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DYNAMIC RESPONSE OF SPAR WIND TURBINE MOORED BY DYNAMIC CATENARIES UNDER RANDOM WIND AND WAVE LOADS

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ABSTRACT

As offshore wind turbine is developed toward larger water depth, the dynamics coming from structural and fluid inertia and damping effects of the mooring-line gets more obvious, that makes the response analysis of the large floating wind turbine under wind&wave load more challenging. In this study, the dynamic response of a spar floating wind turbine under random wind and wave loads is examined by the modified FEM simulations. Here an integrated system including flexible multi-bodies such as blades, tower, spar and mooring-lines is considered while the catenary dynamics is involved.

The dynamic restoring performance of the catenary mooring-line is analyzed based on the vector equations of 3D curved flexible beam and its numerical simulations. Then the structural responses, e.g. the top tension, structural displacements and stress of the tower and the blade, undergoing random wind&wave loads, are examined. Morevoer, the influences of the catenary dynamics on its restoring performance and the hysteresis behavior are presented. Our numerical results show: the dynamics of mooring-line may significantly increase the top tension, and, particularly, the snap tension could be more than 3 times larger than the quasi-static one. Moreover, the structural response under random wind&wave load gets smaller mainly because of the hysteresis effect coming from the mooring-line dynamics. The floating body displacement at surge frequency is around 20% smaller, and the tower root stress at bending frequency is about 30% smaller than the quasi-static values respectively.

Keywords: structural response, catenary dynamics, floating wind turbine, hysteresis, random loads

NOMENCLATURE

q	distributed force
ρ	density of catenary
A	cross section area
r	position vector
EI	bending stiffness
λ	effective tension
ε	strain
θ	rotation angle
M_{ij}	element of mass matrix
K_{ij}	element of stiffness matrix
C_{ij}^{str}	element of damping matrix
U_j	displacement component
F_j	load component
I	the turbulence intensity
V_{10min}	the average wind speed
l	the scalar value
f	the wind frequency
α	a constant
g	the gravity acceleration

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ω	the wave frequency
ω_p	the peak wave frequency
H_s	the significant wave height

INTRODUCTION

Due to the advantages of high wind speed and more steady wind resources, the wind energy industries have been developing towards deeper ocean area. Generally, the floating wind turbines like spar and semi-submerged type are controlled in a certain range of ocean area by the mooring system. Comparing with onshore wind turbine, both the offshore environment loads and turbine system are more complicated. Therefore the dynamic response analysis of floating wind turbine is more challenging. Moreover, for a large-sized wind turbine, the dynamic coupling between the flexible parts is more significant, and it should be considered.

The quasi-static method is commonly used to calculate the mooring-line restoring force during the analysis of the floating wind turbine dynamic response[1-4]. Employing the experimentally tested static stiffness curve, Karimirad[1] examined the dynamic response of a Spar wind turbine based on FEM simulations. Using quasi-static model to obtain the mooring-line restoring force, Giusti[3] studied the main influence parameters of dynamic response and the coupling effect between different degrees of freedom of floating platform of wind energy, and Barooni[4] developed the coupled methods of floating wind turbine and programmed the integrated codes to analyze response under wind and wave loads. But in deep sea area the mooring-line length get larger, and its dynamic behavior becomes more remarkable[5,6]. In order to include the mooring-line dynamics, the lumped-mass model was developed and popularly used. Hall[7] pointed out that the quasi-static method may under-estimate the tension of mooring-line, and 30% error of fatigue load could be introduced based on his numerical simulations[8]. Azcona[9] pointed out that involving the mooring line dynamics, the tower base loads and mooring line tension can be significantly changed.

The multi-degree of freedom method and multi-body method are two popular methods to model the wind turbine structural body[10-12]. Jeon[10] studied the global response of a spar wind turbine with catenary mooring-lines under irregular waves, where the top nacelle and blades were considered as an lumped mass. The motions of rigid-body, rather than flexible-body, of a floating wind turbine under wind and ocean wave were presented by Christiansen[11], where the wind load on the rotor was acted as a thrust force at the hub. In these two methods, lumped-mass or multi-degree-of-freedom body are actually used to model those flexible bodies, e.g. elastic blade and tower, which, to some extent, neglects the structural flexibility and their coupling between each other.

To consider the flexible bodies and the interaction between the flexible bodies, an integrated FEM wind turbine model we developed in a previous study[13] is used, which includes flexible blades, tower, floating body and catenary mooring-lines. And the influence of the mooring system dynamics on response of the floating wind turbine, e.g. the top tension, structural displacements and stress of the tower and the blade, undergoing random wind&wave loads, is examined. And the hysteresis character of the restoring stiffness and the influences of the mooring-line dynamics on its restoring performance are analyzed.

1 The Floating Wind Turbine Model

1.1 Governing Equations of the Wind Turbine System

Using quasi-static method only the static restoring force of the mooring system is involved. Here, the dynamic governing equations based on 3d curved flexible beam approach is applied to include the nonlinear geometry, structural and fluid dynamics. The dynamic governing equations of a mooring-line (see Fig.1) in terms of vectors [13] can be written as:

$$-(EIr'')''+(\lambda r')'+q=mr' \tag{1}$$

$$r'\cdot r'=(1+\varepsilon)^2 \tag{2}$$

where λ is a scalar variable represents the effective tension, r is the position vector of the catenary, q is the distribute force, m and is mass per unit length, EI is the structural stiffness, and $\boldsymbol{\varepsilon}$ is the strain of the catenary. If the value of the bending moment in Eq.(1) is zero, we will have the dynamic equation of a catenary of which the external loads include the gravity, buoyancy and hydrodynamic forces.

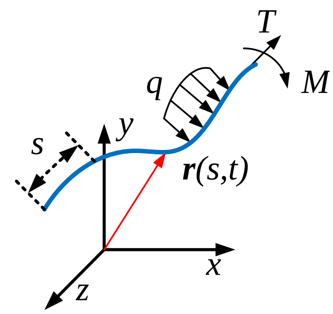


FIGURE 1: CATENARY MOORING-LINE MODELS

To model the characteristic of the catenary, in our modified finite element simulations, the two beam elements connected at one node have different rotation degrees of freedom at this node. Then the rotational angles of the system $\boldsymbol{\theta}$ change into $\boldsymbol{\theta},\boldsymbol{\theta}'$. The displacement vector of beam element can be write as:

$$\begin{aligned}\mathbf{U}_i &=[u_i,v_i,w_i,\theta_i,u_{i+1},v_{i+1},w_{i+1},\theta_{i+1}]^T \qquad i=1,N\\ \mathbf{U}'_i &=[u_i,v_i,w_i,\theta_i,\theta'_i,u_{i+1},v_{i+1},w_{i+1},\theta_{i+1},\theta'_{i+1}]^T \quad i=2,\cdots,N-1\end{aligned} \tag{3}$$

where $\mathbf{U}_i$ is the displacement vector. Here, only the translation displacement in $\boldsymbol{x}$-$\boldsymbol{y}$ plane [u_i,v_i] and one rotation around $\boldsymbol{z}$ axis $\theta_{i,}$ of per node, are considered. Here the original shape and top tension based on traditional static catenary theory is used as the definite conditions to model the real catenary mooring-line.

The blade and tower are flexible bodies, and their axial length is much larger than the lateral size, so both the blade and tower are modeled with beam elements. Due to that the spar is a cylinder with an axial dimension much larger than the lateral dimension, the spar is also modeled as elastic beam. Then we can give the governing equation of the integrated wind turbine system as[14]:

$$M_{ij}(U,t)\ddot{U}_j + C_{ij}^{str}(U,t)\dot{U}_j + K_{ij}(U,t)U_j = F_i(U,\dot{U},\ddot{U},t) \quad (4)$$

where M_{ij} is the element of mass matrix and U_j is the displacement. t is the time. K_{ij} and C_{ij}^{str} are the elements of structural stiffness and damping matrices respectively. F_i is the external load including the fluid force and restoring force of the mooring-lines. The external load acting on the floating body include three parts: the inertia force of the added-mass, the restoring force coming from the dynamic mooring-lines and the hydrodynamic force[13].

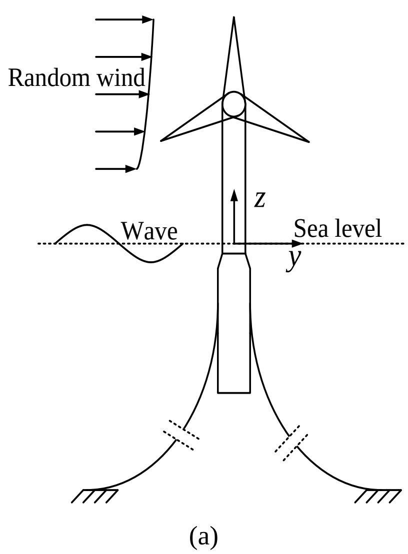
For the spar floating body and the catenary mooring-lines in this paper the Morison equation is used to calculate the hydrodynamic force and the drag coefficient for the spar and mooring-line are 0.6 and 1.2[16]. To run the dynamic response analysis, the Newmark method is employed to solve the nonlinear dynamic equations of the integrated wind turbine.

1.2 The Wind Turbine Parameters and the Verification of the FEM Model

The geometric, structural and material parameters of OC3-Hywind spar wind turbine[15,16] are presented in Table 1. In the FEM model, every single mooring-line was divided into 200 beam elements as mentioned in Section 1.1, and the hydrodynamic force acting by fluid flow on the catenary is involved.

TABLE 1. THE GEOMETRIC, STRUCTURAL AND MATERIAL PARAMETERS OF THE 5-MW SPAR WIND TURBINE

Parameters	Value
Tower height above water	87.6m
Material density of tower	8500.0kg/m^3
Depth to spar base below water	120.0m
Spar total mass	7466330.0kg
Equivalent mooring-line weight in water	698.1N/m
Depth to anchors below water	420.0m
Radius to anchors from platform centerline	706.0m
Mooring-line length	800.0m
Blade mass	17740.0kg



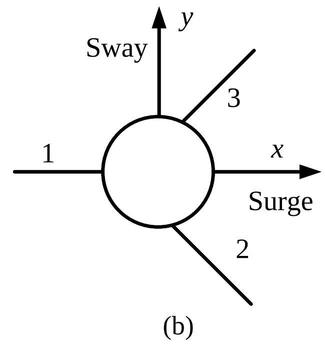


FIGURE 2: SCHEMATIC OF THE FLOATING WIND TURBINE (a) THE FLOATING WIND TURBINE (b) THE MOORING-LINE DISTRIBUTION

Regarding the good stability of heave motion[14], here only the surge and pitch motions will be examined. The dynamic characteristics of the integrated system are calculated and compared with the experimental results of Ref.[16] so as to verify our FEM model, as shown in Table 2. Our numerical results are in good agreement with the experimental results, and the error is less than 5% differences. And it should be note that the periods of the first bending mode of the tower and blade, are among the periods of the wave. That may lead to larger amplitude responses at high frequencies, which could influence the structure fatigue life and should be paid attention during dynamic response analysis.

TABLE 2. COMPARISON OF THE NATURAL PERIODS OF THE FLOATING WIND TURBINE

Mode	Numerical Result /s	Ref.[15] /s	Difference /%
Surge	120.00	125.60	4.46
Sway	120.00	125.60	4.46
Pitch	28.00	28.50	1.75
Roll	27.70	28.50	2.81
Tower first bending	2.28	/	/
Blade first bending	1.37	/	/

1.3 The Random Wind and Wave Loads

In order to generate the time history of the random wind, the mostly used Kaimal spectrum[17] is chose here to calculate an time history approximation of wind speed and consequent wind load. The wind speed spectrum is:

$$PSD(f) = \frac{I^2 V_{10\min} l}{(1+1.5\dfrac{fl}{V_{10\min}})^{5/3}} \quad (5)$$

where I is the turbulence intensity. $V_{10\min}$ is the average wind speed in ten minutes at the given point. l is the scalar taking value. As we know, the wind speed change little as the height increases. It is assumed that the wind load is uniformly acting on every blade, and the value of wind speed is the same with that at the hub height. The drag force of wind acting on the tower and blades is given by the empirical expression[18].

$$F(t) = \frac{1}{2} C_D \rho A v^2(t) \quad (6)$$

where C_D is the drag coefficient, ρ is the air density, A is the windward area of the blade, and $v(t)$ is the instant wind speed.

As for the random wave loads, we use the JONSWAP spectrum, an empirical relationship that defines the distribution of the wave energy to generate the time history of the ocean wave speeds. The equation of the JONSWAP spectrum is

$$S(\omega)=\frac{\alpha g^2}{\omega^5}\exp\left[-\beta\frac{\omega_p^4}{\omega^4}\right]\gamma^a \tag{7}$$

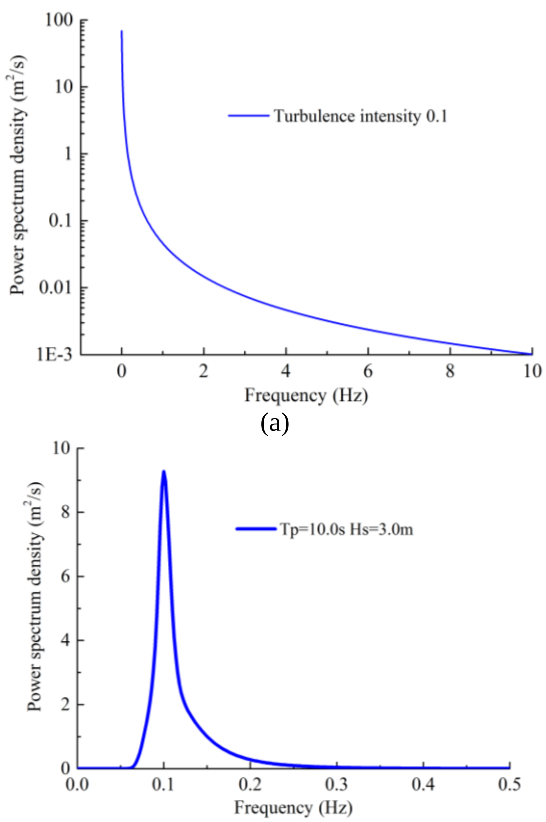
where

$$a=\exp\left[-\frac{(\omega-\omega_p)^2}{2\omega_p^2\sigma^2}\right]$$

$$\sigma=\begin{cases}0.07 & \omega\le\omega_p\\ 0.09 & \omega\ge\omega_p\end{cases}$$

$$\beta=1.25$$

And α is a constant, ω is the wave frequency and ω_p is the peak wave frequency, g is the gravity acceleration. In this study, the random wind with average wind speed 11.4m/s and irregular wave with significant wave height 3.0m and wave period 10s[1] are considered for the dynamic response. The wind and wave spectrums are shown in Fig.3.



(b)

FIGURE 3: SPECTRUMS OF THE RANDOM WIND AND WAVE (a) KAIMAL WIND SPECTRUM (b) JONSWAP WVAE SPECTRUM

2 The Mooring-Line Restoring Performance and Dynamic Response of the Wind Turbine

During the running of dynamic response, initially, the displacement and velocity of structural body are set to be zero. To compare with the static results, the quasi-static model is developed and its responses is also presented.

2.1 The Dynamic Mooring-Line Restoring Behavior

The top tension response of the catenary mooring-line 1 are presented in Fig. 4. Fig.4a shows obvious difference between the quasi-static and dynamic tensions at the 10s period 3m spar surge amplitude, e.g. the dynamic tension (1300kN) is 23.8% larger than the static value (1050kN), and the gap value gets about 2 times larger. Fig.4b shows that the top tension gets larger with the increase of the spar surge frequency and/or amplitude.

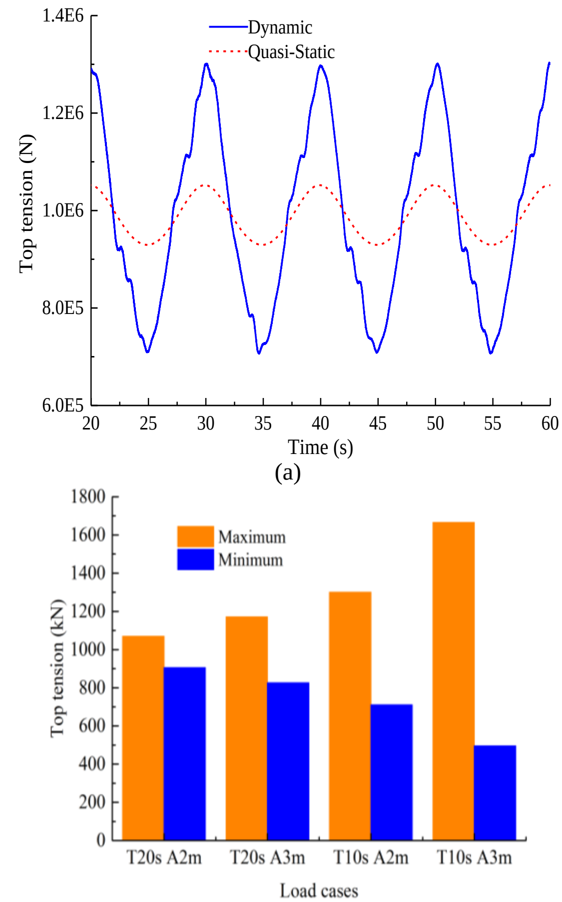


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FIGURE 4. TOP TENSION OF THE MOORING-LINE (a) TIME HISTORY OF TOP TENSION (b) TENSION VARIATION AT DIFFERENT SPAR MOTION CASES

The slack-taut with larger value of snap force is seen, e.g. at 0.1Hz frequency and 6m amplitude in Fig.5, where after the top tension approaches to almost zero, the maximum top tension sharply gets, around 2 times, larger than (or 3 times of) the quasi-static value mainly because the mooring-line dynamics is involved here.

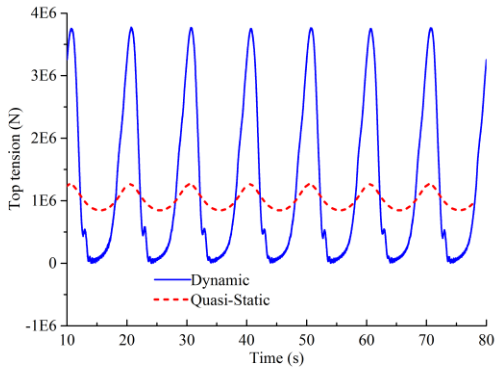


FIGURE 5. TOP TENSION OF THE MOORING-LINE

As presented above, the mooring-line dynamics could introduce an increase of top tension and tension amplitude difference. In fact, because of involvement of dynamic behaviors, i.e. the inertial and damping effects, the restoring stiffness may change too. Thus, the restoring stiffness under conditions of different top spar amplitudes, i.e. A=8 and 4m, along with different periods, i.e. T=20 and 40s is examined here. The selected results are presented in Fig.6 and 7.

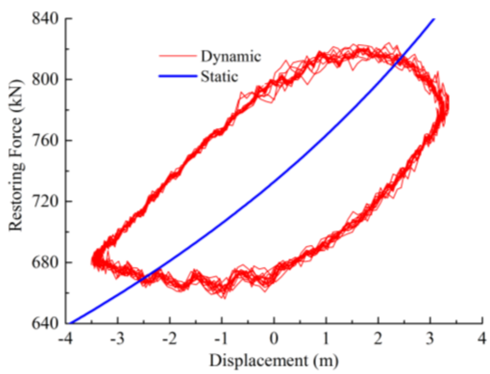


FIGURE 6. THE MOORING-LINE RESTORING STIFFNESS

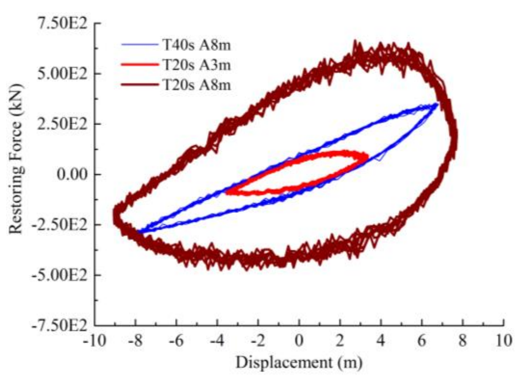


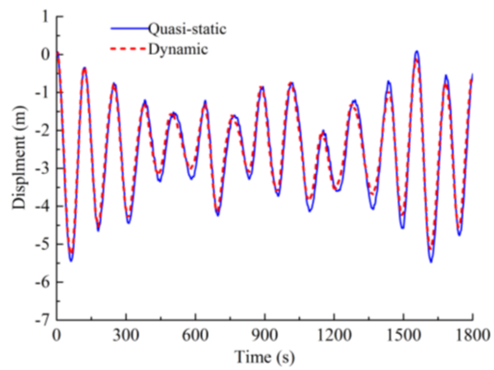
FIGURE 7. RESTORING PERFORMANCE OF THE MOORING SYSTEM

Fig.6 shows the restoring stiffness curve of line 1, at 20s period and 4m amplitude, and also the static curve as a comparison. It is noted that the plot of dynamic stiffness is approximately an elliptical shape, which is called hysteresis loop. The hysteresis character of the dynamic stiffness is mainly due to the damping effect coming from the structure and fluid of the mooring-line. As for the overall dynamic stiffness of the whole mooring-lines system, the typical stiffness, at various periods and amplitudes, are presented in Fig.7. The hysteresis gets more profound as the frequency and amplitude increases.

2.2 The Dynamic Responses of the Floating Wind Turbine under Environmental Loads

The integrated wind turbine response under wind&wave load is calculated during 1800s time duration, and the wind and wave are assumed in the same direction, e.g. the direction of spar surge.

The displacements of the floating spar and the displacement spectrum, are presented in the Fig.8. It can be seen that the displacement amplitude with dynamic restoring force is smaller than the quasi-static ones. The large displacement component at 0 Hz is mainly caused by the average wind velocity, and the dynamic response is dominated by the spar surge (at 0.0083Hz) and pitch (at 0.0357Hz) motion, while some higher-frequency elastic bending modes can be found in the spectrum.



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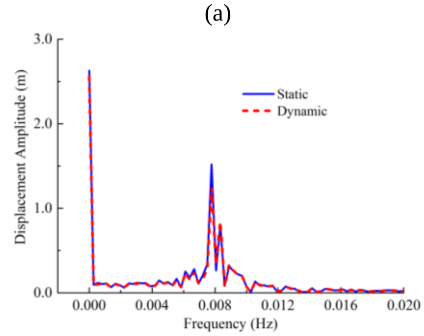

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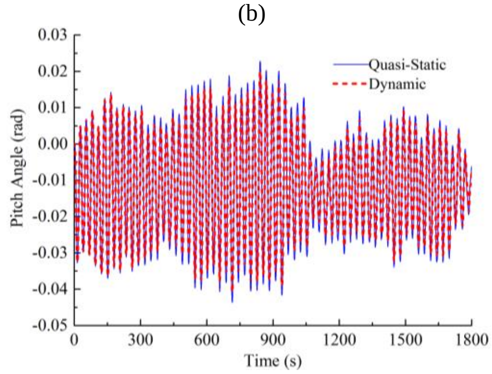

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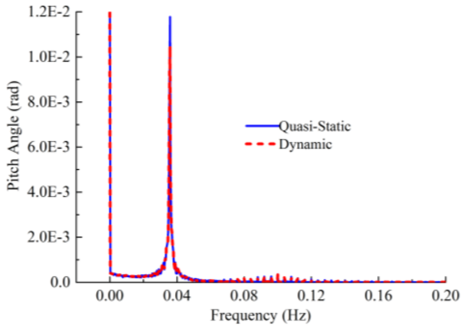

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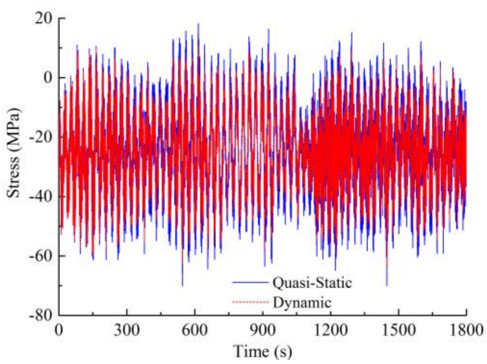
FIGURE 8. THE SPAR DISPLACEMENT (a) TIME HISTORY OF THE SPAR SURGE (b) SURGE SPECTRUM OF THE SPAR (c) TIME HISTORY OF THE SPAR PITCH (d) PITCH SPECTRUM OF THE SPAR

The structural stress and its spectrum, of the tower root and the blade root, are presented in the Fig.9. The difference between the dynamic and the quasi-static value is obvious, especially at high order mode. And the structural stress is dominated by high order elastic mode, e.g. the higher values at tower bending frequency (0.43Hz) and blade bending frequency (0.72Hz). As the integrated FEM model can presents more modes of the flexible bodies, there are some additional peaks in the spectrum shown in Fig. 9b and d. So we can give the higher-order response of the wind turbine system under random wind&wave loads, which is crucial to the fatigue life of the structure. Comparing the dynamic and quasi-static stress, it can be seen that the value of spar displacement at surge frequency is about 20% smaller than the quasi-static one; and values of the stress components are up to about 30% smaller than the quasi-static ones.



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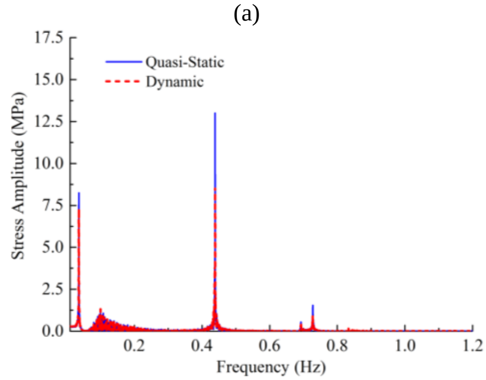

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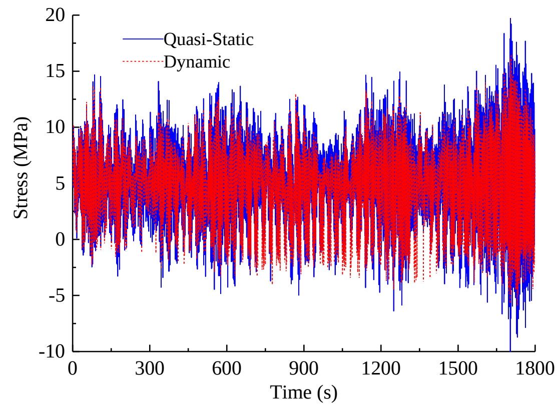

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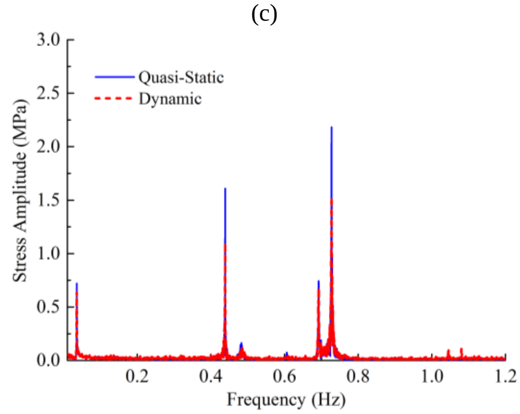

(d)

FIGURE 9. STRUCTURAL STRESSES OF THE WIND TURBINE (a) TIME HISTORY OF THE TOWER ROOT STRESS (b) SPECTRUM OF THE TOWER ROOT STRESS (c) TIME HISTORY OF THE BLADE ROOT STRESS (d) SPECTRUM OF THE BLADE ROOT STRESS

3 Conclusions

The structural dynamic responses of a large-sized floating wind turbine, undergoing random wind&wave loads, are examined by the integrated approach including the flexible blades, tower, spar and mooring-lines. To consider the catenary dynamics and the coupling between the flexible multi-bodies, the integrated approach uses the vector model of the mooring-line together with the modified FEM model. The impacts of the catenary dynamics on mooring-line stiffness and restoring performance and the structure response of the integrated wind turbine are presented. Our numerical results show:

The maximum top tension of the mooring-line could rise remarkably due to the mooring-line dynamics. The top tension gets larger with the increase of the spar motion, and, particularly, the snap tension is 3 times larger than the quasi-static value. The structural response under random wind&wave loads gets smaller principally because of the hysteresis effect coming from the mooring-line dynamics. For examples, the spar displacement at surge frequency is about 20% smaller; the tower root stress at bending frequency is about 30% smaller than the quasi-static value.

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