Importance of Empirical Particle Motion Measurements for Monitoring Underwater Noise from Wave Energy Converters

Original
Importance of Empirical Particle Motion Measurements for Monitoring Underwater Noise from Wave Energy Converters / Chicco, C., Niosi, F., Issoglio, D., Buscaino, G., Papale, E., Ceraulo, M., Giorgi, G.. - In: INTERNATIONAL MARINE ENERGY JOURNAL. - ISSN 2631-5548. - 9:1(2026), pp. 1-7. [10.36688/imej.9.1-7]

Availability:
This version is available at: 11583/3015368 since: 2026-09-11T08:30:41Z

Publisher:
IMEJ

Published
DOI:10.36688/imej.9.1-7

The Importance of Empirical Particle Motion Measurements for Monitoring Underwater Noise from Wave Energy Converters

Carola Chicco, Francesco Niosi, Davide Issoglio, Giuseppa Buscaino, Elena Papale, Maria Ceraulo and Giuseppe Giorgi

Abstract—**Underwater noise from Marine Energy Converters (MECs), including Wave Energy Converters (WECs), is a recognized stressor for marine organisms. Current monitoring guidelines focus on scalar pressure, but particle motion is equally important, especially in complex shallow-water environments where WEC systems can affect the soundscape. Many marine species detect sound primarily through particle motion, highlighting the need to include it in monitoring frameworks. This work underscores the importance and role of sound in marine habitats. Using a 3D accelerometer and hydrophone, we collected acoustic data near an Inertial Sea Wave Energy Converter (ISWEC) off Pantelleria, Sicily. Our initial measurements showed discrepancies between pressure and particle motion and higher variability along the vertical axis. These results stress the necessity of incorporating particle motion alongside pressure in underwater noise assessments, with potential implications for benthic and demersal species. They also highlight the need for deeper investigation into particle motion dynamics, particularly in the context of marine energy converter operations in shallow-water environments.**

Index Terms—**Environmental Impact Assessment, Substrate vibration, Fish, Marine Renewable Energy**

I. Introduction

MARINE Renewable Energy (MRE) holds significant promise for sustainable power generation and coastal decarbonization. However, concerns remain about its ecological impacts, particularly habitat disruption and biodiversity loss. To align with the ”2030 Sustainable Development Goals” of the United Nations, environmental assessments must follow the 'no significant harm' principle. As offshore spaces are increasingly shared by diverse activities, understanding and accurately assessing both individual and cumulative environmental effects is essential. In response, researchers have intensified efforts to monitor the ecological effects of MRE. The latest OES-Environmental report [1] highlights seven key stressor-receptor interactions linked to MRE development: collision risk, underwater noise, electromagnetic fields, habitat changes, entanglement, alterations in oceanographic systems, and species displacement. Among these concerns, underwater noise has received growing attention. In particular, interest in monitoring Wave Energy Converters (WEC) noise emissions has increased. Recent studies have measured sound pressure levels at varying distances from WECs, often finding levels to be negligible or similar to ambient ocean noise (e.g., [2]–[5]). However, these studies primarily focus on sound pressure, often neglecting the particle motion component of sound waves, which plays a vital role in how many marine species perceive their environment [6]. Research on particle motion remains very limited, both in scope and in the development of effective measurement techniques in the context of MRE noise assessment. Furthermore, the small number of deployed MRE devices means that available evidence is scarce, and there is a lack of rigorous standards for assessing environmental effects [7].

This work highlights the importance of underwater sound and its effective management, emphasizing the need for in-situ data collection within the context of environmental monitoring for WECs. We provide insights supported by preliminary results from a case study on an Inertial Sea Wave Energy Converter (ISWEC) installed in the Sicilian Channel.

A. Sound in the sea

Most marine organisms have evolved to rely primarily on acoustic signals for critical life functions, providing them with information about their environment. This reliance is due to the physical properties of sound in water, where it travels faster and over greater distances than other sensory signals such as light or chemical cues [8]. Consequently, diverse marine taxa are capable of perceiving sound, and some use it actively for communication. Research in recent years has confirmed the importance of sound across diverse

Part of a special issue for EWTEC 2025. Original version published in EWTEC 2025 proceedings at doi.org/10.36688/ewtec-2025-810.

This paper has been subject to single-blind peer review by a minimum of two reviewers.

This publication is part of the project PNRR-NGEU which has received funding from the MUR-DM 118/2023

C. Chicco is with the Politecnico di Torino, Department of Environment, Land and Infrastructure Engineering, Turin, Italy (e-mail: carola.chicco@polito.it).

F. Niosi, D. Issoglio and G. Giorgi are with the Marine Offshore Renewable Energy Lab, Politecnico di Torino, Turin, Italy (e-mails: francesco.niosi@polito.it, davide.issoglio@polito.it, giuseppe.giorgi@polito.it).

G. Buscaino, E. Papale and M. Ceraulo are with the Institute of Anthropic Impact and Sustainability in the Marine Environment, National Research Council, Torretta Granitola, Italy (emails: giuseppa.buscaino@ias.cnr.it, elena.papale@ias.cnr.it, maria.ceraulo@ias.cnr.it).

Digital Object Identifier: https://doi.org/10.36688/imej.9.1-7

groups, including marine mammals [9], pinnipeds [10], fish, and invertebrates [11].

The acoustic environment of both terrestrial and aquatic ecosystems can be described by the term *soundscape* (ISO 18405), which encompasses the spatial, temporal, and frequency characteristics of all sound sources in a given area or habitat. The soundscape is typically categorized into three components: *biophony*, which includes sounds produced by living organisms; *geophony*, which includes natural physical sounds; and *anthropophony*, which refers to sounds generated by human activities [12], [13].

Marine animals inhabit complex and naturally dynamic soundscapes shaped by wind, waves, rain, cracking ice, underwater geological events, and biological sounds from snapping shrimp, urchins, chorusing fish, and other marine animals [14], [15]. However, since the industrial revolution, anthropogenic sources, particularly shipping and offshore industrial operations, have added a persistent layer of noise to the environment [16].

The concern is that this anthropogenic noise might interfere with marine mammal biological functions. Figure 1 illustrates how the frequency ranges of many anthropogenic sound sources overlap with the hearing ranges of various marine species, highlighting the potential for human-generated noise to affect the soundscape [17].

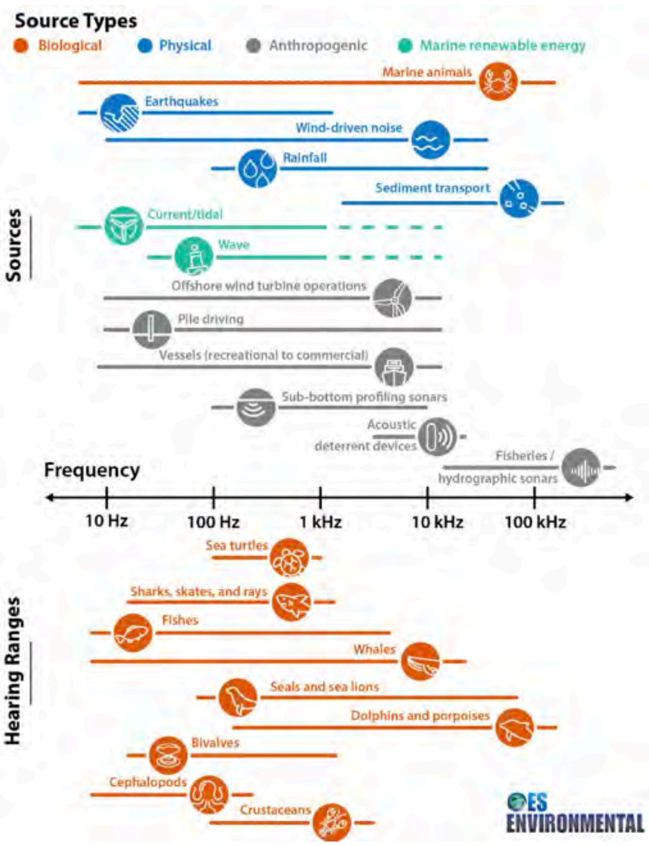

Fig. 1. Examples of typical soundscape source types (top) and hearing ranges of different species (bottom), highlighting frequency overlaps [7].

Adverse reported effects of anthropogenic noise to animals range from communication masking and behavioral disruptions (e.g., impaired orientation, communication interference, and habitat displacement) to more severe consequences, including hearing damage, physiological alterations (e.g., metabolic shifts and increased stress), developmental abnormalities, and even mortality [11], [18], [19]. These effects vary across species and individuals, influenced by factors such as life stage, age, sex, prior exposure history, and seasonal context [20], [21].

The impacts of anthropogenic noise can be proximate, involving immediate behavioral or physiological responses, or ultimate, affecting survival and reproductive success over time. Although these effects are initially expressed at the individual level, their accumulation can alter population dynamics, including changes in population structure, reproductive rates, and distribution. Over time, such changes may scale up to influence ecosystem function and stability, disrupting species interactions, food webs, and habitat use.

B. Underwater noise standards

In response to these concerns, the European Commission included underwater noise as a potential pollutant in the Marine Strategy Framework Directive (2008/56/EC), under Descriptor 11 (D11). As a result, EU Member States are now legally required to implement noise emission controls and establish monitoring programs.

WECs and other MRE devices produce underwater noise through components such as mooring systems and generators. Moreover, many different working principles of wave energy conversion exist, spanning from point absorbers [22], terminators [23], attenuators [24], inertial [25], oscillating water columns [26]; their related potential noise emission is likely to be case-specific. Consequently, monitoring their noise emissions (i.e., frequency content and amplitude) is recommended during all stages of development. The International Energy Agency (IEA) has established guidelines and standards for underwater noise monitoring, including minimum technical requirements (i.e., IEC TS 62600-40).

According to established standards, underwater acoustic measurements are typically conducted using systems designed to capture sound pressure levels (IEC 60500:2019; ISO 18406:2017). These standards also outline recommended performance specifications for acoustic sensors (ISO 18406; IEC 60565). To ensure data quality and relevance, system settings should be tailored to the specific monitoring objectives and post-processing requirements.

C. Particle Motion vs. pressure

Any underwater sound source generates two key measurable proprieties: *sound pressure* and *particle motion*. Sound pressure refers to scalar fluctuations in acoustic pressure within the water column and is typically expressed in pascals (Pa), with a standard underwater reference value of 1 μPa. In contrast, particle motion is a vector quantity that describes the physical displacement of water particles caused by a sound wave. It also conveys directional information about the sound source [6]. It can be quantified in terms of displacement, velocity, or acceleration, with standardized underwater reference values of 1pm, 1nm/s, and 1 $\mu\mathrm{m/s}^2$, respectively [27]. These measurements are typically obtained using accelerometers, velocity sensors, or hydrophone arrays [28].

Together, sound pressure and particle motion are fundamental to the study of underwater acoustics, as marine species differ in their sensitivity and response to each component [29], [30]. For example, fish and many aquatic invertebrates, composed largely of water, are acoustically well-coupled to their surrounding medium. When exposed to sound waves, their entire bodies vibrate. Denser internal structures, such as otoliths or other calcareous elements, move out of phase due to their higher inertia, functioning as biological accelerometers [31]. This mechanism explains their ability to detect particle motion, especially at low frequencies. Indeed, many of these species are most sensitive to frequencies below 100 Hz, although some fish can detect sounds up to 1–2 kHz [32].

Sound pressure and particle motion are directly related, but only under specific conditions, such as when sound propagates as a plane wave. In these ideal cases, a simple mathematical relationship between the two quantities can be described. A plane wave occurs when the wavefront is flat, which typically happens far from the sound source, in homogeneous media and in the absence of reflecting boundaries, where propagation can be approximated as linear rather than spherical or complex [6]. In more complex environments, such as shallow waters and low-frequency ranges where fish and invertebrates live and communicate, deriving particle motion from pressure is not always reliable. Other factors, such as cut-off frequency and sound wavelength, also influence the plane wave approximation [6], [33]. As such, direct measurements of particle motion remain the most reliable method.

Another biologically important component of sound in shallow water environments linked to particle motion is seabed vibration. Acoustic waves that travel through the substrate and along the interface between the substrate and the water column, result in mechanical movements of the seabed. Growing evidence suggests that this type of vibration is used by fish and invertebrates in a similar way to how pressure and particle motion in the water column are used. However, the levels of substrate-borne sounds, both natural and human-made, are not well documented [34], [35].

Despite growing awareness of its ecological relevance, there are still no established guidelines for measuring particle motion, and monitoring efforts by public agencies remain focused solely on sound pressure [33]. This limits our ability to fully assess the acoustic environment and its effects on marine organisms. The acoustic characteristics of MECs are still poorly understood, mainly due to the diversity of device types and the lack of consistent deployment data. Most MECs operate in coastal areas where conditions are suitable for particle motion measurements, and because they are anchored to the seabed, they are likely to transmit vibrations into the substrate [36]. Yet, data on particle motion and seabed vibration generated by MECs are virtually absent from the literature.

Recent studies have begun to highlight the need for dedicated research in this area, calling for targeted data collection to better understand particle motion and its biological relevance [35], [37].

In this context, the present work aims to emphasize the importance of particle motion measurements around WECs, explore the possibility of estimating particle motion from pressure data, and investigate the type of information that particle motion can reveal beyond what is captured by pressure alone.

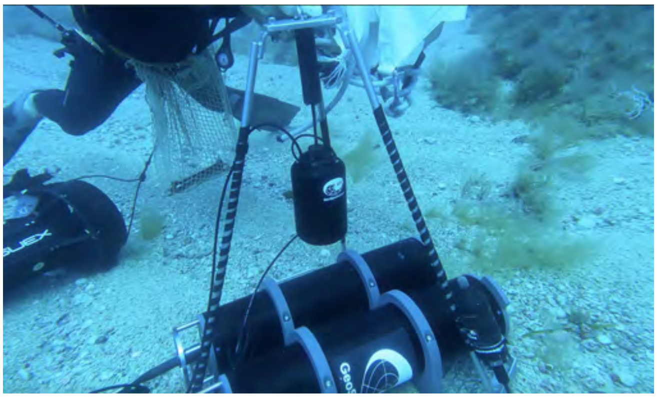

Fig. 2. Deployment of 3D accelerometer (M20-105 sensor) at the seabottom near ISWEC.

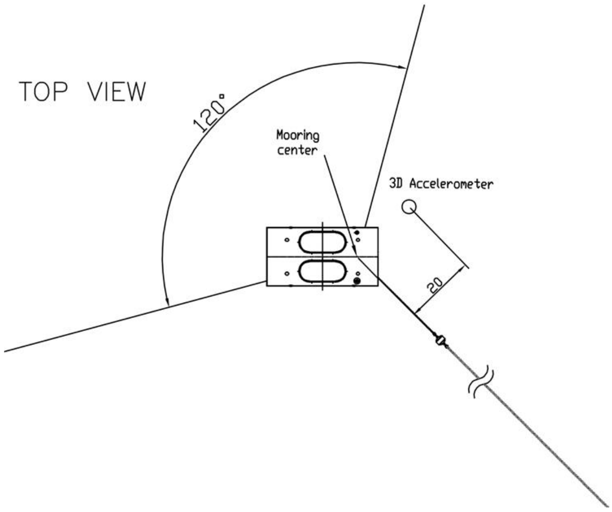

Fig. 3. Schematic diagram of the three ISWEC mooring lines and the deployment location of the 3D accelerometer.

II. Materials and methods

A. Study area: Pantelleria

Pantelleria is an island located southwest of Sicily. ISWEC was installed at 800 meters from the coast with a depth of 30 meters [38]. The acoustic underwater emission of ISWEC was already measured by [3], considering wave height and generator noise. Here, we provide new data taken with shorter time windows to propose preliminary results on particle motion. However, for this work, the generator was turned off during the recordings, hence only sound from mooring and hull were recorded.

B. Data collection and acoustic analysis

Data were collected using an acoustic sensor (a 3D accelerometer and integrated hydrophone, shown in Figure 2). This sensor (M20-105 manufactured and calibrated by Geospectrum Technologies Inc. Dartmouth, Canada; sensitivity follows a curve from 0 to 4000 Hz) was set for continuous recordings at 8 kHz sampling rate, 24-bit. The acoustic sensor is equipped with 4 channels: the first three for the 3 axes (x, y, z) to measure particle motion, while the fourth is an omni-directional hydrophone to measure pressure. A schematic representation of the mooring lines and the acoustic sensor deployment position is shown in Figure 3 The analysis was performed using paPAM software [6]. Power Spectral Density (PSD) was performed for 10 files of 30 minutes each; spectrograms of the pressure, particle velocity and acceleration were computed in Hamming window of 1 s length with no overlap for each audio file; a bandpass filter was applied to select only the frequency band of 10-2500 Hz. Given the preliminary nature of this study, a comprehensive characterization of all acoustic events produced by ISWEC is beyond its scope. Therefore, shorter time windows from the collected data were manually selected instead of analyzing continuous long-term recordings. The analyzed recordings were selected to isolate periods representative of diverse environmental conditions, with significant wave height (Hs) ranging from 0.2 to 0.7 meters as obtained from an in-situ buoy (Directional Wave Spectra Drifter developed by Lagrangian Drifter Laboratory, San Diego University). This selection was further refined based on the clear presence of ISWEC's acoustic signature and the absence of other significant interfering noise sources, such as anthropogenic sounds (e.g., shipping traffic) or persistent biological sounds (e.g., fish choruses).

III. RESULTS

Based on the available data, a total of 5 hours of data were analyzed to observe trends and potential variations across different days. As shown in Figure 4, the PSD of pressure for all 10 recordings displays higher intensity at lower frequencies, consistent with findings from previous studies on the same device [3].

However, the absolute maximum sound levels do not exceed 75 dB re 1 μPa^2/Hz, suggesting moderate ambient noise levels in the presence of the installed WEC during its non-operational state in the selected frequency bands. Variability between recordings is generally low, though some differences are observed in the frequency range around 100 Hz and 1000 Hz, where certain files exhibit increased intensity, with a maximum difference of 23 dB re 1 μPa^2/Hz between files.

Interestingly, frequency spikes are observed at higher frequencies. Notably, a spike occurs around 1200 Hz, exceeding 60 dB re 1 μPa^2/Hz.

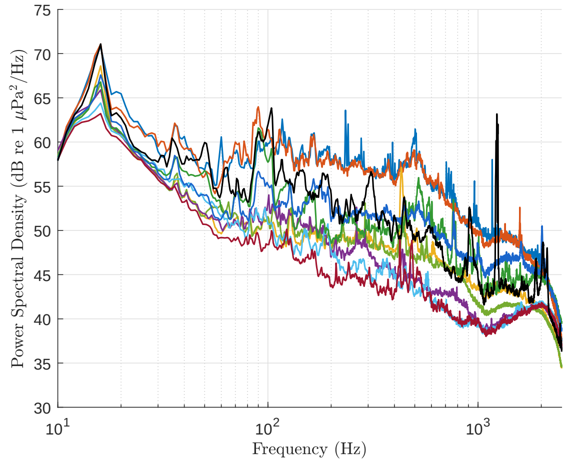

Fig. 4. Power Spectral Density of sound pressure (dB re 1 μPa^2/Hz, bandpass 10-2500 Hz) of ten different audio file of 30 minutes, each. Each colored line represents a different audio file.

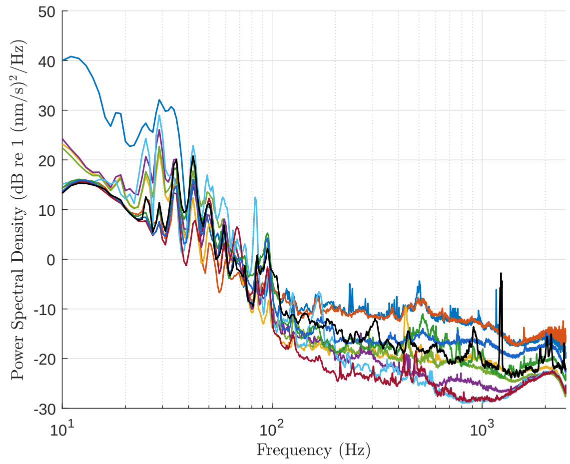

Fig. 5. Power Spectral Density of Sound Velocity (dB re 1 (nm/s)^2/Hz bandpass, 10-2500 Hz) of ten different audio file of 30 minutes, each. Each colored line represents a different audio file.

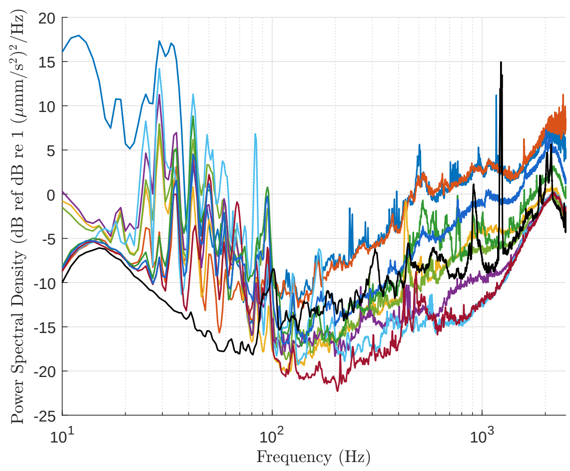

Fig. 6. Power Spectral Density of Sound Acceleration (dB re 1 (μm/s^2)^2/Hz, bandpass 10-2500 Hz) of ten different audio file of 30 minutes, each. Each colored line represents a different audio file.

Figure 5 and 6 show the velocity and acceleration data recorded directly from the accelerometer.

The PSD curves for various files are plotted as the sum of the three acceleration components along the three fixed axes. The three spectra generally follow a similar pattern to the sound pressure (Figure 4): higher intensities at lower frequencies, with a decreasing trend as frequency increases. This trend is more pronounced in the sound velocity data, which shows a steeper decline in intensity. In contrast, the sound pressure data maintain higher values from 100 Hz onward, though variability across files remains consistent.

These preliminary results show that the acoustic intensity is concentrated in the lower frequency range, with sound velocity levels reaching 30–40 dB re 1 (nm/s^2/Hz) up to 100 Hz, and dropping significantly at higher frequencies. Acceleration data shows a rise in intensity at higher frequencies (Figure 6).

However, the most notable difference between pressure and particle motion data appears in the very low-frequency bands, where certain curves report significantly higher values. These trends are not mirrored in the pressure data for particular file audios. This is clearly visible in Figure 5 and 6, where certain PSD curves show high intensity levels in low frequencies (e.g., this is particularly visible for the blue line curve).

Figure 7 offers a detailed breakdown of particle velocity across individual measurement channels. The plots display the overall mean values derived from 10 data files, illustrating the general trend for each channel alongside percentile ranges. The X, Y, and omnidirectional channels exhibit similar acoustic signatures, while the Z channel demonstrates significantly higher intensity between 10 Hz and 80 Hz compared to the other channels. The PSD curves for the vertical channel align with the elevated low-frequency values observed in Figures 5 and 6.

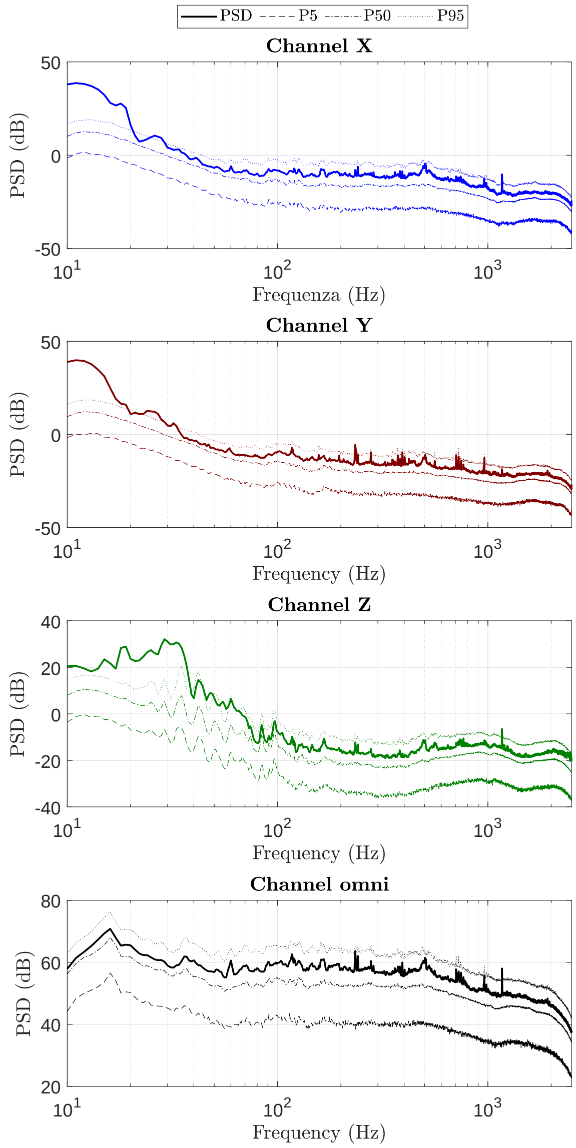

Fig. 7. Mean spectral density of sound velocity (dB re 1 (nm/s)^2/Hz) across 10 audio files, shown for each channel (X, Y, Z, and omnidirectional pressure), including the 5th, 50th, and 75th percentiles.

IV. DISCUSSION

As previously mentioned and further confirmed by these preliminary findings, the relationship between particle motion and pressure is not always direct or straightforward, particularly in complex environments, at low frequencies, and when considering areas close to the seabed or near the source (near-field). This suggests that pressure alone, when used to estimate particle motion, can lead to underestimation of lower frequencies. The preliminary result highlights a significant variability in the vertical axis (z channel) compared to the other axes. Substrate contact of ISWEC may generate vibrations that propagate into the seabed, producing waves known as interface waves or ground-roll, which predominantly travel along the vertical axis. These waves typically move along the surface of the substrate and are characterized by low frequency and high amplitude [37]. To clarify the source of this variability and its possible relation to substrate-induced vibrations, further analysis and data collection are essential.

Despite discrepancies between particle motion and pressure, overall trends of noise recorded during the brief deployment did not report high intensity values, confirming the WEC's limited contribution to background noise. Other studies reported that WEC noise contributions are predominantly confined to lower frequencies [2], [39], with measurable differences between operational and non-operational state. However, in high-noise environments, WEC-generated sound becomes indistinguishable from ambient noise [39].

The role of particle motion in the ecology and biology of marine species remains largely unknown, despite growing evidence of its potential importance [35]. It is well-established that demersal or benthic fish species, which reside near the seabed, are particularly sensitive to these seabed vibrations. These species rely on such vibrations as critical cues for various vital activities, such as foraging, detecting predators, and communication with potential mates [40]. At present, no standardized guidelines or measurement protocols exist for assessing particle motion [20], [33]. This gap can be attributed to the lack of recognition of the importance of substrate vibrations and particle motion by researchers [35], as well as the challenges associated with the acquisition of the instrumentation necessary to measure these signals [33], [37]. A recent analysis of data gaps in Offshore Wind Farms and similar underwater sound sources has provided some guidance on priorities [41].

The field of WEC underwater noise research remains nascent due to the wide variety of prototype designs, each potentially producing distinct acoustic signatures. This variability is particularly evident in mooring systems, where different configurations may generate unique acoustic profiles [36], [39]. Crucially, seabed vibration patterns may vary significantly depending on mooring technology, as different systems could differentially transmit energy into the substrate. Further data collection across various WEC designs is essential to better understand these relationships [36].

Acknowledgement

This work was supported by the Italian Ministry of University and Research (MUR) under DM 118/2023 within the PNRR–NGEU framework.

References

[1] L. Garavelli, A. E. Copping, L. G. Hemery, and M. C. Freeman, "Oes-environmental 2024 state of the science report: Environmental effects of marine renewable energy development around the world," 2024. [Online]. Available: https://doi.org/10.2172/2438585

[2] J. Walsh, I. Bashir, J. K. Garrett, P. R. Thies, P. Blondel, and L. Johanning, "Monitoring the condition of marine renewable energy devices through underwater acoustic emissions: Case study of a wave energy converter in falmouth bay, uk," *Renewable Energy*, vol. 102, pp. 205–213, 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0960148116309144

[3] G. Buscaino, G. Mattiazzo, G. Sannino, E. Papale, G. Bracco, R. Grammauta, A. Carillo, J. M. Kenny, N. De Cristofaro, M. Ceraulo *et al.*, "Acoustic impact of a wave energy converter in mediterranean shallow waters," *Scientific reports*, vol. 9, no. 1, p. 9586, 2019. [Online]. Available: https://doi.org/10.1038/s41598-019-45926-1

[4] K. Raghukumar, K. Heal, G. Chang, and F. Spada, "Acoustic characterization around the calwave wave energy converter," in *Proceedings of the European Wave and Tidal Energy Conference*, 2023. [Online]. Available: https://tethys.pnnl.gov/publications/acoustic-characterization-around-calwave-wave-energy-converter

[5] J. L. Harding, L. A. Preston, E. Johnson, J. D. Roberts, C. A. Jones, K. Raghukumar, and E. Hafla, "Modeling the acoustic noise from a wave energy converter farm and its impact on marine mammals at the pacwave south site, offshore newport oregon," *Renewable Energy*, vol. 209, pp. 677–688, 2023. [Online]. Available: https://doi.org/10.1016/j.renene.2023.04.014

[6] S. L. Nedelec, J. Campbell, A. N. Radford, S. D. Simpson, and N. D. Merchant, "Particle motion: the missing link in underwater acoustic ecology," *Methods in Ecology and Evolution*, vol. 7, no. 7, pp. 836–842, 2016. [Online]. Available: https://besjournals.onlinelibrary.wiley.com/doi/abs/10.1111/2041-210X.12544

[7] L. Garavelli, L. Hemery, D. Rose, H. Farr, J. Whiting, and A. Copping, "2024 state of the science report - chapter 3: Marine renewable energy: Stressor-receptor interactions," sep 2024. [Online]. Available: https://doi.org/10.2172/2438589

[8] R. J. Urick, "Principles of underwater sound-2," 1975. [Online]. Available: https://archive.org/details/principlesofunde00uric

[9] P. L. Tyack and E. H. Miller, *Vocal anatomy, acoustic communication and echolocation*. Oxford, UK: Blackwell Science (Wiley-Blackwell), 2002, pp. 142–184.

[10] I. Van Opzeeland, S. Van Parijs, H. Bornemann, S. Frickenhaus, L. Kindermann, H. Klinck, J. Plötz, and O. Boebel, "Acoustic ecology of antarctic pinnipeds," *Marine Ecology Progress Series*, vol. 414, pp. 267–291, 2010. [Online]. Available: url={https://doi.org/10.3354/meps08683}

[11] M. Solé, K. Kaifu, T. A. Mooney, S. L. Nedelec, F. Olivier, A. N. Radford, M. Vazzana, M. A. Wale, J. M. Semmens, S. D. Simpson *et al.*, "Marine invertebrates and noise," *Frontiers in Marine Science*, vol. 10, p. 1129057, 2023. [Online]. Available: https://doi.org/10.3389/fmars.2023.1129057

[12] B. Krause, "Bioacoustics, habitat ambience in ecological balance," *Whole Earth Review*, vol. 57, no. 472, pp. 14–18, 1987.

[13] B. C. Pijanowski, L. J. Villanueva-Rivera, S. L. Dumyahn, A. Farina, B. L. Krause, B. M. Napoletano, S. H. Gage, and N. Pieretti, "Soundscape ecology: The science of sound in the landscape," *BioScience*, vol. 61, no. 3, pp. 203–216, 03 2011. [Online]. Available: https://doi.org/10.1525/bio.2011.61.3.6

[14] P. Dahl, J. Miller, D. Cato, and R. Andrew, "Underwater ambient noise," *Acoustics Today*, vol. 3, no. 1, pp. 23–33, jan 2007. [Online]. Available: https://acousticstoday.org/wp-content/uploads/2019/10/UNDERWATER-AMBIENT-NOISE-Peter-H.-Dahl.pdf

[15] C. Erbe, A. J. Duncan, A. Gavrilov, M. Landero, R. D. McCauley, I. Parnum, C. Salgado-Kent, and E. Sidenko, *Sources of Underwater Noise*. Cham: Springer Nature Switzerland, 2025, pp. 85–178. [Online]. Available: https://doi.org/10.1007/978-3-031-77022-7_2

[16] G. V. Frisk, "Noiseonomics: The relationship between ambient noise levels in the sea and global economic trends," *Scientific reports*, vol. 2, no. 1, p. 437, 2012. [Online]. Available: https://doi.org/10.1038/srep00437

[17] A. N. Popper and A. D. Hawkins, "An overview of fish bioacoustics and the impacts of anthropogenic sounds on fishes," *Journal of Fish Biology*, vol. 94, no. 5, pp. 692–713, 2019. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1111/jfb.13948

[18] A. N. Popper, A. D. Hawkins, O. Sand, and J. A. Sisneros, "Examining the hearing abilities of fishes," *The Journal of the Acoustical Society of America*, vol. 146, no. 2, pp. 948–955, 2019.

[19] C. Erbe, R. Dunlop, and S. Dolman, *Effects of Noise on Marine Mammals*. New York, NY: Springer New York, 2018, pp. 277–309. [Online]. Available: https://doi.org/10.1007/978-1-4939-8574-6_10

[20] A. D. Hawkins, A. E. Pembroke, and A. N. Popper, "Information gaps in understanding the effects of noise on fishes and invertebrates," *Reviews in fish biology and fisheries*, vol. 25, pp. 39–64, 2015. [Online]. Available: https://doi.org/10.1007/s11160-014-9369-3

[21] C. M. Harris, L. Thomas, E. A. Falcone, J. Hildebrand, D. Houser, P. H. Kvadsheim, F.-P. A. Lam, P. J. Miller, D. J. Moretti, A. J. Read *et al.*, "Marine mammals and sonar: Dose-response studies, the risk-disturbance hypothesis and the role of exposure context," *Journal of Applied Ecology*, vol. 55, no. 1, pp. 396–404, 2018. [Online]. Available: https://doi.org/10.1111/1365-2664.12955

[22] M. Rava, P. Dafnakis, V. Martini, G. Giorgi, V. Orlando, G. Mattiazzo, G. Bracco, and A. Gulisano, "Low-cost heaving single-buoy wave-energy point absorber optimization for sardinia west coast," *Journal of Marine Science and Engineering*, vol. 10, no. 3, 2022. [Online]. Available: https://doi.org/10.3390/jmse10030397

[23] B. Battisti, G. Giorgi, and G. V. Fernandez, "Balancing power production and coastal protection: A bi-objective analysis of wave energy converters," *Renewable Energy*, vol. 220, 2024. [Online]. Available: https://doi.org/10.1016/j.renene.2023.119702

[24] J. C. McNatt and C. H. Retzler, "The performance of the mocean m100 wave energy converter described through numerical and physical modelling," *International Marine Energy Journal*, vol. 3, no. 1, pp. 11–19, 2020. [Online]. Available: https://doi.org/10.36688/imej.3.11-19

[25] F. Niosi, E. Begovic, C. Bertorello, B. Rinauro, G. Sannino, M. Bonfanti, and S. Sirigu, "Experimental validation of orcaflex-based numerical models for the pewec device," *Ocean Engineering*, vol. 281, p. 114963, 2023. [Online]. Available: https://doi.org/10.1016/j.oceaneng.2023.114963

[26] U. Singh, N. Abdussamie, and J. Hore, "Hydrodynamic performance of a floating offshore owc wave energy converter: An experimental study," *Renewable and Sustainable Energy Reviews*, vol. 117, p. 109501, 2020. [Online]. Available: https://doi.org/10.1016/j.rser.2019.109501

[27] S. Robinson and L. Wang, "Terminology for ocean ambient noise monitoring. report of the eu interreg joint monitoring programme for ambient noise north sea (jomopans)," EU INTERREG Joint Monitoring Programme for Ambient Noise North Sea (JOMOPANS), Deliverable 3.1, JOMOPANS WP3, 2021. [Online]. Available: https://northsearegion.eu/jomopans

[28] B. Martin, D. G. Zeddies, B. Gaudet, and J. Richard, "Evaluation of three sensor types for particle motion measurement," in *The effects of noise on aquatic life II*. Springer, 2016, pp. 679–686. [Online]. Available: https://doi.org/10.1007/978-1-4939-2981-8_82

[29] S. Dijkgraaf, "The supposed use of the lateral line as an organ of hearing in fish," *Experientia*, vol. 20, no. 10, pp. 586–587, 1964. [Online]. Available: https://doi.org/10.1007/BF02150313

[30] A. D. Hawkins and A. A. M. Jr., "Hearing and sound communication under water," in *Bioacoustics: A Comparative Approach*. London, UK: Academic Press, 1983, pp. 347–405.

[31] C. R. Schilt, T. W. Cranford, P. Krysl, R. E. Shadwick, and A. D. Hawkins, "Vibration of the otoliths in a teleost," in *The Effects of Noise on Aquatic Life*. Springer, 2012, pp. 105–107. [Online]. Available: https://doi.org/10.1007/978-1-4419-7311-5_23

[32] F. Ladich and R. R. Fay, "Auditory evoked potential audiometry in fish," *Reviews in Fish Biology and Fisheries*, vol. 23, pp. 317–364, 2013. [Online]. Available: https://doi.org/10.1007/s11160-012-9297-z

[33] S. Nedelec, M. Ainslie, M. Andersson, S. Cheong, M. Halvorsen, M. Linne, B. Martin, A. Nojd, S. Robinson, L. Wang, and J. Ward, "Best practice guide for underwater particle motion measurement for biological applications," University of Exeter, Tech. Rep., oct 2021. [Online]. Available: http://dx.doi.org/10.25607/OBP-1726

[34] L. Roberts and M. Elliott, "Good or bad vibrations? impacts of anthropogenic vibration on the marine epibenthos," *Science of the total environment*, vol. 595, pp. 255–268, 2017. [Online]. Available: https://doi.org/10.1016/j.scitotenv.2017.03.117

[35] A. N. Popper and A. D. Hawkins, "The importance of particle motion to fishes and invertebrates," *The Journal of the Acoustical Society of America*, vol. 143, no. 1, pp. 470–488, 2018. [Online]. Available: https://doi.org/10.1121/1.5021594

[36] A. N. Popper, J. Haxel, G. Staines, S. Guan, S. L. Nedelec, L. Roberts, and Z. D. Deng, "Marine energy converters: Potential acoustic effects on fishes and aquatic invertebratesa)," *The Journal of the Acoustical Society of America*, vol. 154, no. 1, pp. 518–532, 07 2023. [Online]. Available: https://doi.org/10.1121/10.0020150

[37] A. D. Hawkins, R. A. Hazelwood, A. N. Popper, and P. C. Macey, "Substrate vibrations and their potential effects upon fishes and invertebrates," *The Journal of the Acoustical Society of America*, vol. 149, no. 4, pp. 2782–2790, 2021. [Online]. Available: https://doi.org/10.1121/10.0004773

[38] G. Cervelli, L. Parrinello, C. Moscoloni, and G. Giorgi, "Comparison of the era5 wave forecasting dataset against buoy record," *Instrumentation Mesure Metrologie*, vol. 21, no. 3, p. 87 – 95, 2022. [Online]. Available: https://doi.org/10.18280/i2m.210301

[39] J. Tougaard, "Underwater noise from a wave energy converter is unlikely to affect marine mammals," *PLOS ONE*, vol. 10, no. 7, pp. 1–7, 07 2015. [Online]. Available: https://doi.org/10.1371/journal.pone.0132391

[40] L. Roberts and A. N. Rice, "Vibrational and acoustic communication in fishes: The overlooked overlap between the underwater vibroscape and soundscape," *The Journal of the Acoustical Society of America*, vol. 154, no. 4, pp. 2708–2720, 2023. [Online]. Available: https://doi.org/10.1121/10.0021878

[41] A. N. Popper, L. Hice-Dunton, E. Jenkins, D. M. Higgs, J. Krebs, A. Mooney, A. Rice, L. Roberts, F. Thomsen, K. Vigness-Raposa *et al.*, "Offshore wind energy development: research priorities for sound and vibration effects on fishes and aquatic invertebrates," *The Journal of the Acoustical Society of America*, vol. 151, no. 1, pp. 205–215, 2022. [Online]. Available: https://doi.org/10.1121/10.0009237