Characterization of Low-Cost Transducers for Underwater Communications

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***Abstract*—Acoustic transducers for underwater communications are one of the most expensive components of underwater acoustic modems and their applications. Their production involves the use of expensive materials, such as piezoelectric ceramic rings, tubes, or spheres, and molding materials, which are difficult to operate due to their sensitivity to humidity, temperature, and vibrations. Moreover, it is not easy to automate this process, which mostly results in a specialized operator spending a few hours to manufacture and calibrate each hand-made transducer, and in a final price that is often more than 2000 USD per unit.**

Therefore, such transducers are used only in high-power underwater acoustic modems for defense and Oil&Gas applications, making them not suitable for low-cost deployment such as communication systems for divers, Autonomous Underwater Vehicle (AUV) swarms [1] or sensors networks for coastal monitoring. To enable such applications, different alternatives have been proposed, from using other components, such as fish-finders and hydrophones with low transmitting voltage response [2], to home-made low-cost transducers [3]. In this paper, we discuss the advantages and disadvantages of both solutions, presenting our experience and the lessons we learned while producing our low-cost transducer, which is a key element for underwater communication and its application in coastal monitoring deployments.

***Index Terms*—underwater acoustic piezoelectric transducers.**

I. Introduction

Underwater acoustic modems are typically used in Oil&Gas and defense applications such as Intelligence, Surveillance, and Reconnaissance (ISR) and Rapid Environmental Assessment (REA) [4]. This often involves the need for calibrated and high-depth rated equipment able to perform high power transmissions (up to 100 W) to obtain a transmission range of several kilometers, resulting in sophisticated and expensive products.

In recent years, the benefit of using underwater acoustic modems in other contexts, including coastal monitoring, aquaculture, fishing industry (e.g., developing ropeless fish traps), diver communication, and low-cost Autonomous Underwater Vehicle (AUV) swarms have been widely discussed and some low-cost acoustic modems have been developed [1]. To cut production costs and allow acoustic modems to be used in these scenarios, off-the-shelf components must be employed, and transmission power needs to be reduced by one order of magnitude, e.g., accepting lower performance. Although this may already reduce the cost of the modem by a factor of 10, there is still a very expensive component that needs to be replaced, namely the underwater acoustic transducer (i.e., the underwater antenna).

In fact, transducers for underwater acoustic communication are typically very expensive, as to maximize the transmission and reception performance of the modem they require a flat Transmitting Voltage Response (TVR) and Receiving Voltage Response (RVR) in the bandwidth of the modem, that should be as wide as possible. In addition, they must withstand high operating voltage, be waterproof, and have some specific mechanical properties, so their production involves the use of expensive materials, such as custom-made piezoelectric tubes and resins. The fabrication of transducers often requires the use of vacuum hoods and ovens to maintain a controlled production environment, as resins are sensitive to factors such as humidity, temperature, and vibrations. Such a procedure is usually performed by specialized operators, that dedicate a few hours per transducer in order to manufacture it and then verify its characteristics through calibration, resulting in a quite high cost of production that makes the final price of the transducer easily reach 2000 USD, making it unsuitable for low-cost modems.

To solve this problem, researchers and companies developing low-cost acoustic modems are using two different approaches: i) using acoustic transducers made for different

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applications; ii) making their own transducers, as we did and will describe in this paper. In fact, low-cost transducers tailored for different applications, such as echo-sounders and fish-finders, and hydrophones with low TVR, are available in the market. While the former can perform high-power transmissions, their bandwidth is very narrow, hence their use is not suitable for underwater communications as they will limit the bitrate of the modem. In contrast, hydrophones with low transmission abilities [2] have a wider bandwidth, but their TVR is quite low, which prevents them from performing long-range transmissions. However, this approach seems to have been adopted by the research community [5], [6]. A step forward would require making the transducer in house [7], [8], trying to reduce production costs by selecting low-cost and easy-to-handle components and choosing the resins and piezoelectric ceramics that best satisfy the requirements of the developed modem. This approach has the main advantages of further reducing costs, while still obtaining a transducer that respects the requirements of the system. The main drawback is that the development of transducers is not trivial and is quite hard to automate, as every step of the procedure requires special care.

The rest of this paper is structured as follows: Section II presents how to make a low-cost transducer step by step, highlighting the issues that can be encountered in its development. Section III presents the methodology for the calibration of the transducer and Section IV presents the characterization of the transducer. Finally, Section V concludes the paper.

II. Making a low-cost transducer

In this section we present a possible way to make low cost piezoelectric transducers potted in urethane resin: although the core of the procedure is very similar to those described in other existing works [3], [8], we believe that details such as the exact make of the resin being used, which is subject to local availability, and other choices regarding the pouring procedure, can vary the result in terms of both aesthetics and functionality.

The complete procedure for making underwater hydrophones is provided in [3], including what resin to use, the source file for the 3D printed mold, the circuit for an optional analog preamplifier, and many tips and tricks. Taking this as a starting point, we decided to slightly change its design to suit our requirements. For the sake of clarity, we report the complete procedure as follows.

First, piezoelectric ceramic tubes with resonance frequencies of 25 kHz and 43 kHz have been acquired to make, respectively, MF or HF transducers. Then, the two wires from the audio cable are soldered one to the inner face and the other to the outer face of the tube. When soldering, attention must be paid not to exceed the Curie temperature, of 320°C in our case, after which the material loses its piezoelectric properties, nor to overheat the silver coating as it will peel off. For this we used solder paste with a 3% silver content and a melting temperature of 217°C. As will be shown in Figure 2, the transmission performance of the transducer can be improved if the inner side of the tube is kept empty and thus free to vibrate. To do so, we glued two plastic caps to the top and bottom of the tube to prevent the resin from filling its interior. As the top cap must have a hole to accommodate the wire that comes from the inner tube side, special care must be taken to seal it with glue. Another option would be to use a custom-cut piece made of compressible material such as cork or foam to be placed inside the tube. Both solutions present the drawback of having a horizontal surface that can trap air bubbles when the resin is poured: this can change the characteristics of the transducer, either altering its beam pattern or adding secondary unwanted resonant peaks. A solution for this can be found in [8] where the mold is designed to be tilted at 45° while casting.

The next step is preparing the mold: in fact, since it was 3D printed, it is essential to make it as clean and regular as possible, removing all small roughness and scratches that will make the resin adhere to the mold walls, making the unmolding procedure more complex. To further simplify the removal of the potted transducer from the mold, we used a spray release agent that should be used with care, however, to avoid bubble formation. An alternative approach would be to make the mold with a plexiglass tube, whose perfectly smooth surfaces will greatly simplify the unmolding procedure.

Another crucial step is placing the piezo tube inside the mold, keeping it centered with respect to the edge. Special care should be taken during the molding process, as the addition of the resins to the mold and the potential presence of bubbles trying to jump to the surface may move the ceramic tube, causing the whole process to fail.

The final step is the molding process. The resin selection must be done with care, not only trying to have a resin with an acoustic impedance that best adapts the mismatch between the impedance of water and the ceramic element, but also caring for the stirring and cure time. For example, Smooth Cast 65D resin has only 2.5 minutes of pot time (that is, from the time you start mixing components A and B to the moment it becomes too dense for potting) and 15 minutes of cure time, that is, when it becomes solid at room temperature of 23°C. This has on the one hand the advantage of a fast production process, but on the other hand the disadvantage that there is not enough time to remove the bubbles formed in the chemical reaction that happens when mixing the A and B components, and to perform any adjustments if something goes wrong during the molding process. Adding color is also an option, but this may modify the acoustic impedance and increase even more the formation of bubbles. Slower resins exist and are used in the production of professional transducers, with 1 hour pot time and 1 day of cure time when kept at 50°C: this allows the use of vacuum hoods to remove the bubbles before the molding process and make all the necessary arrangements. The disadvantages are that they are twice as expensive as normal urethane resins and that special ovens and vacuum hoods are needed to optimize the molding and cure process. The final results of the procedure can be seen in Figure 1.

TABLE I
SUMMARY OF ELECTRICAL AND TUNING PARAMETERS

		Untuned			Parallel tuning		Series tuning		
Name	f_r	C_{LF}	$\|Z\|$	$\angle Z$	L_p	R_T	L_s	R_T	ΔTVR
MF	32.5 kHz	19.4 nF	276.8 Ω	-67.9°	1.46 mH	737.5 Ω	1.25 mH	103.9 Ω	+8.51 dB
HF empty	41 kHz	6.5 nF	590.5 Ω	-72.6°	2.40 mH	1.98 kΩ	2.19 mH	176.5 Ω	+10.49 dB
HF full	43.5 kHz	7.3 nF	524.9 Ω	-75.4°	1.98 mH	2.09 kΩ	1.86 mH	131.9 Ω	+12 dB

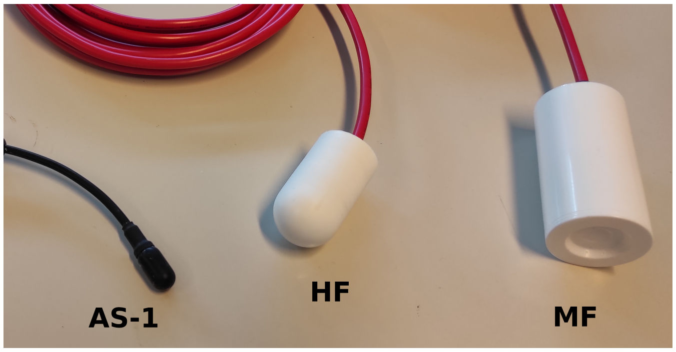

Fig. 1. The commercial AS-1 and the two custom-made transducers

III. CALIBRATION METHODOLOGY AND SETUP

A. Definitions

The purpose of calibration is to measure the TVR, RVR and complex impedance curves of a transducer under test in a given range of frequencies. The TVR is defined as the ratio of the amplitude of the free-field far-field pressure generated by a transducer to its excitation voltage, at the standard distance of 1 m. The value is typically expressed in dB re 1 μPa/V and is a measure of how well the transducer operates as a projector. Conversely, the RVR or Free Field Voltage Sensitivity (FFVS) determines the sensitivity when operating as a hydrophone. It is defined as the open-circuit voltage at the electrical terminals divided by the incident pressure wave amplitude and expressed in dB re 1 V/μPa.

It is important to emphasize the conditions under which the measurements must take place. The emitter is considered in *far-field* when it can be modeled as a point source radiating spherically divergent waves [9]. This requirement is easily met with a large enough separation between the projector and the hydrophone. On the other hand, *free-field* measurements require the medium to be boundless, and thus free of reflections and standing waves that would interfere with the direct wave.

The easiest method to perform such measurements in tanks of limited size is by using signal gating [9]: the projector transmits a short burst consisting of a few periods of a sinusoidal signal at the test frequency. Ideally, for a sufficiently short burst length, the output of the hydrophone would consist of delayed and attenuated copies of the transmitted signal corresponding to different propagation paths. Since the direct time of arrival is known, any activity recorded by the hydrophone after this time is due to reflections, and shall be discarded.

B. Setup

The setup used for the calibration consisted of a water tank measuring 3 by 3 with a depth of 2.5 meters with a calibrated bidirectional transducer to be used as reference. The device under test is first brought to thermal equilibrium with the water at 22.7°C and then placed at a depth of 1.1 m and sufficiently far apart from the reference to be considered in far-field; the actual distance is determined from the time of arrival of the direct signal and used to normalize the TVR and RVR values to 1 m. During RVR sweep, the reference transducer acts as a projector, the test transducer acts as a hydrophone, and vice versa for TVR. Measurements are performed by a computer-controlled test setup consisting of a function generator, a 20 MSPS digital oscilloscope, a power amplifier for the projector, and a JFET input preamplifier for the hydrophone. The smallest dimension of the tank imposes an upper limit on the burst length, and thus the lowest test frequency. With this setup, accurate measurements are not possible below 5 kHz. Furthermore, the bandwidth of the instrumentation limits the highest measurement frequency to 100 kHz.

C. Impedance and tuning

The impedance in free-field conditions is measured during the TVR sweep by recording the voltage across and current through the device under test, respectively, with a differential probe and a current transformer. The complex impedance is obtained in post-processing by their ratio in phasor form. This measurement includes the effects of the capacitance and resistance of the cable. For acoustic transducers, the admittance $Y = G + jB$ rather than the impedance is usually desired, as it can be linked to various properties of the system. For example, the frequency of mechanical resonance is identified by a pronounced peak in the conductance plot [9]. The admittance locus in the complex plane (also known as the "admittance loop") is also useful in identifying primary and possibly secondary resonances, which appear as loops in this plot.

Knowledge of impedance or admittance is also necessary to size the transmission amplifier for a given output source level. In particular, the presence of a strong reactive component may complicate the design of the output power amplifier, reduce its efficiency, or even introduce stability concerns. For these reasons, an impedance matching network is often placed before the transducer to make it appear as a pure resistive load to the transmitter. The simplest option is to use an inductance, in either series (L_s) or parallel (L_p) to the output, sized to resonate with the capacitive component of the impedance at the mechanical resonance frequency of the system. This allows to obtain the maximum power coupling to the acoustic medium for a given constant-voltage excitation. Inductance values can be obtained directly from admittance data with the following equations:

$$L_p = \frac{1}{2\pi f_r B_r} \qquad\qquad L_s = \frac{B_r}{2\pi f_r (G_r^2 + B_r^2)}$$

Where f_r is the resonance frequency, and G_r and B_r the conductance and susceptance at resonance, respectively. While parallel tuning does not affect the TVR curve of the transducer, series tuning should reduce the equivalent input resistance R_T and thus slightly increase TVR at resonance by a factor ΔTVR; these values are theoretically found using the following equations [10]:

$$R_T = \frac{G_r}{G_r^2 + B_r^2} \qquad\qquad \Delta TVR = 10\log_{10}\left(\frac{1}{G_r R_T}\right)$$

This simple matching method, whose parameters are summarized in Table I, does not offer control over R_T, which remains completely determined by the transducer. If this is not desired, more complex networks such as L-sections and transformer-based solutions should be investigated.

IV. Frequency Response Results

In this section we comment on the result of the calibration: Figures 2,3 and 4 show the frequency response of our transducers, where `HF_full` is the transducer with the 43 kHz tube filled with resin, while `HF_empty` has a pocket of air inside. The values of the Aquarian Scientific AS-1 transducer [2] are also provided for reference.

A. Transmission

In Figure 2 we present the TVR results: the highest values are obtained for the `MF` transducer with 139 dB and a -3 dB bandwidth of 16 kHz around its radial resonance frequency of 25 kHz. Interestingly enough, two other significant peaks of 137 dB can be found at 57 and 63 kHz. These peaks are located slightly below the longitudinal mode resonance frequency of the piezoelectric element, which is estimated to occur at approximately 67 kHz based on the geometry. The two HF transducers are based on a tube with a resonance frequency of 43 kHz, but for `HF_full` the actual peak of 114 dB was found at 49 kHz, with a bandwidth of 14 kHz around it, while `HF_empty` instead shows local peaks of 132 dB at 32 kHz, 130 dB at 43 kHz and an absolute maximum of 136 dB at 91 kHz. From this we can see a performance boost of 16 dB for the empty projector compared to the one filled with resin.

B. Reception

Figure 3 shows that the `MF` shows a mean sensitivity of -195 dB from 5 to 35 kHz, and the `HF_full` a mean sensitivity of -197 dB from 14 to 57 kHz. While the `HF_empty`

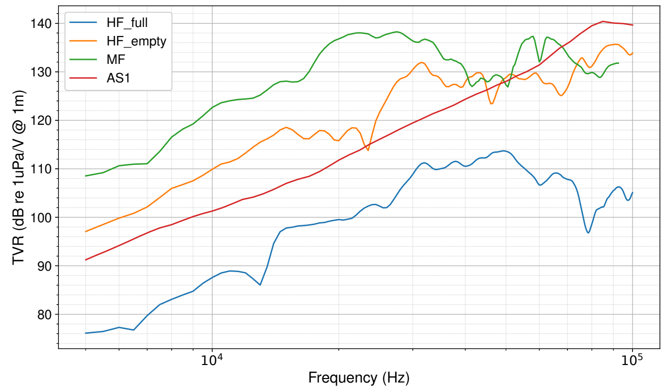

Fig. 2. Transmitting Voltage Response

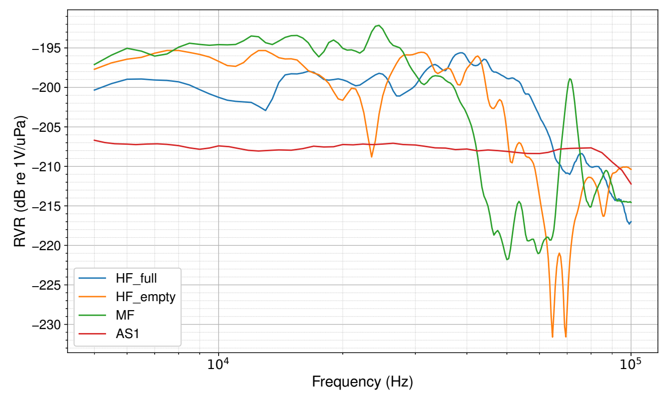

Fig. 3. Receiving Voltage Response

has a higher initial sensitivity, it presents a strong notch at 23 kHz and a steeper degradation above 49 kHz. Due to the irregularity of the `HF_empty` plot, we plan to carry out further measurements on different samples to assess whether the cause lies in some defects introduced during the manufacturing process.

C. Impedance

In Figure 4 the `MF` has an impedance of 320 Ω at 25 kHz with a minimum of 80 Ω at 60 kHz, near the secondary TVR peaks already observed in Figure 2. For the `HF_full` and the `HF_empty` we respectively measured impedances of 520 and 620 Ω at 43 kHz, decreasing with frequency.

D. Remarks

These plots suggest that home-made transducers can have a more irregular frequency response, with spikes and notches that are probably due to the hidden presence of trapped air bubbles. Characterizing these irregularities introduced by tolerances in the manufacturing process would require repeating the measurements on multiple transducers of the same type, which could not be done because of the limited time availability of the testing facilities. However, the plots also show that these transducers have equal or greater sensitivity in both reception and transmission around their intended transmission bands of

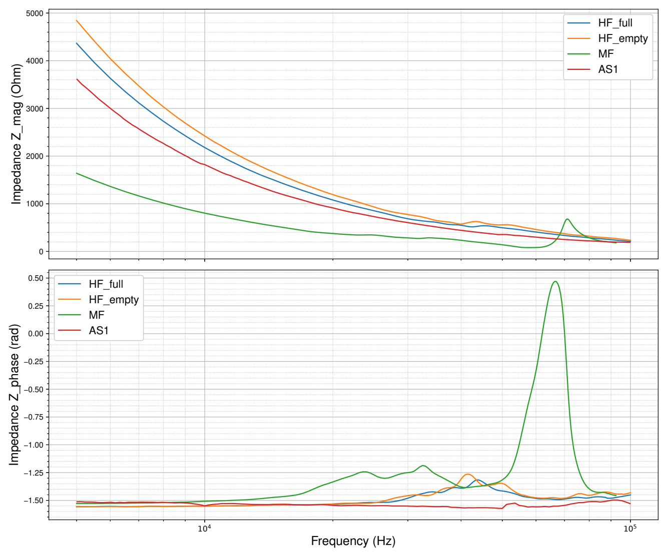

Fig. 4. Impedance

TABLE II
COMPARISON OF TRANSDUCERS

Model	TVR (dB)	RVR (dB)	Fr (kHz)	Price
TD0720 [13]	149	-190	25	A
BT-28UF [14]	143	-190	28	A
T257 [15]	136	-190	24	B
AS-1 [2]	140 (126)	-208	90 (43)	C
MF	139	-195	25	C
HF	132	-197	43	C

25 and 43 kHz when compared to the AS-1. In addition, their impedance makes them suitable for use with a low-cost acoustic software-defined modem such as SuM [11]. In this case, since SuM has an output of 30 dBV, when connected to the MF projector it can produce 169 dB of acoustic pressure in the water. In Table II we summarize the characteristics of some acoustic transducers. Since the retail price of commercial transducers depends on the quantity of purchase and other factors, we divide the cost into three classes: A from 1700 to 2500 euros, B from 1000 to 1700 and C below 1000 euros. The MF and HF transducers we presented in this paper fall in the latter class, which accounts for both production costs and a fair commercial price mark-up. In the same class we included AS-1, one of the cheapest commercial transducers and widely used in research projects. It should be noted that AS-1 has a resonance frequency and maximum TVR at 90 kHz, which is a frequency not suitable for long-range communications, since the absorption loss according to the Francois–Garrison formulas [12] is around 20 dB/km higher than at 43 kHz. For this reason, in the table we also report, in brackets, the TVR of AS-1 at 43 kHz for a better comparison with our HF transducer.

V. CONCLUSIONS

This work presents an effective approach for the fabrication and characterization of low-cost ultrasonic transducers designed for underwater communications. The availability of inexpensive transducers is a crucial enabler for the deployment of cost-efficient autonomous underwater vehicles (AUVs) and sensor networks for coastal monitoring, as well as for advancing the feasibility of an Internet of Underwater Things (IoUT), analogous to its widespread application in terrestrial environments.

Future work will include refinements of the production and calibration processes, the execution of repeated measurements on different transducers of the same type to obtain a characterization of manufacturing tolerances, and an evaluation of the transducers in terms of communication performance in a complete underwater setting.

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