Influence of Adaptive Controlling Strategies of Floating Offshore Wind Turbine on Corrosion Fatigue Deterioration of Supporting Towers

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Abstract. Floating offshore wind turbines (FOWTs) demonstrate very promising potential in unlocking the plentiful wind resource in deep-water oceans. Meanwhile, the combination of the harsh marine environment and strong dynamics complicate the long-term deterioration of FOWT-supporting towers, specifically the escalating corrosion fatigue (C-F) coupled deterioration in critical connections. Unlike traditional engineering structures, an interoperable control is available in FOWTs, such as the pitching, yawing and torque controllers, which can mitigate structural oscillation and loads. With the recent advances in smart sensing, a better prognosis of current and future deterioration can be guaranteed with increasingly accessible data. Thus, a refined adaptive control strategy is hence deemed essential based on the site-specific data, to curb the operation and maintenance (O&M) costs of FOWT towers based on the structural condition. The present work elaborates on the influence of various adaptive controlling strategies of FOWTs on the C-F deterioration of supporting towers, lending itself to preliminary references for balanced trade-offs between power generation and structural reliability. Multiphysics simulations of FOWTs are initially carried out to establish fatigue stress spectra from site-specific wind-wave distribution, using various types of control strategies. Structural reliability assessment is then conducted by incorporating the spectra into a time-variant C-F deterioration model in which the ambient corrosivity is accounted for. The result suggests a compelling C-F deterioration faced by FOWT towers due to strong wind-wave loads, high corrosivity and improved structural flexibility. More critically, the finding underscores the apparent influence of controlling strategies on the C-F deterioration of FOWT structures, especially under certain regimes of wind velocities. In addition, preliminary but innovative perspectives are elucidated on the delicate balance and conflict between generation efficiency and structural reliability.

Keywords: Floating offshore wind turbine (FOWT) · Adaptive Control · Supporting Tower · Corrosion Fatigue (C-F) · Structural Reliability

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1 Introduction

Floating offshore wind turbines (FOWTs) enable the exploitation of redundant renewable energy in deep waters, but they face structural challenges from corrosion fatigue (C-F) of bolts in ring-flange [1] These bolts are crucial for the tower and nacelle assemblies, but suffer from cyclic stresses and marine corrosion. As a result, the coupling effect of corrosion and fatigue (usually called as corrosion fatigue) will accelerate the deterioration process, and risk premature failure of bolts [2]. The prominence of C-F issue in FOWTs has been illustrated in a list of studies [3]. Thus, an interdisciplinary approach is needed, involving improvements in materials engineering, stress analysis, and predictive maintenance strategies to increase the durability and reliability of FOWTs (Fig. 1).

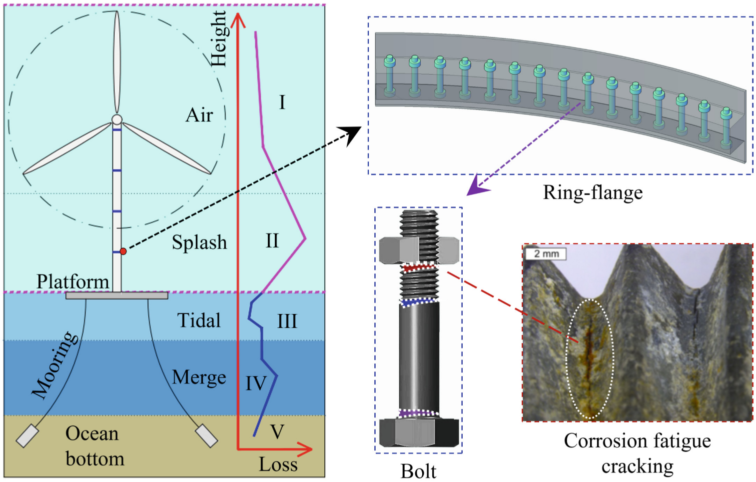


Fig. 1. Corrosion fatigue of high-strength both in ring-flange of FOWT towers.

Mitigating fatigue deterioration in wind turbine towers is a multi-faceted challenge that necessitates a deep understanding of both the physical phenomena involved and the innovative control strategies that can be applied. From the state-of-the-art notes provided and supplemented by recent scholarly articles, it is evident that proactive and adaptive control strategies form the backbone of mitigating such fatigue. These strategies include individual pitch control, where each blade's pitch angle is independently controlled to reduce asymmetric loads and thus mitigate fatigue [4]. Another method involves the use of online structural health monitoring systems that adaptively adjust operational parameters to reduce stress and enhance the service life of the structure [5]. Moreover, preventive control strategies are being explored, leveraging advanced forecasting techniques to predict and prepare for incoming gusts or turbulence, thus allowing preemptive adjustments that minimize fatigue loads. These methods aim to strike a balance between optimal energy capture and load reduction, thereby extending the service life of turbine components. The integration of real-time data analytics into control systems is also increasingly common, facilitating dynamic adjustments based on immediate assessments of structural integrity and environmental conditions.

This work investigates how adaptive controlling strategies can reduce the corrosion fatigue (C-F) damage of supporting towers in floating offshore wind turbines (FOWTs), which affects their operational dynamics and structural integrity. The paper adopts a systematic approach, starting with an overview of the challenges and opportunities of FOWTs, followed by a comprehensive analysis of different controlling strategies, their implementation, and their impact on the C-F performance of the towers. The study then presents a multi-physics simulation framework that integrates structural, hydrodynamic, aerodynamic, and C-F models to evaluate the effectiveness of the controlling strategies. A probabilistic model is also developed to assess the uncertainty and reliability of the C-F life prediction. The paper concludes with a discussion of the main findings and their implications for the future design and operation of FOWTs.

2 Multi-physics Simulation

2.1 Probabilistic Corrosion Fatigue Modelling

In order to incorporate the degradation in fatigue performance by corrosion, a time-variant probability-stress-life (t-PSN) model is developed according to the report [8], as shown in Fig. 2. The three-dimensional representation correlates fatigue strength with loading cycles and service life, taking into account both the mean and the statistical variability ($\pm 2\sigma$) around this mean, thereby encapsulating the expected range of material behavior under operational cyclic stress.

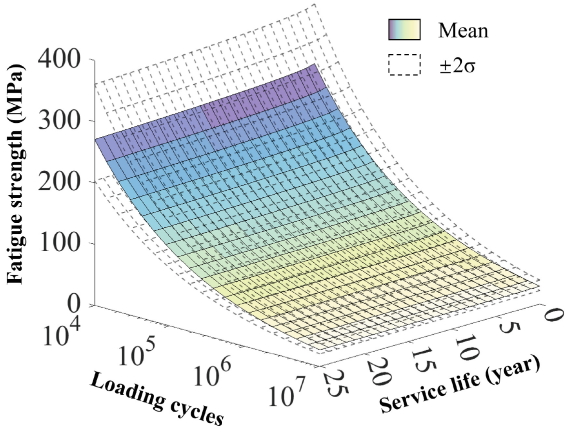


Fig. 2. Probabilistic corrosion fatigue modelling of high-strength bolts.

The proposed t-PSN model adeptly captures the diminishing fatigue strength as a function of time, attributing this decline not solely to the repetitive loading but also to the progressive corrosion that inherently accompanies service in corrosive environments such as marine atmospheres. As the bolt undergoes cyclic stress, the concurrent corrosive effect impairs its resistance to fatigue, accelerating the deterioration process beyond what would be expected from mechanical fatigue alone. The shaded area delineated by the ±2σ boundaries on the plot emphasizes the uncertainty in the rate of degradation, underscoring the significance of corrosion in expanding the dispersion of fatigue strength values over time. By integrating the time-dependent nature of corrosion into the fatigue analysis, the t-PSN model provides a more realistic and robust basis for assessing the structural integrity of components exposed to harsh environments. This is particularly crucial for floating offshore wind turbines, where the synergy between mechanical loading cycles and the harsh maritime climate can significantly shorten the expected service life of supporting towers and other critical structures.

2.2 Derivation of Fatigue Stress Spectra

The IEA 15MW reference turbine is selected [6], which is installed on a 150-m-tall tower erected on the UMaine VolturnUS-S floating platform [7]. The diameter of the tower shells varies from 10 m at the bottom to a narrower dimension at the hub, with the thickness ranging from 55 mm at the pile to 44 mm at the transition piece. The design accommodates the dynamic marine conditions and supports the substantial size and forces of the 15MW turbine, ensuring stability and efficiency in offshore environments.

This work assumes the wind speed distribution at the Station CAPE ELIZABETH [9], as shown in Fig. 3. The histogram bars indicate the actual observed frequencies of wind speeds, with a notable peak around the mean wind speed of 6.03 m/s, reflecting the predominant wind conditions recorded at the station, which is located approximately 83.34 km northwest of Aberdeen, Washington. The Weibull distribution, characterized by its red curve, closely matches the empirical data, suggesting that it accurately models the wind speed distribution for this offshore location.

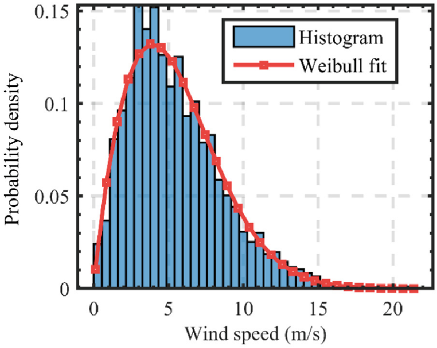


Fig. 3. Wind speed distribution and fitting.

Figure 4 shows the correlation between the wind speed and wave height at the selected station. The data suggest a trend where wave height increases with wind speed, reflecting the energy transfer from wind to water surface. However, the spread of points indicates variability, with some higher wind speeds not resulting in proportionally higher waves, likely due to the complex dynamics of local meteorological conditions. This correlation is crucial for understanding the environmental loading on offshore structures, such as wind turbines, where both wind and wave forces critically influence design and operation. For simplification purposes, a deterministic curve has been fitted from the data to illustrate the correlation between the wind speed and wave height.

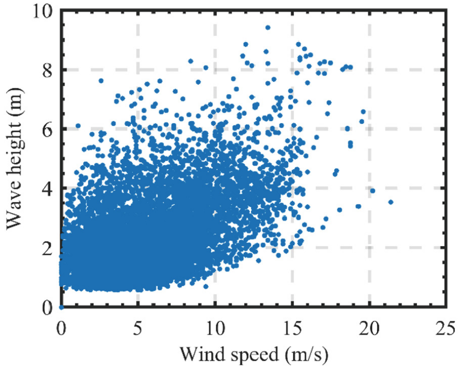


Fig. 4. Correlation between wind and wave.

Based on the wind-wave data, the multi-physics simulation has been applied to derive the fatigue stress spectra at the critical bolt, as illustrated in Fig. 5. Commencing with the synthesis of wind conditions through a wind rose, which quantifies the probabilistic wind speed distribution and directional prevalence, the process advances to the application of OpenFAST [10], a sophisticated simulation tool that models the dynamic interplay between wind forces and the mechanical and control systems.

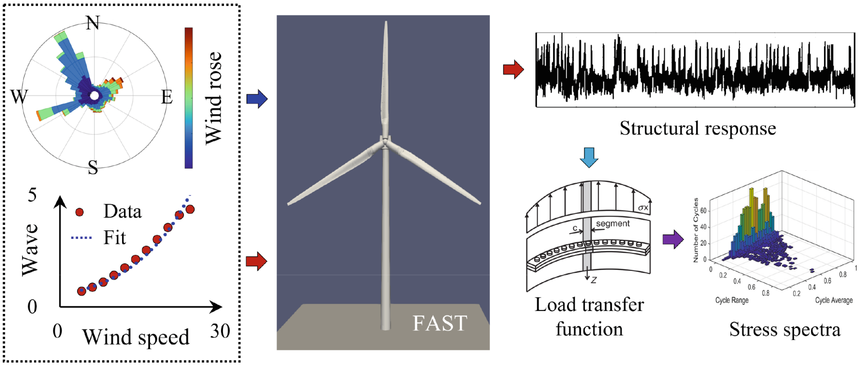


Fig. 5. Derivation of fatigue stress spectra by multi-physics simulations.

Following this, a load transfer function [11] (*e.g.,* Schmidt and Neuper approach) is applied, effectively mapping the complex dynamic responses to the corresponding structural loads. These loads are then translated into stress spectra, providing a comprehensive profile of the cyclic stresses experienced by each turbine segment, and moreover, by the critical bolt.

In this study, the fatigue strength of bolts is treated as a random variable to account the prominent uncertainties in fatigue. It is assumed to follow a log-normal distribution with a mean value of 54.88 MPa and a coefficient of variation of 0.15.

2.3 Probabilistic Deterioration Prognosis

Figure 6 provides a quantitative depiction of the reliability index [12] over the service life of the critical bolt subjected to corrosion fatigue deterioration. Initially, the reliability index starts at a higher value, indicating a low probability of failure. As the service life progresses, the index exhibits a monotonic decrease, reflecting the cumulative damage from corrosion fatigue and the consequent increase in the probability of failure. The marked threshold at an index value of 1.7 corresponds to a service life of approximately 13.6 years, beyond which the reliability falls below the acceptable limit. This inflection point serves as a critical juncture for maintenance or replacement decisions, emphasizing the need for diligent monitoring and proactive intervention to sustain the structural integrity of the bolt within the operational lifespan of the wind turbine system.

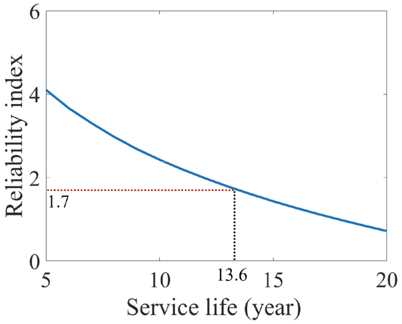


Fig. 6. Time-variant reliability of the critical bolt.

3 Adaptation of Controlling Strategies

3.1 Variation in Controlling Strategies

Three distinct control strategies have been considered in the work, i.e., C0 (the benchmark), C1 (early rated and early cut-off), and C2 (late cut-in, early rated and early cut-off). Figure 7 depicts the three strategies, each defined by their operational parameters at key wind velocities: cut-in, rated, and cut-off. More details can be found in Table 1. Strategy C0 has a cut-in wind speed of 3 m/s, at which point the turbine begins to generate power, a rated speed of 10.59 rpm corresponding to its rated power of 15 MW at a wind speed of 25 m/s, beyond which the cut-off speed is reached, and power generation is halted to prevent damage [6]. In contrast, strategies C1 and C2 share a lower rated rotor speed of 7 rpm, resulting in a rated power of 13.8 MW but differ in their cut-in speeds; C1 commences power production at a wind speed of 3 m/s, whereas C2 waits until the wind reaches 5 m/s. Both C1 and C2 have a cut-off wind speed of 20 m/s. The pitch angle behavior for each strategy varies accordingly [13]; C0 maintains a steady increase in pitch angle with wind speed, C1 exhibits a steeper ascent post-cut-in before leveling off near the rated wind speed, and C2 remains flat until its higher cut-in speed is achieved, then follows a similar trend to C1. These control strategies reflect trade-offs between energy capture efficiency and structural load management, with each approach offering distinct benefits and limitations depending on the wind speed profile and desired turbine performance characteristics.

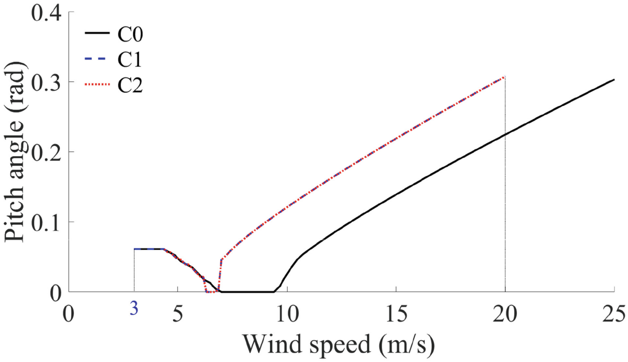


Fig. 7. Different types of controlling strategies.

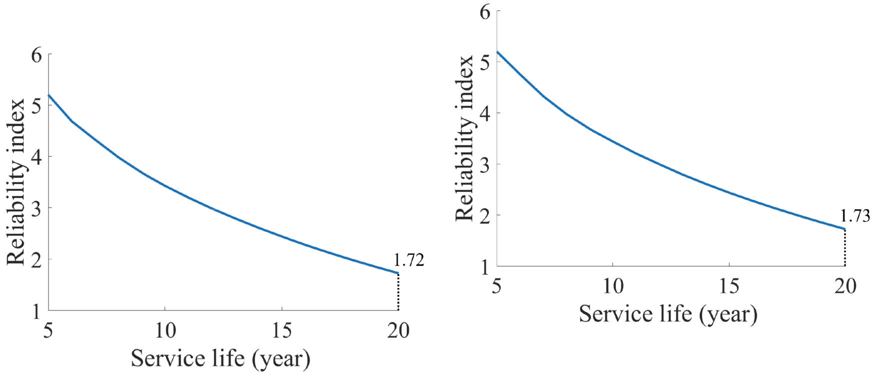
Table 1. Different controlling strategies and parameters.

Strategy	Wind velocity (m/s)			Rated rotor speed (rpm)	Rated power (MW)
	Cut-in	Rated	Cut-off		
C0	3	10.59	25	7.6	15
C1	3	7	20	7	13.8
C2	5	7	20	7	13.8

3.2 Results and Discussion

Figure 8 presents the reliability evolution of the critical bolt under the two different control strategies, C1 and C2. Recalling benchmark scenario (Fig. 6), the reliability index of the bolt decreases uniformly with time, reaching the threshold value of 1.7 at approximately 13.6 years, indicating the point at which the bolt's reliability is compromised.

Comparatively, Fig. 8a, representing Strategy C1, shows a similar downward trajectory but with a slightly higher reliability threshold of 1.72, reached just beyond the 20-year mark. Strategy C2, depicted in Fig. 8b, exhibits a near-identical pattern to Strategy C1, with the reliability index threshold marginally higher at 1.73, also surpassed just after 20 years. Both strategies demonstrate an improvement in the bolt's reliability over the benchmark, albeit marginally, suggesting that these control strategies may extend the service life of critical components. The comparison elucidates that while Strategies C1 and C2 offer a slightly extended service life over the benchmark, the differences are minimal, indicating that further optimization of control strategies may be necessary to achieve a more substantial increase in component longevity. This underscores the importance of refining control strategies to enhance the reliability and hence the service life of critical turbine components under the persistent challenge of corrosion fatigue.



(a) (b)

Fig. 8. Influence of different strategies on the reliability evolution of the critical bolt: (a) Strategy C1; (a) Strategy C2.

Table 2 provides a comparative analysis of power generation under the three wind turbine control strategies, in terms of the consequent annual power generation. Strategy C0 yields the highest annual power generation of 56,502 MWh. This strategy takes full advantage of the lower wind speeds for power generation, which corresponds to a more aggressive energy capture approach but may contribute to a faster deterioration in the reliability index of critical components, as suggested by the lower reliability threshold of 1.7 reached after 13.6 years (Fig. 6).

In contrast, Strategy C1, with identical cut-in and higher cut-off wind speeds as compared to C0 but a lower rated rotor speed of 7 rpm, generates less annual power, 51,142 MWh. Strategy C2 is more conservative with a higher cut-in wind speed of 5 m/s, the same rated rotor speed, and cut-off wind speed as C1, leading to the lowest power generation of 45,073 MWh. Both C1 and C2 exhibit slightly higher reliability thresholds of 1.72 and 1.73, respectively, surpassing the benchmark after 20 years (Fig. 8), suggesting that these strategies may be more conducive to preserving the structural integrity of the critical bolt over time. When correlating power generation with the reliability indices, it's evident that more conservative controlling strategies - C1 and C2 - while producing

Table 2. Power generation under different controlling strategies.

Strategy	Wind velocity (m/s)			Annual power generation (MWh)
	Cut-in	Rated	Cut-off	
C0	3	10.59	25	42,102
C1	3	7	20	39,520
C2	5	7	20	35,271

less energy annually, potentially extend the service life of critical components, offering a trade-off between immediate energy yield and long-term structural reliability. This analysis highlights the strategic decisions to be made between operational efficiency and durability in wind turbine management.

4 Conclusions

Based on the major findings in the present study, the following conclusion can be drawn.

- The choice of control strategies has a profound effect on the rate of corrosion fatigue in FOWT supporting structures, with direct implications for the service life of critical connections.
- While Strategy C0 (the original benchmark) maximizes power generation, it detrimentally impacts bolt reliability, hastening the approach to critical reliability thresholds. Alternatively, Strategies C1 and C2, through conservative operational limits, effectively prolong the structural integrity of bolt connections, suggesting a strategic prioritization of long-term durability over immediate power maximization.
- The work also highlights the necessity to integrate control strategy with real-time structural health monitoring and to leverage advancements in material science to fortify the FOWTs against the harsh marine environment.
- Future works are suggested to explore next-generation predictive operation and maintenance protocols, like digital twins, to further the operational efficacy and durability of FOWTs.

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