Acoustic Impact of a Floating Wind Turbine Prototype in the Mediterranean Sea

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Contents

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Abstract

The installation of floating offshore wind farms in the Mediterranean Sea is attracting interest for their role in the energy transition and environmental implications. Yet limited research exists on the underwater noise of floating systems, especially in this biodiversity hotspot already affected by human pressures. This study evaluates the acoustic impact of the SAIPEM Hexafloat scaled-prototype floating platform, monitored at the MaRELab site in Naples from September to December 2023. An autonomous recorder positioned 30 m from the turbine collected data. Noise levels varied monthly and daily, reflecting the complexity of the site's soundscape. Multiple sources were present: intense maritime traffic, waves, and biological sounds such as crustacean impulses, fish choruses, and occasional dolphin clicks. To isolate the turbine contribution, analyses accounted for temporal trends and overlapping sources including traffic, waves, and wind. Turbine noise was lower than maritime traffic or wave noise, concentrated at low frequencies up to 1 kHz. For the 1/3 octave bands at 63 and 125 Hz, turbine activity increased levels by about 4 dB when waves were under 1 m. A tonal component around 400 Hz appeared at maximum blade speed, and the anchoring system produced impulses and tones up to 8 kHz. According to Southall et al. (Aquat Mamm 47(5):421–464, 2021), noise levels do not suggest physiological risk for marine organisms, though short-term masking effects on fish communication may occur. Test sites with scaled-down turbines and anchoring systems facilitate the testing of new technological solutions and environmental impact assessments. However, further evaluation is needed to extrapolate these findings to large-scale scenarios involving multiple turbines with their respective anchoring systems.

Keywords

Floating wind turbine · Offshore renewable energy · Underwater noise · Anthropogenic noise · Marine Soundscape

Introduction

Offshore wind energy is rapidly expanding worldwide as part of the transition toward low-carbon energy systems, and floating wind technology is increasingly considered a key solution for deep and semi-deep waters. Unlike bottom-fixed installations, floating turbines rely on mooring lines and dynamic foundations, introducing additional mechanical components that may influence the underwater acoustic environment. Understanding their acoustic footprint is particularly important in regions such as the Mediterranean Sea, a biodiversity hotspot already under significant anthropogenic pressures, including maritime traffic, coastal industry, and urbanization.

The need to evaluate and manage underwater noise has been formally recognized by the Marine Strategy Framework Directive (MSFD; EU Directive 2008/56/EC), which identifies underwater noise as a key pollutant under Descriptor 11. This descriptor focuses on both impulsive and continuous low-frequency sound, requiring Member States to monitor anthropogenic noise sources, such as shipping, construction, and offshore energy infrastructure, and assess their potential impacts on marine ecosystems. Within this regulatory context, understanding the acoustic emissions of emerging renewable technologies, including floating offshore wind turbines, is essential to support environmental compliance and sustainable development.

Previous studies on the acoustic output of offshore wind farms have mainly focused on bottom-fixed turbines, showing that operational noise typically occurs at low frequencies (<1 kHz) and may include tonal components linked to blade rotation and generator mechanics (Madsen et al. 2006; Tougaard et al. 2009). More recent research has begun to explore floating platforms, suggesting that platform motion and mooring-line dynamics may introduce additional impulsive or tonal noise not present in fixed-foundation systems (Harris et al. 2025). In the studies on underwater noise at the Hywind Scotland floating offshore wind farm (Risch et al. 2023; Burns et al. 2022) authors reported a continuous tonal signal associated with rotor and generator components below 500 Hz, which was clearly evident and showed a correlation with wind speed. From the same studies, another prominent feature was frequent broadband transient noise, linked to strain and friction in the mooring system and strongly correlated with wave height. Directional analyses indicated that this noise originated mainly from mooring components near the floating spar. At Hywind Tampen (approximately 140 km northwest of Bergen, Norway), turbine noise was dominated by narrowband tones below 200 Hz, especially around 25 and 75 Hz, whose frequencies and levels were closely linked to rotor RPM and wind speed (Welch et al. 2025). Additional low-level tones, likely related to auxiliary equipment and control systems, contributed to the spectra to a lesser extent. Unlike Hywind Scotland, almost no mooring-related transient noise was identified at Tampen, indicating a fundamentally different acoustic signature between the two sites. In the Mediterranean Sea, studies have highlighted the importance of quantifying the potential acoustic impact of emerging floating wind technologies in a basin already under significant anthropogenic pressure, although experimental research remains notably absent. Baldachini et al. (2024, 2025) showed that Mediterranean coastal environments, characterized by dense maritime traffic and rich biophonic activity, pose unique challenges for detecting turbine-related noise and assessing its ecological implications. The modeling of three proposed floating wind farms in the Strait of Sicily estimated that operational turbine noise might be detectable up to tens of kilometers (even ~67 km) from the source, and, under conservative assumptions, could exceed behavioral-disturbance thresholds for marine mammals as far as ~68 km from the wind farms' boundaries; at the same time, it was found that audibility above ambient noise depends strongly on background noise levels, and that risk of auditory damage appears limited to very close proximity (tens of meters) and long exposure times. However, despite these advances in modelling efforts, empirical data from scaled prototypes or real-world test sites remain scarce, particularly in the Mediterranean, where complex soundscapes (Buscaino et al. 2016) complicate the detection and attribution of turbine-generated signals. Key knowledge gaps remain in the underwater soundscapes of floating wind turbine systems, both in general and at site-specific scales, including how operational noise varies across locations and turbine designs, which mooring components contribute most to tonal and transient signals, and how environmental and operational factors shape noise signatures (Harris et al. 2025).

In this context, the present study provides the first preliminary assessments of the underwater noise generated by the SAIPEM Hexafloat floating wind turbine prototype deployed in the Gulf of Naples. By combining long-term passive acoustic monitoring with turbine operational data and environmental parameters, it was evaluated how turbine activity contributed to the local soundscape and discuss its potential ecological relevance in the context of MSFD Descriptor 11. This approach supports emerging efforts to standardize underwater acoustic observations and to guide environmentally responsible marine renewable energy development.

Materials and Methods

Acoustic Data Acquisition

The experimental measurement campaign began on June 26, 2023, with the deployment of an underwater acoustic recorder, retrieved on December 22, 2023. Although data were collected from June onward, the turbine was installed in August and began operating in September. The analysis presented here focuses on data from 14 September onward, when the turbine was operating (see Table 1).

The position of the recorder, turbines, and anchors, along with their respective distances, are shown in Fig. 1. The anchoring scheme of the underwater acoustic recording system is illustrated in Fig. 2. To avoid additional noise, the mooring buoy was kept underwater, and no metal components or shackles were included in the mooring system, which was deployed and recovered by a diver. The bathymetry at the recorder site was 30 m, and the hydrophone was positioned about 2.5 m above the seabed.

Table 1 Summary data of the acoustic monitoring campaign after turbine installation

Recorder information	Duty cycle, %	File format, sampling frequency and resolution	Start date	End data	Coordinate, grade N—grade E and bathymetry
ST600HF Ocean Instruments (New Zealand), distance recorder-turbine 31 m	40% (2 min on, 3 min off)	wav, 192,000, 16 bits	14 September 2023	22 December 2023	14.268–40.832, 30 m

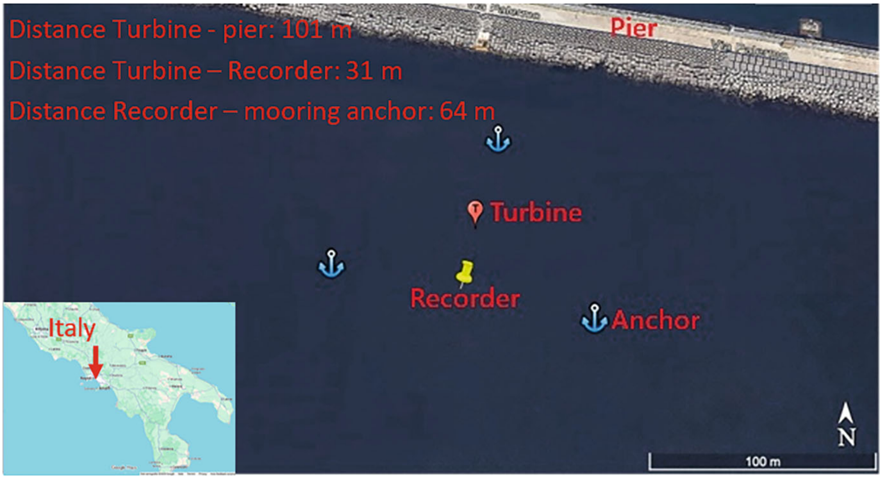


Fig. 1 Positions of the acoustic recorder and distances from the main noise sources. At the top, the Naples harbor pier

Data were processed using custom-developed proprietary MATLAB code based on the *poctave* function. The code provided noise levels across the octave band from 4 Hz up to the 64 kHz. Additionally, third-octave band intensity levels were computed for the two central frequencies specified in the Descriptor 11 of the Marine Strategy (i.e., 64 and 125 Hz). All levels were averaged over each 2-min recording segment.

Hexafloat Turbine Operating Data and Meteorological Data

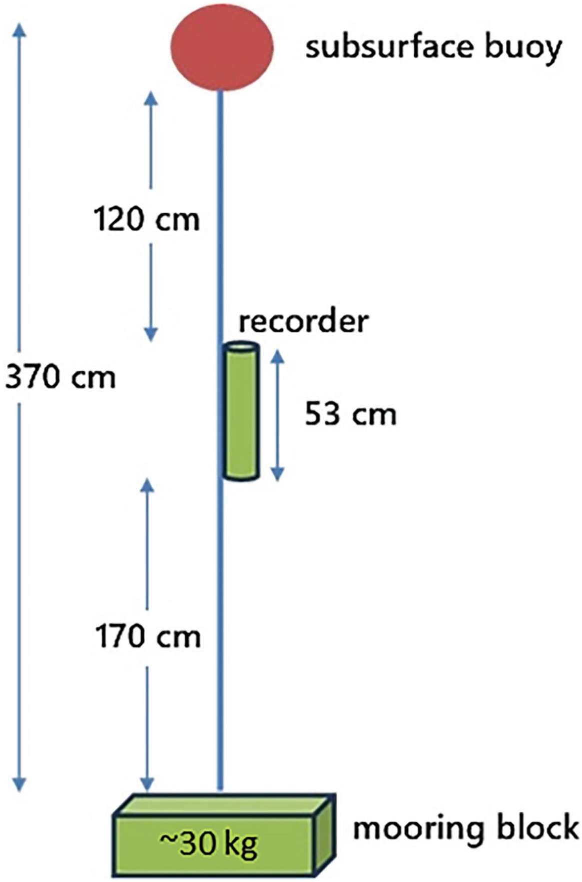
The SAIPEM Hexafloat scaled-prototype floating platform was installed at the MaRELab test site in Naples (40.83° N–14.27° E, ~100 m from the harbor pier). The turbine prototype stands 10 m above the water surface and has a blade length of 6.5 m. A representation of the turbine is shown in Fig. 3.

The turbine operating data used in the analyses included the number of blade rotations per minute (rpm) and power output (kW). Wind speed (m/s) was recorded by a weather station mounted on the turbine and cross-checked with nearby land-based weather stations, which also provided the absolute wind direction. Additionally, wave height data (maximum sea surface height—VCMX, m) at the installation site were obtained from the Copernicus database.

Statistical Data Analysis

The data were analyzed considering temporal factors (both seasonal and hourly) and meteorological conditions (i.e., wind and wave height). In particular, wave height and wind is known to influence low-frequency noise levels (Wenz 1962), as

Fig. 2 Schematic of the anchoring system with the acoustic recorder and distances between the main components



observed in studies on Mediterranean coastal ecosystems (Buscaino et al. 2016; Ceraulo et al. 2018).

Two turbine operating states were considered: **Turbine ON** (active) and **Turbine OFF** (inactive), as well as four specific operational levels:

0: Not in operation
1: Blades rotating but no electricity produced
2: Blades rotating with electricity generation
3: Blades rotating near the limit threshold

To quantify the turbine's contribution to underwater noise and assess its significance, noise levels were compared across the four turbine operating conditions (from 0 to 3), or ON/OFF condition, stratifying the data by month, time and wave height. The months of October and November, combined with wave-height from 1 to

Fig. 3 A schematic view of Hexafloat turbine and its mooring system

2 m, provided sufficient observations for each operating condition. Noise levels within these subsets were compared using the non-parametric Kruskal–Wallis test. Where significant differences were found, a multiple comparison procedure was applied to identify which individual conditions differed.

Preliminary Results

The main source of low-frequency noise at the site was maritime traffic (Fig. 4, vertical lines inside the red rectangle in the upper spectrogram), including large cargo ships, passenger vessels (ferries and hydrofoils), fishing boats, and recreational crafts (source: EMODnet). Regarding biophony, i.e., the sounds produced by marine organisms, a manual inspection of a subset of file (about 5%) revealed choruses of snapping shrimps, fishes, and, less frequently, echolocation clicks from delphinids.

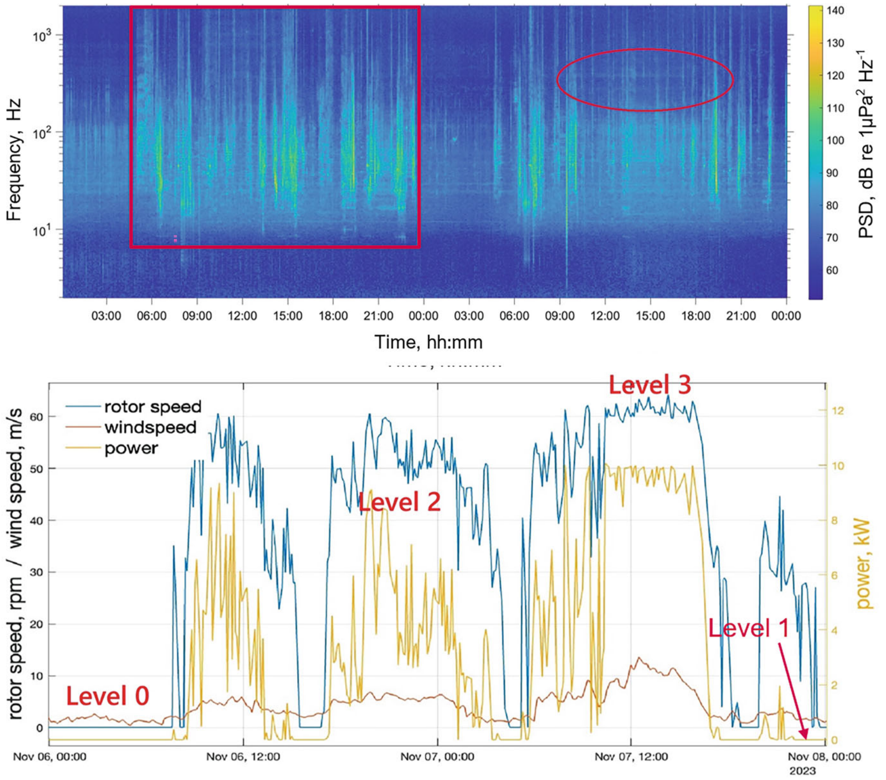


Fig. 4 Example of a spectrogram (above) from 2 days of recording (6 and 7 November) in the 1–1100 Hz frequency band and, for the same period (bottom graph), turbine operational parameters (and operational levels) and wind speed. The red oval in the spectrogram indicates the tonal noise corresponding to turbine operational level 3. The yellow vertical lines inside the red square in the spectrogram represent noise from multiple vessel traffic passages. Spectrogram was obtained using PamGuide (Merchant et al. 2015) with these parameters: FFT size: 4000 (sampling frequency 4000 Hz), window: Hann, overlap: 50%

The noises generated by the Hexaflot turbine anchoring system are both clearly visible and audible. The metal chains produce signals of different types. Figure 5 shows two examples: the upper spectrogram displays short-duration, broadband signals with intensity peaks around 3 kHz, while the lower spectrogram shows tonal signals of longer duration and higher frequencies, up to 10 kHz. These noises appear to be associated with turbine movements as well as the intensity of wind and waves.

Within the same wave-height class (0–1 m and from 1–2 m), the largest differences among turbine operating phases occur at lower frequencies (up to 1 kHz), exceeding 5 dB, particularly between the turbine conditions 3 and 0 ($p < 0.001$). Considering the condition ON versus OFF states, for the 1/3 octave bands centered at 63 and 125 Hz, those specified by Descriptor 11 of the Marine Strategy, the turbine

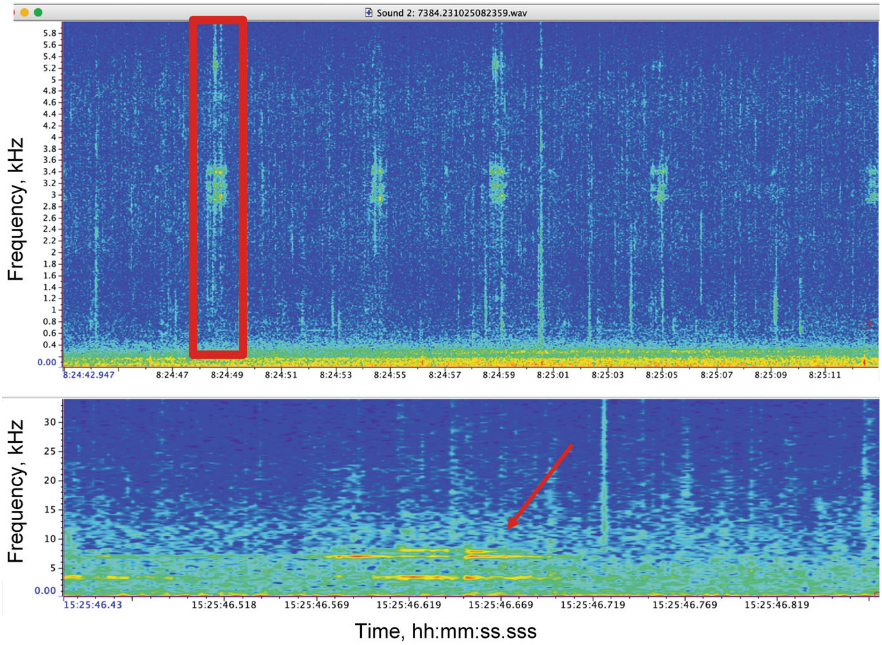


Fig. 5 Examples of spectrograms showing noise due to the movement of the mooring system chains (red rectangle and arrow). A clear metallic sound can be heard in the audio. Sampling frequency: 12,000 Hz; FFT size: 1024 points, overlap: 50%. Abscissa: time in UTC (recordings from 25 October and 7 November). Ordinate: frequency in kHz. Color scale: relative signal intensity

increases noise levels by approximatively 4 dB when wave heights remain below 1 meter.

Noise variations over the day were examined for the 500 Hz octave band (see also Fig. 4 upper spectrogram, showing the tonal noise at ~400 Hz), with the dataset restricting to wave heights between 1 and 2 m (see Figs. 6 and 7). In the Fig. 6, for clarity, only hourly medians are shown. Noise levels increases during daytime and decrease at night, reflecting reduced vessel traffic as well as lower wind and wave height. A clear difference among turbine operating conditions is evident, with values exceeding 5 dB and consistently higher noise levels observed for operational level 3 (black line).

At 03:00 UTC, the quietest period of the day, median noise levels in the 500 Hz octave band showed a clear increase with turbine operational statis (Fig. 7). Levels 0, 1, and 2 exhibited similar median values, whereas level 3 exhibited a marked rise in noise, whereas level 3 a pronounced rise in noise along with a wider interquartile range. The Kruskal–Wallis test indicated significant overall differences among operational levels ($H = 38.41$, $p < 0.001$). Post-hoc multiple comparison tests revealed that level 3 differed significantly from all other levels (0, 1, and 2), and

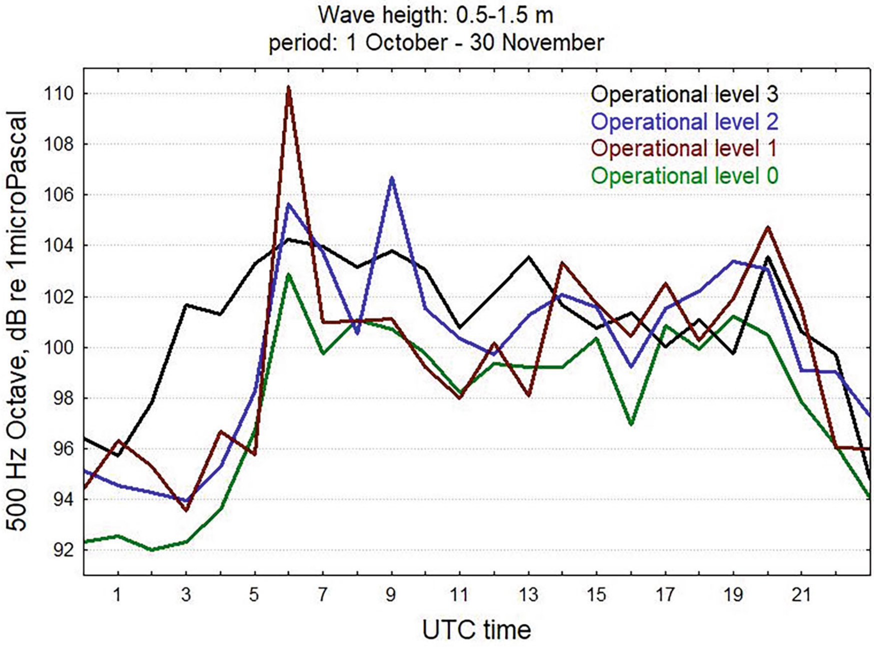


Fig. 6 Hourly noise level trends averaged over the months of October and November, for wave heights between 0.5 and 1.5 m. To facilitate the interpretation of the plot, only median values are shown. Frequency band: one-octave band centered at 500 Hz

level 2 also differed significantly from level 0. No significant differences were observed between operational levels 0 and 1 or between levels 1 and 2.

Discussion

The acoustic monitoring of the Hexafloat prototype demonstrates the challenges of isolating turbine-related noise in a dynamic coastal environment such as the area near the Port of Naples. Throughout the study period, ambient noise was largely dominated by maritime traffic and natural geophysical sources, such as waves, which drove strong daily and seasonal variability. In this context, identifying the turbine's contribution required careful stratification of the data by environmental and operational conditions.

Despite these challenges, the turbine produced a detectable acoustic signature, particularly under moderate wave heights and reduced vessel presence. Significant differences among operational levels were found mainly below 1 kHz, with operational level 3 showing the most pronounced increase (over 8 dB compared to level 0), along with a tonal component near 400 Hz at maximum blade speed.

Noise generated by the anchoring system was also evident, producing both impulsive and tonal sounds up to 8–10 kHz. Although localized and short-lived,

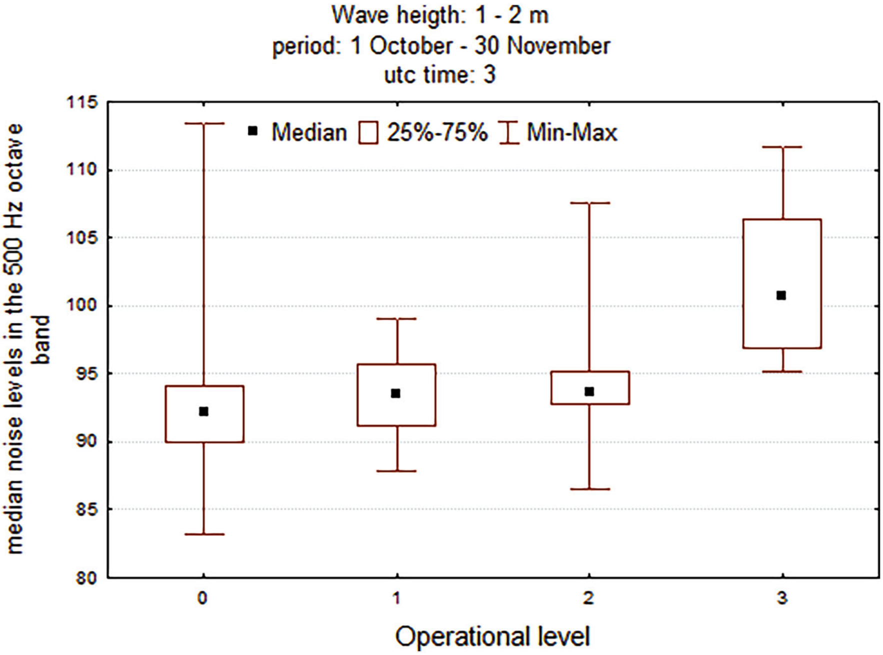


Fig. 7 Median noise levels in the 500 Hz octave band for each operational level during UTC time 3. Boxplots show the median (black square), interquartile range (25–75%; box), and minimum–maximum values (whiskers). The Kruskal–Wallis test indicated significant overall differences among operational levels ($H = 38.41$, $p < 0.001$). Multiple comparison tests revealed significant pairwise differences between levels 0–2, 0–3, 1–3, and 2–3, while differences between levels 0–1 and 1–2 were not significant

these signals highlight the importance of considering all mechanical components of floating platforms when assessing acoustic impacts (Harris et al. 2025).

From an ecological perspective, recorded noise levels remained below thresholds for physiological effects on marine organisms (Southall et al. 2021). However, short-term behavioral responses, particularly masking of fish communication, cannot be excluded, especially when turbine-related noise overlaps temporally and spectrally with biological choruses (Buscaino et al. 2019).

This study provides the first empirical assessments of a floating wind turbine prototype in the Mediterranean Sea. While the turbine's contribution is relatively small compared to shipping and wave noise, these findings underscore the value of prototype test sites for evaluating new technologies. Further research is needed to understand how these results scale to full-size turbines and multi-unit arrays, where cumulative noise and mooring interactions may create different acoustic scenarios.

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Competing Interest Declaration The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

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