DOI: 10.61782/fa.2025.0641

FORUM ACUSTICUM EURONOISE 2025

OFF-COUSTICS: PREDICTING THE UNDERWATER ACOUSTIC FOOTPRINT OF OFFSHORE WIND TURBINES

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ABSTRACT

The growing demand for offshore wind energy has driven a rapid increase in wind turbine size and the development of large-scale wind farms, often comprising more than 100 turbines. However, the environmental impact of underwater noise emissions remains largely unaddressed. The Off-coustic project (ERC Consolidator Grant Ref. 101086075) develops numerical methods and experiments by integrating wind turbine noise prediction techniques to predict the wind turbine acoustic footprint.

Here, we present an approach to calculating the transmission of aerodynamic noise into underwater acoustics, taking into account the air-water impedance and the penetration angle (governed by Snell's law). Our calculations show that aerodynamic noise from offshore wind farms may affect marine life. In addition, we present the capabilities of our solver, HORSES3D, to simulate wind turbines in offshore environments. This solver will soon be capable of simulating acoustics in offshore environments.

Keywords: *Wind turbine Noise, Offshore energy, Underwater noise, Marine life, high order discontinuous Galerkin*

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1. INTRODUCTION

The rapid expansion of offshore wind energy has led to large-scale wind farms with more than 150 turbines (1). Although turbine designs prioritise power output (2; 3; 4), their acoustic emissions remain largely unexamined. Aerodynamic noise from the blade trailing edge and blade-turbulence interactions is well studied for onshore turbines, but remains unexplored offshore. Aerodynamic noise scales with rotor diameter (D^5) and aggregates between turbines ($\sim 20\log_{10}(N)$) (5; 6). Although prior research focused on mechanical noise (7; 8; 9; 10; 11; 12), the transmission of aerodynamic noise in water is still poorly understood. Governed by Snell's law, only sound waves within $\sim 13°$ of normal refract into water, with further attenuation due to impedance differences. However, offshore wind farms can generate detectable underwater noise, raising concerns for marine species dependent on sound (13; 14; 15; 16).

In response to this emerging environmental challenge, the *Off-coustic* project introduces a novel methodology that merges advanced aerodynamic noise prediction techniques. This framework enables estimation of the underwater noise levels generated by large offshore turbines and their assemblies. By quantifying the acoustic footprint and comparing it with the auditory thresholds of diverse marine species, our approach offers insights into the environmental impacts of offshore wind energy and paves the way for noise-mitigating design strategies.

2. ACOUSTIC UNDERWATER FOOTPRINT OF AEROACOUSTIC NOISE

2.1 Acoustic analysis

Aerodynamic noise is the dominant noise source in modern wind turbines, generated by the turbulent interaction of flow with blades (17). This noise comprises two main components: leading edge noise (LE) from the impingement of atmospheric turbulence on the blade front and trailing edge noise (TE) from the interaction of the turbulent boundary layer with the finite trailing edge. Due to the wide range of turbulent scales—from hundreds of metres in the atmosphere to millimetres along the blade—this noise exhibits a broadband spectrum that can affect marine species with different hearing thresholds.

The turbine blade is divided into n segments, each modelled as a two-dimensional airfoil. For each segment, LE and TE noise are computed as uncorrelated sources using Amiet theory (18; 19) (with corrections for finite chord effects (20)). The overall blade noise is obtained by summing the contributions from all segments and applying a Doppler correction to account for the motion relative to the observer. The transmission of sound from air to water is governed by Snell's law, which confines the effective propagation to a narrow cone (approximately 13°relative to normal); see figure 1a. In addition, we account for the transmission loss across the air-water interface (due to the change in media), which is 29.5 dB. Underwater propagation is modelled via cylindrical spreading, while atmospheric attenuation (21; 22). Finally, for a wind farm consisting of N turbines, the overall noise level scales as $10\log_{10}(N)$ when each turbine is considered an uncorrelated noise source. This framework provides a concise method for predicting aerodynamic noise emissions and their potential impact on marine life.

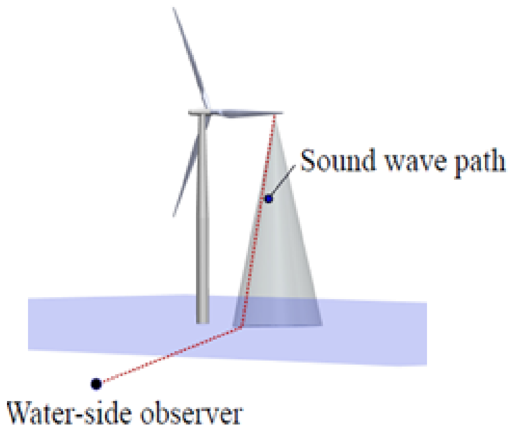
We consider the IEA 22 MW (5). The IEA 22 MW offshore wind turbine represents a significant advancement in turbine design for large-scale energy production. It features a hub height of 170 m and a massive rotor diameter of 284 m, which enables it to capture more wind energy even at relatively low wind speeds. The turbine is designed to operate at a nominal wind velocity of 11.78 m/s, with a rotor angular velocity of 7.1 rpm. This results in a high blade tip speed of 102.0 m/s, ensuring efficient aerodynamic performance. In addition, the turbine employs a blade pitch of 6.6°, which is crucial for optimising power output and reducing aerodynamic loads.

Figure 1 shows the far-field aerodynamic noise spectra generated by a single wind turbine and groups of 100 and 150 wind turbines for each case, compared to the hearing thresholds of various functional hearing groups, i.e., low-, mid-, and high-frequency cetaceans and pinnipeds (14; 23; 24). The figure shows that aerodynamic noise from the three wind turbines affects the low-frequency hearing group even when considering only a single wind turbine. When considering farms, the figure shows that a group of 100 turbines causes a general increase in the amplitude of aerodynamic noise spectra, with a footprint underwater of 25 dB louder than the hearing threshold of some marine animals, for the 22 MW wind turbine. In these cases, the aerodynamic noise of offshore farms is much larger than the hearing threshold of several groups of marine species, which can potentially mask the natural sound present in the environment. Further details of the methodology and analysis of other turbines can be found in our paper (25).

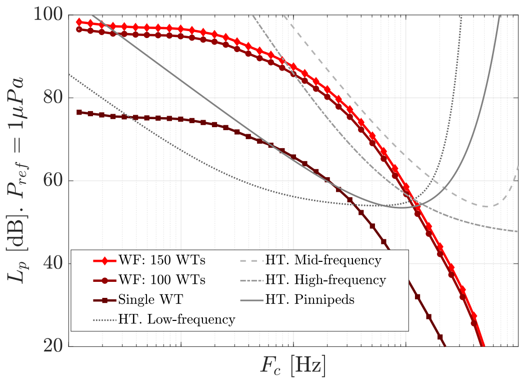
2.2 Simulations using the high order solver HORSES3D

Having identified a potential problem, our aim is to develop accurate tools that allow deeper studies. We are currently developing the open source solution HORSES3D (26; 27; 28) at the ETSIAE-UPM School of Aeronautics in Madrid, and available on Github (`https://github.com/loganoz/horses3d`). This solver is a high-order discontinuous Galerkin (DG) tool capable of addressing a wide array of flow applications. These applications encompass compressible flows, incompressible flows, multiphase flows, and aeroacoustics, see Figure 2. Furthermore, HORSES3D is equipped to manage body-fitted, immersed boundaries, and actuator lines.

One of the main advantages of DG methods is their ability to accurately capture high-order spatial and temporal variations of the solution, which makes them particularly suitable for simulating flows with sharp gradients and complex flow phenomena. DG methods also exhibit good numerical stability and conservation properties because of the local nature of the approximation and the use of fluxes at the interfaces of the elements. In HORSES3D, rotating turbine blades can be modelled using either actuator line methods or sliding meshes, while the air-water interface is captured using a robust Cahn-Hilliard formulation; see figure 3. Additional components, such as tower, nacelle, and platform, can be incorporated through immersed boundary techniques(29; 30; 31; 32; 33), offering exceptional flexibility. We include a robust local p-adaptation based on reinforcement learning to enhance ac-



(a) Sketch of wind turbine with Snell's cone for air and water: cone of 13° angle with respect to the air-water interface normal vector, that encompasses acoustic waves that penetrate underwater.



(b) IEA 22 MW wind turbine. One-third octave far-field noise spectra for a Water observer (10 m deep) at 100 m downwind of the turbine. Overlaid are hearing threshold of marine animals. WT: wind turbine; WF: wind farm with 100 and 150 WTs; HT: hearing threshold. Color scales from 20-100 dB in figure (d).

Figure 1: Acoustic analysis to quantify the underwater acoustic footprint of offshore wind turbines.

curacy at an affordable cost. Finally, we demonstrate the solver's capabilities through large eddy simulations of offshore wind turbines to soon provide a characterisation of their noise emissions and underwater footprint.

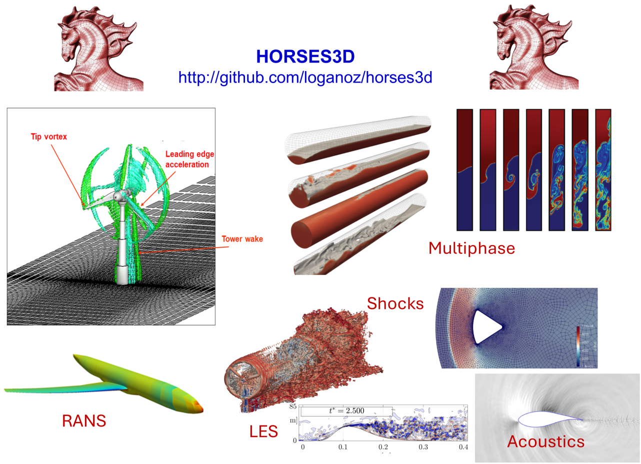


Figure 2: Summary of HORSES3D features (Ferrer et al. 2023).

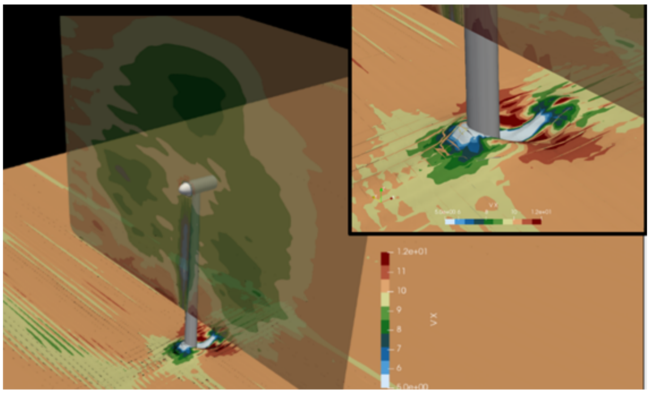


Figure 3: Example of offshore wind turbine simulated with actuator lines and free-surface using a Cahn-Hilliard formulation.

3. CONCLUSIONS

Achieving sustainable offshore energy means addressing environmental impacts, particularly the underwater noise of wind turbines, which can harm marine life. Traditional designs often focus on energy output while overlooking aerodynamic noise transmission into water.

We introduce a methodology that integrates noise models, offering manufacturers and policy makers a versatile tool for predicting underwater noise in both low- and high-fidelity scenarios. For the first time, we quantify the acoustic footprint of a 22 MW turbine and scale emissions to wind farms of 100–150 turbines, confirming that aerodynamic noise—especially from trailing edges—is a significant environmental challenge.

Furthermore, our ongoing development of the HORSES3D solver will advance underwater acoustic predictions for offshore wind turbines, filling a current gap in capabilities.

4. ACKNOWLEDGMENTS

This research has received funding from the European Union (ERC, Off-coustics, project number 101086075). Views and opinions expressed are, however, those of the authors only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them.

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