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OPTIMIZATION OF CAVITIES AND SUSPENSIONS IN UNDERWATER ACOUSTIC PROJECTORS: ANALYTICAL AND EXPERIMENTAL STUDY

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ABSTRACT

This paper focuses on the design and analysis of an underwater acoustic projector based on a conventional loudspeaker, with particular emphasis on the role of the intermediate cavity between the loudspeaker and the radiating diaphragm, as well as the suspension properties of both components. The design, which eliminates direct contact between the loudspeaker and the diaphragm, presents unique challenges in efficiently transmitting mechanical energy from the former to the latter while minimizing losses.

The study explores how the cavities volume and suspension characteristics (linearity, stiffness, and damping) influence the low-frequency response by analyzing the first modes of the diaphragm. Using analytical approaches and experimental models, comparative studies are presented to optimize the system configuration.

This arrangement offers a significant advantage by eliminating the need for compensating the fluid pressure exerted on the diaphragm in shallow waters, without affecting the coil rest position within the magnetic gap.

Keywords: *Underwater projector, loudspeaker, radiating diaphragm, cavity volume.*

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1. INTRODUCTION

The purpose of this work is to analyze the behavior of the cavities that form the projector, particularly their influence on the response and passband. Additionally, it aims to define the type of suspension and dimensions based on the piston size to optimize the low cutoff frequency and performance in water, for submersions up to 3 meters deep, while avoiding nonlinearities caused by the static displacement of the resting point of the coil.

In this type of design, numerous references exist for audio applications [1, 2, 3], highlighting the possibility of varying the passband or efficiency [2, 3], as well as limiting low frequency displacement due to the membrane being loaded on both sides. A vent is typically used because of the ease of tuning the enclosure to the desired frequency. The use of a passive diaphragm has been described on some occasions [3, 4], but no practical or commercial applications are known in this field.

2. PROJECTOR DESCRIPTION

To protect the inside loudspeaker from the effects of hydrostatic pressure when submerged in water, a system has been conceived based on the symmetrical loading system used in some speaker enclosures. This system consists of placing the loudspeaker inside an enclosure formed by two cavities (Fig. 1, 2). The rear cavity (V1) is airtight, while the other (V2) contains a passive diaphragm that allows sound to propagate outward.

2.1 Design of the prototype

This design, reminiscent of one previously presented in an earlier communication [5], differs primarily in the absence of the element that connected the loudspeaker coil to the external diaphragm. This significantly reduces the displacement of the coil from its resting point due to the hydrostatic pressure exerted on the diaphragm. This aspect is crucial since, as will be discussed later, the aim is to use a loudspeaker with a very short voice coil.

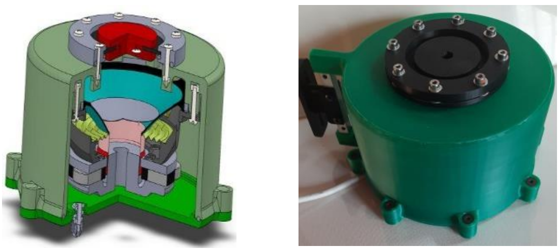

Figure 1. Section of the projector (left), and prototype photo (right)

This type of assembly is derived from the sealed back chamber bandpass enclosure, used in audio systems for very low-frequency applications. It is characterized by a frequency response like a bandpass filter, with a bandwidth of slightly more than two octaves. Since the loudspeaker is loaded on both sides, it exhibits minimal displacement. This allows for the use of a voice coil with a very short winding width. As a result, with all the turns remaining within the magnetic gap, both efficiency and power handling capacity are improved.

2.2 Construction

Obviously, models that radiate into the air require a large loudspeaker size and a significant volume to achieve a low cutoff frequency with high sensitivity. In the case of the described model, due to the difference in radiation impedance between air and water, a small diaphragm with a relatively high mass is used (Fig. 2).

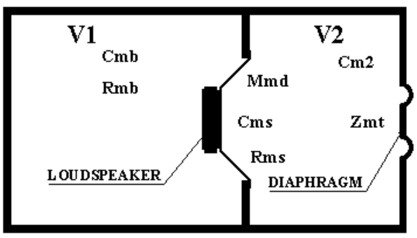

Figure 2. Band pass cabinet

3. ELECTRO-MECHANICAL CIRCUIT

Fig. 3 shows the mechanical circuit, with all the elements involved in it.

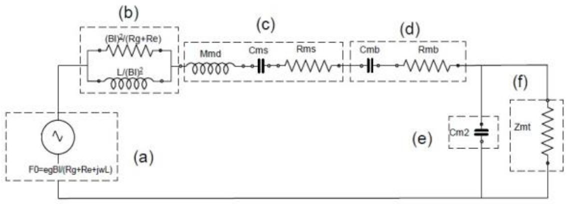

Figure 3. Mechanical circuit of the direct-radiator loaded on both sides: (a) force, (b) electrical components referred to the mechanical side, (c) mechanical elements of the loudspeaker, (d) rear side box, (e.) front side box, (f) mechanical impedance of the passive diaphragm

4. RESULTS AND DISCUSSION

Based on previous model experience, a free air resonance frequency is established around 100 Hz, as the increase in moving mass—due to the added mass of water—will shift the main mode below this value, which is the requested low cutoff frequency for this model.

4.1 Passive diaphragm characteristics

To minimize the efforts induced by hydrostatic pressure, the area is reduced to one-fourth of the total area of the membrane. A suspension with the required stiffness is employed to match the properly required free air resonance, as described above. To confirm this value, a known mass is applied, and the resulting displacement is measured using a laser sensor (Fig. 4).

Figure 4. Measurement of the resting point (left), and the displacement with a known mass (right)

This experiment is conducted using the same piston diameter, but with different suspension areas.
The first suspension, (model C), has a smaller area than model D. This difference has a strong impact on stiffness K and in the free air resonant frequency, (Tab. 1). The diaphragm mass is defined by the material and production conditions, in this case printing 3D techniques.

Table 1

Diaphragm Model	Suspension Area cm^2	K N/m	Diaphragm Mass Kg	Fs Hz
C	4,5	30430	0,038	142
D	9,5	9360	0,038	79

4.2 Parametric study

Different measurements are conducted on both the active and the passive model, while also analyzing the influence of the cavities. Because the nature of the components, an impedance measurement of the 5” loudspeaker (active model), will be done. On the other hand, the passive diaphragm has no way to achieve a direct electrical measure, so a sensor (accelerometer) will be affixed to the piston, to see how it performs.

4.2.1 Influence of the passive diaphragm

The accelerometer is placed on the back side of the piston and is excited by the loudspeaker in all the audible range of frequencies (Fig. 5).

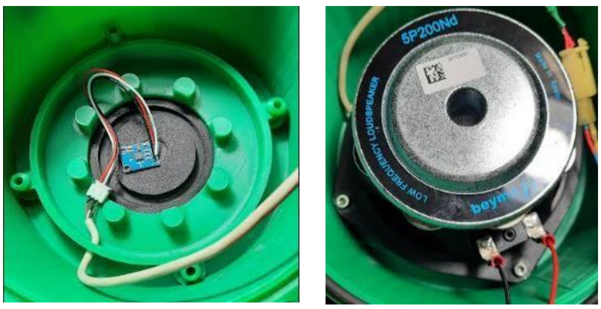

Figure 5. Accelerometer fixed on the back side of the piston (left) with the 5” unit mounted inside the cabinet (right)

Figure 6 shows the shift in the first peak of impedance when replacing the diaphragm. In the case of model C, this peak is located around 200 Hz (solid line), whereas in model D, a downward shift is observed, placing it around 105 Hz (dashed line).

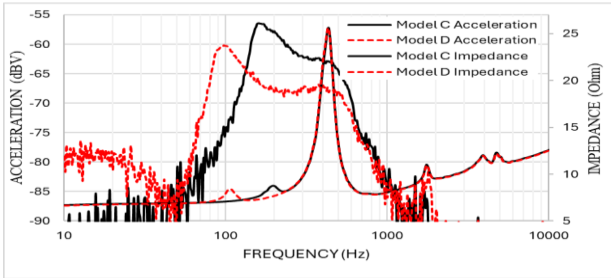

Figure 6. Impedance and Acceleration, with models C and D diaphragms

The first mode has a very low amplitude due to the air load enclosed in both cavities, on both sides of the loudspeaker. The second mode remains unchanged in both frequency and amplitude. The tuning frequency, which is the minimum value between both peaks, is also clearly modified. The acceleration measurements show a broader frequency response for diaphragm D (dashed line), while for model C, the response is substantially reduced at lower frequencies (solid line). As the passband widens, efficiency decreases.

4.2.2 Influence of the front cavity

This cavity, located between the loudspeaker and the diaphragm, behaves as a low-pass filter. Therefore, it should affect the response at the upper cutoff frequency. Figure 7 exhibits the behavior, with the first peak located around 150 Hz, and the second one, at 445 Hz.

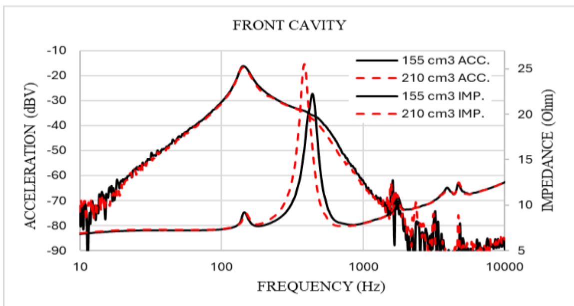

Figure 7. Impedance and acceleration for different volumes

After modifying the volume, increasing up to 210 cm^3, the first peak remains at the same value, meanwhile the second is placed at 390 Hz. The amplitude of the peak rises due to the increase of the air chamber compliance.

4.2.3 Influence of the rear cavity

The rear cavity is completely sealed, loading the loudspeaker from the rear side. The air enclosed inside represents an added rigidity to the loudspeaker suspension. The volume of his cavity increased from 800 cm^3 (Fig. 8) to 1300 cm^3, while the original front volume of 155 cm^3 remains unchanged.
It can be observed a shift in the first two peaks toward the lower frequency region.

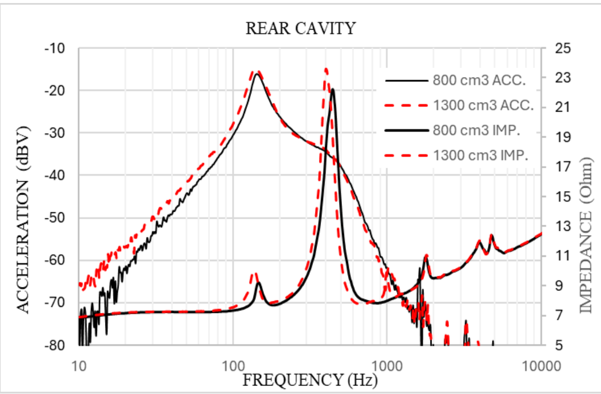

Figure 8. Impedance and acceleration when modifying the rear volume

Additionally, a peak appears at 1 kHz, likely caused by a resonance due to the larger cavity size and the absence of damping material.
The increase in the rear volume V1 affects the low frequency cutoff, and very lightly the higher cutoff frequency.
Meanwhile, the variation in the front volume, that behaves as a low pass filter, has some incidence in the higher cutoff frequency, but none in the low frequency.

4.3 Analytical results

A parametric study, leveraging a MATLAB-based implementation of the mechanical model (Fig. 3), revealed strong agreement between theoretical predictions and experimental outcomes (Fig. 9)

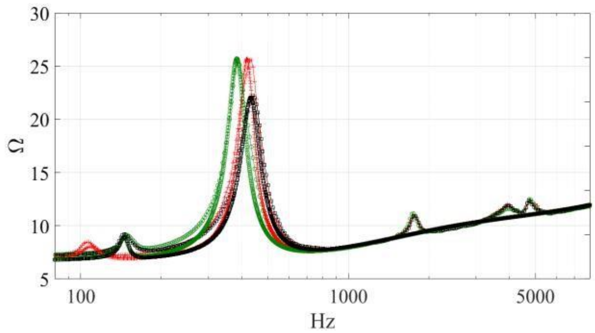

Figure 9. Validation of the analytical model: Diaphragm model D, (lines); 210 cm^3 front volume cavity: (squares); 1300 cm^3 rear volume cavity:
(circles)

4.4 Pressure frequency response

Although this model is intended for underwater applications [6, 7], SPL measurements in free air are carried out to confirm the previously described results (Fig. 10).

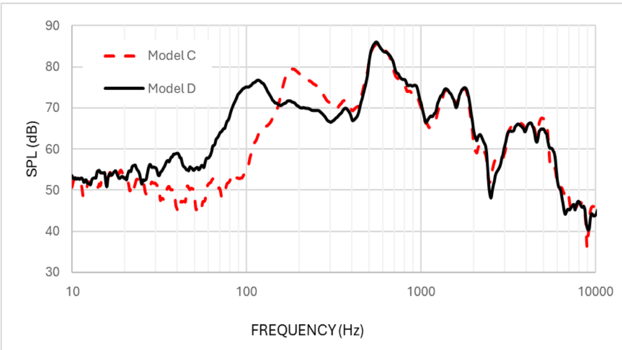

Figure 10. Frequency response at free air

It is possible to verify that the SPL aligns well with the measurements performed with the accelerometer, and verifies the wider response of model D but also the higher efficiency of model C.

5. CONCLUSION

This study has investigated an innovative underwater projector design, inspired by electrodynamic loudspeaker principles, which introduces a novel decoupling mechanism to mitigate hydrostatic pressure effects on the

voice coil at rest. By eliminating direct mechanical coupling between the external diaphragm and the loudspeaker assembly, the proposed configuration demonstrates a marked reduction in static load-induced deformations.
The analysis further reveals that careful optimization of the diaphragm suspension system yields substantial improvements in both frequency response linearity and acoustic sensitivity, while the dimensions of the front and rear cavities exhibit measurable influence on bandwidth behavior, their impact plays a secondary role compared to suspension tuning.
Notably, the striking concordance between experimental measurements and analytical predictions validates the theoretical framework as a robust predictive tool.
The validated model provides a foundation for optimizing similar pressure-resilient projectors, particularly in applications requiring precise acoustic performance in shallow-water environments. Future work should explore the long-term stability of the decoupled assembly under cyclic loading and investigate advanced materials to further enhance sensitivity without compromising structural robustness.

5 ACKNOWLEDGMENTS

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