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Numerical Study of Aerodynamic Performances of Floating Offshore Wind Turbine with Rotation and Pitching Motion

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ABSTRACT

To obtain the aerodynamic loads of a floating wind turbine with rotation and pitching motion, a numerical simulation method based on FAST is established. The OC3 Hywind-NREL 5MW is taken as the research object, the aerodynamic load coefficient and energy utilization coefficient at different wave period were analyzed. The results show that the time history curve of the aerodynamic coefficient and energy utilization coefficient have obvious periodic fluctuations. The fluctuation frequency of aerodynamic load coefficient and energy utilization coefficient curve depends on wave frequency; The average value of the fluctuation depends on the aerodynamic load coefficient and energy utilization coefficient of the wind turbine when it does not surge. The amplitude of the fluctuation increases with the increase of wave period. On this basis, the damping and added mass coefficients are obtained based on the least square method. The amplitude of aerodynamic coefficient and energy utilization coefficient of wind turbine have big correlation with damping coefficient. The research findings can provide relevant data for studying the coupled motion of floating wind turbine.

KEY WORDS: Floating wind turbine; FAST; Coupled analysis; Aerodynamic coefficient;

INTRODUCTION

The problems caused by traditional fossil energy are increasingly serious, and people are now actively developing clean and renewable energy. Wind energy is a renewable and non-polluting energy source that has received increasing attention in recent years. The concept of floating wind turbines was first proposed in 1972 by Professor Heronemus (Heronemus, 1972) at the University of Massachusetts, Amherst, USA. In 2009, Hywind, the world's first floating wind turbine, was commissioned off the coast of Norway. The wind turbine is invested and built by Equinor, Norway. In 2011, Principle Power developed the WindFloat and installed a sea trial prototype which is a single Vestas V80-2.0MW wind turbine. In 2017, the first floating offshore wind project was commissioned. Because of the advantages of stable operation, high efficiency and large installed capacity, floating wind turbines have attracted widespread attention from experts and scholars in various countries. (Wan and Cheng, 2017)

The first-order and second-order hydrodynamic forces of floating structures are usually expressed in the form of hydrodynamic coefficient. The wind turbine aerodynamic forces are often calculated using BEM theory. The strong coupling between the aerodynamic loads and the motion of floating wind turbines makes it difficult to express in form of hydrodynamic coefficient, so the analysis of wave motion response of floating wind turbines requires time-domain coupling method and relatively longer calculation time. So, it is necessary to research the aerodynamic performance of the floating offshore wind turbine, and some studies focusing on different aspects have been performed. Han and Tang (2016) proposed a computational model for wind loads based on the blade element momentum theory and considered the effect of floating foundation motion on the relative incoming wind speed at different radial positions of the blade. Liu and Han (2018) developed a Matlab non-constant aerodynamic load calculation program to study the aerodynamic characteristics of floating horizontal axis wind turbines. Qian (2019) completed the ALM (Actuation Line Method), which integrates the whole aircraft blade, nacelle and tower, and coupled with RANS, LES and PANS turbulence models for the wake flow study.

This paper investigates the numerical simulation of the coupled motion response of a floating wind turbine in waves. The least squares method is used to obtain the aerodynamic coefficients of the wind turbine motion response, making possible the coupled motion analysis in waves by frequency domain algorithms. In this paper, OC3 Hywind-NREL 5MW is used as the research object, and the calculational models of floating wind turbine, floating platform and mooring system are established in FAST software. The coupled motion of a floating wind turbine is simplified for some specific operating conditions under uniform flow and shear flow. The relationship between the motion response amplitude, wind turbine load, energy utilization coefficient and wave period is established for the single degree of freedom motion. The least squares method was used to obtain the aerodynamic coefficients of the wind turbine motion response, and the variation law of the aerodynamic coefficients with wave parameters was analyzed.

MATHEMATICAL MODEL

In real sea conditions, the presence of waves causes a motion response of the floating body, which drives the oscillating motion of the floating wind turbine. Because the actual working situation is very complex, the problem needs to be simplified to some extent.

(1) Wind turbine and floating body fixed connection;
(2) Wind turbines without tower shadow effect;
(3) Neglecting the effect of waves on the incoming current velocity, assume that the incoming flow velocity is constant;
(4) Only single-degree-of-freedom longitudinal motion is considered. (Wang and Zhang, 2021)

Taking the above assumptions as a premise, to study the forced motion of a floating wind turbine under the action of uniform wind and regular waves.

Aerodynamic coefficient analysis method

From Newton's second law, we know that the six-degree-of-freedom equation of motion of the structure in the flow field can be expressed in the following form:

$$M_{kj}\ddot{\eta}_j = -C_{kj}\eta_j - \sum_{j=1}^{6}\left(\mu_{kj}\ddot{\eta}_j + \lambda_{kj}\dot{\eta}_j\right) + f_k e^{i\omega t}\,(k=1,2\ldots 6) \tag{1}$$

η_j, $\dot{\eta}_j$, $\ddot{\eta}_j$ are the displacements, velocities and accelerations of the structure in the six directions of freedom, respectively. M_{kj} is the generalized mass matrix of the structure, μ_{kj}, λ_{kj} are added mass and damping matrix respectively, f_k is the wave disturbance force acting on the structure.

Generally, the structure can be divided into large scale and small scale structures. The radiation and bypassing effects of large scale marine structures on the flow field are obvious, and the fluid viscous forces are negligible. Small-scale marine structures are smaller in scale, it can be considered as having no effect on the wave flow field, however, the wake and vortex shedding caused by fluid viscosity has an important effect on structural loads. For large scale marine structures, the hydrodynamic calculations are mainly based on potential flow theory, while for small scale marine structures, the Morison formula is generally used.

Calculation method of aerodynamic coefficients

This paper uses FAST software to numerically simulate the forced motion of a floating wind turbine under uniform wind and regular waves, and obtain the time history curves of axial load coefficient and energy utilization coefficient during surge motion.

$$\xi = \xi_0 \sin\omega t + \mathrm{C} \tag{2}$$

$$\dot{\xi} = \xi_0\omega\cos\omega t \tag{3}$$

$$\ddot{\xi} = -\xi_0\omega^2\sin\omega t \tag{4}$$

In the above equation, ξ_0, ω are the amplitude and frequency of the longitudinal motion, respectively. ξ, ξ_0, ξ_0 are the surge displacement, surge velocity and surge acceleration, respectively.
By numerical simulations, the forces on the structure in the incoming wind direction can be obtained. The load for the surge motion of the wind turbine can be written as the following expression:

$$F = F_0 + \mu\dot{\xi} + \lambda\ddot{\xi} \tag{5}$$

Where, F is the load on the wind turbine, and it contains the load in phase with the surge motion and the load intersecting the phase of the surge motion.

Combining Eq. 3 and Eq. 4 can be written in the following form:

$$F = F_0 + F_a\cos\omega t + F_b\sin\omega t \tag{6}$$

Where, F_0 is a constant term independent of motion; F_a and F_b are the amplitudes of the damping force and the added mass force obtained after decomposition, respectively.

Eq. 6 is used as the fitting formula to fit the time history curve of the aerodynamic load coefficient and the time history curve of the energy utilization coefficient. And we can obtain the damping coefficient and the added mass coefficient of the structure as follows:

$$\mu = \frac{F_a}{\xi_0\omega}, \quad \lambda = -\frac{F_b}{\xi_0\omega^2} \tag{7}$$

Numerical analysis method

By numerical simulation, we are able to obtain the time history curves of the axial force and energy utilization coefficient of the wind turbine. To further analyze the data curves of the numerical simulation results, The best fitting formula needs to be chosen to replace the calculated curve. In this paper, the least squares method is used for function fitting.

If a set of data $(x_i, y_i)(i = 0,1,2,\ldots,m)$ is known, suppose there is a general function expression for $\delta = \{\delta_0, \delta_1, \cdots, \delta_n\}$, to find such a function, let the sum of squares of the errors satisfy Eq. 8, It can be expressed geometrically as a least squares curve fit.

$$\|\sigma\|_2^2 = \sum_{i=0}^{m}\sigma_i^2 = \sum_{i=0}^{m}\left[s^*(x_i) - y_i\right]^2 = \min_{s(x)\in\delta}\sum_{i=1}^{m}\left[s(x_i) - y_i\right]^2 \tag{8}$$

In Eq. 8, $s(x) = a_0\delta_0(x) + a_1\delta_1(x) + \cdots + a_n\delta_n(x), \quad (n < m)$

If we consider the weighted sum of squares in $\|\sigma\|_2^2$,

$$\|\sigma\|_2^2 = \sum_{i=0}^{m} w(x_i)\left[s(x_i) - f(x_i)\right]^2 \tag{9}$$

where $w(x) \geq 0$ is called the weight function $(x_i, f(x_i))$ and characterizes the different weights at different data points. Let

$$Q(a_0, a_1, \ldots, a_n) = \sum_{i=0}^{m} w(x_i)\left[\sum a_j\delta_j(x_i) - f(x_i)\right]^2 \to \min \tag{10}$$

$$\frac{\partial Q}{\partial a_k}=2\sum w(x_i)\left[\sum_{j=0}^{n}a_j\delta_j(x_i)-f(x_i)\right]^2\delta_k(x_i)=0(k=0,1,\ldots,n) \tag{11}$$

The above equations can be written in matrix form, and since $\delta_0,\delta_1,\ldots,\delta_n$ is linearly independent, there is a unique solution to the system of equations. This yields the least squares solution of $f(x)$ as:

$$s^*(x)=a_0^*\delta_0(x)+a_1^*\delta_1(x)+\cdots+a_n^*\delta_n(x) \tag{12}$$

Calculation model of aerodynamic coefficients for floating wind turbines under surge conditions

In the operating condition of floating wind turbine, the wind turbine rotates normally and there is surge motion. The wind wheel is affected by both the wind turbine rotation frequency and the surge frequency, so the calculation method of the general marine structure hydrodynamic coefficient cannot be applied directly.(Wang and Li, 2021)

In this paper, the aerodynamic coefficients of floating wind turbine are analyzed based on the numerical simulation results of FAST software. We define the basic parameters of the longitudinal motion as follows：

Dimensionless surge velocity

$$\bar{u}_{zd}=\frac{A_{zd}\omega_{zd}}{U}\cos(\omega_{zd}t) \tag{13}$$

Dimensionless surge acceleration

$$\bar{a}_{zd}=-\frac{A_{zd}\omega_{zd}^2R}{U^2}\sin(\omega_{zd}t) \tag{14}$$

Dimensionless pneumatic load (axial load factor)

$$C_Z=\frac{\mathrm{F}}{\frac{1}{2}\rho U^2A} \tag{15}$$

Expression of axial load factor of wind turbine

$$C_Z=C_Z^F+n_{zd}\bar{u}_{zd}+m_{zd}\bar{a}_{zd} \tag{16}$$

where: A_{zd} is the surge amplitude in m; ω_{zd} is the surge frequency in rad/s; U is the uniform flow velocity in m/s, defining the direction of flow of the incoming velocity as positive on the Z-axis. R is the radius of the wind wheel in m; A is the surface area of the wind turbine in m2; $\bar{u}_{zd}$ is the dimensionless surge velocity; $\bar{a}_{zd}$ is the dimensionless surge acceleration; C_Z is the axial load factor of the wind wheel during the surge motion; n_{zd} is the damping factor; m_{zd} is the added mass factor.(Sheng and Jing, 2016)

NUMERICAL SIMULATION

The floating wind turbine system mainly consists of floating body, wind turbine tower, nacelle, wind turbine and mooring system. The upper wind turbine is the 5MW wind turbine proposed by National Renewable Energy Laboratory (NREL). The OC3-Hywind is used as a floating body support structure in the lower part.

The main parameters of computational model

In this section, the main parameters of the calculational model are described. The calculational model in this case is a 5MW wind turbine which is proposed by Renewable Energy Laboratory in the United States. The main body of the NREL 5MW wind turbine tower is a hollow cylinder with progressively varying radius and wall thickness. The blades are the part that has a decisive influence on the aerodynamic characteristics of the floating wind turbine. The OC3-Hywind float is a single column Spar type float. The main body is cylinders with different two diameters, which are distributed in the upper and lower sections and connected in the middle by a circular table. The platform has a draft of 120m, and the connection between the floating body and the tower is at a distance of 10m from the still water surface. The schematic layout of OC3-Hywind's mooring system is shown in Fig.1 (J Jonkman and Musial, 2010). The specific design parameters of the wind turbine, floating body and mooring lines are shown in Table 1~3 (J Jonkman and Musial, 2010).

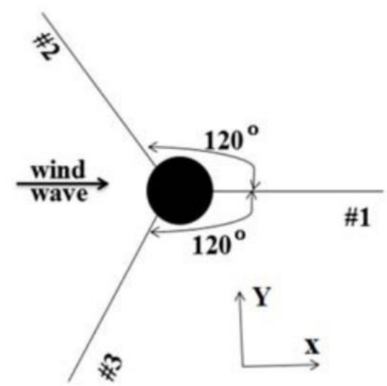


Fig. 1. Mooring system

Table 1. Design parameters of NREL 5MW wind turbine

Design Projects	Design Parameters
Capacity	5 MW
Type	Windward type ; Triple Blades
Control Strategy	Variable speed ; Synchronous pitch
Drivetrain	High-speed multi-stage gearbox
Rotor Diameter	126m
Hub Diameter	3 m
Hub height	90 m
Cut-in /rated /cut-out wind speed	3 m/s ; 11.4 m/s ; 25 m/s
Cut-in/rated rotor rate	6.9 rpm; 12.1 rpm
Rated tip speed	80 m/s
Overhang axis length / inclination / pitch angle	5 m; 5° ; 2.5°
Rotor mass	110000 kg
Nacelle mass	240000 kg
Tower mass	347460 kg
Total mass	8130315.388 kg
Position of the center of mass	(-0.2 m, 0.0 m, 64.0 m)

Table 2. The specific parameters of the tower and the design parameters of blades

Tower parameters		Blade Parameters	
Design Projects	Design parameters	Design Projects	Design parameters
Tower height	87.6 m	Blade length (from the blade root along the pitch axis to the blade tip)	61.5 m
Tower mass	347460 kg	Total blade weight	1774 kg
Tower mass center position	(0.0 m, 0.0 m, 38.2 m)	Total center of gravity of the blade (distance from the blade root along the pitch axis)	20.47 m
Structural damping ratio	1%		
Diameter of the bottom end of the tower	6 m		
Thickness of the bottom end of the tower	0.027 m		
Diameter of the top of the tower	3.87 m		
Thickness of the top of the tower	0.019 m		

Numerical simulation results under different incoming winds

In this section, we will perform a numerical simulation of the single-degree-of-freedom surge motion using FAST.

Numerical simulation results under uniform flow

In order to study the effect of wave periods on the aerodynamic load of horizontal axis wind turbine. In this section, four calculation conditions with wind turbine speed of 8rpm, wave height of 6m and wave period of 4s, 6s, 8s and 12s are selected. FAST is used to calculate the magnitude of the surge displacement of the wind turbine for two calculation conditions, the time history curve of the surge displacement for each working condition is shown in Fig. 2.

As seen in Fig. 2, the surge displacement of the floating wind turbine is fluctuating periodically under the regular wave periodic fluctuations. In order to obtain the relationship between the surge displacement and the wave parameters, we fit the curve as a function by fitting software, and the fitting results are shown in Table 4.

Table 3. OC3-Hywind floating body, mooring main parameters

OC3-Hywind floating body main scale and weight center of gravity		OC3-Hywind mooring system	
Design Projects	Design parameters	Design Projects	Design parameters
Number of mooring lines	3	Total draft	120 m
Angle between adjacent cables	120°	Platform height above waterline	10 m
Distance from anchor point to still water surface (water depth)	320 m	Distance from the waterline on the surface of the round table	4 m
Distance of cable guide hole from hydrostatic surface	70 m	Distance from the waterline on the lower surface of the round table	12 m
Horizontal distance of anchor point from platform centerline	853.87 m	Cylindrical diameter of the part above the round table	6.5 m
Horizontal distance of cable guide hole from platform centerline	5.21 m	Cylindrical diameter of the part below the round table	9.4 m
Mooring line unextended length	902.21 m	Platform weight	7466330 kg
Single cable diameter	0.09 m	Platform center of gravity along the centerline downward distance from the waterline	89.92 m
Single cable equivalent line density	77.7066 kg/m	Platform to center of gravity transverse rocking moment of inertia	4229230000 kg m^2
Equivalent line weight of single cable in water	698.094 N/m	Platform to center of gravity longitudinal rocking moment of inertia	4229230000 kg m^2
Equivalent tensile stiffness of single cable	384243000N	Platform to center of gravity bow-rocking moment of inertia	164230000 kg m^2
Additional Bow Sway Stiffness	98340000 Nm/rad		

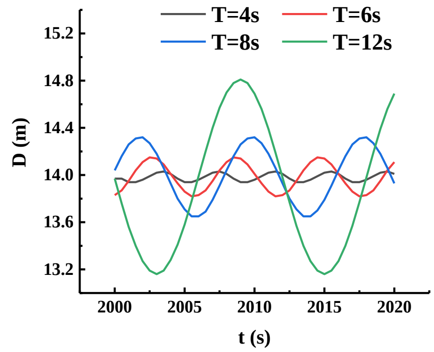


Fig. 2 Time history curve of surge displacement

Table 4. The result of surge displacement fitting

Wave period	Surge displacement fitting function	Fitting accuracy
4 s	$\xi=0.0463 sin(1.5690\ t+5.536)$ $+13.958$	SSE: 0.0030 R-square: 0.9772
6 s	$\xi=0.1662 sin(1.0470\ t+2.767)$ $+13.958$	SSE: 0.0012 R-square: 0.9993
8 s	$\xi=0.3388 sin(0.7858t+106.2)$ $+13.958$	SSE: 0.0016 R-square: 0.9998
12 s	$\xi=0.8217 sin(0.5227t+0.7732)$ $+13.958$	SSE: 0.0013 R-square: 1.0000

In Table 4, the first column shows the calculation conditions, the second column shows the fitting function for the surge displacement, and the third column shows the fitting accuracy parameters. SSE represents the sum of squares of errors, this statistic is the deviation of the measured response fit, the closer to 0 means the better the fit. R-Square represents the coefficient of multiple determination, the magnitude of which ranges from 0 to 1, the closer to 1 indicates that the variables of the equation have more explanatory power for ξ. Furthermore, It can be shown that the sine function is a good fit for the surge displacement curve, and the change in wave period affects the amplitude and frequency of the surge motion. The larger the wave period, the larger the amplitude of the surge displacement fluctuations. The fluctuation frequency of the surge displacement is almost the same as that of the periodic fluctuation of the regular wave.

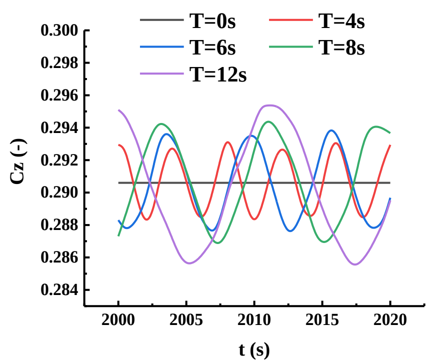


Fig. 3 Axial load coefficient time history curve

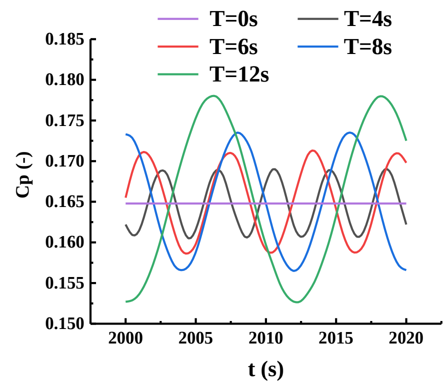


Fig. 4 Energy utilization coefficient time history curve

The curves of C_Z and C_P for different wave periods are given in Fig.4~5. The numbers in the legend indicate the magnitude of the wave period, where T=0s indicates the case when there are no waves. When the floating wind turbine has no wave action, C_Z and C_P are always constant with time. This is a very important aspect that makes horizontal axis wind turbines better than vertical axis wind turbines. C_Z and C_P of the wind turbine fluctuate significantly periodically with the surge of the floating wind turbine. When the wave period is 12s, the fluctuations of the axial load coefficient and energy utilization coefficient can reach about 3.35% and 15.29% of the floating wind turbine without wave action, respectively.

During the surge, the position of surge balance is the time when the aerodynamic load on the wind wheel reaches the maximum (minimum). When the direction of surge is the same as the direction of incoming wind flow, because the velocity direction is the same, so the aerodynamic load reaches the minimum value. When the direction of surge and wind flow direction is opposite, because the speed direction is opposite, so the pneumatic load reaches the maximum. When a floating wind turbine surge, it is equivalent to couple of sinusoidal law flow and uniform flow, then the relative speed at the wind turbine disc is constantly changing. The greater the frequency of the surge, the lower the increase of wave period. However, the overall relative velocity at the turbine raises as the increment of wave period, so the final amplitude of the aerodynamic load tends to increase as the wave period increases.

Numerical simulation results under shear flow

In order to study the influence law of different wave periods on the aerodynamic load of horizontal axis wind turbine, in this section, the wind turbine speed is 8rpm, the wave height is 6m, and the wave period is 4s, 6s, 8s and 12s respectively.

FAST was used to calculate the magnitude of the surge displacement for the wind turbine, and the surge displacement time history curve for each condition is shown in Fig. 5.

Under the periodic fluctuations of regular waves, the surge displacement of the floating wind turbine also fluctuates periodically. To obtain the relationship between the surge displacement and the wave parameters, we fit the curve as a function of the wave parameters by fitting software, and the fitting results are shown in Table 5.

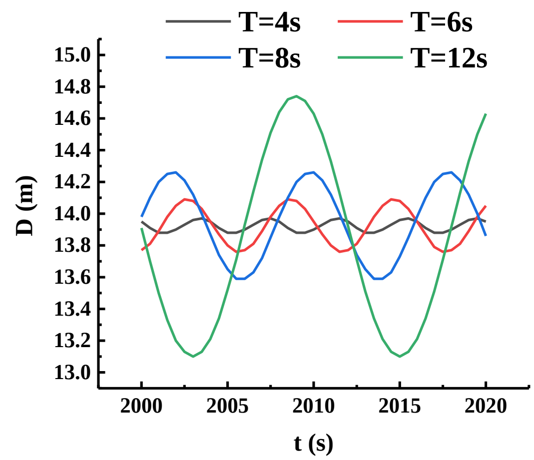


Fig. 5 Time history curve of surge displacement

Table 5. The result of surge displacement fitting

Wave period	Surge displacement fitting function	Fitting accuracy
4 s	$\xi=0.0463 sin(1.569t+5.536)+13.958$	SSE: 0.0030 R-square: 0.9772
6 s	$\xi=0.1662 sin(1.0470t+2.767)+13.958$	SSE: 0.0012 R-square: 0.9993
8 s	$\xi=0.3388 sin(0.7858t+106.2)+13.958$	SSE: 0.0016 R-square: 0.9998
12 s	$\xi=0.8217 sin(0.5227t+0.7732)+13.958$	SSE: 0.0013 R-square: 1.0000

According to the fitting accuracy parameter, it is known that the fitting result of curves is very good and can be seen in the form of a sinusoidal function.

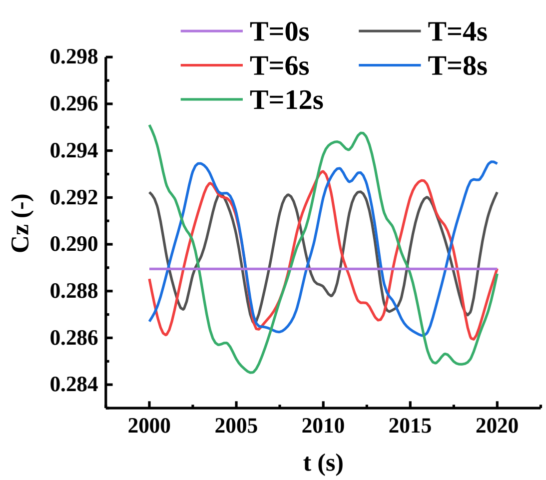


Fig. 6 Axial load coefficient time history curve

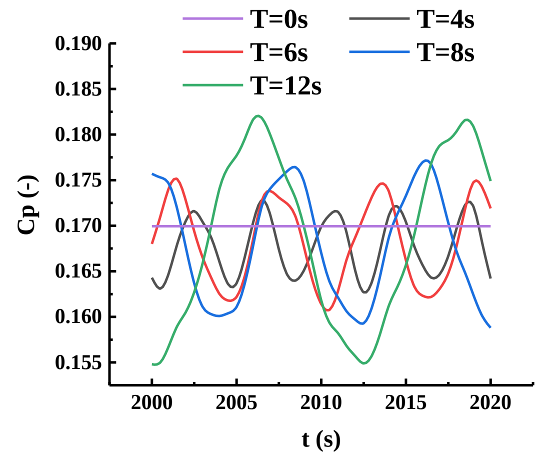


Fig. 7 Energy utilization coefficient time history curve

Fig.6~7 gives the curves of C_Z and C_P for different wave periods. When the wave period is 12s, the fluctuations of the axial load coefficient and energy utilization coefficient can reach about 3.78% and 16.08% of the floating wind turbine without wave action, respectively.

In the surge process, when the surge of a floating wind turbine occurs, it is equivalent to adding a sinusoidal law change to a uniform flow, and then the relative speed at the wind turbine disc surface will change continuously. The greater the wave period, the lower the frequency of the surge. Because of the wave period will lead to an increase in the amplitude of the surge, and the amplitude will lead to a greater relative velocity at the wind turbine, the relative velocity at the wind turbine will become larger under the action of two factors, so the amplitude of the final aerodynamic load has a tendency to increase.

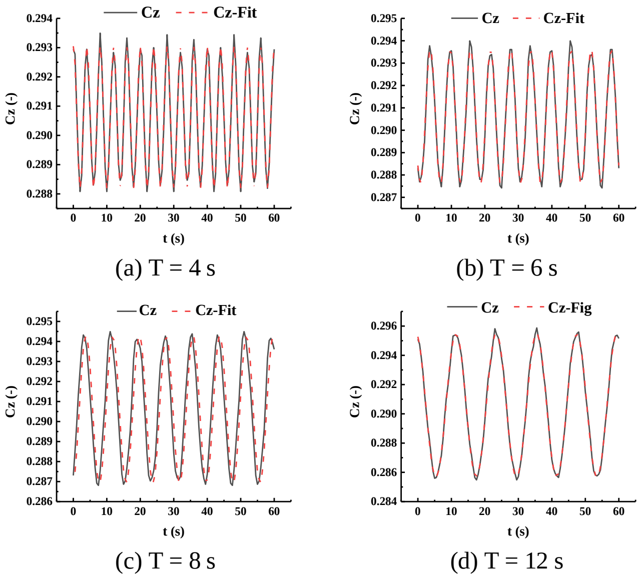
FITTING ANALYSIS OF AERODYNAMIC COEFFICIENTS

In this chapter, the numerical simulation based on FAST is presented to calculate and analyze the numerical magnitude of the aerodynamic coefficients of floating wind turbines under different wave periods and their variation laws.

Aerodynamic coefficients for different wave periods under uniform flow

Under the conditions of wind turbine speed of 8rpm and wave height of 6m, the axial load coefficient and energy utilization coefficient were fitted by the least squares method for the four conditions of wave period of 4s, 6s, 8s and 12s, and the fitted curves were compared with the curves calculated by FAST as shown in Fig. 8~9.

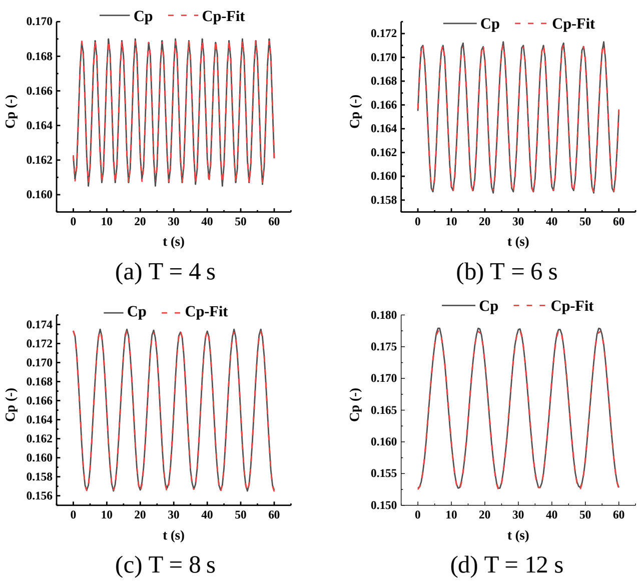
From the figure we can see that the fitted curve and the calculated curve match very well, which initially verifies the accuracy of the fitting method, and then we will calculate the various dimensionless aerodynamic coefficients for surge.



(a) T = 4 s (b) T = 6 s

(c) T = 8 s (d) T = 12 s

Fig. 8 Aerodynamic load coefficient fitting curve



(a) T = 4 s (b) T = 6 s

(c) T = 8 s (d) T = 12 s

Fig. 9 Energy utilization coefficient fitting curve

Table 6. The expansion coefficient of aerodynamic load coefficient

Wave period	C_Z^F	n_{zd}	m_{zd}
4s	0.2906	-0.4442	0.03549
6s	0.2906	-0.2356	0.02646
8s	0.2906	-0.1916	0.02503
12s	0.2906	-0.1640	0.02419

The value of C_Z^F is constant and its magnitude is just equal to the C_Z under static (no surge) conditions, which shows that the fitting method is effective. The magnitude of the absolute value of n_{zd} decreases with increasing wave period, it shows that the change in wave period has an effect on the damping coefficient. The magnitude of m_{zd} decreases slightly with the increase of wave period.

Table 7. The expansion coefficient of energy utilization coefficient

Wave period	C_P^0	n_{pd}	m_{pd}
4s	0.1648	0.8089	0.04314
6s	0.1648	0.5260	0.02566
8s	0.1649	0.4702	0.02289
12s	0.1650	0.4380	0.02164

Therefore, the magnitude of C_Z fluctuates periodically with time, and the average value of C_Z fluctuation depends on the magnitude of C_Z^F. The fluctuation frequency of C_Z is equal to the surge frequency, and the surge frequency is almost equal to the wave frequency. Because the magnitude of n_{zd} is much larger than the magnitude of the change of m_{zd}, and the surge velocity is larger than the surge acceleration, the magnitude of the fluctuation of C_Z depends on the magnitude of the product of n_{zd} and the surge velocity.

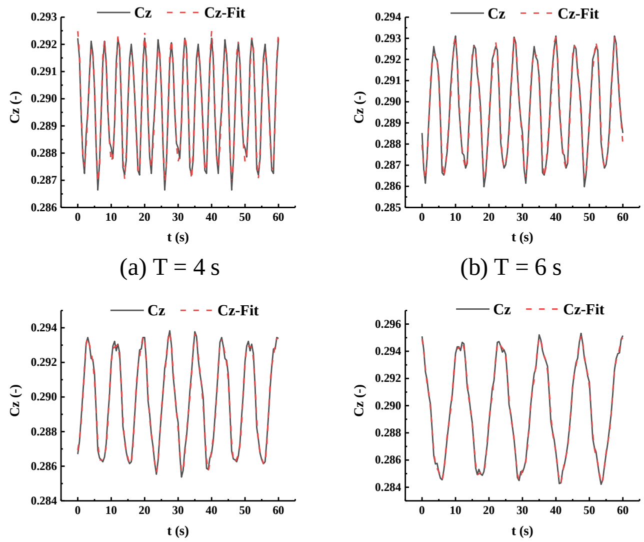
It is obvious from Table 7 that the value of C_P^0 is constant and its magnitude is equal to the axial load coefficient C_P of the wind turbine under static (no surge) conditions. The magnitude of n_{pd} decreases with increasing wave period, in other words, the change in wave period has an effect on the damping coefficient; The magnitude of m_{pd} decreases slightly with the increase of wave period. Therefore, it can be seen that the magnitude of the axial load coefficient C_P fluctuates periodically with time, and the average value of the fluctuation depends on the magnitude of C_P^0. The magnitude of the fluctuation of C_P also depends more on the magnitude of the product of n_{pd} and the surge velocity.

Aerodynamic coefficients for different wave periods under shear flow

Under the conditions of wind turbine speed of 8r/min and wave height of 6m, the axial load coefficients and energy utilization coefficients were fitted by the least squares method for the four conditions of wave period of 4s, 6s, 8s and 12s, and the fitted curves were compared with the curves calculated by FAST as shown in Fig. 10.

From the above figure we can see that the envelope of the amplitude has a certain periodic variation, so we consider the coefficients of the unfolding term in order to consider the effect of the sub-frequency. Then we will calculate each dimensionless aerodynamic coefficient for the surge.

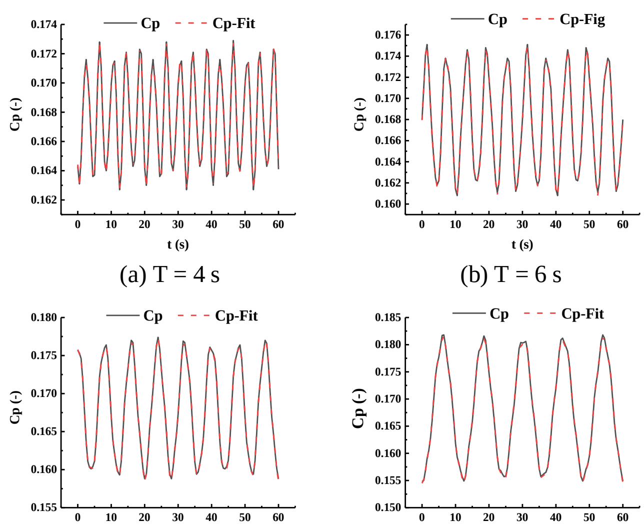
It is obvious from the above table that the magnitudes of and decrease as the wave period increases and the value of is much larger than that of . it indicates the change in wave period has an effect on the damping factor and the main influence on the damping factor is . The magnitudes of and decrease slightly as the wave period increases. The magnitude of the axial load factor fluctuates periodically with time, and the average value of the fluctuation depends on the magnitude of . The fluctuation frequency of is equal to the surge frequency, and the surge frequency is almost equal to the wave frequency, so the fluctuation frequency of depends on the magnitude of the wave frequency. The frequency of the surge affects the magnitude of the surge line velocity, and the magnitude of the fluctuation depends on the product of and the surge velocity.



(a) T = 4 s (b) T = 6 s

(c) T = 8 s (d) T = 12 s

Fig. 10 Aerodynamic load coefficient fitting curve



(a) T = 4 s (b) T = 6 s

(c) T = 8 s (d) T = 12 s

Fig. 11 Energy utilization coefficient fitting curve

As can be seen from Table 9, the magnitudes of and decrease gradually with increasing wave period; the magnitude of decreases slightly with increasing wave period. The magnitude of the axial load coefficient fluctuates periodically with time, the average value of the fluctuation of depends on the magnitude of , the frequency of the fluctuation of depends on the wave frequency; the magnitude of the fluctuation of depends on the magnitude of the product of and the surge speed.

Table 8. The expansion coefficient of aerodynamic load coefficient

Wave period	C_Z^F	C_Z^1	ψ_Z^1	n_{zd}^0	n_{zd}^1
4s	0.2897	0.0004	1.3382	-0.446	0.0390
6s	0.2897	0.0004	1.4491	-0.238	0.0110
8s	0.2897	0.0004	1.4583	-0.193	0.0110
12s	0.2897	0.0004	1.4876	-0.167	0.0053

Wave period	ψ_{zu}^1	m_{zd}^0	C_Z^F	C_Z^F
4s	1.5540	0.0338	0.0066	-1.4977
6s	-0.4105	0.0254	0.0073	-1.5075
8s	-1.0179	0.0241	0.0042	-1.3971
12s	-1.0799	0.0236	0.0026	-1.2135

Table 9. The expansion coefficient of energy utilization coefficient

Wave period	C_P^0	C_P^1	ψ_p^1	n_{pd}^0	n_{pd}^1
4s	0.1678	0.0008	-1.0880	0.8320	0.02855
6s	0.1678	0.0008	-1.0969	0.5379	0.01491
8s	0.1679	0.0008	-1.0923	0.4806	0.00710
12s	0.1680	0.0008	-1.0949	0.4470	0.00255

Wave period	ψ_{pu}^1	m_{pd}^0	m_{pd}^1	ψ_{pa}^1
4s	0.802	0.0432	0.00365	-1.497
6s	-1.415	0.0257	0.00193	-0.879
8s	-0.933	0.0230	0.00104	-0.878
12s	-1.450	0.0218	0.00061	-0.194

CONCLUSIONS

This paper investigates the dynamic response of a floating wind turbine in the presence of uniform/shear winds and regular waves. Using the OC3 Hywind-NREL 5MW as the subject of the study, analyses the aerodynamic coefficients and energy utilization coefficient were carried out and the following conclusions were obtained：

(1) A computational model of the wind turbine, floating platform and mooring system was developed in FAST to calculate the wave motion response characteristics of a floating wind turbine. Through the analysis, the aerodynamic load coefficients are obtained to be linearly related to the surge speed and surge acceleration. Furthermore, the relationship between the aerodynamic load, energy utilization and the wave cycle during the single degree of freedom motion is investigated.

(2) The least squares method is used to "functionally approximate" the axial aerodynamic load coefficient and energy utilization coefficient curves of the wind turbine, to obtain the correlation between them. The wave motion response speed and acceleration, which is the aerodynamic coefficient of the wave motion response of the wind

turbine under the characteristic operating conditions. It can be concluded that the average value of C_Z and C_P depends on the fixed case. The amplitude of fluctuations increases with the increase of wave period. The amplitude of fluctuations of the C_Z and C_P is more correlated with the damping coefficient and less correlated with the added mass coefficient.

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REFERENCES

Heronemus, W.E. Pollution-free energy from offshore winds [C]. *Marine Technology Society. 8th Annual Conference and Exposition*, Washington D.C., United States, Sep. 11-13, 1972.

Jonkman, J., Butterfield, S., Musial, W., and Scott, G. (2009). Definition of a 5-MW reference wind turbine for offshore system development. *Contract*, (February), 1–75.

Jonkman, J., and Musial, W. (2010). Offshore code comparison collaboration (OC3) for IEA task 23 offshore wind technology and deployment. *Contract*, 303(December), 275–3000.

Sheng Q, Jing F, Zhang L, et al. Study of the hydrodynamic derivatives of vertical-axis tidal current turbines in surge motion[J]. Renewable energy, 2016, 96: 366-376.

Wan D, Cheng P, Huang Y, et al. Overview of study on aero-and hydro-dynamic interaction for floating offshore wind turbines[J]. *Chinese Quarterly of Mechanics*, 2017, 38(3): 385.

Wang S, Li C Y, Xie Y, et al. Research on hydrodynamic characteristics of horizontal axis tidal turbine with rotation and pitching motion under free surface condition[J]. *Ocean Engineering*, 2021, 235: 109383.

Wang S, Zhang Y, Xie Y, et al. The effects of surge motion on hydrodynamics characteristics of horizontal-axis tidal current turbine under free surface condition[J]. *Renewable Energy*, 2021, 170: 773-784.