Development of a high-power multilayer PVDF acoustic projector for 40 to 80 kHz band

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***Abstract*— A piston type projector using the PVDF piezoelectric polymer was developed for operating in underwater environment, below 100 kHz. For those frequencies PZT piezoelectric ceramic is usually a preferable choice and PVDF is only considered for frequencies above a few hundreds of kHz. This paper will show that efficient underwater acoustic projectors for frequencies below 100 kHz can be implemented regarding an appropriate impedance adapter is being used. The developed project presents a calibrated transmitting voltage response (TVR) of approximately 166, 160 and 175 dB at 40, 50 and 75 kHz, respectively. The PVDF TVR values are compatible with the PZT projectors available on market with the advantage of having a larger bandwidth than most PZT projectors. To the authors knowledge this is the first time that a PVDF projector attain such characteristics. Although theoretically the PVDF projector bandwidth is larger than 40 to 80 kHz, in practice it was observed that only between those frequencies the project presents a stable operation for the transmission of long-term signals.**

Keywords*— *piezoelectric projector, underwater acoustics, broadband acoustic projectors, PVDF projectors, impedance adapters

I. INTRODUCTION

Current transducer projector technology is a limiting factor in Underwater Acoustic Communications (UWAC), as most modern acoustic projectors are based on piezoelectric ceramic such as PZT [1]. These ceramics are used because they have excellent piezoelectric strain constants, meaning they are good at transducing electric energy into acoustic energy [2]. However, PZT also have a high mechanical quality factor, which reduces their effectiveness as acoustic projectors outside of a narrow bandwidth centered around their resonant frequency, making them highly susceptible to noise interference [3] when used for broadband applications. In addition, PZT also presents a poor phase coherence, which is a limiting factor for coherent UWAC, and the energy transference from the ceramic to the underwater medium is also limited.

To better utilize the available bandwidth, and increase UWAC's robustness against underwater noise, new projector technology is necessary. PVDF has been well researched as an acoustic sensor since its discovery in 1969 [4]. However, its low piezoelectric strain constant has meant it has often been considered unsuitable for projector applications in the underwater environment, as this property limits the force a projector can impart upon the medium, and thus the amplitude of the acoustic pressure wave it can generate [5]. Transducer-projectors constructed using PVDF also have significant challenges related to coupling the projector's piezo elements' impedance to the front-end electronics. However, PVDF has a low acoustic impedance, close to the one of water, and a low mechanical quality factor which give it an excellent bandwidth response, suitable for UWAC or other broadband applications.

Despite its potential benefits, most of the PVDF acoustic projectors for underwater applications reported in the literature where developed for frequencies above 200 kHz, as is the case of 200-1000 kHz in [1]. This paper will detail the development and calibration of a PVDF projector prototype with a large bandwidth, operating at frequencies below 100 kHz. This was achieved with a multilayer structure of 16 layers, which enable an applied voltage of 2 kV which is convenient since the projector acoustic pressure generated is proportional to the applied voltage. These features allow the projector to overcome some of the limitations of PVDF's piezoelectric properties by allowing greater applied voltages to the projector elements, while maintaining the desirable wide bandwidth of the material.

The paper is organized as follow: section II makes a brief state of the art of PVDF projectors; section III describes the projector system namely the PVDF transducer and the electronic

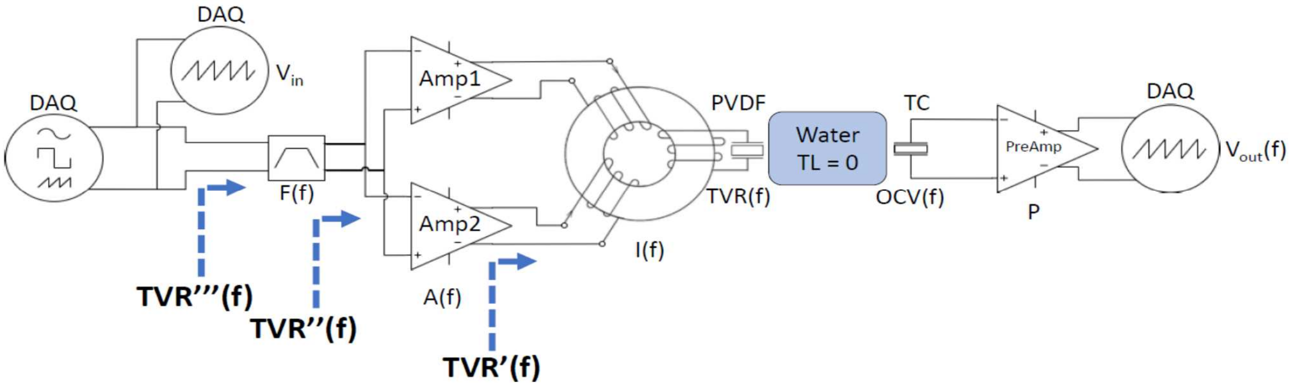

Fig. 1. *Diagram of the PVDF projector system when connected for the calibration operation with a calibrated TC4033 hydrophone. From left to right we have: the DAQ (MC-USB1602) output signal generator and the, channel 1, input signal acquisition; the passband filter with FR, F(f); the amplifier stage with FR, A(f); the impedance adapter with FR, I(f); the PVDF projector with transmitting voltage response, TVR(f); the 1 m of water required for calibration where the transmission loss (TL) is considered to be zero since the TVR is measured by definition at 1 m from the source; the calibrated hydrophone, TC 4033, with the corresponding sensitivity, OCV(f); the charge amplifier ETEC-CA1702; and the DAQ, channel 2, received signal acquisition. TVR', TVR'' and TVR''' represents the transmitting voltage response seen from different stages of the projector system.*

parts; section IV presents the projector calibration results; and section V states some conclusions.

II. STATE OF THE ART OF PVDF PROJECTORS

PVDF has been studied quite extensively as a sensor for a variety of roles since its discovery in 1969 [6], [7, p. 41]. As an acoustic projector, however, its use has been relatively limited due to its low piezoelectric strain constant, which has limited its commercial use to high frequency (usually above 1 MHz) applications where PZT is less suitable [5], [8], [9]. This piezoelectric strain constant determines the amount that a PVDF piezo element deflects under a given voltage differential, and thus the amplitude of the acoustic pressure wave generated. Consequently, PVDF has frequently been considered unsuitable as a material for underwater acoustics projectors and there are few examples of its use as a projector in the sub 500 kHz range [10]. However, some exceptions exist, and the literature includes attempts from the late 1970s onwards [8], [10], [11]. Single-layer methods were broadly unsuccessful, as single layers of PVDF cannot generate sufficient force to be effective projectors, as these single layers cannot tolerate applied voltages above their breakdown voltage to generate the force required unless they are very thick, which lowers their resonant frequency and makes them extremely difficult to manufacture [5, Sec. 1.1], [11], [12]. Multi-layer methods, however, have been more successful. The use of multiple layers of PVDF stacked together and connected electronically allows for a greater force to be generated by the PVDF transducing elements, and thus a greater amplitude of the pressure waves generated at the transducer head, which generally preserve the single-layer bandwidth properties [5], [8], [11], [12]. However, to our knowledge, the electronic and mechanic design for operating at frequencies bellow 100kHz has not yet been established yet.

A recent resurgence of interest in the use of PVDF as a material for acoustic projectors has focused mainly on its use at high frequency for wideband acoustic communications. In this application, PVDFs low density, low acoustic impedance and consequent reduction in ringing effects makes it an interesting material for UWAC [5]. However, significant challenges still exist regards performing the electrical impedance matching of the PVDF piezo elements to front-end electronics [16]. Making PVDF's use viable in the field of UWAC requires the further development of multilayer structures and other electrotechnical techniques to overcome PVDF's piezoelectric limitations. This could be achieved by designing systems that are more efficient at delivering electrical energy to the piezo elements through impedance matching, so as to maximize the acoustic pressure generated by the projectors. Additionally, these impedance matching techniques also open the possibility of adapting the resonance frequency of the transmission system to the requirements of a particular operation or in response to environmental noise, increasing the robustness of the UWAC system to this kind of noise.

III. THE PROJECTOR SYSTEM

This section will present the design considerations for the construction and assembling of the PVDF acoustic projector as well as the electronic circuit requirements namely in terms of impedance adaptation and amplification.

Figure 1 shows the diagram of the PVDF projector circuit when connected for the calibration operation with a calibrated TC4033 hydrophone. In this section only the left part, relative to the projector system will be considered. From write to left the projector system comprises: (i) the PVDF acoustic projector/transducer; (ii) an up-voltage impedance adapter; (iii) two parallel power amplifiers; (iv) a band pass filter.

The assembly process for the projectors began with the treatment of the PVDF piezo elements, which comprised discs of PVDF cut from sheets. These discs had a diameter of $0.07\ m$, and a thickness of $t_p = 28\ \mu m$. The electrical impedance (resistance and capacitance) as a function of frequency of each disc is then determined with a LCR-meter and used for planning the impedance adaptation to the electronic circuit which comprises amplifiers and filters.

A. The PVDF transducer

The acoustic transducer was implemented with polyvinylidene difluoride (PVDF) which is a piezoelectric polymer. Piezoelectric materials are able to convert an applied voltage signal into a vibration. Usually, at high voltages, the projectors operate in the thickness mode which means that the signal voltage and the vibration occur in the same direction, the thickness of the material. The maximum particle displacement is given by

$$\delta_{max} = d_{33}.V_{max} \tag{1}$$

where V_{max} is the maximum voltage applied to a single layer, and d_{33} is the piezoelectric coupling coefficient. When compered with PZT this coefficient is typically 15 times smaller, and that is the main reason why PVDF is not the preferable choice for building acoustic projectors for frequencies bellow 100 kHz. For compensating such limitation, a multilayer structure was adopted thus resulting a maximum displacement of

$$\delta_{max} = d_{33}.V_{max}.n \tag{2}$$

where n represents the number of layers. However, the number of layers cannot be increased infinitely and is limited by the inequality from [1]

$$n\,t_p \leq (2\pi\, c\, \rho\, S_{33}^{E}\, f)^{-1}. \tag{3}$$

where, considering the used PVDF characteristics, $t_p = 28\ \mu m$ is the thickness of the PVDF layers, $c = 2250\ m/s$ is the sound speed, $\rho = 1470\ kg/m^3$ is the density, $S_{33}^{E} = 0.472\ nPa^{-1}$ is the elastic compliance coefficient and $f = 80\ kHz$ the frequency of the applied voltage, it results that for the 16 layers used the inequality (3) becomes $4.48\ 10^{-4} \leq 13.0\ 10^{-4}$. More layers could be used, but since the prototype was in-house implemented mostly in a handcraft manner it was preferring to leave a comfortable distance from the limit.

Electrically the multilayer structure can be built either in series or parallel. Figure 2 shows two examples of multilayer structures: on the left side we have 2 PVDF layers electrically connected in series, and on the right side we have 4 PVDF layers electrically in parallel. The black/red lines represent the PVDF layers with the black representing the negative pole and the red the positive pole, the blue line represents the backplane and the green line an isolation layer. The backplane is required for reflecting the back-propagating wave back to the water side thus increasing the pressure wave applied into the water. Although the mechanical effects of both structures are similar, their electrical characteristics, that is, the impedance, are different. The multilayer series connection increases the resistance and decreases de capacity and the multilayer parallel connection makes the opposite, thus resulting that the parallel connection needs more current to be driven and the series connection needs more voltage. After experimenting different configurations, the parallel connection was discarded for the final prototype implementation since the increase in current can easily overheat the PVDF stack which could be a huge problem since PVDF is a polymer that deforms easily in presence of high temperatures.

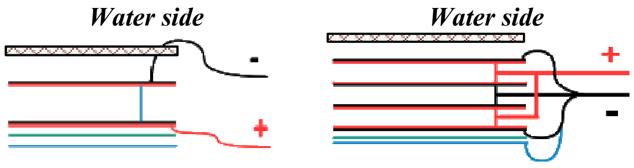

Fig. 2. *Example of multilayer structures: (left) 2 PVDF layers electrically in series; (right) 4 PVDF layers electrically in parallel. The black/red lines represent the PVDF layers with the black representing the negative pole and the red the positive pole, the blue line represents the backplane and the green line an isolation layer; on top, between the PVDF stack and the water the potting compound interfaces the PVDF and the water.*

The vibration generated at the projector propagates to the water as pressure waves, that travel in space and time. However, due to the acoustic impedance difference of the two media, the energy of the produced vibration is partially reflected (back) to the projector [2]. Typically, the reflectivity, the amount of pressure that is reflected, in PZT is around 88% while the PVDF is around 29% [1]. Such reflectivity does not take in account the potting compound that interfaces the PVDF piezo and the water as represented in Figure 2. For having a good transference of vibration from the PVDF to the water the potting should have an impedance value between the water impedance and the PVDF impedance. Since the acoustic impedance is given by $Z = c\,\rho$ and the potting manufactures does not provide the values of sound speed neither the impedance, the potting was selected experimentally and the ElectroLube SC3001 silicone was chosen. The criteria for choosing the potting material was the Sound Pressure Level (SPL) generated by similar PVDF stacks molded with different potting's.

The SPL usually adopted as reference is measured at 1 meter from the transducer and is given, in dBs, by

$$SPL_{1m}(f) = TVR(f) + 20log_{10}(V_{in}(f)) \tag{4}$$

where V_{in} is the applied voltage to the transducer and the Transmitting Voltage Response (TVR) represents the gain from the input voltage up to 1 meter from the transducer, in the water. All quantities in (4) are frequency dependent and TVR is a normalized quantity given by

$$TVR = 20\ log_{10}\left(\frac{p_{1m,1V}}{p_0}\right) \tag{5}$$

where $p_{1m,1V}$ is the pressure generated by an input voltage of *1 V* at *1 m* from the transducer and p_0 is a reference pressure of $1\ \mu Pa$. The TVR can be predicted theoretically, however, for an accurate evaluation an in-field calibration had to be made.

Although the calibration is usually used for calibrating the acoustic projectors it can also include the behavior of the electronic circuits as represented in Figure 1, where TVR only considers the projector, TVR' considers also the electric impedance adaptor, TVR'' considers also the power amplifier and TVR''' also takes in consideration the input filter.

B. The electronic parts

The electronic parts required for supplying the acoustic projector are: up-voltage impedance adapter; two parallel power amplifiers; a band pass filter. Those electronic circuits where developed based on theoretical calculus, lab observations and simulations with the electro-acoustic propagation model (eAPM) reported in [13].

The band-pass filter is required for reducing the low frequency noise signals which generates harmonics in the band of interest between 40 and 80 kHz, and for reducing high frequency noise signals which increases strongly the power consumption of the power amplifier. Such behavior of increasing the power consumption with the frequency was verified experimentally when the power amplifier was connected to the impedance adapter and to the projector.

The Power amplifier is required not only for increasing the voltage but also to supply the impedance adapter with enough current for allowing the step-up impedance adapter to increase the voltage for values greater than 1 kV. Instead of using a single amplifier two were used in parallel, because: (i) with a single one a current required was bigger and that could cause heating and dissipation problems inside the container; (ii) and if one amplifier gets damaged the system keeps working with the other. Figure 3 shows the Frequency Response which results from the filter and one power amplifier, where it is possible to observe a maximum gain of 31.7 dB at 56 kHz, and minimum values of 26.1 and 28.1 dB at 20 and 95 kHz, respectively.

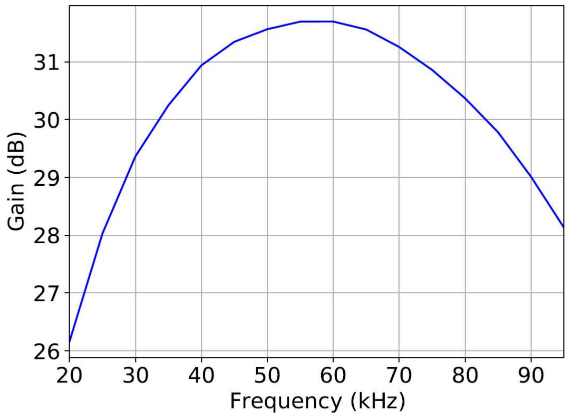

Fig. 3. *Frequency Response between the filter input and one of the Power amplifiers output*

The impedance adapter receives the voltage signal from two power amplifiers through 4 spirals and outputs the signal through 144 spirals. Only considering the spirals effect, the Transformer gain (Tg) is given by

$$Tg = 20\,log_{10}\left(\frac{144}{4}\right) = 31.1\,dB. \qquad (6)$$

When applying the maximum voltage of the amplifier output, 30 V, it results a maximum voltage applied to the projector of 1080 V. In practice it was verified that the voltage applied to the projector increases up to 2000 V for frequencies around 85 kHz and frequencies below 40 kHz. Such higher voltage put significant challenges in the projector prototype development due to the possibility of arc discharge. After several unstable solutions it was possible to arrive to a stable solution which, however, did not solve the heating observed at the PVDF sheets when driven the projector with such voltage during a few minutes.

Equation (6) describe the behavior of the transformer without taking in consideration the electrical impedance characteristics of the impedance adapter connected to the projector which can be seen in figure 4 in terms of resistance (Rs) and reactance (Xs). The nulls in the reactance, at 40 and 77 kHz are the frequencies where the impedance adaptation is better. The slopes around those nulls are the preferable frequencies for signal transmission, thus resulting two preferable bands one between 30 and 50 kHz and the other between 55 and 95 kHz. However, a correct evaluation of those bands and projector acoustic capabilities must be done with calibration.

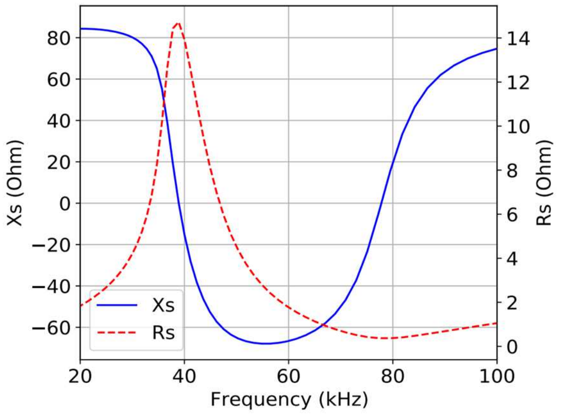

Fig. 4. *Impedance adapter characteristics of Impedance adapter connected with the acoustic projector measured with the LCR-meter KEYSIGHT E4980A: (red) Resistance, (blue) Reactance*

IV. THE PROJECTOR CALIBRATION

As mentioned previously to anticipate the characteristics of a projector system, manly regarding the impedance adaptation and electro acoustic transduction, is difficult and has a high degree of inaccuracy.

The calibration took place in Ria Formosa Lagoon in Faro, Portugal, on 21 of April of 2022. Figure 5 shows the setup schematic (a) and the physical structure (b) used for the calibration. The projector and the hydrophone were place 85 cm apart on a stainless-steel structure hanged with two buoys from the surface. The signal generator signal and the received signal were recorded in the two channels of the DAQ as represented in figure 1.

Before being used for calibration the acquired signals were validated for guarantying that: (i) there is no electric or electro-magnetic transference between the transmit and receive systems; (ii) there is no acoustic transmission thought the stainless-steel structure; and (iii) there is only a single path in the underwater channel between the projector and the hydrophone.

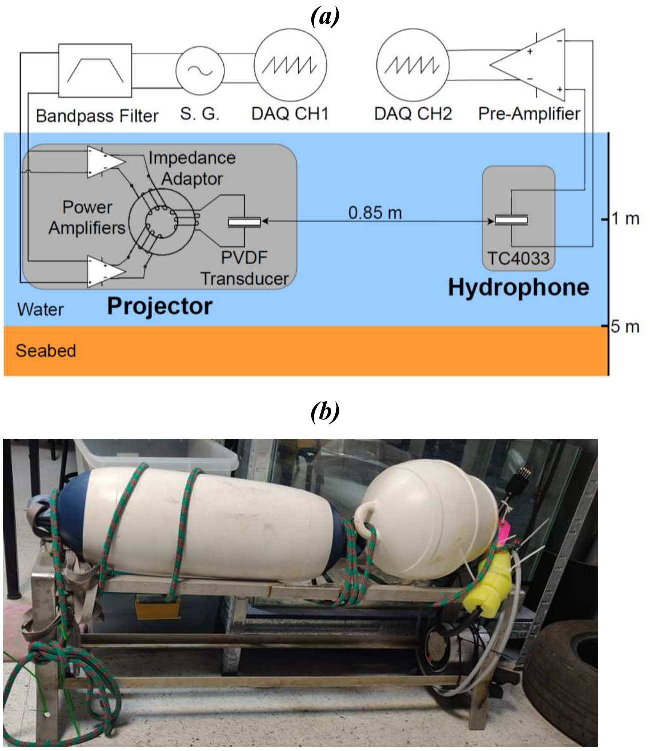

Fig. 5. *Calibration setup. (a) Setup schematic: on left-side the signal generator and the bandpass filter outside the water and the amplifiers, impedance adapter and projector in a container inside the water; on the right-side calibrated hydrophone inside the water, and the charge pre-amplifier and acquisition system outside the water. (b) Physical structure used for the calibration with the projector container visible on bottom-right and the TC4033 (not visible) on the left.*

The calibration was performed based on the sonar equation, that when all quantities are in dB, allows to determine the output signal acquired by the DAQ, in figure 1, $V_{out}(f)$, as

$$V_{out}(f) = V_{in} + F(f) + A(f) + I(f) + TVR(f) + \\ +OCVR(f) + P \qquad (7)$$

where V_{in} represents the input voltage which power does not depends on frequency, $F(f), A(f)$ and $I(f)$ represents the FRs of the filter, amplifier and impedance adapter, respectively, $TVR(f)$ represents the transmitting voltage response of the projector, $OCVR(f)$ the sensitivity of the calibrated hydrophone, and P the FR of the receiver amplifier which gain is considered to be constant with frequency. The known quantities of (7) are: $V_{out}(f)$ and V_{in} that were recorded with the DAQ; $F(f)$ and $A(f)$ that were in-lab measured; $OCVR(f)$ and P that were provider by the manufactures. The impedance adapter FR, $I(f)$, could not be in-lab determined because when oscilloscope probes are applied between the impedance adapter and the projector they change the impedance characteristics and so the measurement. It results that the projector $TVR(f)$ could not be determined, and only TVR'=$I(f) + TVR(f)$ could. The other TVRs in figure 1, TVR'' and TVR''' are the transmitting voltage responses of the system seen from the amplifier and from the filter inputs, respectively.

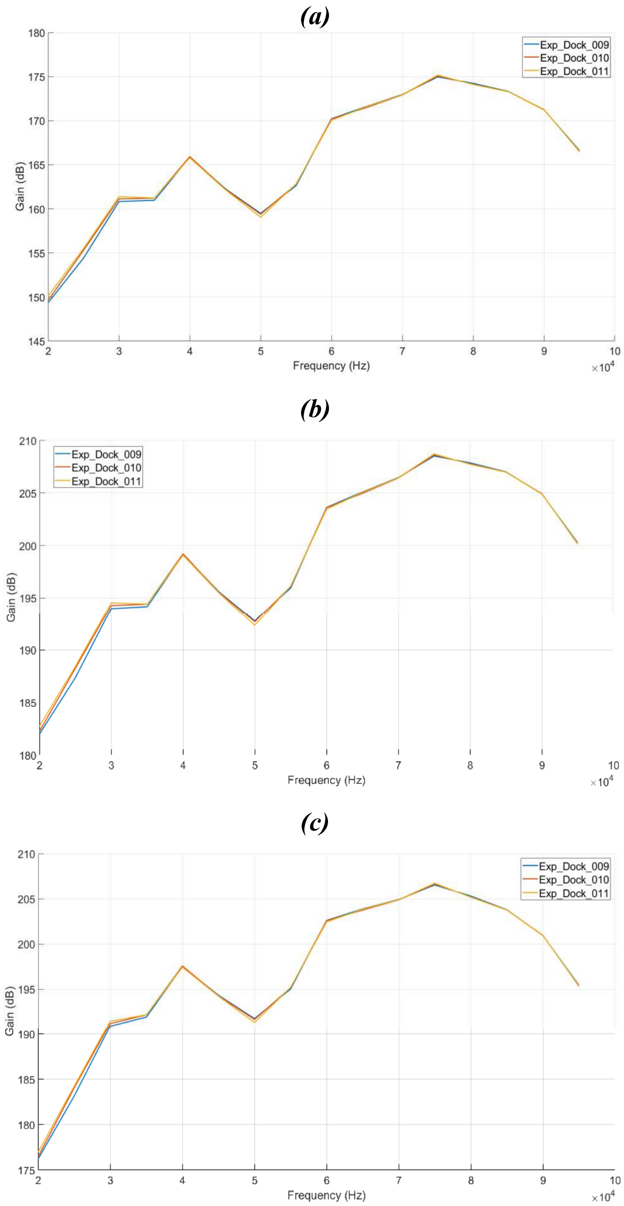

Fig. 6. *Calibration at different stages of the projector system: (a) considering the impedance adaptor and the PVDF projector; (b) considering also the amplifier; (c) also considering the filter.*

The calibration was performed with tones and chirp signals. The tones were transmitted every 5 kHz from 20 to 95 kHz and the chirp increases linearly its frequency from 20 to 95 kHz. The tone signals are the primary choice for calibration, however, the chirps were also used for validating its use as signals for calibration. The signals amplitude applied at the filter input was 0.25 V. In this paper, only the tones calibration will be reported. The calibration was performed with 3 runs of tones which present similar results.

Figure 6 shows the calibration results, with tones, in the different stages of the projector system were: (a) represents TVR'; (b) represents TVR''; and (c) represents TVR'''. TVR' represents the Sound Pressure Level (SPL) produced by 1 V applied at the impedance adapter input at 1 m from the projector.

Figure 6a shows that there is a maximum of 175 dB at approximately 75 kHz, a local maximum of 166 dB at 40 kHz and a local minimum of 159 dB at 50kHz. The maximums coincide, approximately, with the frequencies where the reactance (in figure 4) seen from the impedance adapter input is approximately zero, and the minimum happens, approximately, when the reactance have a minimum. Figure 6b shows TVR'' which takes in consideration the amplifier gains and the difference between the curves of TVR' and TVR'' is approximately a constant of 32 dB which corresponds to the amplifier gain. Figure 6c shows TVR''' which also considers the bandpass filer which attenuates lower and higher frequencies (see figure 3) where the misadjustment of the impedance adapter is higher (see figure 4) and a higher reactive power exists with a consequent loss of performance.

V. CONCLUSION

A piston type acoustic projector was developed using multilayers of the PVDF piezoelectric polymer. PVDF is usually a preferable choice for frequencies above 1 MHz and a few applications were reported for frequencies above 200 kHz. For frequencies below 100 kHz piezoelectric ceramics as PZT are usually a preferable choice manly due to is high piezoelectric coupling coefficient. Exploring favorable PVDF characteristics as the acoustic impedance close to the one of salt water and a larger frequency bandwidth, and with the development of an appropriate impedance adapter and using multilayers of PVDF it was possible to overcome the PVDF weakness and develop a new projector with acoustic power characteristics compatible with PZT, but with higher bandwidth which is of paramount importance for broad band underwater communications.

The impedance adapter predictions agree well with the transmitting voltage response field calibration with a maximum of 175 dB at approximately 75 kHz and a local maximum of 166 dB at 40 kHz where the reactance of the impedance adapter is approximately zero.

To the authors knowledge this is the first time that a PVDF projector attain characteristics compatible with PZT for frequencies below 100 kHz, with the advantage of having a larger bandwidth.

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REFERENCES

[1] M. Martins et al., 'Wideband and Wide Beam Polyvinylidene Difluoride (PVDF) Acoustic Transducer for Broadband Underwater Communications', Sensors, vol. 19, no. 18, p. 3991, Sep. 2019, doi: 10.3390/s19183991.

[2] K. Uchino, 'Piezoelectric ceramics for transducers', in Ultrasonic Transducers, Elsevier, 2012, pp. 70–116. doi: 10.1533/9780857096302.1.70.

[3] K. Uchino, 'Introduction to Piezoelectric Actuators and Transducers', PENNSYLVANIA STATE UNIV UNIVERSITY PARK, Jun. 2003. Accessed: May 06, 2021. [Online]. Available: https://apps.dtic.mil/sti/citations/ADA429659.

[4] Yuan Yiquan, Shi Binwen, and Liu Zongjie, 'A new multilayer planar PVDF standard hydrophone and its applications', IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 42, no. 5, pp. 958–964, Sep. 1995, doi: 10.1109/58.464848..

[5] Measurement Specialities, Inc, 'Piezo Film Sensors Technical Manual', Apr. 02, 1999. https://www.sparkfun.com/datasheets/Sensors/Flex/MSI-techman.pdf (accessed Apr. 10, 2021).

[6] H. R. Gallantree, 'Review of transducer applications of polyvinylidene fluoride', *IEE Proc. Solid State Electron Devices*, vol. 130, no. 5, p. 219, 1983, doi: 10.1049/ip-i-1.1983.0040.

[7] W. W. L. Au and M. C. Hastings, 'Measurement and Generation of Underwater Sounds', in *Principles of Marine Bioacoustics*, New York, NY: Springer US, 2008, pp. 27–56. doi: 10.1007/978-0-387-78365-9_2.

[8] M. Martins, V. Correia, J. M. Cabral, S. Lanceros-Mendez, and J. G. Rocha, 'Optimization of piezoelectric ultrasound emitter transducers for underwater communications', *Sens. Actuators Phys.*, vol. 184, pp. 141–148, Sep. 2012, doi: 10.1016/j.sna.2012.06.008.

[9] F. S. Foster, K. A. Harasiewicz, and M. D. Sherar, 'A history of medical and biological imaging with polyvinylidene fluoride (PVDF) transducers', *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 47, no. 6, pp. 1363–1371, Nov. 2000, doi: 10.1109/58.883525.

[10] B. Woodward and R. C. Chandra, 'Underwater Acoustic Measurements on Polyvinylidene Fluoride Transducers', *Electrocompon. Sci. Technol.*, vol. 5, no. 3, pp. 149–157, 1978, doi: 10.1155/APEC.5.149.

[11] G. J. Kavarnos and E. A. McLaughlin, 'Development of a High-Frequency Multilayer Copolymer Acoustic Projector', NAVAL UNDERSEA WARFARE CENTER DIV NEWPORT RI, Mar. 1994. Accessed: Jul. 29, 2021. [Online]. Available: https://apps.dtic.mil/sti/citations/ADA279718

[12] Q. Zhang, P. A. Lewin, and P. E. Bloomfield, 'PVDF transducers-a performance comparison of single-layer and multilayer structures', *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 44, no. 5, pp. 1148–1156, Sep. 1997, doi: 10.1109/58.655640.

[13] R. Viegas, D. Pozzatti, F. Zabel and A. Silva, "Integrated approach for modeling acoustic propagation and projectors/hydrophones electronics", 2022, to be presented at OCEANS 2022 Hampton Roads.