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Dynamic Reconfiguration of a Floating Vertical Axis Wind Turbine Driven by Progressive Mooring Stiffness Degradation

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Abstract— Mooring systems are essential to the station-keeping and operational safety of floating wind turbines. However, how progressive mooring stiffness degradation affects platform dynamics and rotor performance before failure remains poorly understood. This study develops a coupled computational fluid dynamics (CFD) and finite element method (FEM) framework for a three-bladed floating vertical axis wind turbine (VAWT) on the DeepCwind semisubmersible platform from the Offshore Code Comparison Collaboration Continuation (OC4) project. STAR-CCM+ resolves rotor aerodynamics using an overset mesh, while ABAQUS/AQUA computes platform hydrodynamics, flexible-beam mooring responses and seabed contact. Six computational branches are generated from the same converged intact state by smoothly reducing the effective axial stiffness of either mooring line 1 (ML1) or mooring line 2 (ML2) by 30%, 60% and 90%, representing mild, moderate and severe stiffness loss in this study. Mean horizontal offset, six-degree-of-freedom motion statistics and top-tension statistics for all three mooring lines reveal nonlinear system reconfiguration. Horizontal migration remains limited at 30% and 60% stiffness loss but exceeds 5 m at 90% loss. Its magnitude reflects degradation severity, whereas its direction depends on the degraded line through changes in horizontal restoring-force balance. Motion changes are selective, with amplified sway and yaw but limited changes in heave and pitch. Platform re-equilibration modifies catenary geometry and redistributes mooring loads. Consequently, system-wide mean unloading can coexist with increased cyclic tension in intact lines, and the largest cyclic response does not necessarily occur at the greatest stiffness loss. Despite this dynamic reconfiguration, the mean power coefficient and thrust remain within 1% of their intact values over 200 to 500 s under prescribed-speed operation. Apparently stable aerodynamic performance can therefore conceal a markedly altered platform-mooring dynamic state. Condition monitoring should combine aerodynamic output with equilibrium position, platform motion and multi-line tension indicators.

Keywords—floating vertical axis wind turbine, mooring stiffness degradation, coupled CFD-FEM, platform-mooring dynamics, aerodynamic performance

I. INTRODUCTION

As floating wind expands into deeper waters and towards larger turbine ratings, interactions among platform motion, rotor aerodynamic loads, wave excitation, and mooring restoring forces have become essential to system dynamics and operational safety [1]. Understanding how these interactions evolve before a mooring failure event is

particularly important for condition monitoring and maintenance intervention. This problem applies to different floating wind architectures, although its aerodynamic consequences depend on the rotor configuration. Among these concepts, floating VAWTs offer potential advantages for deep-water deployment, including compact structural arrangements and reduced sensitivity to wind direction [2]. However, the six-degree-of-freedom (6-DOF) motion of the supporting platform modifies the relative inflow, aerodynamic loading, and wake evolution of the rotor, producing strongly nonlinear coupled responses [3]. The mooring system provides the primary station-keeping and restoring capacity. During long-term operation, fatigue cracking, corrosion, and wear can reduce the cross-sectional integrity and residual load-carrying capacity of mooring components [4]. Before complete rupture, the resulting loss of effective axial stiffness may already shift the platform equilibrium and redistribute loads among the mooring lines. This raises a central question: can commonly monitored aerodynamic outputs, such as power coefficient and thrust, reveal the corresponding changes in the dynamic state of the platform and mooring system?

Existing studies of mooring degradation have mainly addressed damage identification and structural health monitoring. Dehkharghani et al. used natural frequencies and artificial neural networks to identify the location and severity of mooring stiffness loss [5]. Sakaris et al. employed a response-only functional model to diagnose tendon connection damage in a multibody platform and reported that mild damage had only a limited influence on the platform dynamic response [6]. Full-scale tests by Lian et al. showed that the dynamic stiffness of damaged polyester mooring ropes decreased with increasing damage severity, load amplitude, and loading period [7]. Sun et al. analysed platform responses as mooring components progressed from creep damage towards failure and identified yaw as the motion most sensitive to structural damage [8]. Anastasiadis et al. investigated synthetic-rope stiffness losses ranging from 10% to 50% in the OO-Star platform [9]. Gorostidi et al. used statistics of the 6-DOF platform responses and autoencoders to identify the health state of the external mooring system of the OC4 DeepCwind platform [10]. Coraddu et al. represented corrosion, wear, and fatigue degradation through a local reduction in chain diameter [11].

A separate body of research has examined the accidental response following complete mooring-line rupture. Yang et al. showed that the sudden rupture of a single mooring line caused platform drift, changed the platform motion response, and redistributed tension among the remaining lines [12]. Park et al. subsequently identified mooring-line failures in a 15 MW floating wind turbine using statistics of the 6-DOF motions. Detection accuracy decreased markedly when mean displacement information was excluded from the motion signals, confirming the importance of mean position offset as a feature for mooring-line failure detection [13]. Complete rupture, however, instantaneously removes both the restoring stiffness and load path of the failed line. It therefore represents an accidental limit state and cannot describe the progressive evolution of a system in which the degraded line remains connected and retains residual load-carrying capacity. In particular, systematic comparisons of severe, line-specific stiffness loss remain limited. It is also unclear whether degradation severity and location provide distinct controls over the magnitude and direction of horizontal equilibrium migration, or how this migration is connected to selective 6-DOF responses and line-by-line tension reconstruction.

To address these gaps, this study employs a coupled CFD-FEM framework to examine how line-specific stiffness loss reorganises the response of a floating VAWT before mooring-line rupture. The analysis focuses on three related questions: how degradation severity and location govern horizontal re-equilibration, how the resulting changes propagate through platform motions and multi-line tension demand, and whether they can be detected from aerodynamic outputs. The remainder of this paper is organised as follows. Section II describes the system geometry and principal parameters, case design and response metrics, and numerical domain and discretisation. Section III analyses the time evolution and horizontal migration, mooring-tension reconfiguration, and the relationship between aerodynamic output and the platform-mooring dynamic state. Section IV presents the main conclusions.

II. NUMERICAL MODEL AND ANALYSIS METHOD

A. Geometry and Principal Parameters

This study considers a three-bladed H-type floating VAWT, as illustrated in Fig. 1. Under combined wind and wave loading, the platform undergoes 6-DOF motion: surge, sway, and heave in translation; roll, pitch, and yaw in rotation. The rotor rotates about its vertical axis while following platform motions.

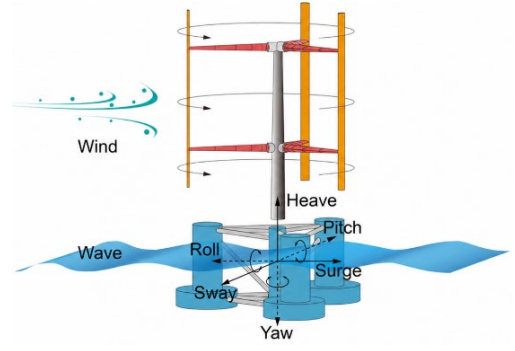


Fig. 1. Schematic of the floating VAWT and its six platform degrees of freedom under combined wind and wave loading.

The rotor configuration follows Huang et al. [14]. It has a blade height of 70.25 m, a rotor diameter of 73.52 m, and DU-06-W-200 blade sections. The floating support adopts the three-column configuration of the OC4 DeepCwind semisubmersible, with a mooring system comprising three catenary lines. Publicly available geometric definitions and model-test data for this platform provide the basis for numerical model development and validation [15], [16]. The rotor speed relative to the platform is prescribed at 6.81 rpm in all cases, corresponding to a tip-speed ratio of 3.28 at the specified inflow speed. The blade pitch angle is fixed at 2° , and no generator-torque or blade-pitch controller is included. The principal geometric, operating, and environmental parameters are summarized in Table I.

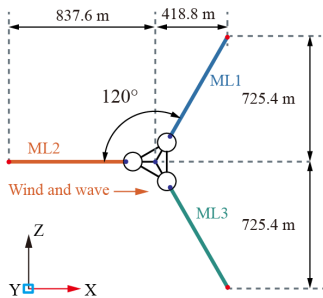
TABLE I. PRINCIPAL NUMERICAL PARAMETERS

Parameter	Value	Parameter	Value
Wind speed	8 m/s	Blade height	70.25 m
Water depth	200 m	Rotor diameter	73.52 m
Wave height	7.58 m	Blade chord	3.512 m
Wave period	12.1 s	Blade pitch angle	2°
Rotor speed	6.81 rpm	Tip-speed ratio	3.28

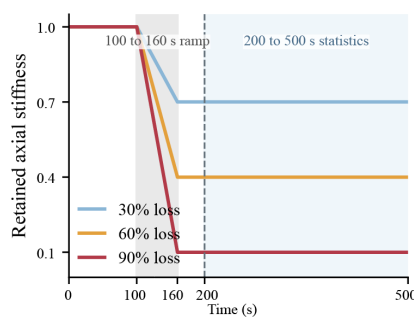
B. Case Design and Response Metrics

Fig. 2 summarises the mooring orientation, mooring degradation cases and two-way coupling method. Fig. 2(a) shows a plan view of the three mooring lines arrangement and the incident wind-wave direction. A stated loss of 30%, 60% or 90% means that the selected line retains 70%, 40% or 10% of its intact axial stiffness. Stiffness remains intact to 100 s, decreases smoothly over 100–160 s, and then remains fixed, as shown in Fig. 2(b). All cases use identical environmental conditions and numerical settings, allowing the effects of degradation location and severity to be isolated.

a OC4 semisubmersible mooring layout



b Seven fully coupled cases



c Two-way coupled simulation

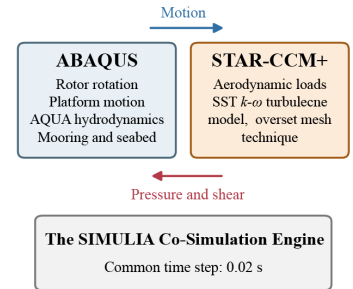


Fig. 2. Equivalent mooring-stiffness degradation cases and two-way coupling framework. (a) Three-line orientation and wind-wave direction; (b) retained axial-stiffness histories; (c) motion and aerodynamic-load exchange between Abaqus and STAR-CCM+.

All cases are simulated using the coupled CFD-FEM framework shown in Fig. 2(c). STAR-CCM+ resolves the rotor aerodynamic loads using the SST $k-\omega$ turbulence model and an overset-mesh technique. ABAQUS/AQUA calculates rotor motion, the 6-DOF platform response, hydrodynamic loading, mooring-line dynamics, and seabed contact. At each common time step, Abaqus transfers the rotor and platform motions to STAR-CCM+, which returns the pressure and shear loads acting on the rotor surface. Data are exchanged through the SIMULIA Co-Simulation Engine using a common time step of 0.02 s.

To quantify degradation-induced changes in platform equilibrium, the mean surge and sway shifts relative to the intact state are defined as

$$\Delta \bar{x} = \bar{x}_d - \bar{x}_o, \Delta \bar{y} = \bar{y}_d - \bar{y}_o \quad (1)$$

where the subscripts d and o denote the degraded and intact states, respectively. All mean values are calculated from responses between 200 and 500 s. The resultant horizontal migration ΔR and its direction θ are defined as

$$\Delta R = \sqrt{(\Delta \bar{x})^2 + (\Delta \bar{y})^2}, \theta = \text{atan2}(\Delta \bar{y}, \Delta \bar{x}) \quad (2)$$

where θ is measured from the positive x -axis, with its sign defined by the coordinate system in Fig. 2(a). The 6-DOF platform motions and the top tensions of ML1 to ML3 are evaluated using the mean, standard deviation, and peak-to-peak range. The rotor power coefficient is calculated from the aerodynamic torque as

$$C_p(t) = \frac{Q_z(t)\Omega}{0.5\rho_a A_r U_\infty^3}, A_r = D_r H_r \quad (3)$$

where Q_z is the aerodynamic torque about the vertical rotor axis, Ω is the rotor angular velocity, ρ_a is the air density, U_∞ is the inflow wind speed, and A_r is the rotor swept area. The quantities D_r and H_r denote the rotor diameter and blade height, respectively. Rotor thrust is defined as the component of the aerodynamic force in the inflow direction:

$$T(t) = F_{aero}(t) \cdot \mathbf{e}_x, F_{aero}(t) = \int_{S_r} \tau_{aero}(t) dS \quad (4)$$

where S_r denotes the rotor blade surface, τ_{aero} is the aerodynamic surface traction comprising pressure and shear contributions, and $\mathbf{e}_x$ is the unit vector in the inflow direction.

It should be noted that the prescribed stiffness reduction is a controlled modelling assumption. The smooth ramp from 100 to 160 s is intended to limit transients caused by an abrupt stiffness change and does not represent an experimentally calibrated degradation history or a physical corrosion or fatigue timescale. The specified losses refer to effective axial stiffness and should not be interpreted as equivalent reductions in material strength.

C. Numerical Domain and Discretization

Fig. 3 presents the fluid computational domain, finite element representation, and CFD mesh distribution. The dimensions of fluid domain are defined using the rotor diameter D as the characteristic length, as shown in Fig. 3(a). The rotor centre is located $5D$ downstream of the inlet and $3.4D$ from the lateral boundary. The domain width and height are both $6.8D$, with a streamwise length of $15D$. The rotor is located within an overset mesh region to accommodate both rotor rotation and the 6-DOF motions induced by the platform.

The structural models implemented in Abaqus are shown in Fig. 3(b). The upper rotor is discretised using shell elements and subjected to a rigid-body constraint, thereby neglecting elastic deformation of the blades and supporting structure. Both the platform and mooring lines are modelled using beam elements, while platform hydrodynamic loads are calculated using ABAQUS/AQUA. Based on the environmental parameters listed in Table I, AQUA generates fifth-order Stokes regular waves and calculates buoyancy, wave loading, and fluid inertia forces acting on the platform and mooring lines. Mooring-seabed contact includes tangential friction with a coefficient of 0.74.

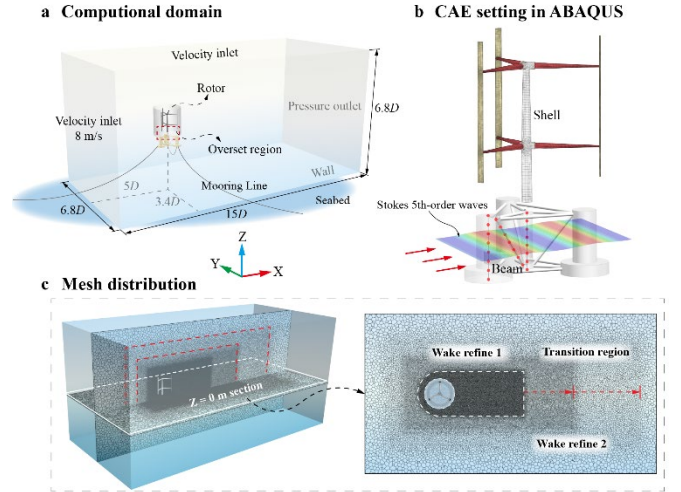


Fig. 3. Computational domain and mesh distribution. (a) Fluid computational domain; (b) finite element representation in Abaqus; (c) CFD polyhedral mesh.

As shown in Fig. 3(c), STAR-CCM+ discretizes the fluid domain using polyhedral cells. Local mesh refinement is applied around the rotor and within the downstream wake, allowing the blade flow and wake evolution to be resolved while controlling changes in cell size. Ref. [14] assessed the framework through comparisons of rotor power coefficients with wind-tunnel measurements, comparisons of OC4 surge and pitch free-decay responses with established FSI and CFD-DFBI models, and mesh and time-step sensitivity studies. These assessments support the modelling approach adopted here; the present stiffness-loss cases extend its application to degraded mooring conditions.

III. RESULTS AND DISCUSSION

A. Time Evolution and Horizontal Migration

Fig. 4 presents representative time-domain responses for the seven cases from 0 to 500 s. Surge and sway are directly influenced by the horizontal mooring restoring forces and therefore capture changes in the platform equilibrium position. These two DOFs are consequently selected to illustrate the platform response. In the intact mooring arrangement, ML2 is aligned with the incident wind-wave direction, while ML1 and ML3 are symmetric about this direction. The tension responses are therefore presented for ML2 and the representative oblique line ML1. Complete statistical results for all three mooring lines are compared in a subsequent subsection.

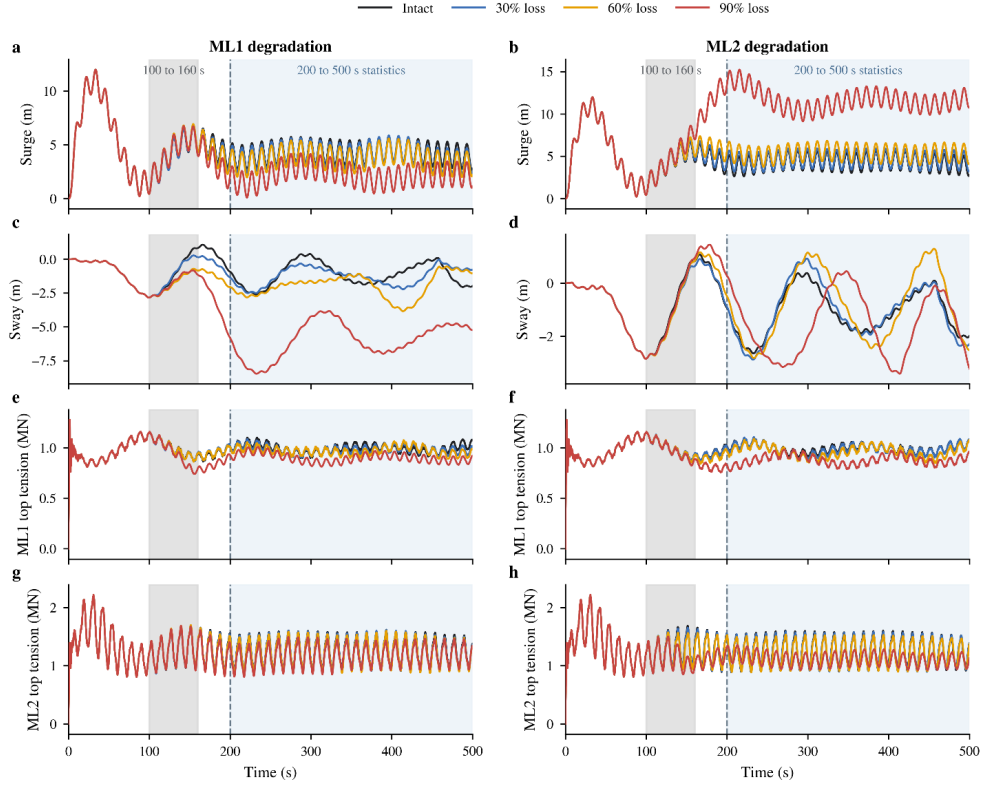


Fig. 4. Time-domain responses of the intact state and three stiffness-loss levels. The left panels, (a), (c), (e), and (g), show surge, sway, ML1 top tension, and ML2 top tension under ML1 degradation. The right panels, (b), (d), (f), and (h), present the corresponding responses under ML2 degradation. The grey region denotes the stiffness-reduction interval from 100 to 160 s, while the blue region indicates the statistical interval from 200 to 500 s.

As shown in Fig. 4, all response histories remain nearly coincident before 100 s, confirming a consistent initial evolution across the seven cases. As the axial stiffness decreases from 100 to 160 s, the response curves begin to separate gradually. After 200 s, each case continues to oscillate about a new mean equilibrium position. The system has therefore moved beyond the parameter-ramp stage, making the selected interval suitable for subsequent statistical analysis.

In Figs. 4(a) to 4(d), the surge and sway responses under 30% and 60% stiffness loss remain close to the intact response, with only limited changes in mean position, amplitude, or phase. A clear separation emerges at 90% stiffness loss. When ML1 loses 90% of its stiffness, the platform migrates in the negative surge and sway directions. When ML2 loses 90% of its stiffness, the migration occurs primarily in the positive surge direction. Across the three sampled loss levels, the horizontal equilibrium position therefore exhibits a strongly nonlinear sensitivity to degradation severity, while the degraded-line location governs the migration direction.

The ML1 and ML2 top tensions show a similar severity-dependent trend, as shown in Figs. 4(e) to 4(h). At 30% and 60% stiffness loss, the tension histories remain relatively close to the intact response. At 90% loss, both tension responses shift towards a lower overall level. Severe stiffness loss moves the platform to a new equilibrium position, altering the catenary geometry and the overall restoring-force level of the mooring system. These changes produce a general reduction in top tension. The time histories in Fig. 4 identify the principal response trends. Statistical changes in the remaining platform DOFs, together with the mean and dynamic tensions

of all three mooring lines, are examined in the following subsections.

To further quantify the migration magnitude, migration direction, and changes in the 6-DOF responses, Fig. 5 summarizes the statistical results from 200 to 500 s.

As shown in Figs. 5(a) and 5(b), under 30% and 60% ML1 stiffness loss, the resultant horizontal migration magnitudes are 0.251 and 0.984 m, respectively. The corresponding values for ML2 degradation are 0.318 and 1.095 m. When the stiffness loss reaches 90%, the migration increases to 5.266 m for ML1 degradation and 7.416 m for ML2 degradation. These values are 5.35 and 6.77 times their corresponding values at 60% loss. ML2's alignment with the wind-wave direction helps explain the larger migration and greater mean unloading at 90% stiffness loss. Figs 5(c) and 5(d) show that limited mean migration can coexist with substantial changes in the platform dynamic response. Under 90% ML1 loss, the standard deviation and peak-to-peak range of sway increase by 55.7% and 53.7%, respectively. Under 90% ML2 loss, the standard deviations of surge, sway, and yaw increase by 46.0%, 42.7%, and 54.7%, while the surge peak-to-peak range increases by 96.9%. Severe stiffness loss therefore predominantly amplifies horizontal and yaw responses.

Overall, a marked change in mean horizontal position occurs mainly under severe stiffness loss, whereas selected motion-variability indicators can respond at lower loss levels. Migration magnitude, migration direction, standard deviation, and peak-to-peak range capture complementary aspects of the response and should be considered together when characterising the reconfiguration of the platform dynamic state.

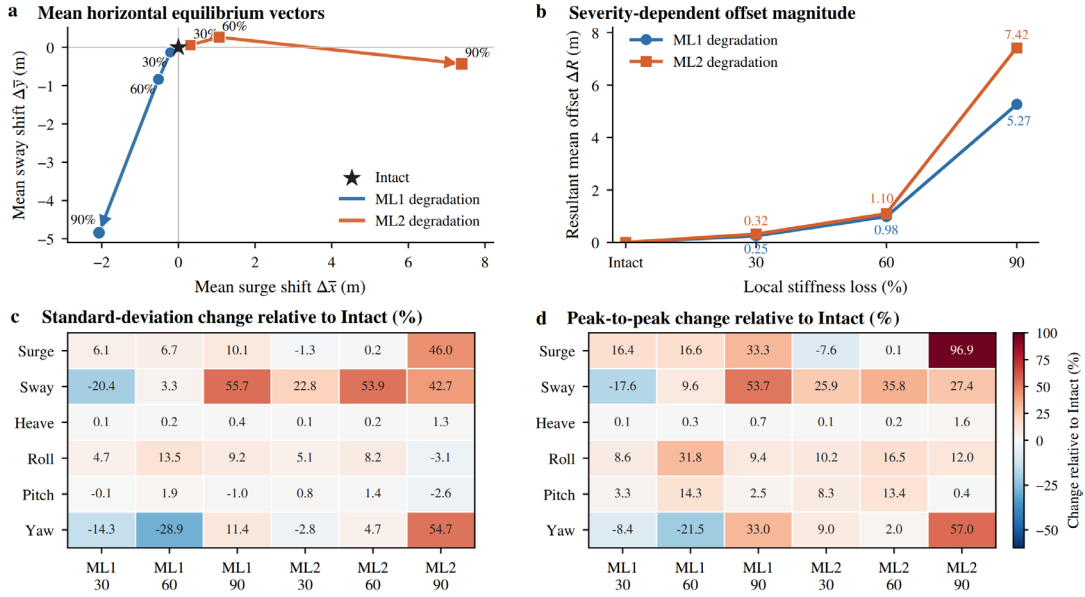


Fig. 5. Horizontal equilibrium migration and selective platform-motion response over 200–500 s. (a) Mean migration vectors; (b) resultant offset; (c) standard-deviation changes; (d) peak-to-peak changes. Heatmap values are relative to the intact state; blue indicates a decrease and red an increase.

B. Mooring-Tension Reconfiguration

Fig. 6 compares collective mean unloading with individual-line mean and cyclic changes. In the intact state, mean top tensions are 993.0, 1245.9 and 921.5 kN for ML1–ML3, totalling 3160.4 kN. The total decreases by less than 1% at 30% loss and by approximately 2% at 60% loss. At 90% loss, it decreases by 8.42% and 11.90% for ML1 and ML2 degradation, respectively.

All three mean tensions fall in the severe cases, confirming a lower mean restoring configuration rather than simple scalar transfer to intact lines. Cyclic demand is non-monotonic. With 60% ML1 loss, intact ML3 peak-to-peak tension increases by 43.8%. With 60% ML2 loss, intact ML1 standard deviation and intact ML3 peak-to-peak tension increase by 24.3% and

25.8%. Conversely, at 90% ML2 loss the degraded line's standard deviation and peak-to-peak value fall by 48.3% and 40.4%. Mean unloading can therefore coexist with increased cyclic demand in an intact line. Cyclic tension depends on both fairlead motion and the local slope of the line force-displacement relation. Platform re-equilibration changes line orientation and catenary geometry, allowing intact lines to experience increased cyclic demand despite lower mean loading. Changes in motion and effective restoring stiffness can reinforce or offset one another, providing a physical explanation for the non-monotonic response. At 90% stiffness loss, the metre-scale platform shifts can also alter touchdown locations and suspended line lengths. Seabed friction resists sliding and dissipates energy when slip occurs.

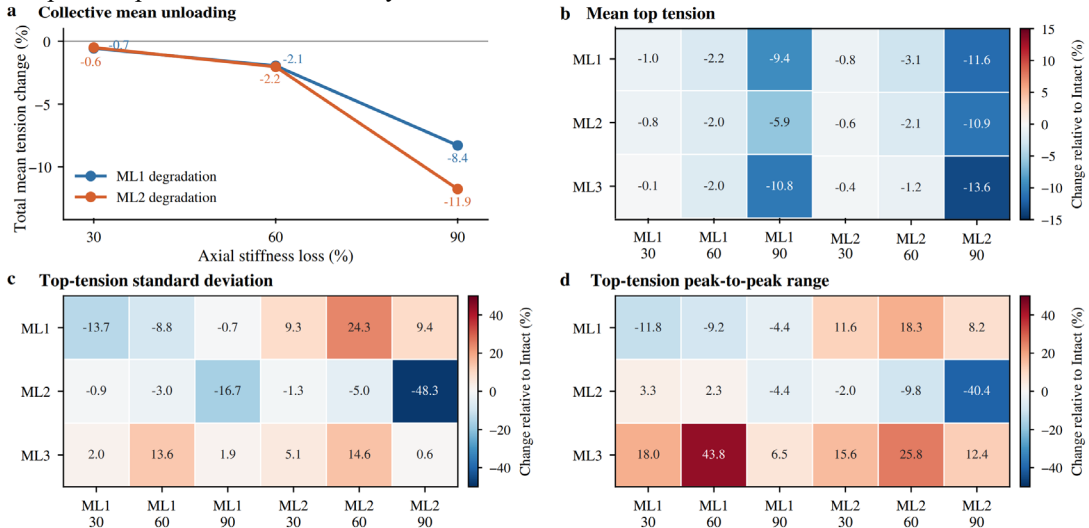


Fig. 6. Mooring top-tension reconfiguration over 200–500 s. (a) Change in the sum of three mean top tensions; relative changes in (b) individual-line mean tension, (c) tension standard deviation and (d) peak-to-peak value

C. Aerodynamic Output versus Dynamic State

The previous subsections show that the two 90% stiffness-loss cases produce the largest equilibrium migration, motion changes, and mooring-tension reconfiguration. To determine whether these changes are visible in conventional

aerodynamic indicators, Fig. 7 compares the power coefficient and rotor thrust of the intact state with those of the two 90% loss cases. Figs. 7(a) and 7(b) present responses from 453 to 477.2 s, covering two wave periods. Fig. 7(c) reports changes in the mean power coefficient and thrust calculated over the full statistical interval from 200 to 500 s.

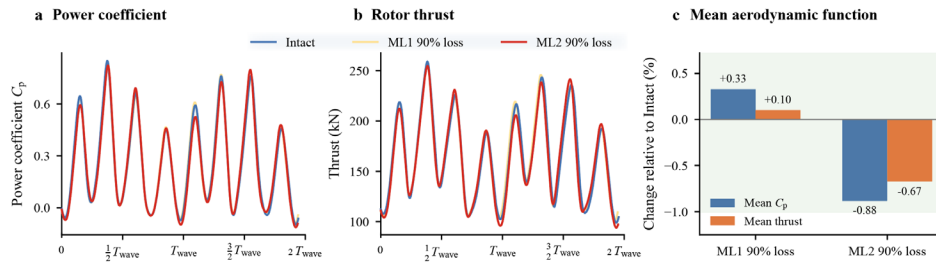


Fig. 7. Aerodynamic output from 453 to 477.2 s, corresponding to two wave periods, for the intact state and the two 90% loss cases. (a) Power coefficient; (b) rotor thrust; (c) changes in mean values calculated over 200 to 500 s relative to the intact state. The shaded band denotes $\pm 1\%$.

In Fig. 7, the power-coefficient and rotor-thrust histories of the intact and two 90% stiffness-loss cases largely overlap over two wave periods. Mean differences over 200 to 500 s remain within 1% of intact values, despite substantial changes in platform equilibrium, motions and mooring load paths. Apparently normal aerodynamic output can therefore conceal system-level reconfiguration and is insufficient for standalone condition monitoring.

These findings are limited to prescribed-speed operation, one wind-wave condition and single-line stiffness loss. Future work should examine combined environmental and operating variations and simultaneous multi-line degradation, accounting for turbulent wind and irregular waves that may obscure degradation-related responses.

IV. CONCLUSIONS

A coupled CFD-FEM model was established to compare an intact floating VAWT with six mooring stiffness-loss cases under identical wind-wave conditions. The main conclusions are as follows.

- (1) Horizontal migration responds nonlinearly to degradation severity. It remains below 1.10 m at 30% and 60% loss but reaches 5.27 and 7.42 m at 90% loss. Migration magnitude and direction provide candidate indicators of degradation severity and location.
- (2) Local stiffness loss produces mean unloading and cyclic-tension redistribution. At 90% loss, aggregate mean tension decreases by 8.42% and 11.90%, while cyclic demand in intact lines can increase at intermediate loss. This response is governed by platform re-equilibration and changing catenary geometry.
- (3) Severe reconfiguration of the platform-mooring system is not captured by changes in aerodynamic output. Mean power coefficient and thrust change by less than 1% despite meter-scale migration and substantial changes in motion and tension. Stable aerodynamic output therefore does not demonstrate an intact dynamic state.

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