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Coupled Response Analysis of an Offshore Articulated Wind Turbine under Different Environmental Loads

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ABSTRACT

In this paper, an offshore articulated wind turbine structure is proposed for the water depth of 70 meters. Considering the influence of different environmental factors, the dynamic responses of the structure are studied. Three dimensional potential flow theory was used to calculate the hydrodynamic characteristics of the structure, and the blade element momentum theory was used to calculate the aerodynamic load, the influence of foundation motion, wave surface elevation and friction damping of articulated joint were certainly considered. The control equation in the time domain is set up and the motion response is solved. It is shown that the aerodynamic load has great influence on the average response amplitude, including the average pitch angle, the rotor thrust and the tension of articulated joint. while the wave load is related to the variation of amplitude. The structure will produce a large coupling low-frequency response in the low-frequency range with wave and wind. Especially, under the action of turbulent wind, the coupling effect increases sharply.

Key words: offshore articulated wind turbine; blade element momentum theory; aerodynamic load; coupling effect

1 INTRODUCTION

At present, there are two main types of foundations to support wind turbine in the offshore wind farm. One is fixed foundation, the other is floating foundation. Among different fixed foundations, the most popular ones are monopole gravity type, tripod type and jacket type. These fixed foundations are mainly used for water depth less than 50 meters. When the water depth exceeds 100 meters, the floating wind turbine may be a better choice. Currently, there are three principal concepts about floating wind turbine are applied. They are Spar type, TLP type and semi-submersible type.

For water depth from 50 to 70 meters, it is lack of appropriate foundation consideration of economic and safety reasons. Due to China's special offshore continental shelf landform, when the water depth reaches 100 meters, the offshore distance will reach 50 kilometers or more, and the cost of laying cables and related supporting facilities will increase sharply. Therefore, combined with China's national conditions and market demand, it is particularly important to develop a new foundation wind turbine which is suitable for the water depth about 70 meters.

For the articulated wind turbine, there is a lack of related research at home and abroad. Wandji WN et. al [1] proposed a design of semi-floating articulated wind turbine, which is applied to 50 meters water depth. The design mainly includes floating system, mooring system and articulated connection system. They use the finite element software to analyze the reliability of the structure and calculate the fatigue load. The numerical response of the sway motion under different working conditions are also calculated. Vivek Philip et. al [2] proposed a three-leg articulated foundation design for a 5MW wind turbine. They used relevant professional software to study the dynamic response of superstructure and articulated foundation under the combined action of wind, wave and flow. The structural response under different wave directions and wind speeds were compared and analyzed. Joy CM et.al [3] conducted a group of experiments on the three-leg articulated wind turbine with a scale ratio of 1:60. They tested the dynamic response of the whole structure in regular waves. And the natural frequency of the structure is measured, which is away from the wave frequency range. Based on previous work, Navin.S.S et. al [4] numerically calculated the tension response of articulated joint under different environmental loads. And then, they loaded tension time history data into the universal joint model to analyze its fatigue performance. Liu liqin et. al [5] proposed a new floating foundation combining semi-submersible and Spar type for medium water depth. Based on three dimensional potential flow theory and blade element momentum theory, the foundation hydrodynamic and motion response characteristics are studied.

At present, the coupled effect between aerodynamic load and hydrodynamic load is not considered in the dynamic response analysis of articulated wind turbines. The structural design of articulated foundation is relatively simple, and the operating depth is not suitable for China's offshore landform. In this paper, a new type of articulated wind turbine structure is proposed. Considering the aerodynamic, hydrodynamic and dynamics theories, a single-degree-of-freedom rigid body analysis model of the articulated wind turbine was established. We adopt the motion control program [6] in the time domain for calculation, and the dynamic response characteristics is under different sea conditions.

2 STUDY METHODOLOGY

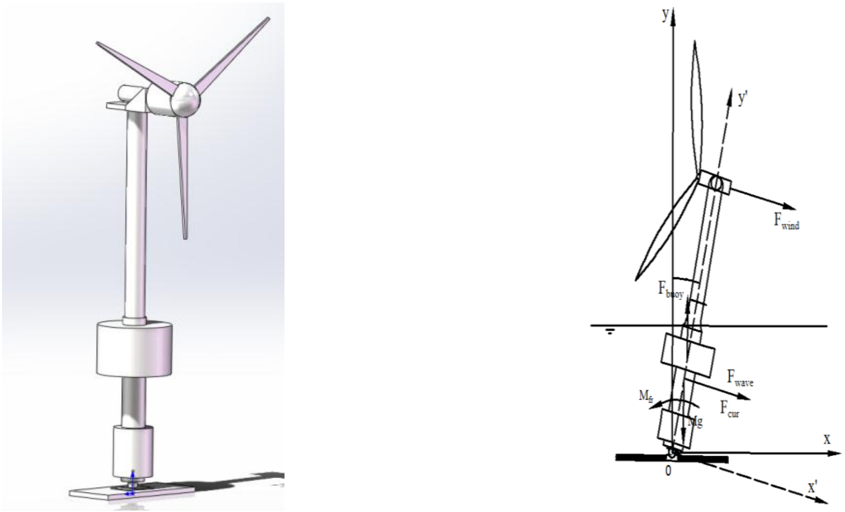
2.1 The physical model

Based on the NREL-5MW wind turbine, we designed a new type of articulated wind turbine. The foundation column is connected to the seabed foundation by the universal articulated ball. The external ballast tank is set at the bottom of the foundation to reduce the center of gravity of the whole structure. The external buoyancy chamber is set near the water surface to make up for the lack of stability. The foundation has a certain air gap height above the water surface and is connected with upper wind turbine tower. The articulated foundation and the upper wind turbine swing together around the universal joint. Main design parameters are shown in table 1.

Table 1: Main design parameters of articulated offshore wind turbine

Parameter	Value	Parameter	Value
Design depth	70 m	Rated power	5MW
Column diameter	6 m	Wind direction	upwind
Ballast tank diameter	10m	Blade quantity	3
Buoyancy chamber diameter	19 m	Rotor radius	63 m
The air gap height	10 m	hub radius	1.5 m
Mass of foundation	2135975 kg	Cut-in wind speed	3 m/s
Center of gravity(foundation)	（0.0 m，0.0 m，38.59 m）	Rated wind speed	11.4 m/s
Total mass	5210387 kg	Cut-out wind speed	25 m/s
Center of gravity (whole structure)	（0.0 m，0.0 m，39.61 m）	Rated speed	12.1 rpm
Total buoyancy	8220100 kg	Hub Height (from the bottom of waterline)	90 m
Center of buoyancy (whole structure)	（0.0 m，0.0 m，45.41 m）	Mass of upper wind turbine	670324 kg
Natural frequency(pitch)	0.225 rad/s	Center of gravity (upper wind turbine,from the bottom of waterline)	68.0 m

In this paper, the physical and theoretical model of articulated wind turbine are established based on the articulated tower platform [7-9]. It is assumed that the articulated foundation and the upper wind turbine are all rigid body, the foundation column and the wind turbine tower are rigidly connected. The whole structure swings around the articulated joint in a single DOF motion, as is shown in figure 1. Rectangular coordinate system is used in this paper. The articulated joint is defined as the origin of system coordinate, the perpendicular direction of wheeling surface is the X-axis direction, and the vertical direction from articulated joint to the hub is the Y-axis direction. In this paper, environmental loads are always considered along the X-axis direction.



(a) Three-dimensional sketch (b)Two-dimensional analytical model

Figure 1: Mode1 of the articulated offshore wind turbine

2.2 Motion governing equation

The hydrodynamic parameters such as the additional moment of inertia, the potential flow damping and the first-order wave force transfer function are calculated by using the hydrodynamic software SESAM. Since the hydrodynamic parameters corresponding to any frequency cannot be directly substituted into the time-domain equation in irregular waves, the additional rotational moment of inertia and potential flow damping are converted into hysteresis functions by the convolution integral method. The first-order wave force transfer function is converted into the wave load at each moment according to the wave frequency component and substituted into the governing equation. Finally, we use the fourth order runge-kutta numerical method to solve each time step motion, and the time domain motion response is obtained.

The time-domain motion governing equation of the structure can be expressed as:

$$[I+I_A(\omega)]\ddot{\theta}+(C_1(\omega)+C_2)\dot{\theta}+M_{fr}(\dot{\theta})+M_{gb}(\theta)=F_{wave}+F_{wind}+F_{cur} \tag{1}$$

In the formula: I is the moment of inertia of whole system, $I_A(\omega)$ is the additional moment of inertia, $C_1(\omega)$ is the potential flow damping, C_2 is the viscous damping, $M_{fr}(\dot{\theta})$ is the friction moment of articulated joint, $M_{\mathrm{gb}}(\theta)$ is the system restoring moment, F_{wave} is the wave force, F_{wind} is the aerodynamic force of impeller and wind force on tower, F_{cur} is the current force.

2.3 Wind loading

Before conducting the aerodynamic performance analysis of the wind turbine, it is necessary to simulate the random wind field. In this paper, the wind field under two characteristics of constant wind and turbulent wind are mainly considered.

In the case of the constant wind, the wind shear model is used to calculate the wind speed changing with height [10]. Based on the wind speed of the hub, the wind speed at each blade element can be obtained.

The turbulent wind is simulated by NPD wind spectrum. For strong wind condition, the design wind speed *u(z,t)* ($t \le t_0$=3600s) is calculated as follows:

$$u(z,t)=U_z\left[1-0.41\cdot I_u(z)\cdot\ln\left(\frac{t}{t_0}\right)\right] \tag{2}$$

$$I_u(z)=0.061+0.043\cdot U_0\left(\frac{z}{10}\right)^{-0.22}$$
$$U_z=U_0\left[1+C\cdot\ln\left(\frac{z}{10}\right)\right] \tag{3}$$
$$C=5.73\times10^{-2}(1+0.15\cdot U_0)^{0.5}$$

In the formula, U_z is the 1-hour average wind speed at z meters above sea level, $I_u(z)$ is the turbulence intensity factor, U_0 is the 1-hour average wind speed at 10 meters above sea level, the following spectrum functions are used to generate the time-varying wind speed.

$$\begin{cases} S(f)=\dfrac{320\cdot\left(\dfrac{U_0}{10}\right)^2\cdot\left(\dfrac{z}{10}\right)^{0.45}}{\left(1+f_m^n\right)^{\frac{5}{3n}}} \\ f_m=172\cdot f\cdot\left(\dfrac{U_0}{10}\right)^{-0.75}\cdot\left(\dfrac{z}{10}\right)^{2/3} \end{cases} \tag{4}$$

Where, $\mathrm{n}=0.468$; $S(f)$ is the spectrum density function; f is the frequency, and the range of value is: $1/600H_z\le f\le0.5H_z$ .Therefore, turbulent wind at z meters above sea level can be interpreted by superposition of design wind speed and time varying wind speed. It is calculated by the following formula:

$$U_{turbence}=u(z,t)+\sqrt{2\cdot S(f)\cdot df}\cdot\cos(2\pi\cdot f\cdot t+\theta) \tag{5}$$

Where, θ is the random phase, and the simulation time t is 3600s. In this paper, we take the rated wind speed (11.4m/s) for example, considering the wind shear effect, the design wind speed amplitude at the hub is calculated according to the Eq. (2), and the time-varying wind speed was generated by combining the spectrum density function according to the Eq. (4). The 1 hour simulation result was taken to draw the diagram, and the turbulent wind time history curve was obtained below.

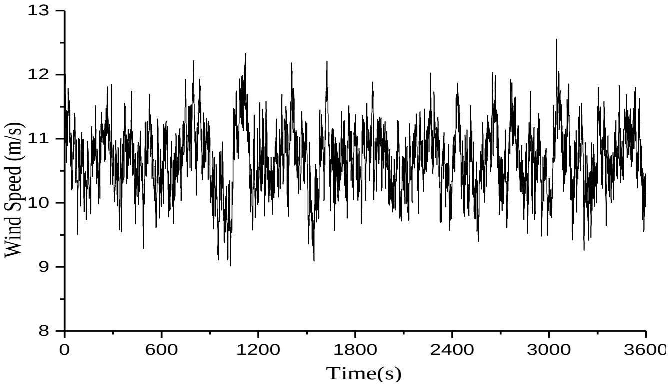


Figure 2: Turbulent wind time history curve at the hub

The wind loads of the system include the aerodynamic load on the impeller and the wind pressure load on tower. The aerodynamic load is calculated by using blade element momentum theory, and the blade is divided into a large number of segments along the spreading direction, which are called as blade elements. For each blade element, the momentum theory is used to solve the force and moment, and results are integrated along the spreading direction to obtain the axial thrust and rotational moment on the whole blade.

The computational formulas of total velocity seen by blade element and induction factors are equivalent to:

$$a=\frac{1}{\dfrac{4F\sin^2\phi}{\sigma_r(C_L\cos\phi+C_D\sin\phi)}+1} \tag{6}$$

$$a'=\frac{1}{\dfrac{4F\sin\phi\cos\phi}{\sigma_r(C_L\sin\phi-C_D\cos\phi)}-1} \tag{7}$$

$$V_{\mathrm{rel}}=\sqrt{(v_0-v_0a)^2+(wr+wra')^2} \tag{8}$$

$$F=\frac{2}{\pi}ar\cos\left(\exp\left(-\frac{B}{2}\frac{R-r}{r\sin\phi}\right)\right)\cdot\frac{2}{\pi}ar\cos\left(\exp\left(-\frac{B}{2}\frac{r-R_{hub}}{r\sin\phi}\right)\right) \tag{9}$$

Where, a is the axial induction factor, a' is the tangential induction factor, $\sigma_{\mathrm{r}}=cB/2\pi r$ is the local solidity, r is the local radius, c is the chord length, R_{hub} is the hub radius, w is the rotor rotational speed, ϕ is the local flow angle, C_L and C_D are respectively the lift coefficient and drag coefficient. The solution of the induction coefficient is a iterative process until it converges to a reasonable value.

Where, F is the prandtl coefficient which combined tip-loss and hub-loss, it is a modification of the assumption that the number of blades is infinite. When the induction factor is greater than 0.4, the simple momentum theory is no longer applicable, so the glauert correction is introduced. Where $a_c=0.2$, the formula is equivalent to:

$$a=\begin{cases}\dfrac{1}{K+1} & a\le a_c\\ \dfrac{1}{2}\left[2+K(1\text{-}2a_c)-\sqrt{\left[K(1-2a_c)+2\right]^2+4(Ka_c{}^2\text{-}1)}\right] & a>a_c\end{cases} \tag{10}$$

The axial thrust and tangential torque of each blade element in the blade are calculated as follows. The axial thrust and tangential torque of the entire blade are obtained by integrating the obtained results along the spreading direction.

$$\mathrm{dT}=\frac{1}{2}\rho V_{rel}{}^2B\mathrm{c}(C_L\cos\phi+C_D\sin\phi)Fdr \tag{11}$$

$$\mathrm{dM}=\frac{1}{2}\rho V_{rel}{}^2B\mathrm{c}(C_L\sin\phi-C_D\cos\phi)Fdr \tag{12}$$

The wind load on tower is calculated according to the CCS document, as is shown in Eq. (13) below.

$$F_{wind}=0.613\sum_{j=1}^{n}\left(C_hC_sA_i(\alpha)V_{\mathrm{r}}{}^2\right) \tag{13}$$

In the formula, j is the number of component; n is the quantity of components; C_h is the height coefficient of component; C_s is the shape coefficient of component; $A_i(\alpha)$ is the projected area of component i on the α wind direction; V_r is the relative velocity between the wind and component.

The total wind moment is calculated by the following formula:

$$M_{\mathrm{w}}=T\cdot L_1+F_{wind}\cdot L_2 \tag{14}$$

Where, T is the rotor axial thrust; L_1 is the distance from rotor thrust to the articulated joint; L_2 is the distance from wind component to the articulated joint.

2.4 Wave loading

The wave load of articulated wind turbine is solved by using three-dimensional potential flow theory considering the diffraction and radiation effect. Velocity potential can be divided into: the incident potential, the diffraction potential and the radiation potential. Velocity potential on each element can be solved by the surface element method. The water pressure of the fluid is solved according to Bernoulli equation, and the wave load of the floating body is integrated along the whole surface.

2.5 Current loading

Current load on the foundation column is calculated in accordance with CCS document from the following formula:

$$F_{cur} = \frac{1}{2} C_D \rho_W A V_{cur}{}^{2} \tag{15}$$

Where, C_D is the drag force coefficient; ρ_W is the density of sea water; A is the projected area of the component on the plane perpendicular to the current velocity.

3 NUMERICAL RESULTS AND ANALYSIS

3.1 Ocean conditions parameters

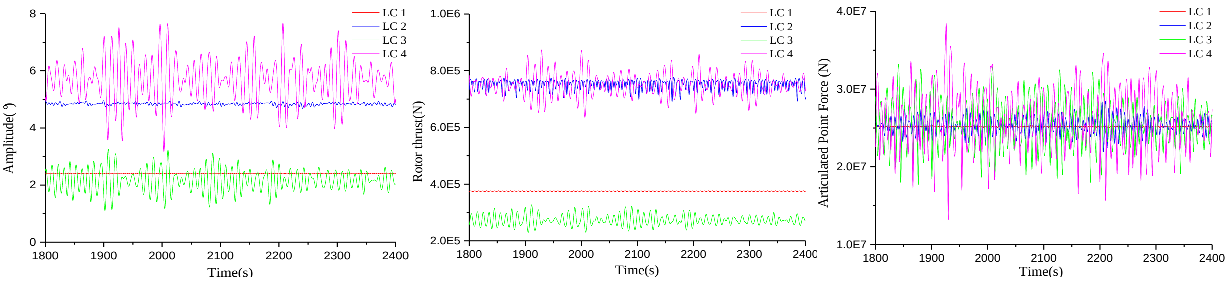
The design water depth of the articulated offshore wind turbine is 70 meters, and considering the combined effect of wind, wave and current. Random waves generated by JONSWAP wave spectrum were used to describe irregular wave. Wave incident direction is positive along the X-axis. For wind load, constant wind and turbulent wind are both studied in this paper. The influence of flow is small, so constant flow is sufficient for the calculation. Eight conditions are conducted, the first seven are power generation conditions, the last one is the limit condition. The specific condition parameters are shown in table 2 below.

Table 2: Condition parameters

Conditions	Wind speed（m/s）		Significant wave height（m）	Peaked period（s）	Flow speed（m/s）
LC 1	Constant wind	8.0	1.0	3.5	0.2
LC 2		11.4	3.0	6.3	0.4
LC 2-1		——	3.0	6.3	——
LC 2-2		11.4	——	——	——
LC 2-3		11.4	3.0	6.3	——
LC 2-4	Turbulent wind	11.4	3.0	6.3	0.4
LC 3	Constant wind	25.0	8.0	10.6	1.0
LC 4	Constant wind	40.0	11.0	12.0	1.5

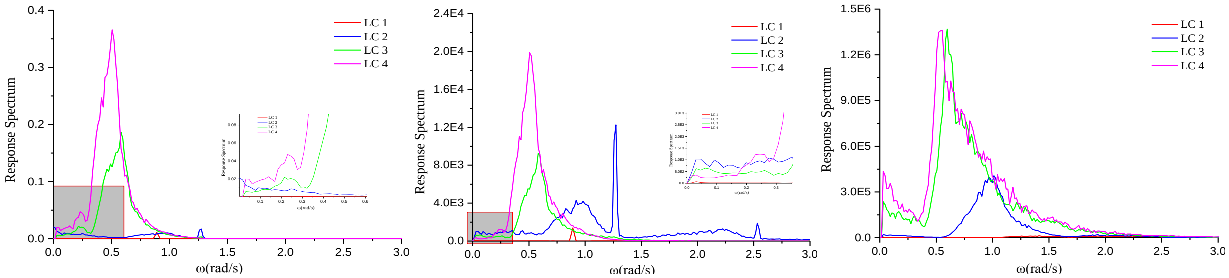
3.2 Dynamic response analysis under the combined effect of wind, wave and current

For LC1/2/3/4 these four different conditions, we conducted dynamic response analysis under the combined effect of wind, wave and current. The simulation time was 3600s, and the data in stable stage of 30-40min were taken to make a graph. The time-history results were converted to the frequency domain by using Fast Fourier Transformation.



(a) Average pitch angle (b) Rotor thrust (c) Articulated joint tension

Figure 3 Time history of the dynamic response under combined effect of wind, wave and current



(a) Average pitch angle (b) Rotor thrust (c) Articulated joint tension

Figure 4 Response spectrum of the dynamic response under combined effect of wind, wave and current

As can be seen from time history figures, with the increase of condition grade, response amplitude of average pitch angle and rotor thrust increase first, and reach the extreme value at rated wind speed condition, then decrease. The maximum pitching angle is 4.91 degree at rated wind speed condition, which fully meet the requirement of power generation condition(no more than 5 degree) [11-12]. Average pitch angle and rotor thrust were mainly affected by axial component of aerodynamic load. When the wind speed exceeded the rated wind speed, in order to maintain the constant power generation, the blade pitch angle would be adjusted to change the lift and drag coefficients. In this way, the tangential moment component of the wind turbine would keep constant, while the axial thrust component decreased gradually. When the wind speed exceeded the cut-out wind speed, the rotor would stop, and the wind load increased with the increase of the wind speed.

The articulated joint tension could be divided into horizontal tension and vertical tension. The horizontal tension was mainly affected by environmental loads such as wind, wave and current, while the vertical tension was mainly affected by residual buoyancy. With the increase of condition grade, the average response amplitude almost keep unchanged, indicating that the residual buoyancy dominates the overall tension, and the variation of amplitude increased gradually under the influence of wave load.

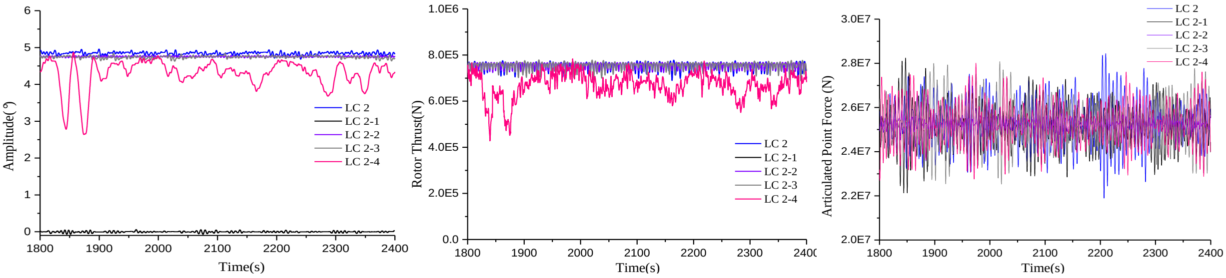
It can be seen from the response spectrum that the response amplitude of the average pitch angle, rotor thrust and the articulated joint tension were mainly caused by the wave frequency load. Under the rated wind speed condition, the coupled low frequency response caused by aerodynamic and hydrodynamic loads increased to the maximum. In the rotor thrust response spectrum, for the rated wind speed condition, 1P load frequency component at 1.27 rad/s and the coupling high frequency component at 2.5 rad/s had significant effect. There is no large response and resonance near the natural frequency, the motion performance of the structure is great.

3.3 Dynamic response analysis under different environmental factors

The numerical simulation is carried out for investigating the effect of different environmental factors due to:

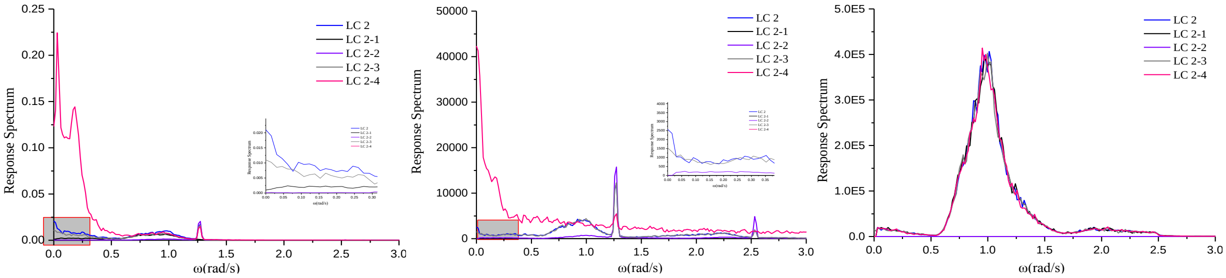
(i) Wave only
(ii) Wind only (constant wind)
(iii) Wind and wave acting together(constant wind)
(iv) Wind, wave and flow acting together(constant wind)
(v) Wind, wave and flow acting together(turbulent wind)

Characteristics of sea states are shown in table 2 above, we chose LC 2/2-1/2-2/2-3/2-4 these five conditions for numerical calculation.The simulation time was 3600s, and the data in stable stage of 30-40 minutes were taken to make a graph. The time-history results were converted to the frequency domain by using Fast Fourier Transformation.



(a) Average pitch angle (b) Rotor thrust (c) Articulated joint tension

Figure 5 Time history of the dynamic response under different environmental factors



(a) Average pitch angle (b) Rotor thrust (c) Articulated joint tension

Figure 6 Response spectrum of the dynamic response under different environmental factors

For figures above, the first four are constant wind conditions, and the last one is turbulent wind condition. Based on the rated wind speed, we conducted dynamic response study on different environmental conditions.

As can be seen from time history figures, compared with the single wind load or wave load, response amplitude of average pitch angle, rotor thrust and articulated joint tension increased significantly under the combined action of wind and wave. Turbulent wind reduced the average amplitude of response to a certain extent, but significantly increased the variation of amplitude.

As can be seen from response spectrum figures above, compared with the single wind load or wave load, when wind and wave act together, a relatively significant low-frequency response less than 0.2rad /s appeared in the figure. This is the low frequency resonance response caused by the coupling of aerodynamic and hydrodynamic load, and the peak of the low frequency response even exceeds the peak of the wave frequency response. For average pitch angle and rotor thrust response, the turbulent wind induced a larger coupling effect at the low frequency. At the same time, the wave frequency response near 0.99 rad /s and 1P load frequency response near 1.27 rad/s were suppressed to some extent. So the turbulent wind weakens the influence of wave load and rotor rotation on the dynamic response of the structure. It can be seen from response spectrum of articulated joint tension that the response amplitude is mainly affected by the wave frequency response.

4 CONCLUSION

For 70 meters water depth, this paper puts forward a new type of articulated offshore wind turbine. Considering the aerodynamic, hydrodynamic and dynamics theories, a single-degree-of-freedom rigid body analysis model of the articulated wind turbine was established. According to the results above, the following main conclusions are drawn.

(i) Considering the combined action of wind, wave and current, the articulated wind turbine has both good motion performance in power generation condition and the limit condition. Motion parameters can fully meet the normal power generation requirement under the working condition, and self-survival requirement under the limit condition is also satisfied.

(ii) Under the rated wind speed condition, the dynamic response caused by aerodynamic load plays a major role in the overall structural response, while for other wind speed conditions, the structural dynamic response is mainly affected by the wave frequency response. At the same time, the aerodynamic load has a great influence on the average response amplitude, while the wave load is related to the variation of amplitude.

(iii) When wind and wave act together, a large coupling low-frequency response will be generated within the low-frequency range. Especially under the influence of turbulent wind, the coupling effect increases significantly. The turbulent wind reduces the average amplitude of the response to a certain extent, but increases the variation of amplitude. So the turbulent wind weakens the influence of wave load and rotor rotation on the dynamic response of the structure as a whole.

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