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# Stochastic Turbulent Wind Influence on Mooring Line Tensions for Floating Offshore Wind Turbines

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**SUMMARY:**
Floating Offshore Wind Turbines remain constrained by technological challenges, notably the coupled wind–wave loading that drives complex dynamics and complicates design and operational reliability, particularly for the mooring system. This study investigates the influence of stochastic turbulent wind combined with irregular waves on mooring line tensions using a fully coupled aero-hydro-servo-elastic model. Validated against benchmark results reported in the literature, the model simulates wave-only and combined wave–wind conditions across different turbine operating states. Results indicate that wind and turbine operating conditions are the dominant factors affecting mooring tensions, producing asymmetric loads, while wave effects remain secondary. Tension trends are analyzed, and the influence of wind and operational state is quantitatively assessed. Rated and extreme wind scenarios are identified as the most critical for mooring system safety. These findings provide guidance for the safe and reliable design of mooring systems under realistic environmental conditions.

*Keywords: Floating offshore wind turbines, Mooring system, Irregular waves, Stochastic turbulent wind, Numerical investigation*

## 1. INTRODUCTION

Despite their high energy potential and low environmental impact, Floating Offshore Wind Turbines (FOWTs) face limitations for large-scale deployment due to technological challenges, including the simultaneous action of wind and wave loads, which generates a highly coupled dynamic response that complicates both design and operational reliability (Lauria et al., 2024a). Although extensive experimental and numerical studies have investigated the overall dynamic response of FOWTs under combined wind and wave loading (Guo et al., 2026; Yang et al., 2026), the specific effects of these factors on mooring line tensions have received comparatively little attention. However, as the mooring system governs station-keeping and platform stability and represents one of the main cost drivers (Loprieno et al., 2026), a thorough understanding of these effects is vital for enhancing design safety, maintaining system reliability (Jiang, 2025), and plays a crucial role for cost control. In a previous study (Lauria et al., 2024b), the dynamic response of a spar-type FOWT was investigated using a scaled numerical model validated against experimental data, with emphasis on the influence of wind and operational states on mooring line tensions under controlled conditions with regular waves and steady wind. Building upon this work, the present study extends the analysis to a full-scale FOWT to reduce scaling uncertainties and examines the effects of stochastic turbulent wind combined with irregular waves on mooring line tensions through a fully coupled aero-hydro-servo-elastic numerical model. The objective is to provide a more realistic evaluation of the influence of wind and turbine operating conditions on mooring tension response.

## 2. MATERIALS AND METHODS

The case study considers the OC3-Hywind spar platform coupled with the NREL 5-MW reference wind turbine, moored by a three-line non-redundant catenary system. A fully coupled aero-hydro-servo-elastic model was developed in OpenFAST, with the mooring system implemented through MAP++. The wave field was generated using a JONSWAP spectrum to reproduce irregular sea states, and the wind input was defined as a three-dimensional turbulent full-field consistent with IEC 61400 prescriptions, including mean profile, turbulence intensity, coherence, and stochastic fluctuations. The model was validated against benchmark results (Figure 1) published in (Jonkman and Musial, 2010). Once validated, first, simulations with

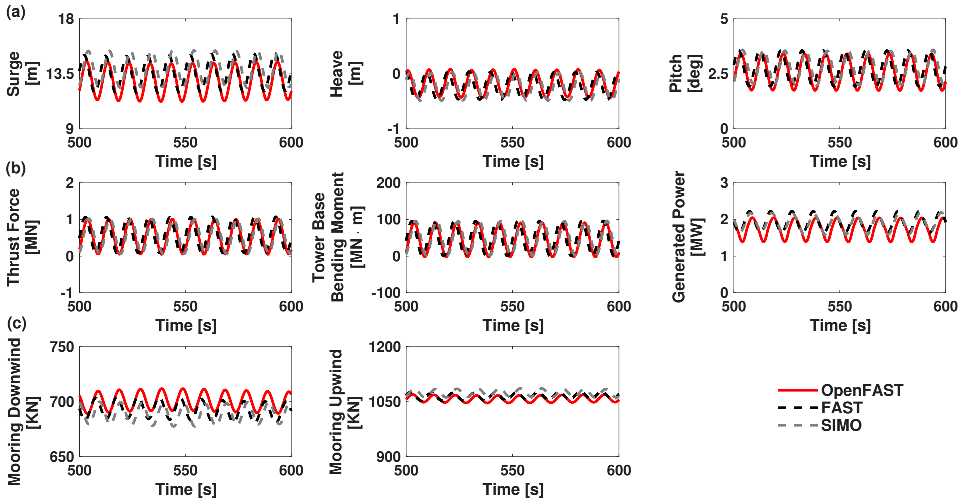


**Figure 1.** Validation of the numerical model developed through comparison with literature results obtained for the same structural configuration (Jonkman and Musial, 2010), under regular waves and steady wind: (a) hydrodynamic response; (b) aerodynamic response and power generation; (c) mooring system tension response.

irregular waves only were conducted to isolate their effect on mooring line tensions. Subsequently, combined wave–wind simulations were performed, pairing the same wave conditions with various wind scenarios representative of different turbine operating states (Figure 2). This approach allowed the effects of waves and wind separately on mooring line tensions to be assessed for each operational condition of the turbine.

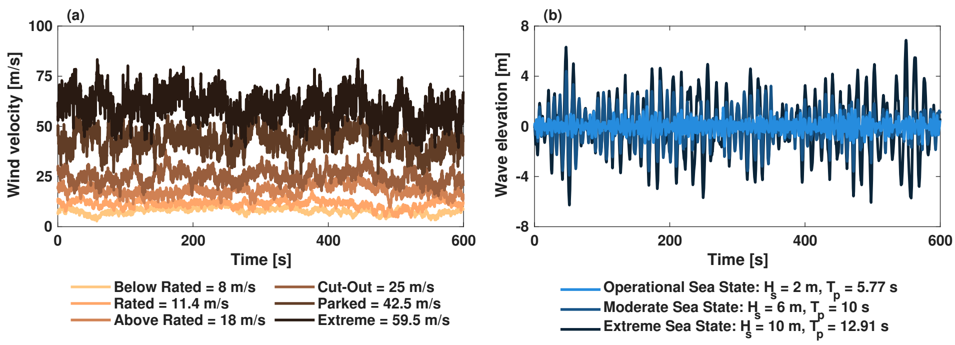


**Figure 2.** Environmental conditions: (a) wind velocity along the rotor axis for the selected operational states; (b) free-surface elevation for the selected sea-state conditions.

## 3. RESULTS AND DISCUSSION

Wind and turbine operating conditions are the primary drivers of FOWT displacements, producing asymmetric mooring line loads, with downwind lines experiencing decreases and upwind lines experiencing increases in tension. For design purposes, it is therefore essential to consider minimum tensions in downwind moorings and maximum tensions in upwind moorings to prevent both slack and overstress (Figure 3). Wave-induced variations in tension are generally minor compared to those caused by wind and turbine operation, with the only notable exception occurring under wave-only loading, indicating that wind can partially mitigate wave effects. Tension trends in upwind moorings are strongly dependent on the turbine operating state. Below rated wind speed, tensions increase monotonically with wind and rotor speed. Above rated wind speed, pitch control regulates blade angles to maintain constant power and reduce aerodynamic loads, producing a monotonic decrease in tension. Following cut-out, in the parked rotor condition, tensions increase again with wind. Minimum tensions in downwind moorings exhibit a symmetric behavior. Figure 4 and Tables 1 and 2 report the percentage variations in mooring line tensions relative to the wave-only condition, normalized to the corresponding wave-only tensions. These results quantify and corroborate the trends described above, providing a precise measure of the contribution of wind and turbine operating conditions to mooring loads. Two critical cases are identified: during turbine operation, the rated wind condition induces the largest effect, while in the parked rotor condition, extreme wind represents the worst-case scenario.

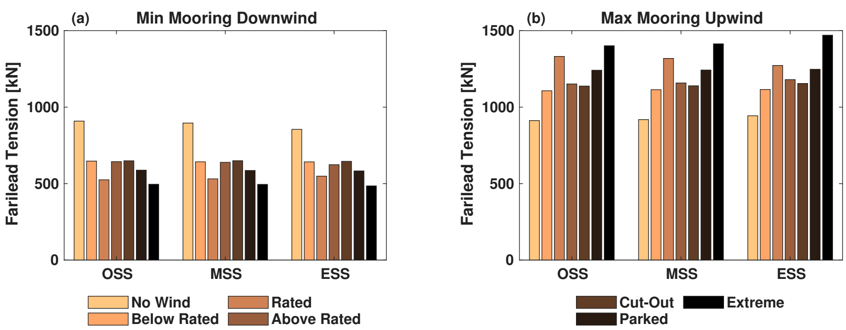


**Figure 3.** Comparison of mooring line tensions obtained from the different simulations performed: (a) comparison of the minimum values for the least loaded mooring line; (b) comparison of the maximum values for the most loaded mooring line.

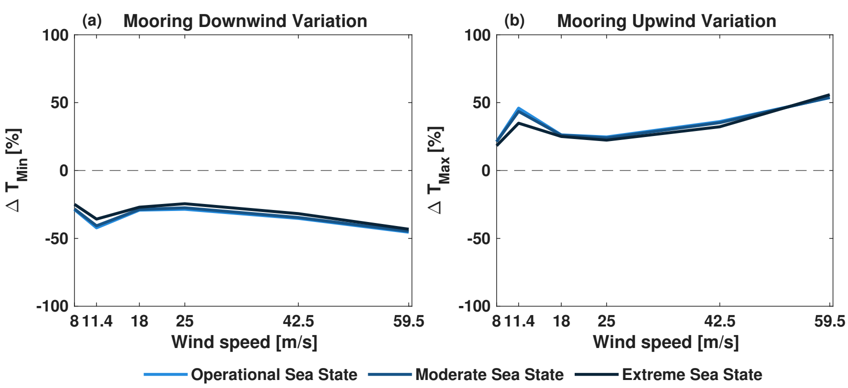


**Figure 4.** Percentage variation of mooring line tensions for the different wind speeds analyzed with respect to the wave-only condition: (a) variation trend of the minimum values for the least loaded mooring line; (b) variation trend of the maximum values for the most loaded mooring line.

**Table 1.** Percentage increase in tension associated with aerodynamic loads for the upwind mooring lines, with reference to Figure 4(a).

| $\Delta T_{Max}$ [%] | Below Rated | Rated | Above Rated | Cut-out | Parked | Extreme |
|---|---|---|---|---|---|---|
| **OSS** | 21 | 46 | 26 | 25 | 36 | 54 |
| **MSS** | 21 | 44 | 26 | 24 | 35 | 54 |
| **ESS** | 18 | 35 | 25 | 22 | 32 | 56 |

**Table 2.** Percentage reduction in tension associated with aerodynamic loads for the downwind mooring lines, with reference to Figure 4(b).

| $\Delta T_{Min}$ [%] | Below Rated | Rated | Above Rated | Cut-out | Parked | Extreme |
|---|---|---|---|---|---|---|
| **OSS** | 29 | 42 | 29 | 29 | 35 | 45 |
| **MSS** | 28 | 41 | 29 | 27 | 35 | 45 |
| **ESS** | 25 | 36 | 27 | 25 | 32 | 43 |

## 4. CONCLUSIONS

The results of this study demonstrate that wind and turbine operating conditions are the primary drivers of mooring line tensions in FOWTs, generating asymmetric loads that dominate over wave-induced effects. Tension trends strongly depend on turbine state: below rated wind speed, tensions increase with rotor speed, while above rated wind speed, pitch control reduces aerodynamic loads and tensions decrease; in the parked condition, tensions rise again with increasing wind. Rated wind and extreme wind conditions emerge as the most critical scenarios for design, producing the largest increases in maximum tensions and reductions in minimum tensions. These findings provide quantitative insight into the influence of environmental and operational factors on mooring loads, supporting safer and more reliable design and operation of FOWTs systems under realistic wind and wave conditions.


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