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Mitigating Underwater Noise from Offshore Wind Farms via Individual Pitch Control

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Abstract. This paper proposes a pitch control strategy to mitigate the underwater acoustic footprint of offshore wind turbines, a measure that might soon become necessary to minimize impacts on marine life, which rely on sound for communication, navigation, and survival.

Building upon a previously proposed open-loop individual pitch control approach [1], we extend the methodology to account for varying inflow conditions and wind farm interactions. The IPC strategy modulates blade pitch at the blade-passing frequency to reduce overall sound pressure level and amplitude modulation, while being coupled with a standard collective pitch controller to ensure adaptability under under-rated and over-rated operating regimes. The approach is evaluated for three representative turbine models (NREL 5 MW, DTU 10 MW, and IEA 22 MW) and subsequently applied to a small wind farm configuration. Results demonstrate consistent underwater noise reduction across operating conditions, with lower impact on power production than standard noise reduction operation methods. At the wind farm scale, the proposed control strategy achieves a measurable reduction in underwater noise while maintaining nearly unchanged total power output. These findings indicate that individual pitch control offers a promising pathway toward quieter offshore wind farms without compromising energy generation.

1. Introduction

The combination of turbines of increasing sizes in populated farms facilitates energy production but can lead to non-negligible aerodynamic noise emissions. Noise emissions are a concern in both onshore and offshore scenarios. In onshore locations, they are known to cause a negative perception among the general public, as reported in [2]. While explicit operational noise limits for offshore wind farms are not yet well defined, continuous turbine noise is recognized under the EU Marine Strategy Framework Directive (Descriptor 11), [3]. The absence of binding thresholds does not preclude environmental risk, and ongoing regional initiatives (e.g., OSPAR action plans, [4]) suggest that clearer monitoring requirements and regulatory limits for underwater noise may emerge in the near future.

In this work, we will focus on the noise emissions from offshore wind farms. Research on the underwater soundscape of these sites has traditionally emphasized the noise of foundation installation and mechanical machinery, [5]. But an important, and underappreciated, path remains: the penetration of aerodynamic blade noise from air into the marine environment, [6]. Unlike offshore noise sources previously studied, wind turbine noise persists throughout the life cycle of the wind farm. Aerodynamic noise, generated by blade–airflow interactions, has been extensively characterized in terms of its far-field aerial propagation. When these sound waves impinge on the sea surface, a fraction of their energy can be transmitted underwater, [7]. This anthropogenic underwater noise has the potential to cause a masking problem, interfering with the communication, navigation, and foraging behaviors of marine fauna [8].

Motivated by these side effects of offshore wind energy, our previous work addressed the challenge of balancing power extraction and noise mitigation through an individual pitch control strategy (IPC) [1]. In that study, we quantified the underwater acoustic footprint attributable to aerodynamic sources for a single turbine, and proposed an open-loop IPC strategy to mitigate it. The present study extends the methodology to the wind-farm scale. We demonstrate that the proposed IPC strategy can be integrated with standard collective pitch controllers and deployed for multiple turbines, aiming at a more realistic wind-farm scenario.

2. Methodology

2.1. Wind turbine and noise prediction modeling

Wind turbine simulations in this study were performed using OpenFAST [9]. Aerodynamic noise is computed using the Brooks–Pope–Marcolini (BPM) semi-empirical model [10], implemented within OpenFAST. Among the noise mechanisms included in BPM, only trailing-edge (TE) noise is considered here, as it has been identified as the dominant aerodynamic source, exceeding turbulence inflow (TI) noise contributions [11]. Moreover, offshore environments typically exhibit lower turbulence intensities than onshore sites. Importantly, TE noise is sensitive to blade pitch variations, whereas TI noise depends primarily on ambient inflow conditions. Consequently, the contribution of TI noise to the noise reduction achieved by the proposed IPC strategy is expected to be negligible.

Plane wave theory is used to model air-water acoustic propagation. Following Snell's Law, the acoustic waves are refracted when surpassing the air-water interface. Due to the high sound speed ratio $n = \frac{c_w}{c_a} \approx 4.37$ only the acoustic energy radiated within a conical region from the noise source is effectively transmitted to water [7]. This conical region is defined by its semi-angle of $\phi_{\text{lim}} = \arcsin(n^{-1}) \approx 13°$. We denote that conical region as the "Snell Cone". To model what amount of wind turbine noise is able to penetrate the air-water interface, we consider one noise source per blade and only the noise beneath its "Snell Cone". The overall sound power level would be defined as:

$$\text{OSWL}(t) = 10\log_{10}\left(\frac{1}{p_{\text{ref}}^2}\int_{\mathcal{S}}\sum_{b=1}^{3} S_{pp}^{b}(\bar{x},t)\chi^{b}(\bar{x},t)d\mathcal{S}\right), \tag{1}$$

where $S_{pp}^{b}(\bar{x},t)$ is the total noise produced by the blade b at the location of the observer $\bar{x}$ and at the time instant t, measured in Pa^2 and integrated at all frequencies. $\chi^{b}(\bar{x},t)$ denotes a mask function that activates when the position $\bar{x}$ is inside the "Snell Cone" of the blade b at instant t. Figure 1 illustrates the acoustic refractions due to the air-water propagation for one blade.

2.2. IPC scheme

Two distinct effects can be exploited through IPC to mitigate underwater noise propagation. First, noise perceived by observers beneath the wind turbine exhibits high oscillations associated

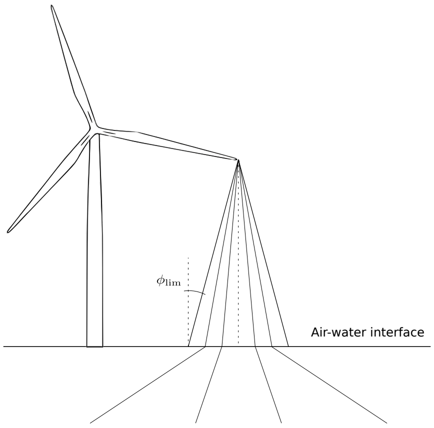


Figure 1. Wind turbine and "Snell Cone" illustration for one blade. The limit angle ϕ_{lim} and some sound rays following Snell's law are shown.

with the blade-passing frequency, as the noise is dominated by the blade in the downward position; see Oerlemans [12]. Second, blade pitch angle is known to significantly decrease both aerodynamic power and noise generation. These two phenomena can be exploited to design an IPC scheme that increases the blade pitch angle only when the blade is oriented downward—i.e., when noise generation is maximal—while maintaining nominal pitch during the remainder of the rotation to preserve power extraction. Accordingly, we propose an IPC strategy that switches between the nominal pitch setting and an increased pitch command following a tanh progression. The proposed IPC law is defined as follows:

$$\theta^b(\Psi^b) = \begin{cases} \theta_{\text{nom}} + \frac{1}{2}\Delta\theta(1 + \tanh((\Psi^b - \Psi_1)k)), & \text{if } \Psi^b \leq \Psi_c \\ \theta_{\text{nom}} + \Delta\theta - \frac{1}{2}\Delta\theta(1 + \tanh((\Psi^b - \Psi_2)k)), & \text{if } \Psi^b > \Psi_c, \end{cases} \tag{2}$$

where Ψ^b denotes the azimuth position of the blade b ($\Psi^b = 0$ is the blade facing upwards), θ_{nom} is the nominal value for the collective pitch angle, k is a parameter related to the pitch rate and $\Delta\theta$ denotes the pitch jump that the IPC performs. The trade-off between power and noise is determined by $\Delta\theta$. This pitch law alternates the nominal pitch value $\theta_1 = \theta_{\text{nom}}$ with a higher pitch $\theta_2 = \theta_{\text{nom}} + \Delta\theta$ while the blade is in the position which corresponds to a higher noise propagation underwater. Figure 2 illustrates this pitch law. This parametrization of the pitch law allows to easily modify the phase width $\Delta\Psi = \Psi_2 - \Psi_1$ and the pitch rate $k = \dot{\theta}/(\Omega\Delta\theta)$. Hence, it is easy to adapt to different wind turbines.

2.3. Wind Farm Integration

Simulating a wind farm with controllers aimed at reducing underwater noise propagation requires control strategies that can adapt to varying inflow conditions. It is standard practice to combine an individual pitch control scheme designed for a specific purpose with a collective pitch controller [13]. The collective pitch controller focuses on maintaining the nominal generator speed under above-rated operating conditions, while the IPC mitigates underwater noise propagation.

In general, the pitch angle commanded for each turbine in the wind farm is given by

$$\theta_i = \theta_{\text{col}}(\Omega_i) + \theta^b_{\text{IPC}}(\Phi^b), \tag{3}$$

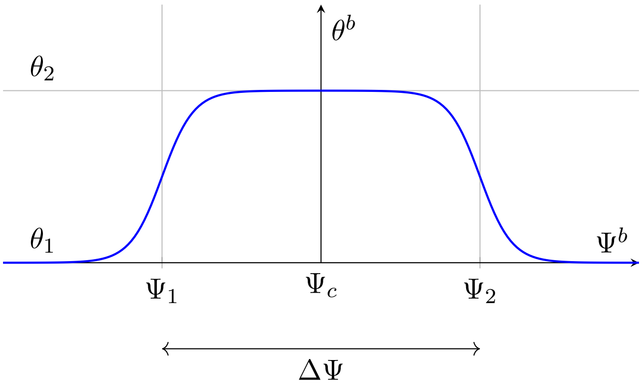


Figure 2. Illustration of the proposed pitch law for each blade depending on its azimuthal phase.

where i denotes the i-th wind turbine on the farm and b indexes its blades. The collective pitch controller used is the DRC controller described in [14], whose implementation was used as a template for the development of the proposed IPC scheme. Wind farm simulations are computed using FAST.Farm [15], which is a multiphysics wind farm solver based on OpenFAST and Dynamic Wake Modeling.

The wind farm noise at an underwater observer can be estimated combining the acoustic plane theory and the noise generation of each wind turbine. An average noise value at the interface can be estimated using the OSWL defined in eq. (1). The average overall sound pressure level at the interface is defined as $\overline{\text{OSPL}}(t) = \text{OSWL}(t) - 10\log_{10}(\mathcal{A}_{SC}(t))$, where $\mathcal{A}_{SC}(t)$ denotes the area within each "Snell Cone" of the three blades at each time instant. The overall noise at an observer considering all the wind turbines contributions can be estimated as

$$\text{OSPL}(\bar{x}, t) = 10\log_{10}\left(\sum_{i=1}^{N} 10^{\left(\overline{\text{OSPL}}_i(t) + \Delta L_{a-w} - 10\log_{10}(|\bar{x}-\bar{x}_i|)\right)/10}\right). \tag{4}$$

According to plane acoustic theory, the air-water transmission loss is of 29.5 dB for the energy [7]. However, this loss occurs due to the medium impedance. The actual pressure value doubles after trespassing the water, see [16]. Notice that as $\Delta L_{a-w} = 6\text{dB}$ is the same for all wind turbines, the effect of the air-water transmission loss can be applied directly over the sum of noise contributions, $\text{OSPL}(\bar{x}, t) = 10\log_{10}(\sum \ldots) + \Delta L_{a-w}$. Therefore, the dB reduction due to the IPC strategy is not affected by the air-water loss modeling.

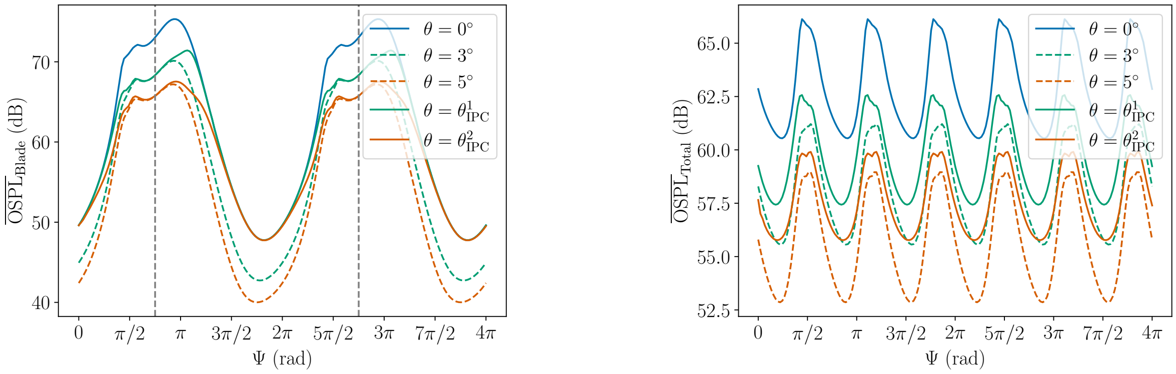
3. Results

In this section, the IPC scheme proposed in section 2.2 is evaluated in several scenarios. First, the performance of the IPC strategy is assessed under nominal operating conditions to quantify its impact on the propagation of wind turbine noise to underwater receivers. Next, the proposed strategy is integrated with a standard collective pitch controller to demonstrate its effectiveness under varying wind conditions. Finally, a small wind farm configuration is simulated, and the resulting reduction in the overall underwater noise footprint of the farm is quantified.

3.1. IPC under nominal conditions for one turbine

This IPC scheme is evaluated for three offshore wind turbines of increasing size: the NREL 5 MW [17], the DTU 10 MW [18] and the IEA 22 MW [19]. Simulations are performed under nominal conditions and two different pitch jumps values of $\Delta\theta^1 = 3°$ and $\Delta\theta^2 = 5°$ are considered.

Figure 3 illustrates the average overall sound pressure level in the "Snell Cone" regions (where the noise is transmitted to the water) for this IPC strategy compared with constant pitch values. It can be seen how the IPC curve strongly reduces the maximum $\overline{\text{OSPL}}$ produced by the wind turbine respect to the non-pitching strategy.



(a) Wind turbine noise radiated underwater generated by one blade. The dashed lines denotes the central phase Ψ_c of eq. (2).

(b) Total wind turbine noise radiated underwater. Ψ denotes the azimuth phase of the first blade.

Figure 3. Comparison of the averaged overall sound pressure level on the "Snell Cone", $\overline{\text{OSPL}}$, for different pitch strategies on for the DTU 10 MW wind turbine for two rotor revolutions.

To quantitatively assess the efficacy of the IPC scheme, three metrics are computed. The power loss respect to nominal conditions, the average OSPL in the "Snell Cone" region and over a rotation and finally, the amplitude modulation of the noise signal, [20]. Table 1 presents these results for the three wind turbines of interest.

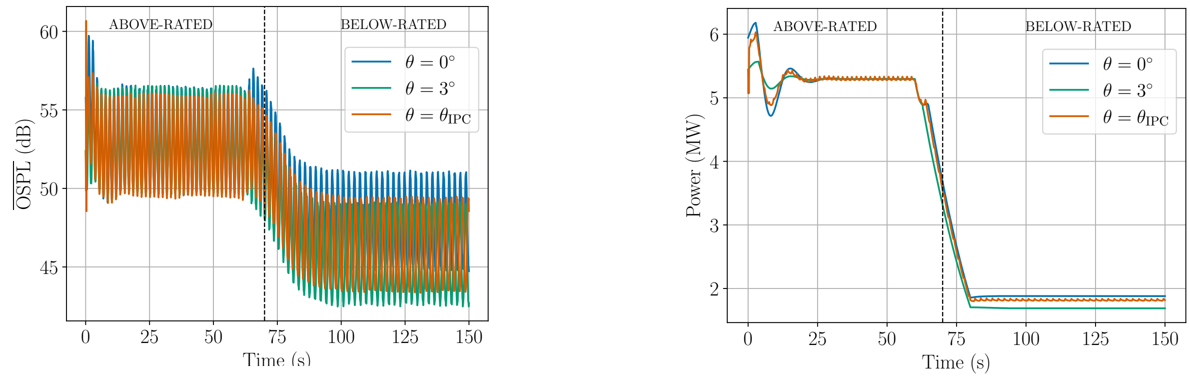
WT	**Metric**	θ_{nom}	3°	5°	θ^1_{IPC}	θ^2_{IPC}
NREL	Power loss (%)	0.00	10.16	23.05	3.19	8.45
	$\widehat{\text{OSPL}}$ (dB)	55.97	53.68	52.82	54.36	53.45
	AM (dB)	7.58	7.79	8.02	7.30	7.22
DTU	Power loss (%)	0.00	4.89	15.39	1.36	5.21
	$\widehat{\text{OSPL}}$ (dB)	63.39	58.66	56.25	60.14	57.90
	AM (dB)	6.42	6.62	7.10	5.97	5.00
IEA	Power loss (%)	0.00	18.62	36.65	6.17	14.73
	$\widehat{\text{OSPL}}$ (dB)	64.34	59.15	56.96	60.81	58.58
	AM (dB)	6.80	7.50	7.75	5.90	5.10

Table 1. Comparison of three performance metrics for different pitch strategies across three offshore wind turbines. The evaluated pitch strategies are: the nominal pitch angle (θ_{nom}), fixed pitch increments of 3° and 5°, and two IPC schemes designed to alternate between the nominal condition and these respective increments.

This preliminary pitch exploration shows the power-noise trade-off produced by the IPC strategy. A noise reduction of 2-3 dB can be obtained with almost negligible power losses for the three wind turbines studied. Meanwhile, a greater noise reduction of 5 dB requires higher power losses, exceeding 5%. More details on the effect of the IPC strategy under nominal conditions can be found in our previous work [1].

3.2. Integration with collective pitch controller

In this section, the IPC scheme is combined with a standard collective pitch controller and evaluated under both below-rated and above-rated wind conditions for the NREL 5 MW wind turbine.



(a) Averaged overall sound pressure level on the "Snell Cone".

(b) Power generation.

Figure 4. Underwater noise radiation and power generation of the NREL 5MW wind turbine for above-rated and below-rated conditions. Three different pitch configurations are shown.

To assess whether the combined pitch control strategy defined in eq. (3) can adapt to changing inflow conditions, the following test case is considered. The NREL 5 MW wind turbine is subjected to a uniform incoming wind speed of 12 m/s, which decreases to 8 m/s after 60 s. Figure 4 presents the results for three pitch control configurations: two standard collective pitch controllers with pitch set-points in the below-rated (Region II) regime of 0° and 3°, respectively, and a controller implementing the combined strategy of eq. (3), with a Region II collective pitch set-point of 0°.

In above-rated conditions, all pitch configurations obtain the same power output because the Region III PI controller of the collective pitch aims for the nominal generator torque, see fig. 4b. However, the IPC configuration manages to slightly reduce $\overline{\mathrm{OSPL}}$, that is, the noise in the underwater propagation region; see fig. 4a. However, the greatest improvement of the IPC scheme results during below-rated conditions, where the collective pitch is at his set-point. There, the IPC manages to have a greater reduction in noise of $\sim 2\,\mathrm{dB}$ with a 3% power loss. This result in a more efficient noise reduction technique that the ones used in industry, which usually get a 5% power loss per dB reduced, [21]. Overall, the IPC strategy always manages to reduce the noise propagated through the air-water interface and is able to adapt to different varying wind conditions.

3.3. Wind farm noise reduction

Finally, the proposed IPC strategy is evaluated on a small wind farm consisting of one row of three NREL 5MW wind turbines. The wind farm layout used in this simulation is illustrated in Figure 5, together with the corresponding wind velocity field. The underwater observer at which the averaged overall sound pressure level, $\overline{\mathrm{OSPL}}$, is evaluated is also indicated; the observer is located at a depth of 60 m.

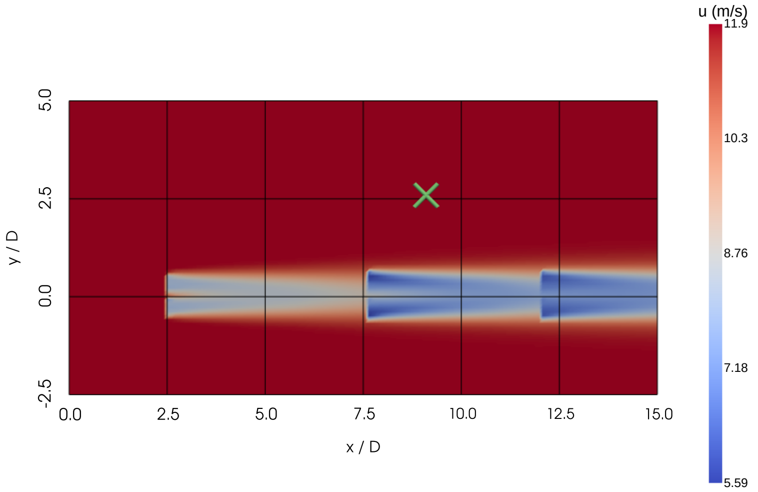


Figure 5. Wind farm layout composed of three NREL 5MW wind turbines. The symbol '×' denotes the location of the underwater observer, which is 60 m deep.

For this configuration, a standard collective pitch controller is compared with the proposed IPC strategy under a uniform incoming wind speed of 12 m/s. The IPC strategy alternates between blade pitch angles of 0° and 3°, with the overall blade pitch command given by eq. (3). The underwater noise at the observer location (marked by a ×) is evaluated using eq. (4).

Figure 6 presents the comparison of the underwater noise generated by the wind farm for the two pitch control strategies. Once the turbine wakes are fully developed, the underwater noise level stabilizes. A noise reduction comparable to that observed in section 3.1 and section 3.2 for the NREL 5 MW turbine is achieved, here demonstrated at the wind farm scale.

Regarding power generation, Table 2 reports the power distribution within the wind farm for both control strategies. Since the first turbine operates in the above-rated region, both strategies yield identical power output. The downstream turbines, however, operate in Region II (below-rated conditions). While the second turbine produces slightly less power when using the IPC strategy, it generates a weaker wake, enabling increased power extraction by the third turbine. As a result, the total wind farm power output remains nearly unchanged between the two strategies, with a marginally higher overall power production observed when employing the IPC.

3.4. Limitations and Sources of Uncertainty

The present analysis relies on several modeling assumptions that introduce uncertainty in the quantitative results. First, aerodynamic noise is computed using the semi-empirical BPM model, and the reference turbine models considered in this study lack dedicated acoustic measurements for direct validation. Second, the analysis focuses on trailing-edge noise, neglecting turbulence

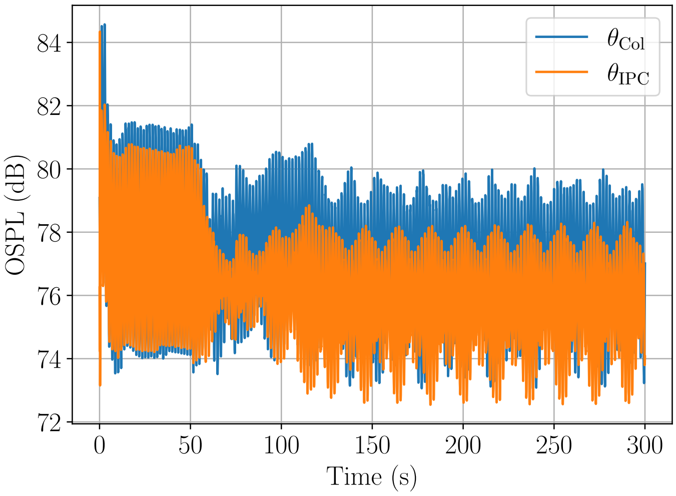


Figure 6. OSPL at the underwater observer '×' using water reference pressure $p_{\mathrm{ref}} = 1\mu\mathrm{Pa}$. Comparison of a standard collective pitch controller against the proposed IPC strategy.

Power (MW)	WT1	WT2	WT3	Farm
θ_{Col}	5.30	3.36	2.10	10.76
θ_{IPC}	5.28	3.23	2.35	10.86

Table 2. Comparison of the power generation of a 3-wind-turbine wind farm for a standard variable-speed controller and our proposed IPC strategy.

inflow noise and other noise sources. Although these contributions are expected to be less significant under typical offshore conditions, they may still contribute under certain inflow regimes that are not analyzed in this study. Third, underwater sound levels are estimated using a simplified air–water transmission model assuming a flat sea surface, whereas realistic sea states may alter acoustic transmission and propagation characteristics.

Despite these simplifications, the proposed control strategy targets the noise generation mechanism at the source, rather than the propagation process. Therefore, while absolute sound pressure levels may vary under more detailed modeling assumptions, the qualitative behavior exploited by the proposed IPC strategy remains robust, the azimuth-dependent directivity and pitch sensitivity of aerodynamic noise is experimentally validated, [12]. Moreover, the relative noise reduction achieved by the control strategy is independent of the propagation model, as it primarily depends on changes in the emitted acoustic field rather than on transmission effects, see Section 3.3.

Therefore, the present work should be interpreted as a proof-of-concept study. While quantitative levels may vary with more detailed modeling, the physical mechanisms exploited by the proposed IPC strategy remain robust.

4. Conclusions

In this work, we quantified the extent to which aerodynamic noise generated by large horizontal-axis offshore wind turbines can penetrate the air-sea interface. To mitigate this airborne-to-underwater noise pathway, we extended and evaluated the open-loop IPC strategy proposed in our previous work [1].

By modulating the blade pitch at the blade-passing frequency, the proposed IPC approach substantially reduces the overall sound pressure level and attenuates amplitude modulation, a phenomenon known to cause annoyance in humans and likely to affect marine fauna in a similar manner. The method was analyzed for three representative offshore wind turbine models (NREL 5 MW, DTU 10 MW, and IEA 22 MW), quantifying the achieved sound pressure level reductions under nominal operating conditions.

To enable operation under varying inflow conditions, the IPC strategy was coupled with a standard collective pitch controller. The resulting control framework was evaluated under above-rated conditions, below-rated conditions, and within a wind farm configuration. In all cases, the method achieved noise reductions comparable to those obtained under nominal conditions, demonstrating its robustness and adaptability when integrated with conventional collective pitch control.

The proposed IPC strategy achieves acoustic mitigation with reduced impact on power performance, confirming a pitch modulation amplitude of $\Delta\theta \approx 3^\circ$ as an effective compromise between underwater noise reduction and energy production.

Finally, in the wind farm case presented in section 3.3, the IPC strategy achieved a measurable reduction in underwater noise without any loss of power at the farm level. Although this assessment is based on a preliminary mid-fidelity modeling framework, the results indicate a promising pathway toward silent offshore wind farms without sacrificing power generation.

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