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A digital twinning framework for intelligent operation and maintenance of floating offshore wind turbines under corrosion-fatigue

Jiaxin Zhang[1], Junlin Heng[2,3], You Dong[1], Charalampos Baniotopoulos[3*] and Yasmin Ali[2,4]

[1] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong, Hong Kong SAR, China
[2] Department of Civil Engineering, Sichuan University, Chengdu, Sichuan, China
[3] Department of Civil Engineering, University of Birmingham, Birmingham, United Kingdom
[4] Department of Civil Engineering, Delta University for Science and Technology, Gamasa 11152, Egypt

[*]E-mail: c.baniotopoulos@bham.ac.uk

Abstract. Floating offshore wind turbines (FOWTs) present a significant opportunity for harnessing deep-water wind resources, yet their operational longevity is challenged by the harsh marine environment, particularly through corrosion fatigue (C-F) in critical structural connections like ring-flanges. This paper introduces an intelligent Digital Twin (DT) framework designed to mitigate C-F and enhance the operation and maintenance (O&M) of FOWT structures by enabling adaptive control strategies. The framework integrates data from Supervisory Control and Data Acquisition (SCADA) and Structural Health Monitoring (SHM) systems with multi-physics simulations and a time-variant probability-stress-life (t-PSN) C-F model. A case study on the IEA 15MW reference FOWT, under site-specific environmental conditions, was carried out to demonstrate the DT's application. Three distinct adaptive control strategies (CS1-Baseline, CS2-Rated speed 7 m/s, and CS3-Rated speed 9 m/s) were evaluated for their impact on the C-F reliability of ring-flange connections. Results indicate that adaptive control strategies CS2 and CS3 significantly extend the reliable operational lifespan beyond 20 years, compared to approximately 15 years under the baseline CS1, before reaching critical reliability thresholds. For instance, at 20 years, ring-flange reliability indices under CS2 remained robust (≈3.5-3.7). Also, the change in control strategies also results in different level of compromise in power generation. The study underscores the DT's capability to predict C-F progression, inform the selection of damage-mitigating control strategies, and provide a foundation for proactive, condition-based maintenance, thereby contributing to enhanced resilient and cost-effective FOWT operations.

1. Introduction

Floating offshore wind turbines (FOWTs) signify a considerable progression in renewable energy technologies, providing a practical avenue to harness the superior wind resources characteristic

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of deep-water environments [1]. The continued development of FOWTs is essential for expanding wind energy production into offshore regions where the installation of conventional fixed-bottom turbines is precluded by substantial water depths, thus making previously inaccessible areas available for wind power generation [2].

Following the successful harnessing of deep-water wind resources by FOWTs, significant operational challenges persist, particularly concerning their long-term structural integrity in harsh marine environments. Corrosion fatigue (C-F) notably emerges as a critical deterioration mechanism, predominantly affecting vital structural connections like bolted ring-flanges, which experience the combined effects of persistent cyclic loading and the aggressive corrosivity of seawater [3]. This synergistic degradation, illustrated in Figure 1 showing typical C-F damage in an FOWT ring-flange, may accelerate material weakening and can lead to premature component failure, thereby impacting the operational reliability and economic viability of these advanced energy systems [3,4].

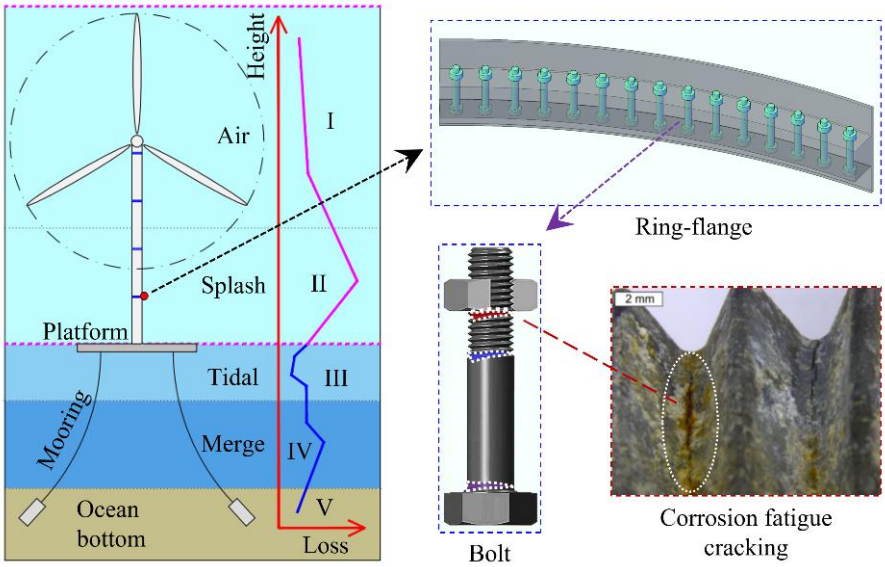


Figure 1. C-F in ring-flange components of FOWT structures.

To such complex degradation processes, Digital Twins (DTs) are increasingly recognized as a transformative technology for enhancing the intelligent operation and maintenance (O&M). They provide a virtual representation of a physical asset, dynamically updated with real-time data and integrated with analytical models, thereby enabling advanced monitoring and predictive capabilities pertinent to structural integrity [5,6]. Within this paradigm, data streams from sensors are assimilated into sophisticated computational models, which can incorporate machine learning algorithms to assess structural performance, predict future maintenance requirements, and optimize O&M strategies [7]. The synergy between artificial intelligence and DTs, particularly in the context of FOWTs, facilitates more precise structural health prognoses and supports proactive, data-driven decision-making to mitigate risks like C-F, ultimately aiming to extend the service life and enhance the operational sustainability of these critical energy assets [6,7].

Consequently, this paper aims to present a DT framework specifically tailored to mitigate C-F in FOWT structures through the strategic application of adaptive control. The scope

encompasses the integration of sensor data and multi-physics simulations within the DT to predict C-F progression and to evaluate how different operational control strategies can enhance structural resilience and extend component lifespan.

The subsequent sections will systematically unfold this investigation. Section 2 delineates the core components and operational logic of the proposed DT framework, encompassing data integration, simulation-based modelling, and C-F prediction. Following this, Section 3 presents a case study applying this framework to an FOWT, specifically evaluating the efficacy of adaptive control strategies in mitigating corrosion fatigue and enhancing structural reliability. Finally, Section 4 synthesizes the principal findings, underscoring the framework's contribution to intelligent operation and maintenance, and suggests paths for future research in this domain.

2. Intelligent digital twin framework and methodology

The proposed DT framework for FOWT O&M, conceptually illustrated in Figure 2, is architected around several interconnected core components designed to facilitate intelligent decision-making for structural integrity management. At its foundation lies the physical asset, the operational FOWT, which is continuously monitored through a data acquisition layer comprising various sensor systems (e.g., Supervisory Control and Data Acquisition (SCADA), Structural Health Monitoring (SHM)). This acquired data feeds into the digital model, a high-fidelity virtual replica that employs multi-physics simulations and material degradation models to mirror the FOWT's behaviour and condition. An analytics engine then processes both real-time data and simulation outputs, utilising techniques such as machine learning and probabilistic modelling to assess current structural health, predict future performance (C-F progression), and evaluate the impact of potential O&M interventions. Finally, the insights generated are channelled to a decision support interface, providing actionable intelligence to operators for optimizing maintenance schedules and implementing adaptive control strategies to enhance the FOWT's operational lifespan.

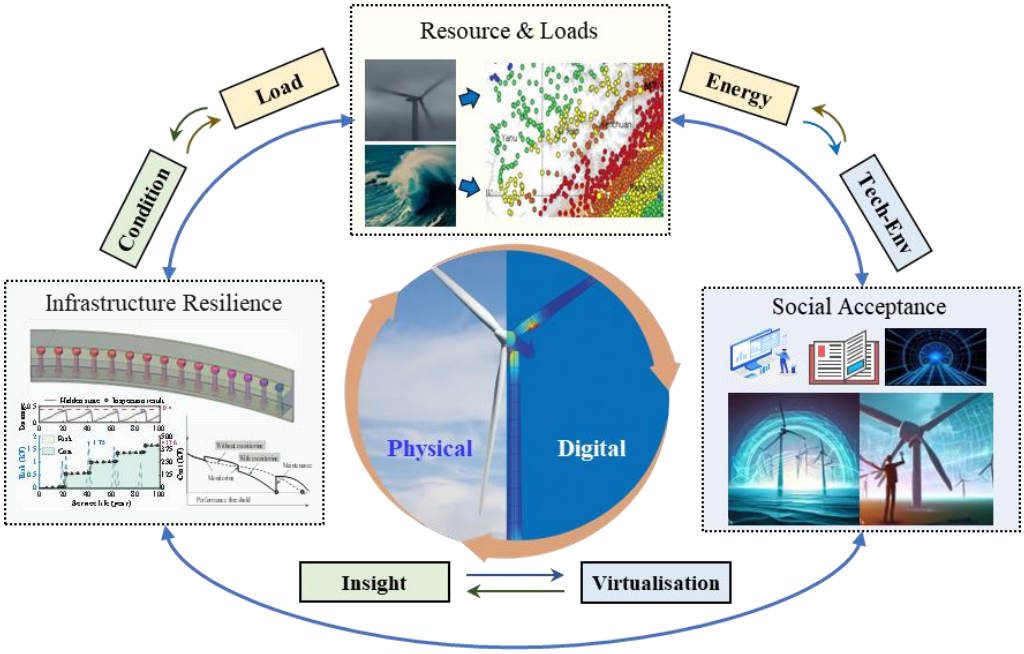


Figure 2. Conceptual DT framework for wind turbine structures.

For data integration, SCADA systems supply crucial operational data, such as turbine power output, rotor speed, blade pitch angles, and nacelle orientation, alongside relevant environmental parameters like wind speed and direction. Complementing this, SHM systems deploy an array of sensors, detailed in Figure 3, to directly measure the structural responses and condition of critical FOWT components. These typically include strain gauges to capture stress distributions, accelerometers for vibration analysis, inclinometers for platform motion, and specialized sensors for detecting corrosion progression or crack initiation in areas like the ring-flange connections. The synchronized assimilation of these diverse data streams provides the comprehensive, real-time input necessary for the digital model to accurately reflect the FOWT's operational state and structural health.

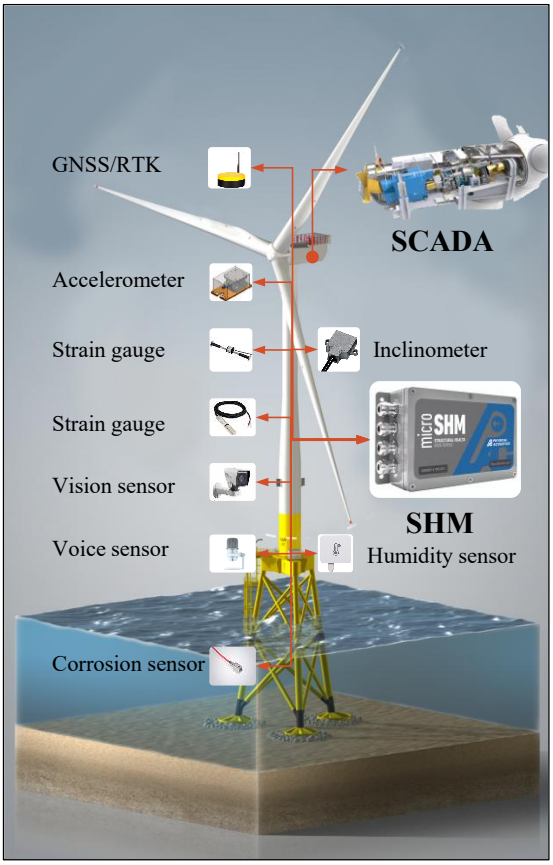


Figure 3. Integrated SCADA and SHM framework for wind turbine structures.

The digital model component of the DT relies heavily on multi-physics simulations to accurately capture the complex dynamic behaviour of FOWTs. These simulations typically employ coupled aero-hydro-servo-elastic modelling approaches, implemented using OpenFAST specialised software [8], to account for the intricate interactions between aerodynamic loads on the rotor, hydrodynamic forces on the floating platform and mooring system, the structural dynamics of the tower and blades, and the turbine's control system responses. This comprehensive modelling allows for the derivation of detailed loading histories at critical locations under varying operational and environmental conditions. As illustrated in Figure 4,

these simulated dynamic responses are subsequently processed through load transfer functions [9] to generate stress spectra. These spectra provide a crucial input for fatigue analysis, quantifying the cyclic stress ranges and frequencies experienced by structural components, particularly in bolted connections like the ring-flange, under realistic operational scenarios.

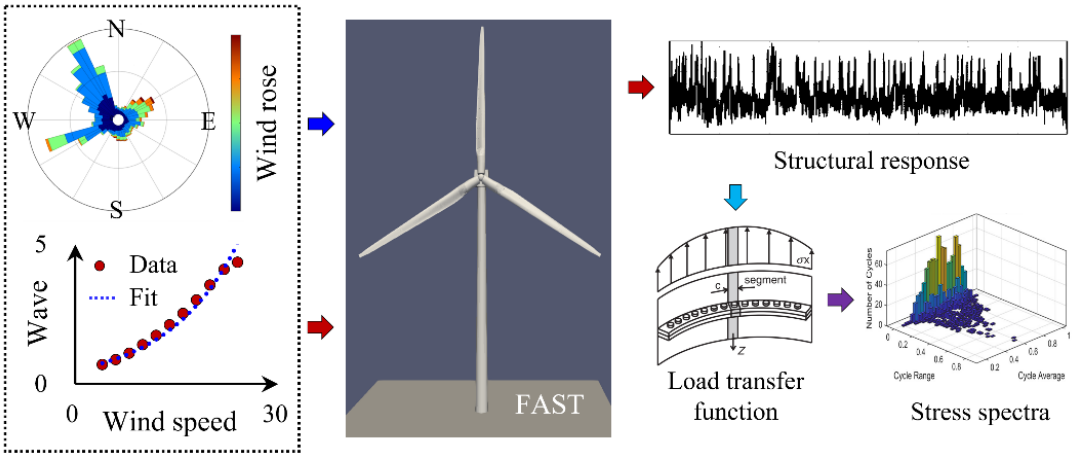


Figure 4. Process for deriving fatigue stress spectra through multi-physics simulation.

Following that, the subsequent step involves robust C-F modelling to predict the progressive degradation of FOWT structural components. To account for the synergistic effects of cyclic loading and the corrosive marine environment, which together accelerate material deterioration beyond what either would cause individually, a time-variant probability-stress-life (t-PSN) model is employed [3,10]. This probabilistic approach (Figure 5) correlates the fatigue strength of the material not only with the number of loading cycles (derived from the stress spectra) but also with the service life, explicitly incorporating the time-dependent degradation due to corrosion [3]. The t-PSN model thereby captures the diminishing fatigue resistance over time and accounts for inherent uncertainties by defining a statistical distribution (mean ± twice the standard deviation (2 σ)) around the expected material behaviour. This allows for a realistic assessment of C-F damage accumulation in critical connections, such as the ring-flange bolts, providing essential input for predicting the remaining useful life and informing proactive maintenance decisions within the O&M strategy.

Building upon that, the DT framework facilitates the implementation of adaptive control strategies aimed at mitigating fatigue damage and extending the operational life of FOWTs. Unlike static control systems, adaptive strategies dynamically adjust key turbine operational parameters, such as blade pitch angles, generator torque, or yaw alignment, in response to real-time environmental conditions, predicted structural loads, or the current assessed state of fatigue damage. The core concept is to proactively modulate turbine behaviour to reduce the magnitude and frequency of stress cycles experienced by critical components, thereby slowing the rate of C-F accumulation. For instance, under conditions forecasted to induce high fatigue loads, the control system would derate power output slightly or adjust blade pitching to alleviate stress concentrations in vulnerable areas like the ring-flange connections. Therefore, these intelligent control adjustments can be optimized to strike a balance between energy capture efficiency and the preservation of structural integrity, leading to an enhanced FOWT operation.

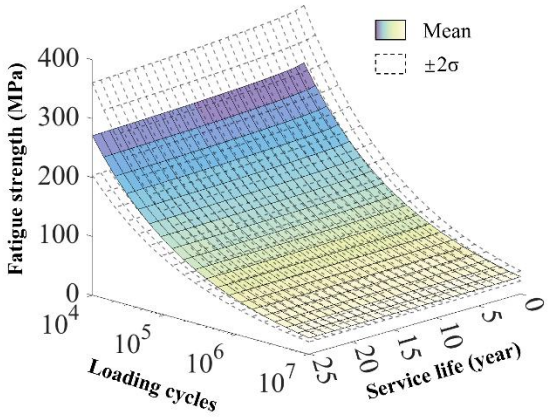


Figure 5. Conceptual representation of the t-PSN model used for corrosion fatigue assessment.

3. Case study details and setup

To demonstrate the application of the proposed DT framework, a case study was conducted based on the IEA 15MW reference wind turbine [11]. This turbine model is mounted on a 150-meter-tall tower and supported by the UMaine VolturnUS-S semi-submersible floating platform [12], a design specifically intended for deep-water offshore applications. The tower features a tapered diameter, from 10 meters at the base to a narrower dimension at the hub, with shell thickness varying accordingly, designed to withstand the substantial dynamic loads inherent in offshore environments.

The simulated environmental conditions for this case study were based on wind data from the Cape Elizabeth station [13]. The wind speed at this location (approximately 83.34 km northwest of Aberdeen, Washington) are featured by a dominant peak around the wind speed of 4.5 m/s. As depicted in Figure 6, the empirical wind speed distribution is closely approximated by a Weibull distribution, making it suitable for realistically modelling the site-specific wind climate that drives the FOWT's operational loads and, consequently, its fatigue behaviour.

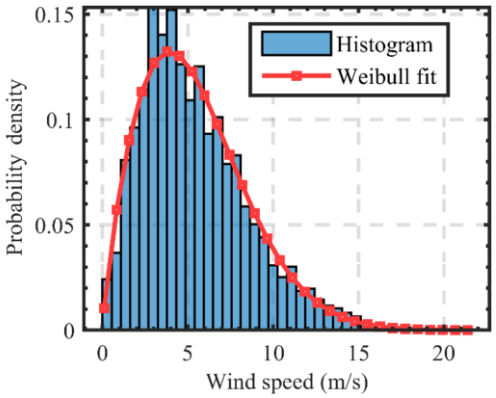


Figure 6. Wind speed distribution at the Cape Elizabeth station.

The DT framework was utilized to evaluate the impact of three distinct adaptive control strategies (denoted CS1, CS2, and CS3) on the C-F performance of the FOWT's ring-flange connections. These strategies are primarily characterized by their operational parameters at key wind speeds: cut-in (the speed at which power generation begins), rated (the speed at which the turbine reaches its nominal power output), and cut-off (the speed beyond which operation ceases to prevent damage).

CS1 represents a baseline or conventional control approach, initiating power generation at approximately 3 m/s and achieving its rated power at a wind speed of around 10 m/s, with blade pitch adjusting steadily with increasing wind speed. CS2 operates with a lower rated rotor speed compared to CS1, also commencing power generation at a cut-in speed of 3 m/s; however, its blade pitch increases more steeply post cut-in, levelling off as it approaches its rated wind speed. CS3 adopts a more conservative approach, delaying the cut-in speed for power generation until the wind reaches 5 m/s. Prior to this higher cut-in, its blade pitch remains relatively flat, after which it follows an operational trend slightly higher than CS2. All three strategies share a common cut-off wind speed of 20 m/s. The operational characteristics of these control strategies, specifically the blade pitch angle as a function of wind speed and the corresponding generator power output, are listed Table 1. Of course, these differing control strategies would inherently lead to varied loading histories on the turbine structure, thereby influencing damage accumulation.

Table 1. Key operational parameters for the investigated adaptive control strategies

Control Strategy	Cut-in Wind Speed (m/s)	Rated Wind Speed (m/s) for Full Power	Cut-off Wind Speed (m/s)	Notes
CS1 (Baseline)	3	10	20	Conventional operation
CS2	3	7	20	Lower rated rotor speed
CS3	5	9	20	Delayed power generation (higher cut-in)

4. Results and discussion

The primary outcome assessed in this case study was the evolution of the reliability index for three representative ring-flange connection locations (denoted RF1, RF2, and RF3) and the tower of the FOWT over their service life, under each of the implemented adaptive control strategies. These ring-flanges are critical structural elements susceptible to corrosion fatigue. Figure 7 illustrates these comparative reliability trajectories.

Under the baseline strategy (CS1), ring-flange reliability indices start near 7.0 and drop to about 1.0 after 20 years, reflecting substantial corrosion-fatigue deterioration. Both adaptive strategies, CS2 and CS3, provide improved reliability and extended component life. With CS2,

initial indices are higher (e.g., RF3 at 8.5) and, notably, RF1 and RF2 maintain values above 3.0 even after 25 years, outperforming CS1's lifespan. CS3 also reduces the degradation rate compared to CS1; at 20 years, RF1 and RF2 indices are around 1.7~2.0, but by 25 years, these drop to 1.0~1.3, indicating CS2 offers more robust long-term reliability than CS3, though both are clear improvements over the baseline.

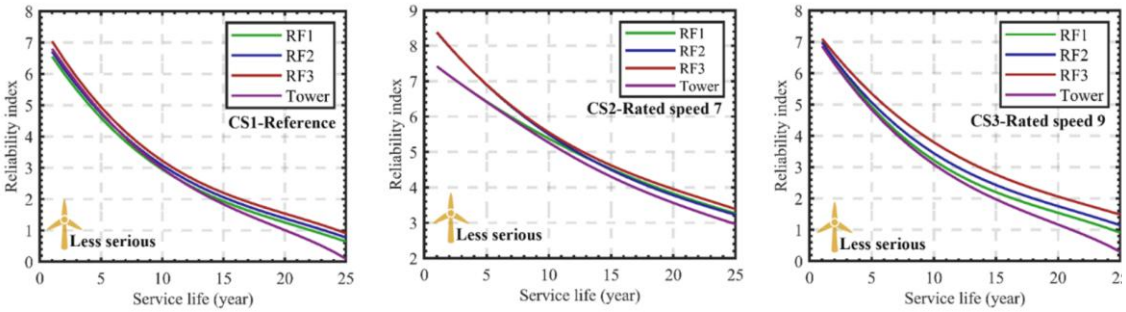


Figure 7. Influence of different adaptive control strategies (CS1, CS2, CS3) on the reliability index evolution of FOWT ring-flanges over service life.

The "tower" reliability index, as shown in Figure 7, represents the global structural integrity of the FOWT tower, capturing the overall resistance to corrosion-fatigue damage across the entire structure rather than at localised ring-flange connections. This is solved by assuming the tower as a linking system consisting of flanges. In all cases, the tower demonstrates higher initial and sustained reliability indices compared to the individual ring-flanges, reflecting its greater redundancy and distributed load-bearing capacity. Notably, under the CS2 (Rated speed 7 m/s) strategy, the tower reliability declines more slowly and remains above 3.0 after 25 years, highlighting the enhanced fatigue mitigation effect of this control scheme on the entire structure.

These divergent reliability outcomes are directly attributable to the distinct operational profiles enforced by each control strategy, which modulate the loading experienced by the FOWT structure. Figure 8 shows that, for all three strategies, solid lines represent blade pitch and dashed lines represent generator power. CS1 gradually increases blade pitch and reaches rated power at 10 m/s. CS2 has a steeper pitch and achieves rated power at a lower wind speed (7 m/s), while CS3 delays both pitch and power changes until after 5 m/s, reflecting a more conservative approach. These operational differences influence fatigue loading and reliability outcomes. These adjustments are specifically designed to reduce the severity and frequency of cyclic loading on critical structural components, thereby mitigating C-F accumulation. The DT, by simulating these complex interactions, allows for the quantitative assessment of such control strategy impacts on long-term structural integrity.

The effectiveness of DT-informed adaptive control is thus clearly demonstrated by the extended service lives before critical reliability thresholds are met. By utilising the DT's predictive capabilities, operators can select or dynamically switch to control strategies that significantly improve structural reliability.

However, these structural benefits may involve trade-offs, particularly concerning power generation. For instance, strategies like CS2 and CS3, which prioritize fatigue mitigation, might result in a slightly reduced overall annual energy production compared to a more aggressive baseline strategy like CS1. The DT framework is instrumental in evaluating these trade-offs,

enabling operators to make informed decisions that balance immediate energy yield with long-term structural health and O&M costs. While specific annual energy production of CS1, CS2, and CS3 is beyond the scope of this study, the principle of balancing these competing objectives is a core function of the DT-driven O&M approach.

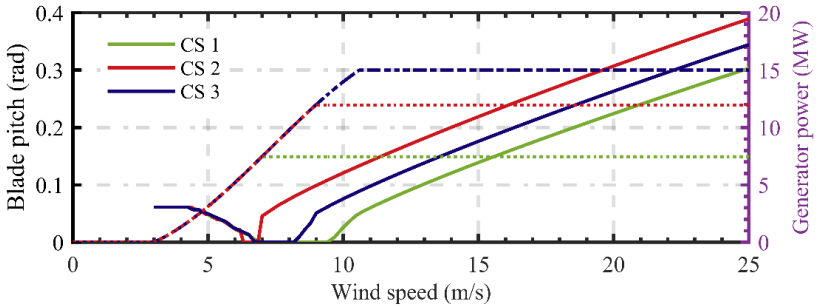


Figure 8. Operational characteristics of the adaptive control strategies (solid line for blade pitch and dashed line for power generation).

The implications for intelligent O&M are profound, particularly in facilitating a move towards proactive maintenance. The ability of the DT to predict C-F progression under various control strategies allows for maintenance interventions to be scheduled based on actual component condition and predicted remaining useful life, rather than fixed intervals or in response to failures. This proactive stance, informed by the DT's continuous assessment, can significantly reduce unscheduled downtime, optimize the allocation of maintenance resources, and minimize the risks associated with catastrophic failures. For example, if the DT projects an accelerated C-F rate due to prolonged operation under aggressive control or harsh environmental conditions, it can trigger alerts for earlier inspections or a shift to a more conservative control strategy. This foresight, which extends beyond mere fatigue life prediction to encompass operational strategy optimization, represents a key advantage of the intelligent DT framework, offering a pathway to more resilient and FOWT operation.

5. Conclusion

This study presented an intelligent DT framework aimed at mitigating C-F in FOWT structures through the strategic application of adaptive operational control. The framework, integrating site-specific data with multi-physics simulations and time-variant C-F modelling, was demonstrated via a case study on the IEA 15MW reference FOWT operating under site-specific environmental conditions. The investigation focused on evaluating the impact of three distinct adaptive control strategies (CS1, CS2-Rated speed 7, and CS3-Rated speed 9) on the long-term reliability of critical ring-flange connections.

The key observations drawn from this study are as follows:

- The DT-informed adaptive control strategies (CS2 and CS3) demonstrably extended the reliable operational lifespan of the FOWT ring-flanges compared to the baseline (CS1). Under CS1, critical reliability (index ≈ 1.7) was reached at approximately 15 years, whereas both CS2 and CS3 maintained reliability indices well above this level beyond 20 years. For instance, at 20 years, ring-flange reliabilities under CS2 remained robust (indices ≈ 3.5-3.7), showcasing a substantial improvement.

- While both adaptive strategies outperformed the baseline, distinct differences in their long-term efficacy were observed. CS2 appeared to offer higher reliability preservation for the ring-flanges at 25 years (indices ≈ 3.0-3.2) compared to CS3, where ring-flange reliability indices dropped to approximately 1.0-1.3 by the same point, highlighting the importance of specific control parameter tuning.
- The DT framework's capability to predict C-F progression under different operational scenarios provides a robust foundation for shifting towards proactive and condition-based maintenance. This allows for optimized maintenance scheduling, reducing unscheduled downtime and associated costs by addressing potential issues before they become critical.

Future work should focus on several key areas to further advance this research. Firstly, real-world validation of the DT framework using operational data from actual FOWTs is crucial to confirm the accuracy of the predictive models and the effectiveness of the proposed adaptive control strategies. Secondly, incorporating more sophisticated artificial intelligence and machine learning algorithms for real-time control optimization and remaining useful life prognostication would enhance the DT's intelligence. Finally, expanding the DT's scope to include economic modelling and a broader range of degradation mechanisms will provide a more holistic lifecycle management tool for FOWT assets.

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