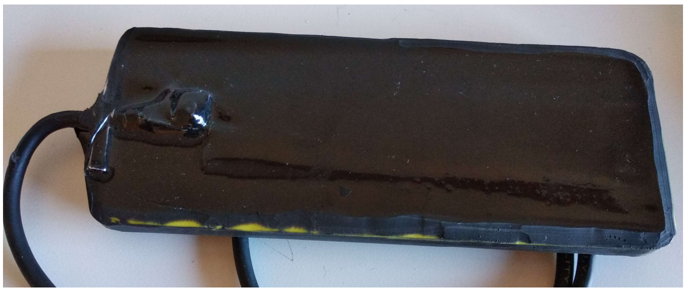


Figure 3: Hydrophone prototype as a solid block to withstand the high pressures.

The polyurethane coat provided the mechanic robustness require to protect the PVDF and the pre-amplifier for the handling, chemical and mechanic aggression from the sea water.

V. EXPERIMETAL SETUP AND RESULTS

The PVDF hydrophone experimental performance evaluation was made in a 25 MPa pressure chamber, designed specifically to test electric components and materials to high pressure environments. Figure 4 shows how the components where placed inside the pressure chamber.

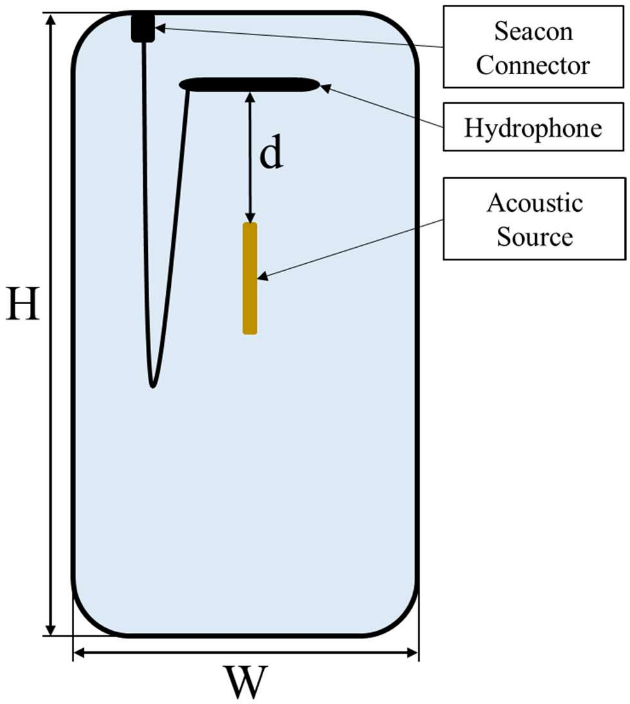


Figure 4: Component arrangement inside the pressure Chamber for the hydrophone evaluation under high pressure.

For the pressure test it was used a steel chamber with 2 m height (H) and 60 cm diameter (W), the acoustic source was placed at 10 cm (d) from the hydrophone and the hydrophone was positioned along the top cover. Figure 5 shows a photograph of the hydrophone and acoustic source placement.

Figure 5: Experimental setup for the hydrophone evaluation under high pressure tests, up to 25 MPa.

The acoustic source used was a Sonotronics Equipment Marker Transmitter EMT-01-2 (the yellow cylinder in figure 5). With a maximum operational depth of 2,5 km and a 3km distance range, the emitter sends a burst of 76 kHz, with period of 1120ms. To connect the hydrophone to the outside, for power supply and signal acquisition, it was available a seacon wet-connector [20] with 12 contacts. For further analysis a digital oscilloscope PicoScope 4227 100 MHz was used to record the measurements.

The hydrophone absolute sensitivity is unknown since it has not yet been made an open circuit voltage response (OCV) with a calibrated instrument. Therefore, will be measured the relative sensitivity as a function of the hydrostatic pressure in order to evaluate variation of performance with increasing pressure. The hydrophone experimental relative sensitivity evaluation was implemented in two cycles from 0.5 to 25 MPa and in each cycle the pressure was increased in 1 MPa steps and in each cycle end the pressure was released softly. Figure 5 presents the sensitivity variation as function of the hydrostatic pressure.

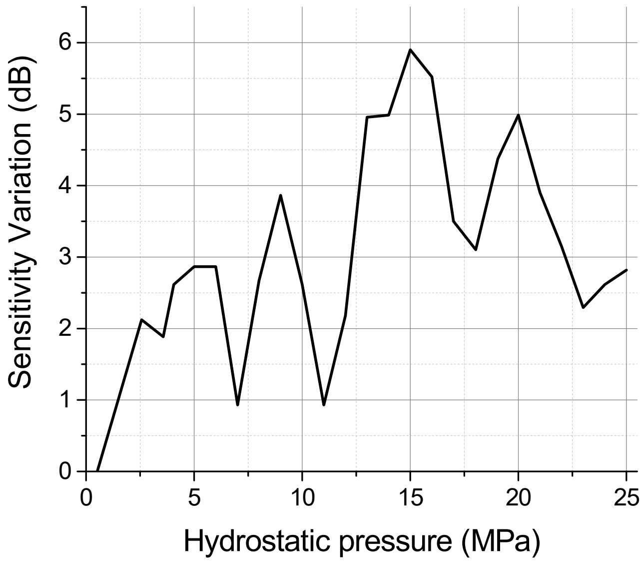
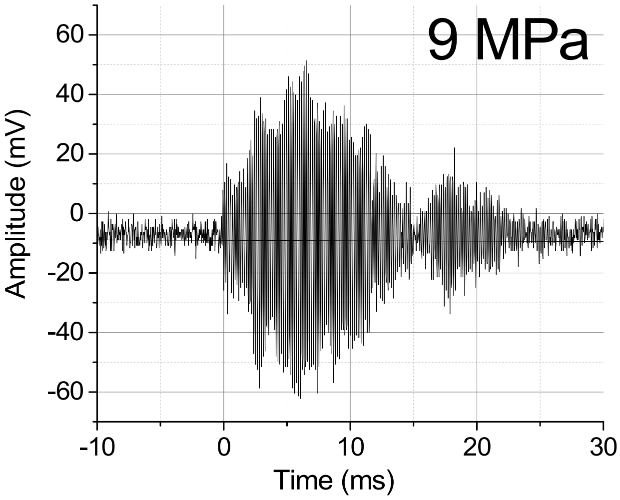
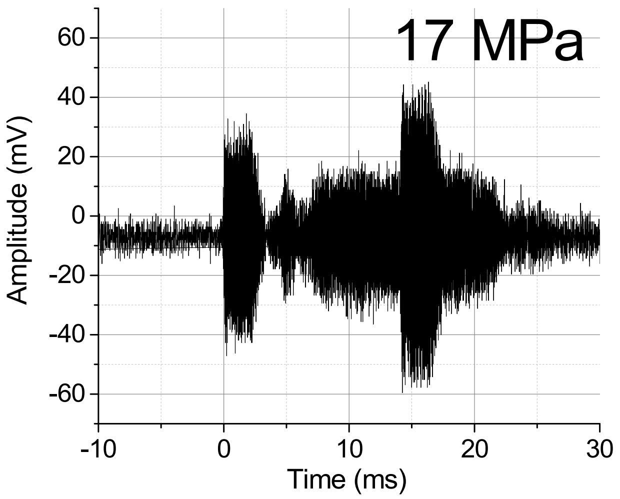


Figure 6: Experimental evaluation of the PVDF hydrophone sensitivity variation as a function of the hydrostatic pressure.

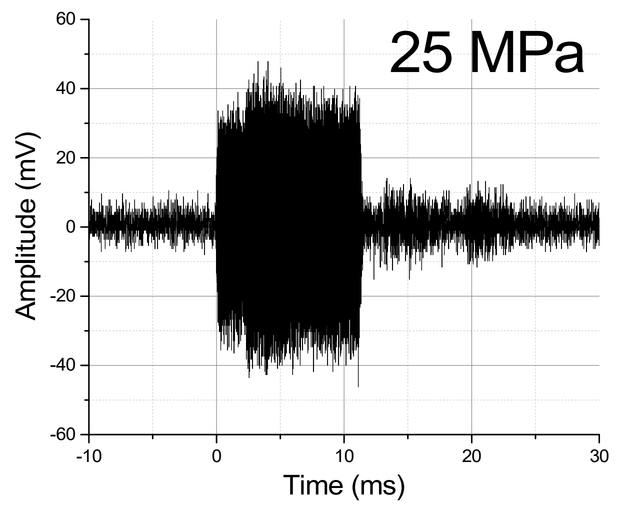
Figure 6 shows that the acoustic sensitivity tends to increase as the hydrostatic pressure increases, reaching an increase of 6 dB. The increasing pressure leads to a reduction in attenuation and an increase in the speed of sound. This leads to performance improvement of the hydrophone, however inside a camera also leads to an increase in echoes with variation of signal amplitude due to the signals overlapping as presented in figure 7.



(a)



(b)



(c)

Figure 7: Signal overlapping comparation for 9 MPa (a), 17 MPa (b) and 25 MPa (c) pressure.

Figure 7 shows that the signal received by the hydrophone changes with pressure due to signals overlapping and may help to justify increased sensitivity. In addition, the acoustical source may also be a potential source of this variation. Nevertheless, the most relevant finding is that PVDF does not show a degradation of its piezoelectric characteristics as the hydrostatic pressure increases. The experiments also demonstrate the resistance of the preamplifier to pressure.

VI. Conclusions

This work presented the development and evaluation of a PVDF hydrophone for deep sea applications. The main objective was to verify the PVDF structural integrity and the evaluation of the relative sensitivity of the PVDF hydrophone under high hydrostatic pressures.

The test showed an increasing of the relative sensitivity with increasing pressure, which may be caused by various types of interference. However, in this test it was not possible to verify the main reason for the relative sensitivity variances. Further experiments will include two acoustic sources and two hydrophones placed in different positions in order to analyze the echo formation. Will be also included reflector surfaces to redirect the echoes.

In conclusion it was possible to verify that the PVDF does not show piezoelectric characteristics degradation with increasing hydrostatic pressure, as well as the resistance of the preamplifier to pressure.

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