Exploring Particle Motion Near a Wave Energy Converter

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Contents

Abstract

There is a growing expectation for the expansion of marine renewable energies (MRE), yet their impacts on marine fauna at both individual and array scales are not yet fully understood. Offshore marine energy installations represent emerging anthropogenic noise sources capable of propagating acoustic energy through the water column and substrate. MRE devices may cause acoustic disturbances, potentially affecting demersal and benthic species of fish and invertebrates.

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However, data on particle motion and substrate vibrations generated by floating structures moored to the seafloor remain scarce. This chapter provides an example of ongoing work involving direct measurements of acoustic particle motion and pressure data collected near ISWEC (Inertial Sea Wave Energy Converter), a wave energy device located off the coast of Pantelleria (Italy), Mediterranean Sea. Data were collected using an acoustic vector sensor equipped with a 3D accelerometer and omnidirectional hydrophone. An example of the acoustic signature of the ISWEC mooring is reported. Results indicate differences in behavior between pressure and particle motion, suggesting that their relationship is not straightforward. These findings highlight the importance of direct measurements for accurate underwater noise assessments and for improving understanding of particle motion behavior.

Keywords

Marine renewable energy · Particle motion · WEC · Noise impact

Introduction

The European Commission and international organizations are claiming for a reduction of carbon emissions by 2030 and a net zero emission by 2050, actively promoting the development of renewable energies. Offshore wind turbines are currently the most established marine renewable energy technology (Soukissian et al. 2023). However, other technologies are also emerging and can be suitable for specific applications, like marine energy converters (MECs), which are renewable energy systems that exploit the energy of the sea to generate electricity. They are particularly well suited for deployment in remote coastal regions and islands, where traditional energy infrastructure can be limited or costly. Such applications align with the sustainable development goals of the blue economy, promoting economic growth based on ocean resources in an environmentally responsible way (LiVecchi et al. 2019). On the other hand, the development of these technologies is accompanied by growing uncertainty about their potential impacts on marine ecosystems. MECs are reported to produce sound during their operation, making them potential new sources of anthropogenic noise in the ocean. Comprehensive monitoring and impact assessments are therefore essential. Although current acoustic assessments of these technologies primarily focus on sound pressure levels, this approach overlooks a critical aspect of underwater sound: particle motion, which is the primary acoustic stimulus for most fish and invertebrates (Popper and Hawkins 2018). These organisms mainly inhabit the coastal and shallow water environments where MEC devices are intended to function most effectively. Particle motion is still not routinely considered in acoustic assessments and estimating it from pressure data may not be straightforward in the complex and variable conditions of coastal environments. As the use of offshore resources continues to grow, there is a need for comprehensive evaluations that account for a broader range of marine organisms to better understand and mitigate the potential long-term impacts of underwater noise.

Wave Energy Converters and Acoustic Emissions

MECs represent an important new generation of renewable energy technologies that harness energy from the movement of seawater, including tidal flows, waves, ocean currents, as well as gradients in temperature and salinity. Energy extraction uses mechanisms such as rotation, oscillation, or the creation of pressure differentials (LiVecchi et al. 2019). Wave energy converters (WECs) are a key class of MEC devices designed to capture and convert energy carried by ocean surface waves into electrical power. During the past decade, numerous prototypes of WECs have been developed, deployed, and tested worldwide, demonstrating the potential of wave power as a renewable energy source (Garavelli et al. 2024). However, the introduction of any new anthropogenic activity can be expected to cause some degree of impact and alteration to marine habitats. For this reason, the scientific community has increasingly focused on investigating the potential environmental impacts associated with WEC and MRE systems more broadly (Copping and Hemery 2024). Recent reports and studies highlight key stressor–receptor pairings associated with MRE and confirm that underwater noise remains a focus of concern. Furthermore, guidelines and measurement standards for underwater noise from marine renewable energy devices have been published by the International Energy Agency Ocean Energy Systems (IEC TS 62600-40).

The sources of underwater noise from WECs are multifaceted and originate primarily from mechanical components involved in energy conversion. These include continuous and impulsive noises produced by generators, hydraulic pumps, turbines, and vibrations transmitted through mooring systems and anchoring chains (Popper et al. 2023). Moorings are critical for WECs because they allow the oscillatory or surging movements essential for energy capture, as opposed to offshore wind turbines, where minimizing structural movement is a priority. The dynamic motion of WECs induces specific acoustic signatures, including low-frequency tones and harmonics, resulting from both component operation and mooring line dynamics (Garavelli et al. 2024; Walsh et al. 2017).

Furthermore, all components of a floating system that are anchored to the seabed can generate noise that transmits into the substrate, producing vibrations that propagate along the seafloor and at its interface with the water column. These vibrations have the potential to affect both demersal and benthic species. Their potential effect and this concern have been widely discussed recently by Popper et al. (2023). The authors also propose priorities and suggestions on research questions to address these uncertainties. However, there remains a notable lack of direct measurements of particle motion and substrate vibrations associated with WEC installations, representing a critical knowledge gap.

Noise emitted by WECs, is unlikely to cause damage to organisms; however, their effect can be perceptual (Tougaard 2015; Popper et al. 2023), if WEC noise emission overlaps hearing sensitivity of animals, it can involve alteration of behavior and a masking effect (Buscaino et al. 2019). The growing anthropogenic noise in marine environments further complicates impact assessments for WECs. The cumulative effect of underwater noise from multiple human activities necessitates robust monitoring frameworks. Standardized measurement protocols, as recommended by international bodies, are vital for ensuring sustainable development of wave energy resources (MSFD 2008/56/EC; Ainslie et al. 2022).

Importance of Particle Motion for Fish and Invertebrates

Underwater sound consists of both pressure and particle motion, yet marine noise studies often focus only on pressure. Particle motion, the oscillatory movement of water particles caused by sound waves, is the main cue for many fish and invertebrates (Nedelec et al. 2016; Popper and Hawkins 2018). As a vector quantity, it provides directional information that is critical for behaviors such as predator avoidance, prey detection, orientation, and communication. While marine mammals have evolved to perceive sound mainly through pressure, invertebrates and fish are most sensitive to particle motion and thus respond to both water-borne and substrate-borne vibrations. Indeed, invertebrates underwater rely on vibrational cues (i.e., particle motion) using specialized mechanoreceptors: crustaceans detect predators and communicate through substrate vibrations; bivalves close their valves in response to certain sound stimuli; and cephalopods sense particle motion via epidermal and statocyst-based systems (Roberts and Howard 2022; Solè et al. 2023).

Moreover, for demersal fish, substrate-borne vibrations are likely particularly advantageous (Roberts and Rice 2023). The strength of acoustic signals is limited in water-borne, especially in shallow water, where propagation is constrained. Substrate vibrations, however, can propagate more effectively through benthic environments, potentially facilitating communication. Additionally, multimodal signaling, combining vibrational, acoustic, and other sensory cues, tends to be more efficient and reliable in complex habitats. This multimodality may enhance key behaviors such as spawning synchronization, territorial defense, and predator detection, although the precise roles of vibrational cues remain uncertain and require further research. Examples include salmonids and sculpins producing vibratory signals associated with communication, benthic fishes like flatfish potentially detecting predators or conspecifics through substrate cues, and species such as drum fish producing substrate sounds during reproductive displays (Roberts and Rice 2023).

Anthropogenic sources, such as vessels, offshore infrastructure, sonar, and WECs, generate noise and vibrations that can interfere with these natural cues, altering organism behavior. Natural sources like earthquakes or wave action also contribute, but human-made vibrations may cause greater disruption through stress, behavioral shifts, or sensory masking (Hawkins et al. 2021). Particle motion and substrate vibrations vary with depth, substrate, and proximity to the source, and differ fundamentally from pressure in both magnitude and frequency content (Hawkins et al. 2021). Ignoring these components risks underestimating the ecological impacts of underwater noise. Thus, understanding particle motion and substrate vibration is vital for effective environmental impact assessments, especially regarding wave energy converters and other underwater infrastructure.

Case Study: ISWEC in the Mediterranean Sea

This preliminary investigation provides the first direct particle motion measurements near a WEC in the Mediterranean Sea, aimed at improving understanding of its acoustic impacts. Data were collected near the ISWEC (Inertial Sea Wave Energy Converter), a WEC deployed at 800 meters from the coast of Pantelleria, an island in the Sicilian Channel (Italy). The installation site is located near *Posidonia oceanica* meadows, which are ecologically important marine habitats and serve as critical refuges for numerous fish species.

Acoustic data were collected using an acoustic vector sensor equipped with a 3D accelerometer and an omnidirectional hydrophone, sampling at 8 kHz and 24-bit resolution (Fig. 1; M20 manufactured and calibrated by Geospectrum Technologies Inc., Dartmouth, Canada). The sensor was deployed within 20 m of the ISWEC mooring center, aligned along one of the mooring lines. The Power Take-Off system (PTO) was not in operation during the monitoring period, meaning that only mooring noise was recorded. A representative setup of the study site is shown in Fig. 1. The instrument was configured to record continuously throughout the deployment. This work presents an example of acoustic analysis based on the mooring's acoustic signature. The power spectral density (PSD) of a 60 seconds segment is presented. All acoustic analyses were performed using the paPAMv2 software (Nedelec et al. 2016, 2021).

Preliminary Findings

Although data analysis is still in progress, an example of acoustic signature from the ISWEC mooring has been included in this work (Fig. 2). Preliminary findings include:

1. Acoustic sounds associated with mooring lines were detected, as illustrated in Fig. 2. These emissions exhibit periodicity that matches the local wave period (around 4 s).

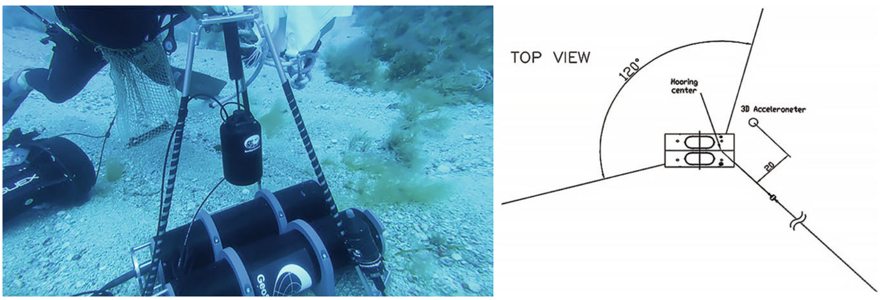


Fig. 1 Left: Acoustic vector sensor (M20) deployed at the seabed. Right: schematic representation of the acoustic vector sensor deployment near ISWEC mooring lines

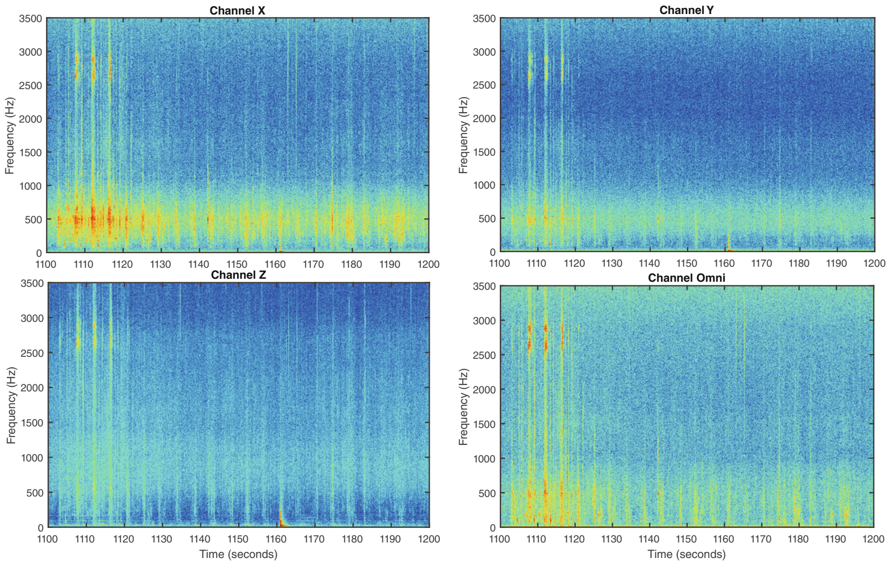
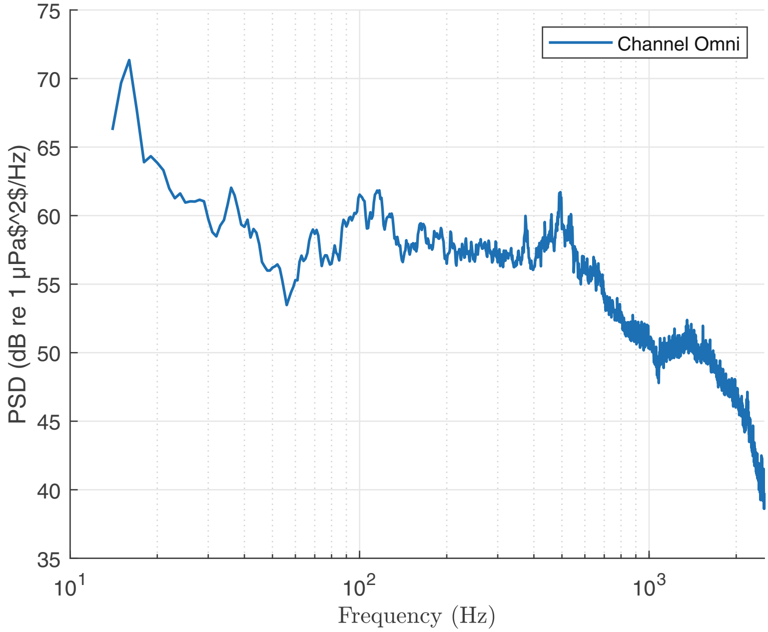


Fig. 2 Spectrogram of 100 s showing an example of noise produced by the mooring chain. The 4 channels of the acoustic vector sensor are reported

2. As shown in the power spectral density (PSD) of Fig. 3, low-frequency, low-intensity noise was observed. A notable peak of intensity in the 2500–3000 Hz frequency bands suggests this is due to harmonics of mooring chain noise
3. Although the PSD curves of the two components show similar peaks, differences between particle motion (i.e., acceleration; Fig. 3) and acoustic pressure were observed, notably a higher variability at low frequencies in particle motion up to 500 Hz, followed by a different trend between 1000 and 2500 Hz.
4. Axis-dependent variations in particle motion were evident, with differences between axes clearly visible in Fig. 3, and higher intensity observed in the Z channel (vertical axis).

Ongoing Work and Future Studies

This work has so far shown differences in the axes of particle motion, indicating a complex relationship between sound pressure and particle motion in open-water environments, as also visible on the example of sound emitted by ISWEC mooring chain. The intensity and duration of these signals require further investigation over extended time periods and environmental conditions to understand their ecological relevance. This study aims to assess whether, under specific conditions, sound pressure alone can serve as a sufficient proxy for evaluating the acoustic impact of WEC technologies, or whether the particle motion component (relevant to fish and invertebrates) is being overlooked. Results are not yet available, as the work is still in progress.



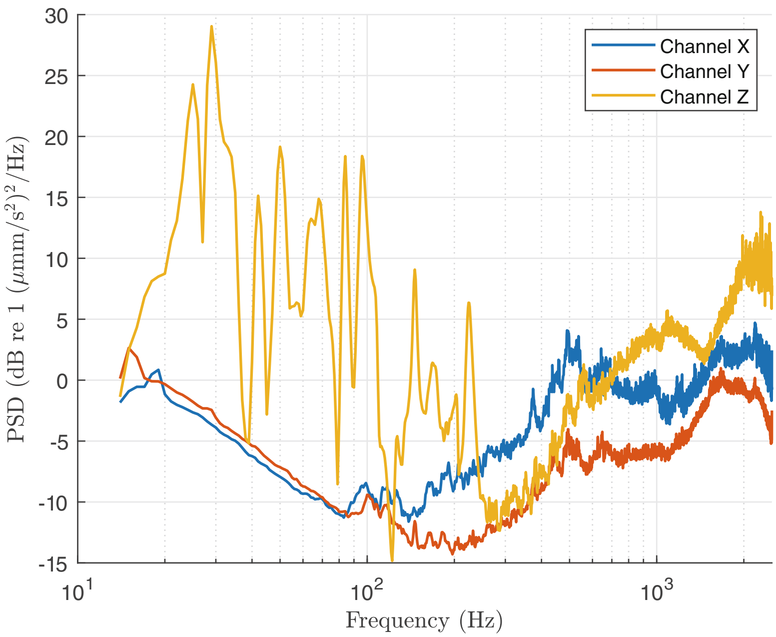


Fig. 3 Left: Power spectral density (PSD) in pressure of 60 s containing ISWEC mooring noise. Right: Power spectral density (PSD) in acceleration of 60 s containing ISWEC mooring noise, different curves represent the 3 channels from the 3 axes of the accelerometer (*X*, *Y*, *Z*)

Characterizing the acoustic signature and intensity of emissions will help determine whether masking effects or perceptual interference in either sound pressure or particle motion are likely to affect marine species. Further collection of particle motion data under real-sea conditions will be instrumental in developing standardized protocols for its quantification. Integrating these data with sound pressure measurements and considering species-specific auditory capabilities will enhance the robustness of environmental impact assessments and support more ecologically informed policy decisions.

Moreover, current understanding of the acoustic emissions from WECs remains limited due to variability in device design, sound characteristics, deployment depth, and substrate type. Future studies should aim to gather particle motion data across a range of WEC technologies and environmental settings. Comparative assessments using standardized methodologies and instrumentation will be critical. Long-term datasets, site-specific baselines, and observations across a wide range of sea states will help to validate or refine the preliminary findings presented in this study.

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