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Transient Response of a TLP-type Floating Offshore Wind Turbine under Tendon Failure Conditions

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Abstract: Among various types of floating offshore wind turbines (FOWTs), the tension leg platform (TLP) floating wind turbines have relatively small motions due to stiff tendons. Similar to TLP applications in the offshore industry, tendon failure may lead to deteriorated stability and large transient responses, which should be considered as part of accidental limit state (ALS) checks at the design stage of the TLP FOWTs. This paper takes the WindStar TLP system as a representative and investigates the transient effects of one-tendon failure on the system responses. A coupled numerical model is first established using the aero-hydro-servo-elastic simulation tool FAST. Subsequent numerical simulations of tendon failure are carried out to consider different tendon breakage and turbine shutdown scenarios in both operational and parked conditions. Response statistics of key design parameters including platform motion, nacelle acceleration, and tendon tension are analyzed. The results indicate that several transient responses of the FOWT under operational conditions may be even higher than the extreme values under 50-year conditions. Our analyses also reveal that the shutdown strategies, if not applied appropriately, may have limited effects in reducing the responses of the FOWT, thus in certain scenarios threaten the safety of the tendon closest to the broken tendon if no other actions are taken. For the considered TLP FOWT, the ALS design requirements dominate over the ultimate limit state requirements. These findings can be relevant to the ALS design of TLP FOWTs.

Keywords: Floating offshore wind turbine (FOWT); Tension leg platform (TLP); Tendon failure; Transient response; Accidental limit state; Time-domain analysis; Coupled aero-hydro-elastic model

1 Introduction

Wind energy is considered as one of the most advantageous and effective renewable energy sources due to its low operating cost and extensive availability [1]. Compared with onshore wind energy, offshore wind energy is more attractive in that offshore winds are more reliable with large reserves and its development needs fewer land resources [2]. With the increase of water depth, floating offshore wind turbines (FOWTs) are more economical than bottom-fixed wind turbines [3].
Currently, the design and manufacturing of FOWTs adopt practices and technology employed in the offshore oil and gas industry [4]. There are three major types of support platforms for FOWTs, namely spar, semi-submersible, and TLP support platforms. By virtue of stiff vertical mooring cables, called tendons, natural frequencies of the vertical motions of TLPs are considerably higher than wave frequencies at which the waves have non-negligible energy, leading to excellent hydrodynamic performances of the TLPs [5-7].

Experiences from the maritime and offshore industries show that mooring systems may fail in mild to severe sea states [8, 9]. During its lifecycle, a mooring system may fail as a result of fatigue, accumulated corrosion, accidental collision, or extreme storms [10-12]. In 2005, many oil-drilling and production platforms in the Gulf of Mexico were hit by hurricanes Katrina and Rita, with some TLPs’ tendons failing [13]. After mooring failure, platform position and orientation change substantially, possibly causing the capsizing and sinking of the platform. Additional risks include loose floating structures colliding with other nearby structures.

Considering the significance of the mooring system for the safety of floating structures, mooring failures have aroused concerns in the oil and gas industry. There has been numerical and experimental research focusing on mooring failure for TLP floaters. Yang et al. [14] discussed the transient effect of tendon disconnection on the performance of ETLP (Extended Tension Leg Platform) in the hurricane, which is one of the earliest publications that analyze tendon failure including transient effect [15]. It was reported that tendon tension is more significantly affected by the transient mode than the motions, and the vertical motions, especially pitch, are more significantly influenced by tendon failure. Kim and Zhang [15] developed a BE-FEM (Boundary Element-Finite Element Method) code to study the transient effects of tendon disconnection on the survivability of a TLP in a hurricane. Yang and Kim [16] studied transient effects of tendon disconnection of an ETLP under linear and second-order wave excitations. They also pointed out that the inclusion of second-order sum- and difference-frequency wave excitations makes the calculation of tendon tensions more accurate. Mansour et al. [17] carried out a numerical simulation and model tests by considering progressive tendons failure of a self-stable TLP. The results showed this TLP can survive under progressive tendons failure. Qi et al. [18] conducted numerical simulations of one-tendon failure of a TLP, which were also validated by model tests. The relation between TLP performance under tendon failure and hull ballast was also detected. Yu et al. [19] studied one-time and progressive tendons failure for a TLP under extreme conditions.

Although there has been so far no reported mooring failure in FOWTs, which have been mostly deployed as pilot projects with just a few commercial projects. Several studies have considered mooring failure in FOWTs, especially under survival conditions with a single broken tendon. Bae et al. [20] developed a numerical tool that combines a floater-mooring-coupled dynamic analysis program, CHARM3D, with an aero-hydro-servo-elastic wind turbine simulation tool, FAST [21], and numerically simulated an OC4 DeepCwind semi-submersible FOWT with a fractured mooring line. They found significant drift distance with one broken mooring line, which may cause the successive failure of a wind farm. Li et al. [22] developed a coupled aero-hydro-elastic simulation tool and investigated the transient response of an OC3 spar-type FOWT with a broken mooring line. The results showed that in certain scenarios, it is more dangerous to shut down the turbine. The effect of mooring failure on the wind farm was also discussed. Le et al. [23] performed a coupled aero-hydro-servo-elastic-mooring analysis of a submerged FOWT with tether failure, in which the quasi-static approach was used to calculate mooring loads. They reported that the FOWT with a broken tether maintained good performance. Ma et al. [24] used simulation program SIMO to study the transient response of an OC4 DeepCwind semi-submersible FOWT due to mooring breakage under typhoon conditions in the South China Sea. They suggested that more mooring lines should be arranged in the direction of the head waves and the upwind, to ensure the positioning capacity of the mooring
system under tendon failures. Several design standards for FOWTs also emphasize the redundancy of the mooring system. The Det Norske Veritas (DNVGL) guideline recommends that the design of a station-keeping system should be checked for the failure of one mooring line, one tendon, or one anchor in the accidental limit state [25]. Both Nippon Kaiji Kyokai (ClassNK) and American Bureau of Shipping (ABS) guidelines suggest two design conditions for single mooring-line failure. The first design condition considers the FOWT oscillating around a new equilibrium position after the failure of a mooring line. In the second condition, the FOWTs exhibit transient motion immediately after line breaking but before settling at a new equilibrium position [26, 27]. ABS [27] specifies that the design sea state should have a 50-year recurrence period when considering the transient responses due to line breaking. ClassNK [26] requires that the design sea state should at least have a 1-year recurrence period and recommends different factors according to whether the transient responses are considered. See Table 1 for a summary of the safety factors and design sea states as suggested by ABS and ClassNK for mooring systems under one broken mooring line.

<table>
<thead>
<tr>
<th>Classification society</th>
<th>Materials of mooring lines</th>
<th>Whether consider transient response</th>
<th>Safety factor</th>
<th>Design sea state</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS</td>
<td>Steel or synthetic fiber</td>
<td>No</td>
<td>1.05</td>
<td>/ 50-year sea state</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ClassNK</td>
<td>Steel</td>
<td>No</td>
<td>1.25</td>
<td>At least 1-year sea state</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yes</td>
<td>1.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Synthetic fiber</td>
<td>No</td>
<td>1.88</td>
<td>1-year sea state</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yes</td>
<td>1.58</td>
<td></td>
</tr>
</tbody>
</table>

Most of the above-mentioned previous studies on the effects of mooring failure considered offshore floating platforms and semi-submersible FOWTs. However, for TLP-type wind turbines, the transient responses due to tendon failure, and the consequences have not been thoroughly discussed in the literature, thus need more dedicated studies. Besides, most previous studies focused on only one specific sea state, while a FOWT will operate in a range of different sea states. Shutting down the wind turbine seems to be a natural option in case of sudden line breakage to avoid overloading of the mooring/tendon system. However, it may have limited positive impact on the mooring integrity of the FOWT according to previous studies on semi-submersible FOWT. Thus, the effects of shutting down will also be studied in operational sea states.

In the present study, taking a TLP-type FOWT, WindStar TLP system as an example, we will investigate the transient effects of tendon failure on system responses in details, including platform motion, nacelle acceleration and tension in the remaining tendons. A coupled aero-hydro-servo-elastic model is established using FAST, and tendons are simulated as finite element models via the FEAM module [28]. As a result, dynamic effects and hydrodynamic loads on tendons are considered, which has rarely been studied in previous studies. Further, eleven environmental conditions (ECs) including operational conditions and the 50-year extreme condition are investigated for a systematic comparative study of one-tendon failure effects. The effect of shutting down the wind turbines will also be discussed. The paper is organized as follows: The analyzed WindStar TLP system is described firstly in Section 2. In Section 3, the numerical methods applied to calculate the dynamic response of
wind turbine are introduced. The ECs and tendon failure cases are presented in Section 4; The numerical results of one-tendon failure cases in various ECs are presented in Section 5, including the dynamic responses of TLP-type FOWT with different broken tendons and turbine shutdown scenarios. Finally, several conclusions are drawn in Section 6.

2 The system configuration of the WindStar TLP

The investigated FOWT is the WindStar TLP system, which was proposed by Zhao et al. [29]. It consists of a 5 MW baseline wind turbine of the National Renewable Energy Laboratory (NREL), a tower, the WindStar TLP support platform, and tendons [30].

The selected turbine is a classic utility-scale multi-megawatt turbine. Its cut-in, rated, and cut-out wind speeds are 3, 11.4, and 25 m/s, respectively. The WindStar TLP support platform comprises columns, pontoons, and tendon support structures (TSS). The columns include one central column and three equivalent radial corner columns. The tower of the wind turbine is fixed at the central column. To ensure the redundancy and robustness of the tendon system, a pair of tendons (two polyester ropes) is attached to each TSS [31]. Previous work has demonstrated that the WindStar TLP system has small dynamic motion responses under environmental loads during operating conditions and parked conditions [32].

The configuration of the WindStar TLP system is shown in Figure 1 with its main specifications listed in Table 2. A right-handed coordinate system \( oxyz \) is used, with its origin located at the center of the mean water-plane area, and the positive \( z \) axis running vertically upward through the center of the platform. The tendons are numbered in clockwise order and tendon #1 lies in \( xz \)-plane.

Figure 1. Configuration of the WindStar TLP system. (a) Three-dimensional view; (b) Top view.
Table 2. Parameters of the WindStar TLP support platform.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre column diameter</td>
<td>4.5</td>
<td>m</td>
</tr>
<tr>
<td>Corner column sectional dimension</td>
<td>5.4 × 4.2</td>
<td>m</td>
</tr>
<tr>
<td>Distance between the centre column</td>
<td></td>
<td>m</td>
</tr>
<tr>
<td>and corner column</td>
<td>20.8</td>
<td>m</td>
</tr>
<tr>
<td>Moulded depth</td>
<td>51.3</td>
<td>m</td>
</tr>
<tr>
<td>Design draft</td>
<td>30.0</td>
<td>m</td>
</tr>
<tr>
<td>CM location of the platform above keel</td>
<td>24.6</td>
<td>m</td>
</tr>
<tr>
<td>Roll inertia about CM</td>
<td>1142000</td>
<td>t·m²</td>
</tr>
<tr>
<td>Pitch inertia about CM</td>
<td>1142000</td>
<td>t·m²</td>
</tr>
<tr>
<td>Yaw inertia about CM</td>
<td>1373000</td>
<td>t·m²</td>
</tr>
<tr>
<td>Total displacement</td>
<td>5466.0</td>
<td>t</td>
</tr>
<tr>
<td>Radius to fairleads</td>
<td>40.7</td>
<td>m</td>
</tr>
<tr>
<td>Tendon diameter</td>
<td>227</td>
<td>mm</td>
</tr>
<tr>
<td>Weight in air</td>
<td>35.4</td>
<td>Kg/m</td>
</tr>
<tr>
<td>Axial stiffness</td>
<td>391.0</td>
<td>MN</td>
</tr>
<tr>
<td>Minimum breaking load</td>
<td>17.26</td>
<td>MN</td>
</tr>
<tr>
<td>Total pre-tension</td>
<td>2370</td>
<td>t</td>
</tr>
</tbody>
</table>

3 Methodology

3.1 Dynamic equation in the time domain

The governing time-domain dynamic equation of the whole wind turbine system can be expressed as follows [33]:

\[
M_{ij}(\eta, u, t)\ddot{\eta}_j = F_i(\eta, \dot{\eta}, u, t)
\]  

where \( M_{ij} \) is the \((i,j)\) component of the inertia mass matrix of the whole system, relying on a nonlinear combination of system displacement \( \eta \), control input \( u \), and time \( t \); \( \ddot{\eta}_j \) is the system acceleration associated with the degree of freedom (DoF) \( j \); \( F_i \) is the force or moment in DoF \( i \), composed of aerodynamic loads, hydrodynamic loads, and mooring loads, depending on a nonlinear combination of system displacement \( \eta \), system velocity \( \dot{\eta} \), control input \( u \), and time \( t \).

3.2 Aerodynamic loads
Blade element momentum is a classical method for calculating aerodynamic loads acting on wind turbine blades. It gives the local aerodynamic loads of blade sections as follows [22]:

\[ dT_b = 4\pi \rho \nu^2 a(1 - a)dr \]  
\[ dM_b = 4\pi^3 \rho \nu \Omega_r (1 - a) a_0 dr \]

where \( T_b \) is thrust, \( M_b \) is torque, \( r \) is the distance of the airfoil section from the blade root, \( \rho \) is the density of air, \( a \) and \( a_0 \) are the axial and tangential induction factors, respectively, \( \nu \) is the velocity of upstream wind, and \( \Omega_r \) is the angular velocity. The aerodynamic performance of the wind turbine, such as thrust and power, can be subsequently analyzed.

3.3 Hydrodynamic loads

The hydrodynamic loads consist of four separate parts [33]:

\[ \mathbf{F}^{Hydrodynamic}_i = \mathbf{F}^{Hys}_i + \mathbf{F}^{Rad}_i + \mathbf{F}^{Exc}_i + \mathbf{F}^{Vis}_i \]  

where \( \mathbf{F}^{Hys}_i \) is the hydrostatic restoring force, \( \mathbf{F}^{Rad}_i \) is the wave-radiation force, \( \mathbf{F}^{Exc}_i \) is the wave-exciting force, and \( \mathbf{F}^{Vis}_i \) is the nonlinear viscous-drag force.

The wave-exciting force \( \mathbf{F}^{Exc}_i \) is composed of first- and second-order components. The first-order wave-exciting force is

\[ F^{Exc(1)}_i = \int_0^t h_i(t - \tau) \eta(\tau) d\tau \]  

where \( h_i(t - \tau) \) is a linear impulse response function. The second-order force is

\[ F^{Exc(2)}_i = \int_0^t \int_0^t h_2(\tau_1, \tau_2) \eta(t - \tau_1) \eta(t - \tau_2) d\tau_1 d\tau_2 \]  

where \( h_2(\tau_1, \tau_2) \) is the quadratic impulse function. \( h_i(t - \tau) \) and \( h_2(\tau_1, \tau_2) \) are respectively related to the linear force transfer function \( f^{wave(1)}_i \) and quadratic force transfer function \( f^{wave(2)}_i \). After solving the force transfer functions, the wave-exciting forces can be obtained.

3.4 Cable dynamics

The elastic rod model is introduced to model tendons, as shown in Figure 2. Compared with the quasi-static model, the elastic rod model takes into account the mooring inertia and drag forces [28]. The position vector \( r(s, t) \), which is a function of rod arc length \( s \) and time \( t \), is introduced to define the space curve.
The equilibrium equations of force and torque of the rod per unit arc length are

\[ F'_r + q = \rho_u \ddot{r} \]  
\[ M'_r + r' \times F'_r + m = 0 \]  

where \( q \) is the distributed force per unit length of the rod, \( \rho_u \) is the mass per unit length, \( m \) is the torque per unit length, \( F_r \) and \( M_r \) are the force and torque along the centerline, respectively, and \( F'_r \) and \( M'_r \) are the differentials of the corresponding variables.

In consideration of rod weight, hydrostatic and hydrodynamic forces, the equations of motion can be written as

\[ \rho_u \ddot{r} + C_a \rho_w \dot{r}^m + (EI\dot{r}')'' - (\ddot{\lambda} \dot{r}')' = \bar{w} + \bar{F}^d_r \]  

where \( C_a \) is the hydrodynamic coefficient, \( \rho_w \) is the density of water, \( EI \) is bending stiffness, \( \ddot{\lambda} \) represents a scalar function related to tension and the curvature of the rod, \( \bar{w} \) is the wet mass of the rod, and \( \bar{F}^d_r \) is the hydrodynamic force.

Assuming that the rod is extensible, and the stretch is linear and small, the stretch condition of \( r \) can be approximated as

\[ \frac{1}{2} (r' \cdot r' - 1) = \frac{T}{A_r E} \approx \frac{\lambda}{A_r E} \]  

where \( A_r \) denotes the cross-sectional area of the rod.

Motion equation (9) together with the stretch condition in (10) constitutes the governing equations for the rod model. However, the governing equations are nonlinear and difficult to solve analytically. The finite element method is therefore applied to transform the differential equations:

\[ \begin{cases} -\rho_u \ddot{r}_i - C_a \rho_w \dot{r}_i^m + (EI \dot{r}'_i)'' + (\ddot{\lambda} \dot{r}'_i)' + \bar{w}_i + \bar{F}^d_{r_i} = 0 \\ \frac{1}{2} (r' \cdot r' - 1) - \frac{\lambda}{A_r E} = 0 \end{cases} \]  

where the subscripts \( i \) range from 1 to 3 for a three-dimensional problem.

3.5 Flow chart of coupled aero-hydro-servo-elastic simulation

In this paper, the time-domain aero-hydro-servo-elastic coupled simulation tool FAST (v8.16) is utilized to study the transient response of the WindStar TLP system under tendon failure conditions. The procedure of this coupled numerical simulation is shown in Figure 3. The aerodynamic module of FAST, AeroDyn [34], is used to calculate the aerodynamic loads. The hydrodynamic coefficients including added mass coefficients, radiation damping coefficients, and wave-exciting force transfer functions are calculated by a frequency-domain hydrodynamic code, Wadam [35]. The hydrodynamic module HydroDyn [36] in FAST is used to generate irregular waves and calculate hydrodynamic loads in the time domain. Additional damping coefficients which were calibrated from previous experiments [37] for WindStar TLP are also applied in HydroDyn to improve the overall accuracy of the model. The mooring analysis module, FEAM [28], calculates mooring loads. Tendon failure is assumed to be an abrupt process in this paper, which may be caused by accidental collision or other incidents. Theoretically, tendon failure can be simulated by setting zero force and moment contributions for a specific broken tendon [20]. Therefore, in the present study, we set \( F_r \)
8 and $M_r$ of the broken tendon to zero upon and after the tendon failure. Thus, the source code of the FEAM subroutine was slightly modified for this purpose, and a special version of FAST was recompiled, which will be used in the present work.

![Fig. 3. Calculation flowchart of the numerical simulation.]

### 3.6 Stiffness matrix of mooring system under tendon failure

Tendon failure will change the stiffness of the mooring system, thus changing the natural periods. The coefficients of restoring stiffness in 6-DoFs can be derived by calculation of force and torque balance after assuming an infinitesimal displacement in each DoF.

The diagonal terms of stiffness matrix under intact tendon condition have been derived in the previous work of WindStar TLP system [38]:

\[
C_{11} = 6(F_{\text{Pre}} + \Delta F_i)/L_{Te} \\
C_{22} = 6(F_{\text{Pre}} + \Delta F_i)/L_{Te} \\
C_{33} = 6\Delta F_3 \\
C_{44} = 6(EA/L_{Te})L_f^2 + \rho_wgV_{dis}GM_L \\
C_{55} = 6(EA/L_{Te})L_f^2 + \rho_wgV_{dis}GM_L \\
C_{66} = 6(F_{\text{Pre}} + \Delta F_i)L_f^2/L_{Te}
\]

where, $F_{\text{Pre}}$ is the initial pretension load at each tendon; $\Delta F_i$ is the tension increase at each tendon due to the unit displacement in the DoF $i$; $EA$ is the stiffness coefficient of tendon; $L_{Te}$ is the length of the tendon.
of tendon; $L_F$ is the radius to fairleads; $V_{dis}$ is the volume of displacement; $GM_L$ is the metacentric height above the keel.

Then the coefficients of restoring stiffness in 6-DoFs under one-tendon failure are derived. For simplicity, static offsets caused by one-tendon failure in calm water are not covered. The relation between tension of each remaining tendon after one-tendon failure $F_a$ and $F^{Pre}$ can be derived by:

$$F_a = [(B - W_{Te}) - (W_{To} - W_{Te})]/5 = 1.2F^{Pre}$$ \hspace{1cm} (18)

where, $B$ is the buoyancy force under intact tendon condition; $W_{Te}$ is the gravity force of one tendon; $W_{To}$ is the total gravity force of the whole WindStar TLP system with an intact tendon system. So, $F_a$ is 1.2 times of $F^{Pre}$.

Following that, the stiffness of WindStar TLP system under tendon #1 failure can be expressed as below:

$$C_{11} = (6F^{Pre} + 5\Delta F'_1)/L_{Te}$$ \hspace{1cm} (19)

$$C_{22} = (6F^{Pre} + 5\Delta F'_2)/L_{Te}$$ \hspace{1cm} (20)

$$C_{33} = 5\Delta F'_3$$ \hspace{1cm} (21)

$$C_{44} = 6(EA/L_{Te})L_T^2 + \rho_w g V_{dis} GM_L$$ \hspace{1cm} (22)

$$C_{55} = 5(EA/L_{Te})L_T^2 + \rho_w g V_{dis} GM_L$$ \hspace{1cm} (23)

$$C_{66} = (6F^{Pre} + 5\Delta F'_6)L_T^2/L_{Te}$$ \hspace{1cm} (24)

where, $\Delta F'_1$ is the tension increase at each tendon due to the displacement in the DoF $i$.

Likewise, stiffness of WindStar TLP system under tendon #3 failure can be written as below:

$$C_{11} = (6F^{Pre} + 5\Delta F''_1)/L_{Te}$$ \hspace{1cm} (25)

$$C_{22} = (6F^{Pre} + 5\Delta F''_2)/L_{Te}$$ \hspace{1cm} (26)

$$C_{33} = 5\Delta F''_3$$ \hspace{1cm} (27)

$$C_{44} = 5(EA/L_{Te})L_T^2 + \rho_w g V_{dis} GM_L$$ \hspace{1cm} (28)

$$C_{55} = 5(EA/L_{Te})L_T^2 + \rho_w g V_{dis} GM_L$$ \hspace{1cm} (29)

$$C_{66} = (6F^{Pre} + 5\Delta F''_6)L_T^2/L_{Te}$$ \hspace{1cm} (30)

where, $\Delta F''_1$ is the tension increase at each tendon due to the displacement in the DoF $i$.

Coefficients of restoring stiffness of WindStar TLP system under intact and broken tendon conditions are summarized in where $T$ is the natural period, $M$ and $A$ are respectively the mass and the added mass of the whole system, and $C$ is the stiffness of the mooring system.
Table 3. The stiffness coefficients in horizontal-plane DoFs (surge, sway, and yaw) almost remain unchanged when one tendon breaks. By contrast, the stiffness coefficients in vertical-plane DoFs (heave, roll, and pitch) decrease under one-tendon failure.

According to the following equation, the natural period could be derived, which will be discussed in the following section

\[ T = 2\pi\sqrt{(M + A)/C} \]  \hspace{1cm} (31)

where \( T \) is the natural period, \( M \) and \( A \) are respectively the mass and the added mass of the whole system, and \( C \) is the stiffness of the mooring system.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Intact tendons</th>
<th>Tendon #1 failure</th>
<th>Tendon #2 failure</th>
<th>Tendon #3 failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_{11} )</td>
<td>( 6(F_{\text{Pre}} + \Delta F_1)/L_{Te} )</td>
<td>( (6F_{\text{Pre}} + 5\Delta F_1')/L_{Te} )</td>
<td>( (6F_{\text{Pre}} + 5\Delta F_1'')/L_{Te} )</td>
<td></td>
</tr>
<tr>
<td>( C_{22} )</td>
<td>( 6(F_{\text{Pre}} + \Delta F_2)/L_{Te} )</td>
<td>( (6F_{\text{Pre}} + 5\Delta F_2')/L_{Te} )</td>
<td>( (6F_{\text{Pre}} + 5\Delta F_2'')/L_{Te} )</td>
<td></td>
</tr>
<tr>
<td>( C_{33} )</td>
<td>( 6\Delta F_3 )</td>
<td>( 5\Delta F_3' )</td>
<td>( 5\Delta F_3'' )</td>
<td></td>
</tr>
<tr>
<td>( C_{44} )</td>
<td>( 6(EA/L_{Te})L_F^2 )</td>
<td>( 6(EA/L_{Te})L_F^2 )</td>
<td>( 5(EA/L_{Te})L_F^2 )</td>
<td></td>
</tr>
<tr>
<td>( C_{55} )</td>
<td>( + \rho_w g V_{\text{dis}} G M_L )</td>
<td>( + \rho_w g V_{\text{dis}} G M_L )</td>
<td>( + \rho_w g V_{\text{dis}} G M_L )</td>
<td></td>
</tr>
<tr>
<td>( C_{66} )</td>
<td>( 6(F_{\text{Pre}} + \Delta F_6)/L_{Te} )</td>
<td>( (6F_{\text{Pre}} + 5\Delta F_6')/L_{Te} )</td>
<td>( (6F_{\text{Pre}} + 5\Delta F_6'')/L_{Te} )</td>
<td></td>
</tr>
</tbody>
</table>

4 Environmental conditions and tendon failure cases

The assumed installation site of the WindStar TLP system is located at 61°20′N latitude and 0°0′E longitude, near the Shetland Islands, northeast of Scotland, UK. The water depth at the site is 160 m [38]. Eleven ECs as shown in Table 4 are considered here for a comprehensive comparative study, EC01 to EC10 are turbine operating conditions with the control system of the turbine fully enabled in a range of wind and wave conditions. EC01 and EC10 are respectively the rated and cut-out conditions, which are two typical normal operation conditions. In EC01, the rotor thrust is the largest at the rated wind speed. EC10 applies a wind speed slightly slower than the cut-out wind speed. EC11 is the 50-year extreme condition, under which the turbine is parked for protection.

Detailed environmental parameters are determined according to the International Electrotechnical Commission (IEC) 61400-3 guideline [39]. The incident wind and waves both approach the turbine in the same direction, set as 0° in this study. For the turbine operating conditions, environmental loads are determined by a combination of normal turbulence model (NTM) and normal sea state (NSS). For the 50-year extreme condition, environmental loads are determined by a combination of extreme wind speed model (EWM) and extreme sea state (ESS). The Kaimal spectrum is used for the generation of turbulent winds, and the JONSWAP spectrum is chosen for the description of irregular waves.
Given the symmetry of the platform and the layout of the tendons, the one-tendon failure events can be modeled by only considering either tendon #1 or tendon #3 as a broken tendon. Cases with intact tendons are also studied for comparison.

The total simulation time for each case in turbine operating conditions and the 50-year extreme condition are 1000 s and 3 h, respectively. Tendon failure occurs at 300s in each case. Each case was simulated six times using six sets of different random seeds for wind and waves. The obtained statistics are therefore average values. And for the same case, only one of the six simulation results is illustrated in the following figures.

### Table 4. Definitions and parameters of selected environmental conditions.

<table>
<thead>
<tr>
<th>ECs</th>
<th>Wind</th>
<th>Wave</th>
<th>Turbine</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model</td>
<td>V(m/s)</td>
<td>Model</td>
<td>H(m)</td>
</tr>
<tr>
<td>1</td>
<td>NTM</td>
<td>11.4</td>
<td>NSS</td>
<td>2.4</td>
</tr>
<tr>
<td>2</td>
<td>NTM</td>
<td>12.6</td>
<td>NSS</td>
<td>2.7</td>
</tr>
<tr>
<td>3</td>
<td>NTM</td>
<td>14.0</td>
<td>NSS</td>
<td>3.0</td>
</tr>
<tr>
<td>4</td>
<td>NTM</td>
<td>15.4</td>
<td>NSS</td>
<td>3.4</td>
</tr>
<tr>
<td>5</td>
<td>NTM</td>
<td>16.8</td>
<td>NSS</td>
<td>3.7</td>
</tr>
<tr>
<td>6</td>
<td>NTM</td>
<td>18.2</td>
<td>NSS</td>
<td>4.1</td>
</tr>
<tr>
<td>7</td>
<td>NTM</td>
<td>19.6</td>
<td>NSS</td>
<td>4.4</td>
</tr>
<tr>
<td>8</td>
<td>NTM</td>
<td>21.0</td>
<td>NSS</td>
<td>4.7</td>
</tr>
<tr>
<td>9</td>
<td>NTM</td>
<td>22.4</td>
<td>NSS</td>
<td>5.2</td>
</tr>
<tr>
<td>10</td>
<td>NTM</td>
<td>23.8</td>
<td>NSS</td>
<td>5.5</td>
</tr>
<tr>
<td>11</td>
<td>EWM</td>
<td>50.0</td>
<td>ESS</td>
<td>13.8</td>
</tr>
</tbody>
</table>

### 5 Results and discussion

This investigation examines the effects of one tendon failure, including the natural periods, motion response, nacelle acceleration, and tendon tension. Statistics, including mean, standard deviation, and observed minimum and maximum values, of the simulated time-domain results, are presented. The analyzed time series includes the transient duration (immediately after tendon failure) and the non-transient phase where the transient effects are less important. Therefore, the presented standard deviations are only valid for the considered time duration, which will change if another duration is considered. In contrast, the mean and maximum values remain the same if a different time duration is considered.

#### 5.1 Natural periods

The natural periods of the WindStar TLP system in both intact and one-tendon-failure conditions are obtained by corresponding free-decay tests in FAST based on the still-water initial condition. The natural periods in intact and one-tendon-broken conditions are shown in Table 5. The natural periods of horizontal-plane motions remain almost unchanged when one tendon breaks. In contrast, the natural periods of vertical-plane motions increase under one-tendon failure: the natural periods are related to stiffness, so a reduction of vertical stiffness is responsible for the observed increase.

Besides, equation (31) is also applied to approximate the natural periods of the motions. The added mass before and after tendon failure is considered unchanged for simplification because the mass of one tendon is much less than the mass of the WindStar TLP system. As shown in Table 5, the
changes of natural periods based on free-decay tests in FAST and Eq.(31) show little differences, which verifies the consistency of the simulation. One of the reasons for the difference is that the free decay tests give coupled natural periods while equation (31) is based on a single DoF assumption. Another reason is that free-decay gives damped natural periods, which will be slightly different from the un-damped natural periods for an under-damped system given by equation (31).

Table 5. Natural periods of the WindStar TLP system in intact-tendon and tendon failure cases.

<table>
<thead>
<tr>
<th>Condition DoFs</th>
<th>Intact tendons</th>
<th>T#1 failure</th>
<th>Difference</th>
<th>T#3 failure</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FAST</td>
<td>Eq. (31)</td>
<td>FAST</td>
<td>Eq. (31)</td>
<td></td>
</tr>
<tr>
<td>Surge (s)</td>
<td>45.50</td>
<td>45.53</td>
<td>0.07%</td>
<td>0</td>
<td>45.53</td>
</tr>
<tr>
<td>Sway (s)</td>
<td>45.50</td>
<td>45.53</td>
<td>0.07%</td>
<td>0</td>
<td>45.53</td>
</tr>
<tr>
<td>Heave (s)</td>
<td>3.66</td>
<td>3.94</td>
<td>7.65%</td>
<td>9%</td>
<td>3.94</td>
</tr>
<tr>
<td>Roll (s)</td>
<td>4.87</td>
<td>4.87</td>
<td>0</td>
<td>0</td>
<td>6.40</td>
</tr>
<tr>
<td>Pitch (s)</td>
<td>4.87</td>
<td>6.40</td>
<td>31.42%</td>
<td>30%</td>
<td>6.40</td>
</tr>
<tr>
<td>Yaw (s)</td>
<td>25.60</td>
<td>25.65</td>
<td>0.20%</td>
<td>0</td>
<td>25.65</td>
</tr>
</tbody>
</table>

5.2 Platform motion

Upon tendon failure, the platform motion quickly reaches a high peak. The motion responses then fluctuate intensely and oscillate around a new equilibrium position. Figure 4 shows the pitch response in the 50-year extreme condition. As shown in Figure 4(a), the maximum pitch under tendon #1 failure is 3.7°, which is about 2.5 times the maximum pitch when all tendons are intact. Another feature during tendon failure is the change of equilibrium position. The mean pitch angle under tendon #1 failure is 1.5°. Under tendon #3 failure, the minimum pitch is -2.2° and the mean is -0.6°. Compared with tendon #3 failure, tendon #1 failure causes greater pitch response. Figure 4(b) shows spectra for the pitch response in the 50-year extreme condition. Compared with the results based on intact tendons, pitch spectra during tendon failure display clear increased responses at wave frequency and pitch natural frequency. The amplitude of the pitch spectrum under tendon #1 failure is larger than that under tendon #3 failure. The increased components of the spectrum reflect remarkable motion change after tendon failure.
Figure 4. Pitch response in the 50-year extreme condition. (a) Time histories; (b) Spectra.

Figure 5 shows the pitch acceleration of the platform in the 50-year extreme condition. The pitch acceleration under tendon #1 failure shows an immediate maximum after tendon failure. And the pitch acceleration under tendon #3 failure shows a transient minimum when tendon breaks. So tendon failure causes immediate peak values of pitch acceleration.
Figure 5. Time histories for pitch acceleration of platform in the 50-year extreme condition.

Figure 6 displays statistics (mean, observed minimum and maximum, and standard deviation) for surge, heave, roll, and pitch in all ECs. The minimum and maximum values are determined as the lowest trough and highest crest of the corresponding time series, respectively. See the definition of pitch acceleration in Figure 5 as an example. Larger longitudinal motions are observed under Tendon #1 failure compared with that under Tendon #3 failure. Figure 6(a) shows that under #1 failure, the mean and minimum values of surge response decreases when the ECs get worse. As seen from Figure 6(a, b, c), the largest maximum surge, heave and pitch responses under tendon #1 failure all occur in the 50-year extreme condition (EC 11), while the maximum responses in cut-out condition (EC 10) are relatively smaller. As the location of tendon #3 is not aligned with the environment load, transverse motions are obviously affected under tendon #3 failure. Figure 6(d) shows statistics for roll responses under tendon #3 failure, the maximum values of roll response increase with increasing sea states. The roll response in the cut-out condition is even larger than that in the 50-year extreme condition.
Figure 6. Statistics for motion responses in all ECs. (a) Surge under tendon #1 failure; (b) Heave under tendon #1 failure; (c) Pitch under tendon #1 failure; (d) Roll under tendon #3 failure

5.3 Nacelle acceleration

Figure 7 shows time histories for nacelle surge acceleration in the rated condition. Transient extreme maximum and minimum nacelle surge acceleration occur after tendon failure, with tendon #1 failure having a greater effect than tendon #3 failure. The maximum nacelle surge acceleration under tendon #1 failure is $4.5 \, m/s^2$, which is 4.5 times of that in intact condition. The minimum transient nacelle surge acceleration under tendon #1 failure is $-3.1 \, m/s^2$, which is 3.3 times of that seen with intact tendons. The mean nacelle surge acceleration in both tendon failure cases and the intact tendons case is consistently zero. Therefore, the tendon failure has greater effects on the peak values of the nacelle acceleration.

Figure 7. Time histories for nacelle surge acceleration in the rated condition.

Tendon #1 failure has a larger effect on longitudinal platform motions and longitudinal nacelle accelerations, while tendon #3 failure has a larger effect on transverse responses, which is related to their respective locations. As a result, Figure 8 displays statistics for nacelle surge acceleration under tendon #1 failure and nacelle sway acceleration under tendon #3 failure in all ECs. Figure 8 displays statistics for nacelle surge acceleration under tendon #1 failure and nacelle sway acceleration under tendon #3 failure in all ECs. Figure 8(a) shows that difference of the statistics for nacelle surge acceleration in all ECs is narrow, and tendon #1 failure in the rated condition causes the maximum amplitude of nacelle surge acceleration. Figure 8(b) shows that the maximum and minimum nacelle sway accelerations under tendon #3 failure are in the cut-out condition. And the absolute extrema of nacelle sway acceleration in the 50-year extreme condition are clearly smaller than those in the turbine operating conditions. The mean nacelle acceleration remains zero under tendon failure, which reflects that tendon failure mainly influences the transient peak value of nacelle acceleration. Turbine operating conditions cause the maximum nacelle accelerations due to the significant aerodynamic load.
Figure 8. Statistics for nacelle acceleration in all ECs. (a) Nacelle surge acceleration under tendon #1 failure; (b) Nacelle sway acceleration under tendon #3 failure

5.4 Tendon tension

Compared with the motion response of the platform, tendon tension more directly reflects the safety state of the mooring system. Only tension at the fairlead is studied as it has the greatest value along the whole tendon. After the failure of one tendon, that closest tendon to the broken tendon suffers the maximum tension [18]. The tendons considered here are therefore tendon #2 under tendon #1 failure and tendon #4 under tendon #3 failure.

Figure 9 displays tendon #2 tension in intact and tendon #1 failure cases under the 50-year extreme condition. As shown in Figure 9(a), after tendon #1 breaks, tendon #2 tension fluctuates. Its maximum reaches 14.35 MN, which is 2.0 times that when all tendons are intact. The mean tendon #2
tension once its neighbor has failed is 2.1 times that before failure. And the occurring time of the maximum tension is not at the time instant of tendon breaking. This is different for nacelle acceleration, which immediately approaches the maximum after the breaking. The spectra for tendon #2 tension with and without neighboring tendon failure under the rated condition are presented in Figure 9(b). Compared with the intact case, the tendon #2 tension spectrum after tendon #1 failure shows a significant increase at the wave frequency and pitch natural frequency.

Figure 10 displays the statistics for the tension on the tendon in all ECs, which is the closest to the broken tendon. As shown in Figure 10(a), the difference of tendon #2 tension statistics between turbine operating conditions is small. The maximum value occurs in the 50-year extreme condition and the maximum mean value is in the rated condition. As shown in Figure 10(b), the maximum and mean values of tendon #4 tension almost presents an increasing trend when the seastate increases. The maximum value and maximum mean value of tendon #4 tension also occur in the 50-year extreme condition.

The tension on tendon #2 under its neighbor’s failure in the 50-year extreme condition is the largest among all tendon failure cases. In this case, the observed maximum tension on tendon #2 is 14.35 MN, corresponding to 87% of its maximum breaking strength (MBS) with a safety factor of 1.05 [27] considered. In a separate study [40] using a similar time-domain model in FAST, the 3-hour most-probable-maximum tension on tendon #2 under intact condition was estimated to be 7.73 MN, which is about 75% of the MBS with a safety factor of 1.67 recommended by ABS [27]. Therefore, in consideration of safety factor margin, ALS requirements dominate over the ULS consideration in the design of the tendon system of the considered WindStar TLP. The fatigue analysis will be considered in our future studies, and thus is not pursued further in this work.
Figure 9. Tendon #2 tension with and without tendon #1 failing in the 50-year extreme condition. (a) Time histories; (b) Spectra
5.5 Consideration of turbine shutdown scenario

As mentioned above, when it comes to turbine operating conditions, the rated condition is the most dangerous condition among all cases under tendon #1 failure, while the cut-out condition is the most dangerous among all tendon #3 failure cases. Therefore, these two relatively dangerous and typical tendon failure cases are studied for turbine shutdown. As shown in Table 6, four pitch rates varying from 2°/s to 8°/s are considered in the simulations, since the maximum pitch rate of NREL offshore 5-MW baseline wind turbine’s control system is 8°/s [41]. Moreover, two grid connection statuses (GS1 and GS2) are simulated. In Table 6, GS1 means that the generator is connected and its torque is zero when the rotor speed is below 6.9 rotations per minute (RPMs) [41]. In GS2, the grid is disconnected and the mechanical brake is ramped up to the full magnitude in 0.6 s after the shutdown is initiated and released when the rotor speed drops below 3 RPMs [42].

Table 6. The tendon failure cases studied for turbine shutdown.

<table>
<thead>
<tr>
<th>ECs V(m/s)</th>
<th>H(m)</th>
<th>Tp(s)</th>
<th>Description</th>
<th>Broken Tendon</th>
<th>Pitch rate (°/s)</th>
<th>GS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.4</td>
<td>2.4</td>
<td>10.9</td>
<td>Rated condition</td>
<td>#1</td>
<td>2,4,6,8</td>
</tr>
<tr>
<td>10</td>
<td>23.8</td>
<td>5.5</td>
<td>13.5</td>
<td>Cut-out condition</td>
<td>#3</td>
<td>1,2</td>
</tr>
</tbody>
</table>

Figure 11 shows time histories for tendon #2 tension after the failure of tendon #1 in the rated condition with different turbine shutdown strategies. It is interesting to note that, the observed maximum tension occurs shortly after the time instant of tendon breaking (actually at 302.9s), which is different from that in 50-year extreme condition. As seen in Figure 9, the maximum tension does not occur near the time instant of tendon #1 breaking (actually at 2010.9s). The main reason for the difference is that, for the studied NREL 5MW wind turbine, it has peak rotor thrust in the rated condition, while in the 50-year extreme condition, the turbine is parked and the rotor thrust is relatively low. In the rated condition, the peak rotor thrust causes the maximum pitch moment on the wind turbine system, and tendon #1 and tendon #2 are the most loaded tendons in the rated condition. As a result, tendon failure in the rated condition causes the instant redistribution of forces.
which brings the occurrence of maximum tendon #2 tension at the time instant of tendon breaking. On the contrary, wave loads play the leading role in the 50-year extreme condition. So tendon failure in the 50-year extreme condition would not cause the same level of strong instant redistribution of forces. Besides, this may be due to the random increase in the 50-year condition, which would cause larger tension in the later stage of the tendon failure. Another possible explanation is that the initial conditions for rigid-body motions of the FOWT are different at the time tendon #1 breaks. For the same ECs, two other results, one without shutdown strategy and the other without wind, are also included in Figure 11 to demonstrate the effect of shutdown strategies. Turbine shutdown reduces the maximum and the mean of tendon #2 tension, which is more obvious at a higher pitch rate. The application of mechanical brake seems to have very little effect. And time histories for tendon #2 tension under pitch rate of 8°/s are similar to those in no wind case, which means that turbine shutdown with the maximum pitch rate could minimize the effect of wind.

Figure 11. Time histories for tendon #2 tension under tendon #1 failure in the rated condition with different turbine shutdown strategies.

Figure 12 displays the statistics of responses under tendon #1 failure in the rated condition. The use of mechanical brake plays a minor role in general. As shown in Figure 12(a), the maximum and mean value of pitch response are reduced due to the shutdown of the turbine. Furthermore, the maximum pitch response is sensitive to the pitch rate in that higher pitch rate causes smaller maximum pitch response. As shown in Figure 12(b), nacelle surge acceleration seems to be insensitive to turbine’s shutdown. As shown in Figure 12(c), like the phenomenon of pitch response, maximum and mean tension on tendon #2 decrease in turbine shutdown scenario. Moreover, the maximum values of these two responses are reduced when the higher pitch rate is applied. As a result, turbine shutdown is beneficial in such case and a higher pitch rate is recommended.
Figure 12. Statistics for responses under tendon #1 failure in the rated condition. (a) Pitch; (b) Nacelle surge acceleration; (c) Tendon #2 tension

Figure 13 shows statistics of responses under tendon #3 failure in the cut-out condition. The application of mechanical brake still has little effect. As shown in Figure 13(a) and Figure 13(b), roll response and nacelle sway acceleration are insensitive to turbine shutdown. As shown in Figure 13(c), the maximum and mean value of tendon #4 tension are increased owing to turbine shutdown and higher pitch rate causes larger maximum tension. So it is not recommended to adopt turbine shutdown under tendon #3 failure in this case. This conclusion is based on the assumption that wind and waves are collinearly from 0 deg. In reality, tendons #1 and #2 on the weather side will experience larger tension, and thus are more likely to break earlier than the others due to overloading.
Figure 13. Statistics for responses under tendon #3 failure in the cut-out condition. (a) Roll; (b) Nacelle sway acceleration; (c) Tendon #4 tension

6 Conclusions

This study investigates the transient dynamic responses of the WindStar TLP system under one-tendon failure conditions. Fully coupled analyses were carried out in the time domain using the aero-hydro-servo-elastic tool FAST, which is recompiled to allow for simulation of a sudden tendon breakage at a certain time. One-tendon failure is considered in eleven ECs including turbine operating conditions and the 50-year extreme condition with collinear wind and waves. Subsequently, the turbine shutdown scenarios with different pitch rates and grid connection statuses are studied. The focus is on the transient effect on platform motion, nacelle acceleration, and tension in the remaining tendons.

The analysis and discussion lead to the following conclusions.

1) The natural periods of vertical-plane motions (heave, roll, and pitch) increase appreciably under tendon failure. Among all the ECs, the maximum longitudinal motions occur in the 50-year extreme condition, while the maximum transverse motions are observed in the cut-out condition. Overall, the WindStar TLP system retains good motion performance under tendon failure.

2) The mean and dynamic responses of platform motion, nacelle acceleration, and tendon tension under tendon failure are greater than those for intact tendons. When the broken tendon is not aligned with the wave direction, great transverse platform motions and nacelle accelerations are seen.

3) The nacelle acceleration under tendon failure is the largest under the operational conditions, while its surge acceleration is highest in the rated condition and its sway acceleration is largest in the cut-out condition.

4) Under a single-tendon failure, the most critical tendon among the rest intact tendons is in the vicinity of the broken one. For the considered WindStar TLP, mooring loads results show that the ALS requirements dominate over the ULS requirement in the design.
(5) It is beneficial to apply turbine shutdown in tendon #1 failure conditions and to apply a higher pitch rate to achieve reduced responses. Additionally, it is unnecessary to apply a mechanical brake during a turbine shutdown since it has limited effect. By contrast, with collinear waves and wind in the longitudinal direction, the turbine shutdown should not be adopted under the tendon #3 failure conditions, which may increase the tension on tendon #4.

Complete separation of the transient and nontransient phases needs much longer simulations than those conducted here, considering that the important natural periods are on the order of 50 s. This will be considered in future studies. Besides, further simulations of real tendon failure scenarios are needed, such as progressive failure cases, tendon failure cases with different breakage durations, and time-transient processes and tendon failure cases under the combined action of wind, waves and current. To analyze tendon failure more completely, model tests should be carried out in the future.

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