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A PRELIMINARY STUDY ON THE PARTICLE MOTION OF UNDERWATER SOUND SOURCES

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ABSTRACT

Underwater acoustics plays a key role for fish to know the marine environment and to communicate between them. In this context, understanding not only how these fishes produce sound but also how they perceive it is of great importance for their preservation and survival. Some recent studies have shown the higher sensitivity of fishes to particle motion than sound pressure and suggest its consideration, especially in the assessment of noisy scenarios. This work gives an insight into the analysis of particle motion of an underwater sound source and its relation to sound pressure level. For this purpose, the radiated sound pressure field of an electrodynamic speaker is used to calculate the corresponding particle motion. Preliminary results highlight the differences between using one magnitude or another, especially in the near-field, and encourage the development of new devices that allow measuring it to better analyze the noise effects on the marine species.

***Keywords* —** Underwater acoustics, fisheries acoustics, particle motion.

1. INTRODUCTION

Underwater acoustics is of great importance for fishes to know the marine environment and to communicate with other species given the limitations of senses such as vision, touch, taste, and smell. More than 800 species of fish over 100 families have been documented to produce sounds whose characteristics differ from one species to another depending on their population, gender, size, motivations… As pointed out by Hawkins and Rasmussen [1], these sounds provide valuable information concerning temporal disputes, competition for food, predatory attacks, courtship interactions, spawning aggregations…; being their study also a key point to better understand the successful reproduction of fish species and their survival in the marine environment.

Unfortunately, anthropogenic noise (i.e., noise generated by human beings) has increased notably over the last decades, especially due to the development of the fishing industry, aquaculture, and oil prospecting [2]. As a result, marine species extract information from a soundscape composed not only of biological and geological sound sources but also of anthropogenic noise sources. As this background noise increases, communication among marine species gets more difficult due to masking effects. In addition to noise harmful effects, some other aspects such as predator detection or reproduction are affected, thus comprising their preservation and survival. Several recent studies indicate that this noise may cause physical trauma, startle alarm behavior, alteration in metabolism-related genes, increase in the level of biochemical stress parameters, changes in protein content related to stress, and sub-lethal physiological changes that yield reduction in the growth and reproduction rates [3]. Consequently, to preserve the marine species it is extremely

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necessary to control and monitor the acoustic energy discharged into the sea.

Most underwater noise studies existing in the literature focus on the analysis of measured sound pressure exposure levels. Nevertheless, Popper and Hawkins [4] highlighted the higher sensitivity of fishes to particle motion rather than sound pressure and suggested its consideration in the assessment of marine environments. In this regard, understanding the significance of particle motion in the hearing physiology of fish is of great importance. There is therefore not only a need for new regulations and standards but also for the development of approaches to estimate and measure this particle motion.

This work shows some preliminary results on the analysis of the particle motion of underwater sound sources. Specifically, acoustic pressure measurements along the axis of an underwater electroacoustic sound source were performed in a water tank with a robotized system and an acquisition platform that used a hydrophone sensor. Particle motion was calculated from experimental pressure data, with results showing a good agreement when compared to theoretical predictions using a point source assumption. Additionally, a discussion on the near-field features of such sources served to illustrate the differences between using the particle motion or the sound pressure level to assess the noise level in the marine environment.

2. PARTICLE MOTION IN UNDERWATER ACOUSTICS

2.1. Definition

Particle motion is related to the kinetic energy of a sound wave, this being more important in the near-field (i.e., close to a sound source) than in the far-field, where it equals the potential energy related to the sound pressure (i.e., compression and expansion of the fluid). Different from sound pressure, particle motion is a vectorial quantity that contains directional info and therefore requires several sensors to be determined. Particle motion ξ along a direction r can be easily obtained upon temporal integration of the Euler's equation as

$$\xi = \int \left(-\frac{1}{\rho}\int \frac{\partial p}{\partial r} dt\right) dt \tag{1}$$

where p is the acoustic pressure, ω the angular frequency, and ρ the fluid density (e.g., the water density).

2.2. Prediction of particle motion

Modeling of particle motion may be of great interest in predicting the potential effects of underwater noise sources on marine species. Although this parameter could be extrapolated from well-known Wenz curves [5], this approach requires assuming free-field conditions, thus not being applicable in the presence of reflections or scenarios close to a vibrating surface, as is the case of shallow water. Alternatively, the use of predictive models allows taking into account temporal and frequential features of the noise source along with the marine media properties that determine the sound speed profile. Besides, these methods avoid the sound pressure to particle motion conversion as this can be directly calculated.

Hovem [6] proposed a modeling technique for the determination of particle motion using ray theory, each ray being considered a plane wave. However, the use of a point source assumption may be more appropriate to calculate the particle motion if the sound source is small compared to the wavelength of interest, especially in the near field where this parameter is more relevant [7]. In this latter case, the sound pressure generated at a distance r from the point source can be obtained from

$$p(r) = A\frac{e^{-jkr}}{r} \tag{2}$$

where A is the pressure amplitude of the spherical wave and $k = \omega/c$ is the wavenumber, being c the sound speed in water.

2.3. Measurement of particle motion

In practice, particle motion can be measured by using vector sensors which may contain both sound pressure and acceleration sensors. Among these, the so-called pressure gradient sensors determine the particle motion along the axis of interest x from the difference between two pressure sensors (e.g., a pair of hydrophones) as [8]

$$\xi(x) = \frac{1}{\omega^2\rho}\left(p(x+\Delta/2) - p(x-\Delta/2)\right) \tag{3}$$

where Δ is the spacing between hydrophones, which determines the sensitivity and bandwidth of the measurement system.

Nedelec et al. [9] proposed a simple formula to calculate the particle motion of a monopole source from the measured near-field sound pressure p at a distance r as follows

$$\xi(r) = \frac{p}{\omega\rho c}\left(1+\left(\frac{c}{\omega r}\right)^2\right)^{1/2} \tag{4}$$

3. MATERIAL AND METHODS

3.1. Underwater sound source

Both humans and fish make use of sound waves to emit and receive information in the marine environment. In this context, the design and development of systems capable of reproducing sound events still constitutes a challenge to scientist and engineers. Most systems make use of an electrodynamic speaker whose basic theory can be retrieved from [10]. In this work, the custom-made electrodynamic speaker whose schematic design assembly drawing is depicted in Fig. 1 was used as a sound source.

3.2. Measurement system

The on-axis pressure response of the electrodynamic speaker was measured and used to calculate the corresponding particle motion. The measurement setup consisted of a water tank of dimensions 9.75 m x 4.88 m x 1.32 m and a robotized system that served to place a miniature hydrophone B&K type 8103 at several distances from the source in the range 0.05-0.5 meters with steps of 0.05 m. Fig. 1 shows a picture of the mounting conditions before immersion in the water tank. The speaker and the hydrophone were connected to an audio power amplifier Bosch PLE-1P120-EU and a Nexus CCLD signal conditioner Type 2693-A, respectively, both being connected to the acquisition platform CLIO FW-02 controlled by a PC with the CLIO software. Once all the devices were connected, a Maximum Length Sequence (MLS) signal was sent to the speaker, and the impulse response at each measurement position was obtained.

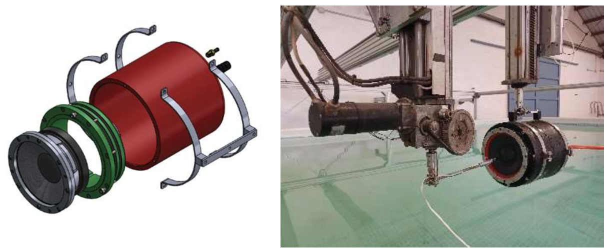

Figure 1. Underwater sound source: (Left) Schematic design assembly drawing, and (Right) picture of the mounting conditions used to measure its on-axis pressure response (before immersion in the water tank).

4. RESULTS AND DISCUSSION

4.1. On-axis pressure response

Fig. 2 shows the measured on-axis pressure response at 0.1 m of the electrodynamic speaker under study. The peak at 45 Hz corresponds to the resonance frequency of the speaker. Below the resonance frequency, it has a slope of +15 dB per octave of frequency, with a flat response curve being observed up to a cut-off frequency of around 450 Hz.

4.2. Particle motion: predictions vs. experiments

Once the frequency response of the underwater sound source was measured, pressure data was used to calculate the particle motion at the resonance frequency both from the finite difference approximation of equation (3) and from the expression proposed by Nedelec et al. in equation (4). Fig. 2 shows the calculated particle motion normalized to the maximum amplitude value at each case, results being also compared to the analytical equation (2) for a point source. It should be noted that the finite difference values were normalized to the analytical value at the closest distance (i.e., $x = 0.075$ m). In general, both experimental approaches show a good agreement when compared to the analytical results.

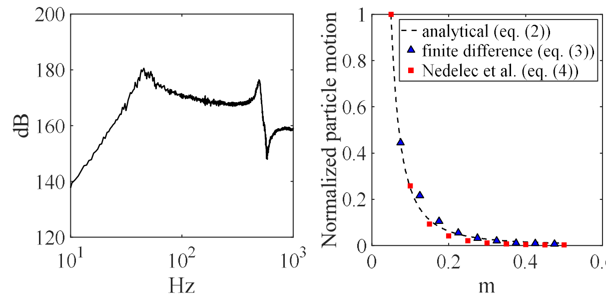

Figure 2. (Top) On-axis pressure response at 0.1 m of the electrodynamic speaker, and (Bottom) Normalized particle motion obtained using different approaches.

4.3. Remarks: particle motion vs. sound pressure level

Finally, let us analyze the acoustic field of the underwater point source described above located in the center of a coordinate plane xy. The radiated sound pressure field at any distance from the source can be obtained from equation (2) by assuming a random amplitude value (e.g., $A = 1$). Equation (3) can then be used to derive the particle motion field by making the calculation both in the x and y directions. Fig. 3 shows the corresponding normalized decibel levels at the frequency of 45 Hz. Significant differences between the particle motion and the sound pressure level patterns can be found (especially for the x-component of the particle motion in the y-axis), the dynamic range of the corresponding decay curves being also different. These discrepancies highlight the drawbacks in the definition of security noise level thresholds from pressure data instead of directly using particle motion data.

5. CONCLUSIONS

The reduction of anthropogenic noise in the marine environment is of crucial importance for the communication and welfare of fish and other marine species. Given that the auditory system of fish is more sensitive to particle motion than to sound pressure, it seems essential to take it into account when quantifying the anthropogenic noise. In this work, it was shown that the on-axis pressure response of an electroacoustic underwater sound source can be used to determine the corresponding particle motion. Results also show that significant differences arise when the sound pressure level is compared to the particle motion level in the near-field. Even though there exist several systems to measure particle motion (e.g., pressure gradient sensors, inertial sensors…), there are still some issues that must be tackled (e.g., interference, low accuracy…). Therefore, the development of approaches that let both measure the particle motion and analyze its effect on the marine species will presumably be a challenge to be faced in the forthcoming years.

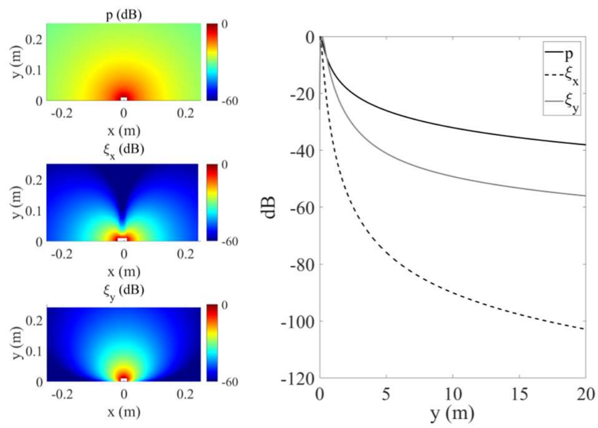

Figure 3. Acoustic pressure and particle motion levels of an underwater point source at 45 Hz: (Left) Spatial patterns, and (Right) *y*-axis response.

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