Unsteady Aerodynamics of a Spar-type Floating Offshore Wind Turbine Induced by Platform Pitch Motion

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Abstract

There are strong interactions between the aerodynamics and hydrodynamics in the floating offshore wind turbine (FOWT) system. The aerodynamic loads of wind turbine acting on the floating support platform via turbine tower enlarge the motion responses amplitudes, which in return alters the aerodynamics of wind turbine. How the platform pitch motion interact with the wind turbine aerodynamics under operating wind-wave conditions is an attractive research. In the present work, the unsteady aerodynamics of the FOWT are investigated numerically with an unsteady actuator line model (UALM) that take the additional relative wind speed induced by the platform motions into consideration. To investigate the influence of platform pitch motion on unsteady aerodynamic characteristic, coupled aero-hydrodynamic simulations of a spar-type FOWT with and without pitch motion under shear wind and regular wave are both performed. The aerodynamic characteristics including the rotor power, thrust, fatigue loads and detailed wake field information are analyzed. Furthermore, the relative wind velocity, attack angle and the bending moments at blade root for different simulation conditions are compared and discussed to explore the intrinsic relationship between platform pitch motion and unsteady aerodynamics. It can be found that the average and oscillating amplitude of pitch responses under operating wind-wave loads increase remarkably due to aerodynamic forces. The dramatic change of aerodynamic loads significantly alters the forces acting on the rotating blades with a result of rapidly increased fatigue loads and instability problem. Thus, complicated control strategies are supposed to apply in the FOWT system to suppress the motion responses of floating platform.

Keywords: Floating wind turbines; Pitch motion; Unsteady aerodynamics; Fatigue loads; Unsteady actuator line model

Introduction

Wind energy is thought to be one of the most promising renewable energy due to enormous reserves, and the wind power technology have become more mature in the past decade [1]. With the depletion of land resources for onshore wind farms, the offshore regions with much stronger and smoother wind become a better choice. In shallow waters, bottom-fixed offshore wind turbines have achieved great success. However, the noise restriction and visual pollution limit its further development and application. The offshore wind turbines are advancing into deep water areas [2][3]. Considering that the cost of offshore wind turbines mounted on bottom-fixed structures increases sharply with water depth, the floating offshore wind turbine (FOWT) is generally believed to an alternative [4][5]. Several countries have planned to build floating wind farms. From the perspective of practical deployment, there are still some challenges for the

FOWT, especially the stability problem. Different from the onshore wind turbine and bottom-fixed wind turbine, the FOWT consisting of a wind turbine, a floating platform and a mooring system is a rather complex system and suffers various environment excitations from winds, waves and currents. There are strong interactions between the wind turbine and floating support platform. The aerodynamic loads of wind turbines acting on the floating support platform via turbine tower will enlarge the motion responses amplitudes, which in return alters the aerodynamics of wind turbine [6]. The study of Sebastian [7] indicated that the unsteady aerodynamics of wind turbine were significantly influenced by the surge, pitch and yaw motions of the floating support platform. The platform pitch motion that results in a non-uniform flow on the turbine rotor and more complex blade-wake interaction significantly affects the aerodynamic performance.

In order to investigate how the platform pitch motion influences the unsteady aerodynamics of wind turbine and explore the interaction mechanism, a number of experimental and numerical researches have been conducted. Leble and Barakos [8] studied the aerodynamic performance of DTU 10MW wind turbine with prescribed sinusoidal pitching and yawing motions. They found that the mean power for pithing amplitudes of 5 deg is 32.8% larger than that without pitching motion. It indicated the pitch motion was advantageous to improve the mean power output of the wind turbine. However, the platform pitch motion also had adverse effects on the stability of aerodynamic power. The numerical research conducted by Tran and Kim [9] showed that the instantaneous aerodynamic power of the NREL 5MW wind turbine varied from 0MW to 15MW when the wind turbine experienced a platform pitch motion with an amplitude of 4 deg and a period of 5s. Besides, they have conducted a series of CFD simulations focusing on the influence of platform pitch motion on the unsteady aerodynamics and wake characteristics. The rotating blades and generated wake vortices were found to have strong interactions with each other. And the aerodynamic loads presented highly unsteady characteristics due to the platform pitch motion [10][11]. Consequently, the aerodynamic performance of the FOWT greatly affected by the platform pitch motion. Several studies have tried to reveal the interaction mechanism between the platform pitch motion and the unsteady aerodynamics of the wind turbine. Wen et al. [12] investigated the influence of the platform pitch amplitude and frequency on the power performance using Free Vortex Method (FVM). It was concluded that the impacts of platform pitch motion on mean power output had great discrepancy when the tip speed ratio changed. And they proposed a platform-pitch-induced (PPI) wind shear model in their later work to explain the influence of platform pitch motion on unsteady aerodynamics and investigated the influencing factors of the PPI wind shear [13]. Wind tunnel experiments were also carried out to model the wake characteristics of wind turbine. Rockel et al. [14] used Particle Image Velocimetry (PIV) technique to observe the development of a model wind turbine wake and discussed the influence of platform pitch motion on aerodynamic power and wake characteristics. Khosravi et al. [15] performed an experimental study with 1:300 scaled model wind turbine to analyze the influence of platform pitch motion on aerodynamic loading and turbine wake characteristics. The fatigue loads were detected to be increased remarkably due to the platform pitch motion, which will lead to the decrease of the lifetime of wind turbine blades.

It can be found that the existing researches about the effects of platform motions on the aerodynamic performance of wind turbine mainly focus on the prescribed platform pitch motion while not the pitch response of floating support platform in realistic environment. In our previous work, the coupling effects between the aerodynamics of the wind turbine and the six-degree-of-freedom platform motions under wind-wave conditions have been investigated by comparing the coupled aero-hydrodynamics including aerodynamic forces, platform motion responses and mooring tensions [16]. Simplified force model that assumes the time-varying aerodynamic forces acting on the floating support platform as constant loads and coupled analysis model FOWT-UALM-SJTU were both applied to simulate the aero-hydrodynamic performance of the FWOT to detect the coupling relationship between aerodynamics and hydrodynamics in FOWT system. However, how the different degree-of-freedom platform motions under realistic wind-wave loads, especially for the pitch responses, influence the unsteady aerodynamics of wind turbine is still to be further discussed. And it is exactly what we concern in the present work. In order to explore the impacts of platform pitch motion on the unsteady aerodynamics and wake characteristics under operating conditions, coupled aero-hydrodynamic simulations for a spar-type FOWT under combined wind and waves are conducted. And the coupled CFD analysis tool FOWT-UALM-SJTU [17] is chosen again to model the aero-hydrodynamic performance. The aerodynamic characteristics including the rotor power, thrust, fatigue loads and detailed wake field information are analyzed to reveal the detailed relationship between the platform pitch motion and the unsteady aerodynamics of wind turbine.

Numerical Method

Unsteady Actuator Line Model

Full scale CFD simulations for the wind turbine are quite time consuming and requires a significant amount of computing resources while detailed flow field information can be obtained. The Blade Element Theory (BEM) and Free Vortex Method (FVM) have the characteristics of fast accurately calculating, but the detailed wake characteristics cannot be acquired. The actuator line model (ALM) proposed by Sørensen and Shen [18], which combined the advantages of these methods, is chosen in the present work to model the aerodynamics performance of the FOWT. The real blade surfaces of the wind turbine are replaced with virtual actuator lines in the ALM. Each actuator line is further discretized into a serial of actuator points and each actuator point represents a section of the blade. The aerodynamic force acting on the blades are calculated from the local attack angle and a look-up table of airfoil data. Then the calculated body forces smeared by regularization kernel function are introduced into the moment equations to reproduce the turbulent wake flow.

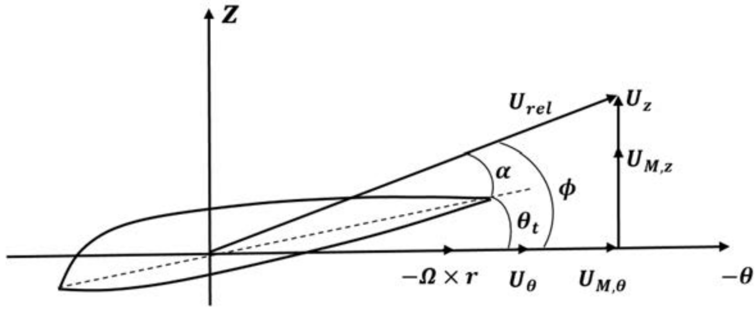


Fig. 1 Velocity at cross-sectional airfoil element

In order to model the unsteady aerodynamic characteristics of the FOWT, modifications are made to the initial ALM. As Fig. 1 shows, the additional velocity $\boldsymbol{U_M}$ induced by the platform motion, which intensify the interaction phenomenon between rotating blades and wake field, is taken into consideration in the calculation of local attack angle. To determine the body forces acting on the blades, a blade element approach combined with two-dimensional airfoil characteristics is used. To illustrate the relationship between different velocities at cross-sectional airfoil element, a cross-sectional element at radius r defines the airfoil at the (θ, z) plane. Denoting the tangential and axial velocity in the inertial frame of reference as $\boldsymbol{U_\theta}$ and $\boldsymbol{U_z}$, respectively.

The local velocity U_{rel} relative to the rotating blade is defined as:

$$\boldsymbol{U}_{rel} = \boldsymbol{U}_{\theta} - \boldsymbol{\Omega} \times \boldsymbol{r} + \boldsymbol{U}_{z} + \boldsymbol{U}_{M} \tag{1}$$

Where Ω is the rotating speed of the wind turbine. Then the attack angle can be calculated by the following equation:

$$\alpha = \phi - \theta_t \tag{2}$$

Where ϕ is the inflow angle. θ_t is the local twist angle. The aerodynamic forces can be obtained by the following equation:

$$\boldsymbol{f} = (\boldsymbol{L}, \boldsymbol{D}) = \frac{\rho |U_{rel}|^2 c N_b}{2rd\theta dz} (C_L \boldsymbol{e}_L + C_D \boldsymbol{e}_D) \tag{3}$$

Where c is the chord length; N_b is the number of blades; C_L and C_D are the lift and drag coefficient, respectively; $\boldsymbol{e}_L$ and $\boldsymbol{e}_D$ denote the unit vectors in the directions of the lift and the drag, respectively.

To reproduce the turbulent wake flow, the calculated aerodynamic forces need to be smeared before they are introduced into the moment equations to avoid singular behavior in numerical simulations.

$$\boldsymbol{f}_{\varepsilon} = \boldsymbol{f} \otimes \eta_{\varepsilon}(d) = \frac{1}{\varepsilon^3 \pi^{3/2}} exp\left[-\left(\frac{d}{\varepsilon}\right)^2\right] \tag{4}$$

Here $\boldsymbol{f}_{\varepsilon}$ is the source term added into the right hand of momentum equation. d is the distance between the measured point and the initial force points on the rotor. ε is a constant which serves to adjust the strength of regularization function.

FOWT-UALM-SJTU solver

Using the UALM to model the unsteady aerodynamics of wind turbine, a coupled CFD analysis tool FOWT-UALM-SJTU for FOWT is established by interpolating the UALM into in-house code naoe-FOAM-SJTU. This tool is utilized in the present work to achieve the coupled aero-hydrodynamic simulations for the FOWT. The in-house code naoe-FOAM-SJTU solver based on the open source CFD toolbox OpenFOAM is developed to investigate typical hydrodynamic problems of ship and marine engineering. It is composed of a 3D numerical wave tank module, a 6DOF motion module, a mooring system module and the interface module with OpenFOAM. It is applied to study the hydrodynamics of the spar-type floating support platform with a mooring system. The volume of fluid (VOF) method with bounded compression technique is utilized to capture the free surface, and a dynamic deformation mesh approach is employed to handle structure motions. The piecewise extrapolating method (PEM) is chosen to solve the constraint of the mooring line system.

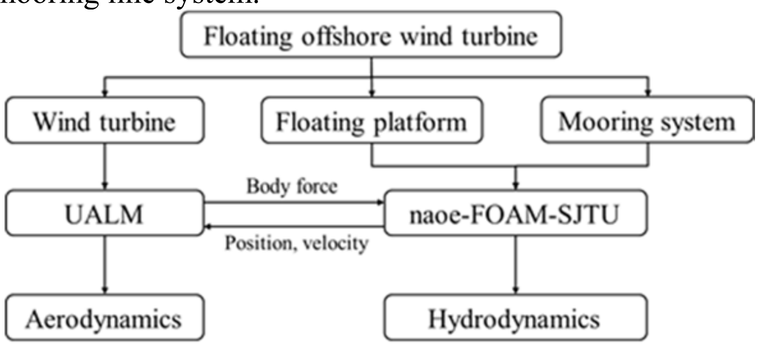


Fig. 2 Schematic diagram of the coupled analysis tool

Governing equations

Considering the wind speed is low, the air phase is regarded as incompressible liquid as the water phase is. The same governing equations are adopted to solve these two-phase flow conditions. The three-dimensional Reynolds-Averaged Navier-Stokes (RANS) equations are selected as governing equations for the FOWT-UALM-SJTU model, and the k-ω SST turbulence model is employed for closure of RANS equations.

$$\nabla \cdot \boldsymbol{U} = 0 \tag{5}$$

$$\frac{\partial \rho \boldsymbol{U}}{\partial t} + \nabla \cdot \left(\rho\left(\boldsymbol{U} - \boldsymbol{U}_g\right)\right)\boldsymbol{U} = -\nabla p_d - \boldsymbol{g} \cdot x \nabla \rho + \nabla \cdot \left(\mu_{eff} \nabla \boldsymbol{U}\right) + (\nabla \boldsymbol{U}) \cdot \nabla \mu_{eff} + \boldsymbol{f}_\sigma + \boldsymbol{f}_s + \boldsymbol{f}_\varepsilon \tag{6}$$

Where $\boldsymbol{U}$ is flow velocity in computation domain; $\boldsymbol{U}_g$ is the velocities of flow field on the grid nodes; $p_d = p - \rho \boldsymbol{g} \cdot x$ is the dynamic pressure; $\boldsymbol{g}$ is the gravitational acceleration vector; ρ is the mixture density with two phases; $\mu_{eff} = \rho(\nu + \nu_t)$ is effective dynamic viscosity, in which ν and ν_t are kinematic viscosity and eddy viscosity respectively; $\boldsymbol{f}_\sigma$ is the surface tension term in two phases model and takes effect only on the liquid free surface; $\boldsymbol{f}_s$ is the source term for sponge layer, which is set to avoid the wave reflection at the end of the computation domain and takes effect only in sponge layer.

Simulation descriptions

Analysis object

A spar-type FOWT consisting of the NREL 5-MW baseline wind turbine and the OC3 Hywind spar-type floating platform with catenary mooring lines is selected in the present work to investigate the influence of platform pitch motion on the unsteady aerodynamics of wind turbine. The NERL 5-MW wind turbine is a conventional three-bladed, upwind, variable-speed and variable blade-pitch-to-feather controlled turbine [19]. The floating support platform a spar-type concept platform called Hywindspar [20]. Three catenary mooring lines are arranged around the platform to limit the platform motions and keep the stability of the FOWT. The sketch of the spar-type FOWT is shown in Fig. 3. To simplify the aerodynamics modelling, the tower, hub and nacelle are not taken into account. And there is no control strategy for the wind turbine. Different from our previous work [16] that simply the aerodynamics of wind turbine with simplified force model to focus on the hydrodynamic responses of floating platform and the coupling effects between aerodynamic and hydrodynamics in the FOWT system, the major objective of the present work is to investigate the unsteady aerodynamics of the wind turbine with realistic platform pitch motion under operating wind-wave loads. In order to detect how the platform pitch motion under operating wind-wave conditions affects the aerodynamics of the wind turbine, two simulation cases with different platform state are performed using FWOT-UALM-SJTU model in the present work. In case 1, the floating support platform remains stationary. While the platform pitch motion is taken into consideration in case 2. Wind and wave conditions in these two cases keep the same, which are referenced to Jonkman's work [20]. The exponential model is adopted to describe the characteristic of height-dependent wind speed. The wind speed at the height of z is defined by following equation:

$$u_Z = u_0 \times \left(\frac{z}{90}\right)^{0.143} \tag{7}$$

Where u_0 is the wind speed at the height of the turbine hub. In this study, the rated wind speed $u_0 = 11.4$m/s is selected for the analysis of unsteady aerodynamics. The corresponding turbine rotor speed is 12.1 rpm. The incident wave is first order Stocks wave. The wave height and wave length are 6m and 10s, respectively. There is no control algorithm for the wind turbine in the present simulations.

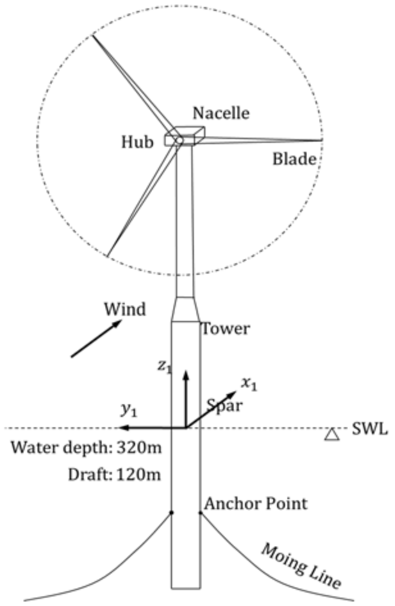


Fig.3 Diagram of the FOWT system

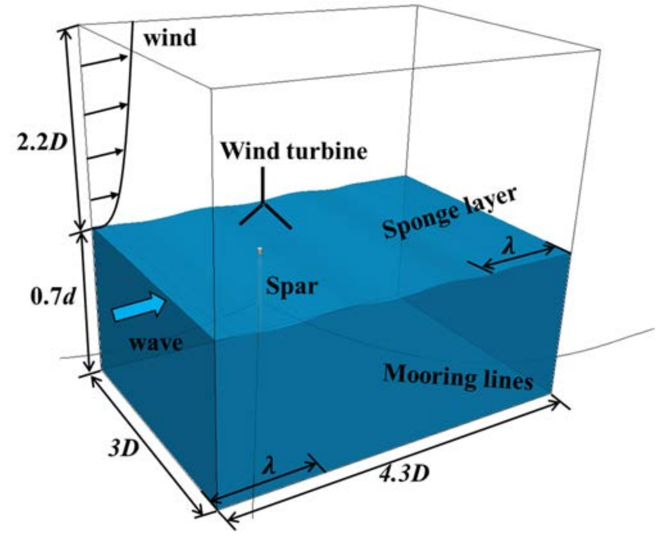


Fig. 4 Computation domain

Computation Domain

A hexahedral computational domain is applied for the present numerical simulations. The length and width are set to 540m and 400m respectively, about a dimension of $4.3D\times 3D$ (D=126m is the diameter of the NREL 5-MW wind turbine). Considering the expansion of turbine wake, the height of the air phase is set to 280m (about $2.2D$). To decrease the grid number and limit the computation resources, the depth of water phase is set to 224m that is the 70% of real water depth (d=320m), for this water depth is deep enough to neglect the influence of water depth on platform motion response. A rectangle sponge layer with length is selected to avoid the effects of wave reflection. The FOWT system is located in the middle of computation domain along the x direction, 1λ (λ=156m is the wave length of incident wave) behind the inlet boundary. The main parameters of the computation domain are shown in Fig. 4.

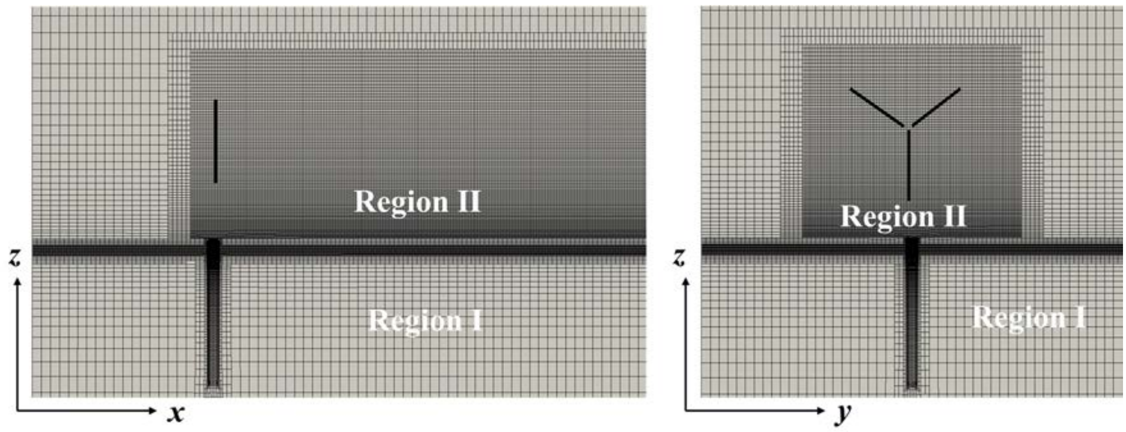


Fig. 5 Grid distribution in longitudinal section and cross section

To capture detailed wake behavior and water surface, the grids behind the wind turbine and near the free surface are refined. As Fig. 5 shows, region I is the background mesh, where the grid size is 8m×8m×8m. Region II represents the refined mesh with the grid size of

2m×2m×2m. And the grids near free surface are generated with the size of 2m×2m×0.5m. The total grid number is 3.5 million, which is affordable to achieve the coupled aero-hydrodynamic simulations for FOWT.

Results and Discussions

Aerodynamic load characteristics

In this study, aeroydnamic performance of the FOWT with platform pitch motion is compared with that of fixed wind turbine to explore the influence of pitch responses the floating support platform in operating wind and wave conditions on the unsteady aerodynamic characteristics. Simulation time for all coupled cases is 180s while only the aero-hydrodynamics in the last 20s are analyzed, as the coupled performance of the FOWT have stabilized during this period. Duo to the contribution of wind loads, the pitch response of floating support platform becomes great and oscillates periodically, which furhtermore makes the aerodynamic characteristics change in the same tendency. It can be seen from the Fig. 6 that the oscillating amplitude of pitch motion for the flaoting support platform under wind and wave loads is nearly 2 degrees, almost half of the average value of the pitch response. The similar phenomenon can also be found in our previous work [16]. This significantly variation of the platform pitch moiton transfers to the turbine rotor via tower and potentially influences the relative wind velocity at the cross sections of rotating blades, amplifying the cyclical change of the local attack angle. To clearly show the effects of pitch motion, the relative wind velocity including the axial and tangential wind velocities during the rotation of blades and attack angle with respect to azimuth angle for the blade #1 at a typical blade section r/R = 0.8 (R=63m is the radius of the turbine blade) are presented in Fig. 7 and Fig. 8, respectively. It should be noted here that the cyclical change of relative wind velocity consisting of axial wind velocity and tangential wind velocity in fixed case is because of the height-dependent characteristics of wind speed.

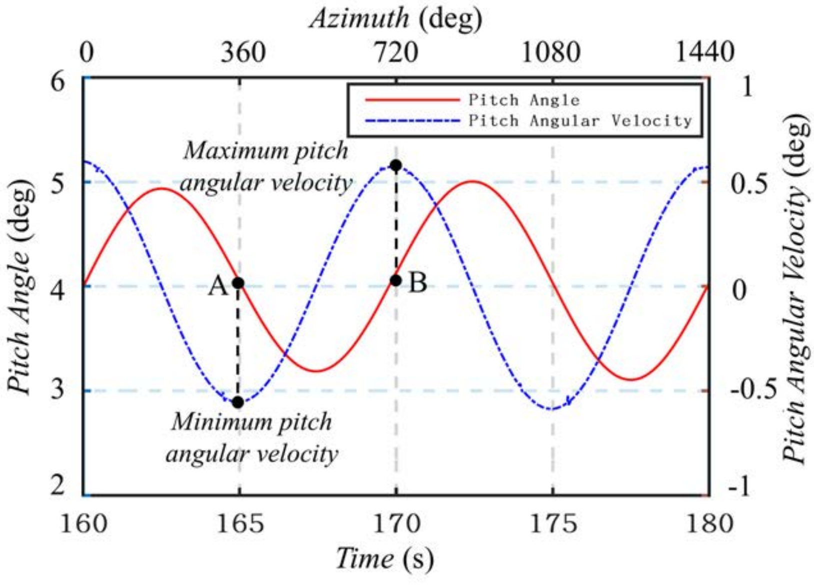
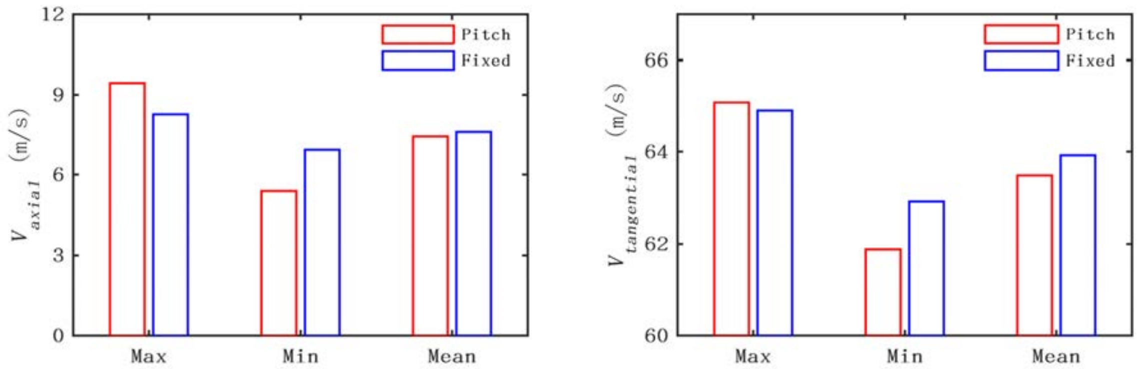


Fig. 6 Pitch responses of the floating support platform under operating wind and wave conditions.

Due to the additional relative wind speed induced by the pitch responses, the amplitudes of the axial wind speed and the tangential wind speed experiencing by the turbine blades both become larger. The pitch angular velocity for the floating support platform shown in Fig. 6 may explain this phenomenon. The relative wind speed reaches the maximum value when the floating platform moves forward passing the equilibrium position (Point A shown in the Fig. 6) corresponding to the minimum value of pitch angular velocity, resulting from that the directions of platform pitch motion and wind speed are opposite. By contrast, the minimum relative wind speed corresponds to the maximum pitch angular velocity (Point B shown in the Fig. 6).



(a) axial wind speed **(b) tangential wind speed**

Fig. 7 Characteristic values of relative wind speed experiencing by blade #1 at a typical blade cross section *r*/*R*=0.8 during the rotation of wind turbine.

The change of relative wind speed will cause the variation of the local attack angle and furthermore influence the lift and drag forces acting on the rotating blades, which leads to the unsteady characteristics of aerodynamic loads including the rotor power and thrust. It is easy to find out that the variation period of local attack angle is about 5s in the fixed case while it is about 10s is the in the pitch case. And averaged value of the attack angle for the rotating blade affected by the platform pitch motion decreases by 7% compared to that of the fixed wind turbine aerodynamics. Moreover, the same changing tendency can also be found in the variation of lift coefficient respected to the azimuth angle shown in Fig. 9. The rotor power and thrust of the wind turbine for different simulation conditions are compared in the Fig. 10. It can be observed that the averaged aerodynamic responses including rotor power and thrust for rotating turbine with platform pitch motion are obviously smaller than those with fixed platform. The rotor power and thrust in the pitch case averaged in 160s~180s are decreased by nearly 11% and 8%, respectively. It indicates that the pitch responses of floating support platform under operating wind and wave conditions have adverse effects on the aerodynamic power output of the wind turbine. In addition, the oscillating rotor power and thrust amplitudes of the wind turbine with platform pitch motion are about 83% (3.94MW) and 41% (272kN) of the corresponding averaged aerodynamic loads. This dramatic change of aerodynamic load will significantly alter the forces acting on the rotating blades with a result of rapidly increased fatigue loads and instability problem, which may cause severe damage to critical system and structures and reduce the service life of turbine blades. As presented in Fig. 11, the characteristic values of bending moments acting on the blade root during the rotation of turbine blades are plotted to show how the platform pitch responses influence the fatigue loads. It can be seen that the axial bending moment responses are obviously greater than that of the tangential bending moment due to the structure characteristics of turbine blades. Moreover, the bending moments along axial direction and tangential direction for the rotating blades with platform pitch motion both have significantly larger variation amplitudes compared to those with fixed platform. The variation amplitude of tangential bending moment in pitch case is nearly 2.86 times of that in fixed case, and this ratio increases up to 3 times for the axial bending moment. Therefore, complicated control strategies are supposed to apply in the FOWT system to suppress the motion responses of floating platform.

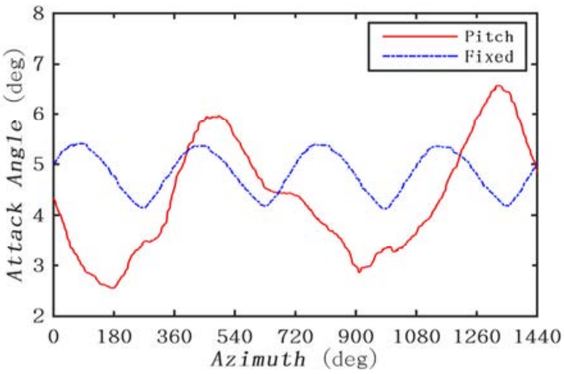


Fig.8 Comparison of the attack angle at *r*/*R*=0.8 of the rotating blade.

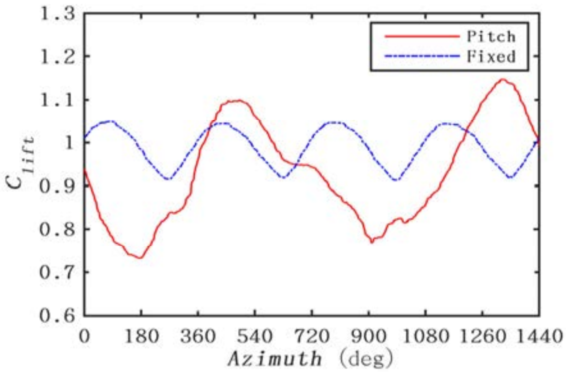
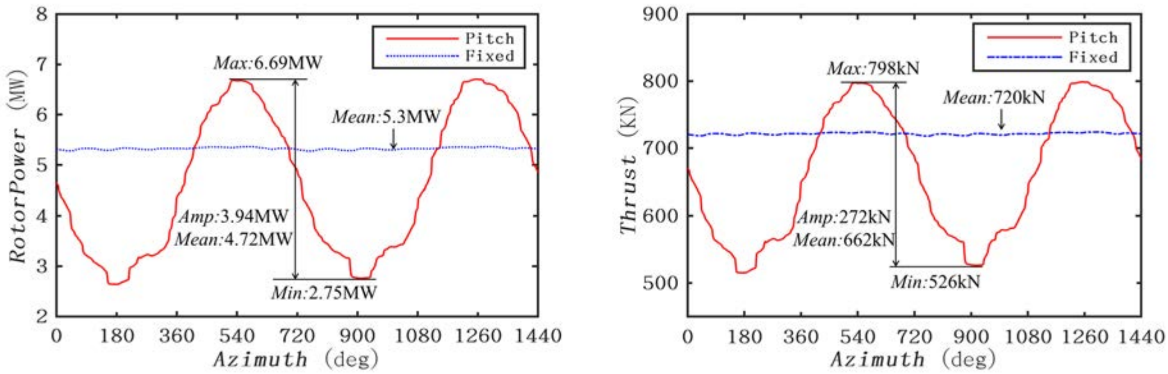
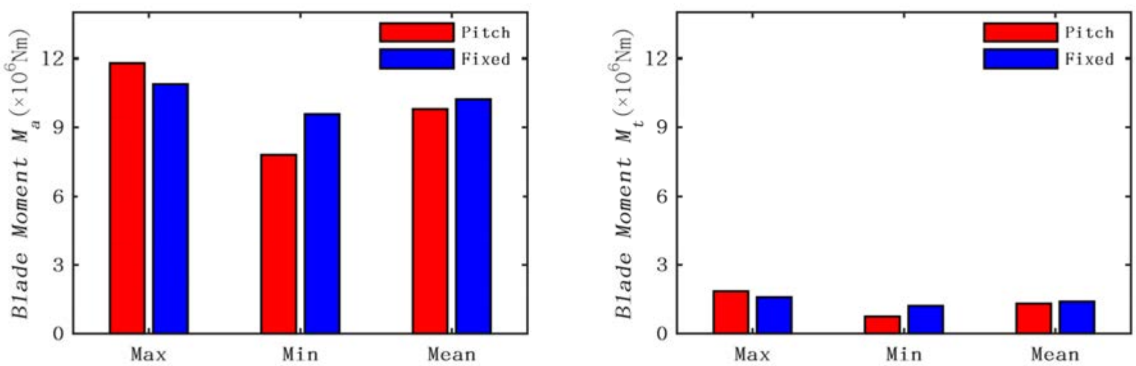


Fig. 9 Comparison of lift coefficients of the blade section at *r*/*R*=0.8.



(a) rotor power **(b) thrust**

Fig. 10 Comparison of the aerodynamic loads for wind turbine with fixed and pitch degree-of-freedom platform.

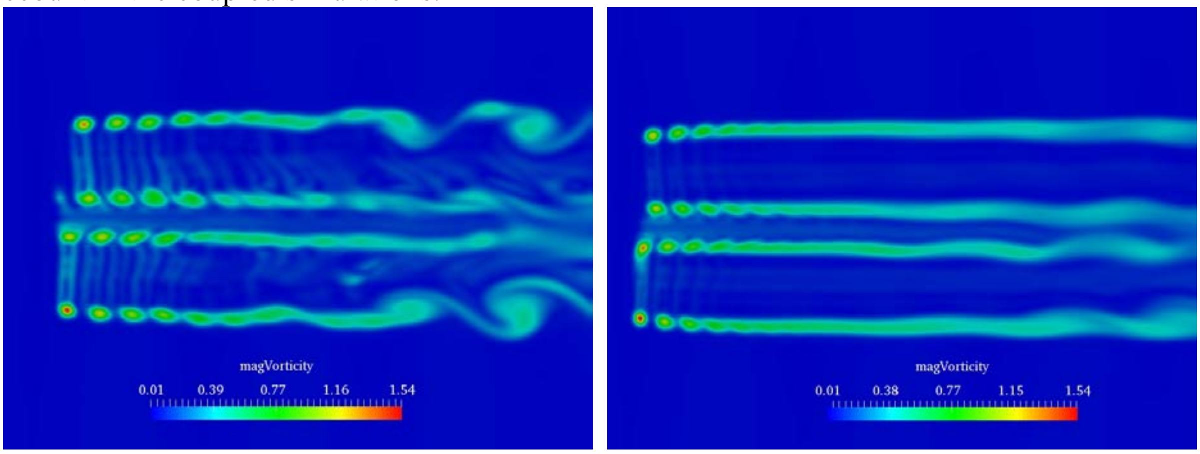


(a) axial bending moment **(b) tangential bending moment**

Fig. 11 Comparison of time-averaged blade root bending moments defined at blade-aligned coordinate system.

Wake field characteristics

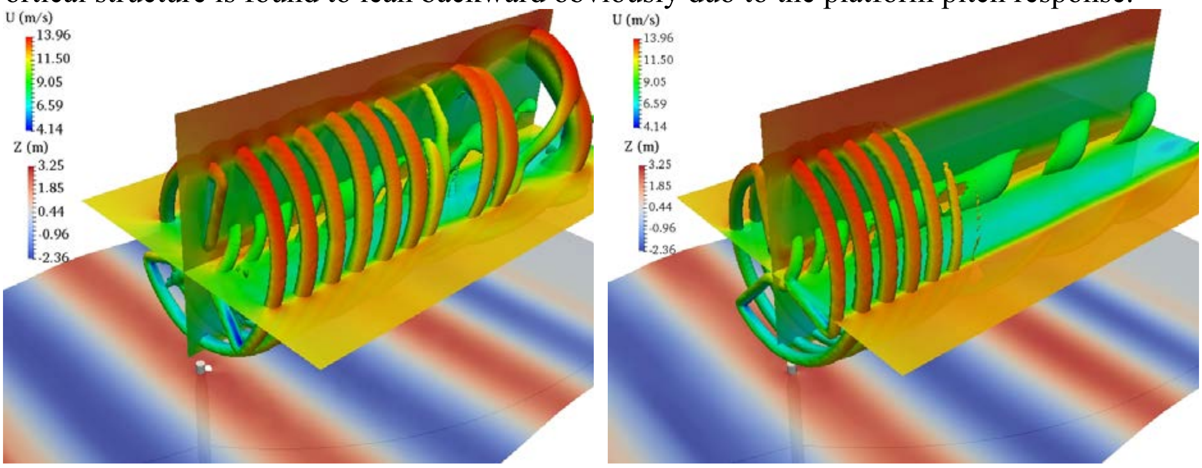
The computational fluid dynamic method is utilized in the present work to investigate the influence of pitch responses of floating support platform under operating wind and wave conditions on the unsteady aerodynamic characteristics of FWOT. Modified body forces model UALM is employed to model the unsteady aerodynamics of wind turbine, which is an effective way to achieve the coupled aero-hydrodynamic simulations for the FOWT with affordable computational resources. Detailed wake information and flow field characteristics for different simulation conditions are compared and analyzed to explore the effects of platform pitch motion on the wake field. It should be noted here that the hub, cabin and tower are not taken into account in the coupled simulations.



(a) pitch case **(b) fixed case**

Fig. 12 Visualization of instantaneous (*t*=170s) vorticity counter at horizontal plane with the height of hub center (z=90m).

As illustrated in Fig. 12, the instantaneous vorticity at the reference horizontal plane with the height of hub center for different simulation conditions are presented. It can be seen that clear vorticities generated from the blade tip and root are captured and the periodic vortex shedding phenomenon is also observed. Duo to additional velocity induced by the cyclic pitch motion of floating support platform, the distance between two adjacent wake vortices in pitch case is larger than that with fixed platform. In fixed case, the tip vortices quickly merge with the adjacent vortex during the development of wake flow. Whereas the vortices generated from the rotating blades with platform pitch motion spear further before they are merged in the downstream of wake field. In addition, it can be obviously found that the wake filed maldistribution is more serious due to the influence of platform pitch motion, which indicates the downstream FOWT will suffer more complicated and unsteady inflow condition. Moreover, the iso-surface plot of the second-order invariant of velocity gradient tensor Q colored by the wind velocity are illustrated in Fig. 13 to visualize the vortices. The vortices generated from the wind turbine with fixed platform are rapidly dissipated in the downstream wake filed. And the vortical structure is found to lean backward obviously duo to the platform pitch response.



(*a*) Pitch case **(*b*) Fixed case**

Fig. 13 Illustration of coupled simulations for the FOWT where the wake vortex is counted by Q=0.01 and colored by wind speed.

Conclusions

In this study, computational fluid dynamic method with modified body force model UALM is employed to simulate the coupled aero-hydrodynamic characteristics of the FOWT with realistic platform pitch responses under combined wind and wave condition. The application of UALM for unsteady aerodynamics of wind turbine makes the coupled CFD analysis for FOWT much more effectively compared with conventional method that consider the actual blade surface. Pitch responses of the floating support platform, unsteady aerodynamic characteristics including the attack angle, relative wind speed, aerodynamic loads, blade root bending moments and detailed wake information are obtained and discussed to investigate the strong interactions between the unsteady aerodynamics and platform pitch motion for FOWT system in operating state. It can be found that the average platform pitch response under operating wind-wave loads is nearly 4 degrees and the pitch amplitude is almost half of average value, about 2 degrees. Due to the contribution of wind loads, both the average and oscillating amplitude of pitch responses increase remarkably. And this cyclical pitch motion in return amplified the unsteady aerodynamic characteristics of FWOT by altering the relative wind speed. The change of relative wind speed causes the variation of the local attack angle and furthermore influence the lift and drag forces acting on the rotating blades, which leads to the periodical change of aerodynamic loads including the rotor power and thrust. The oscillating rotor power and thrust amplitudes of the wind turbine with platform pitch motion are about 83% (3.94MW) and 41% (272kN) of the corresponding averaged aerodynamic loads. And the average rotor power and thrust in the pitch case are decreased by nearly 11% and 8% respectively, indicating the platform pitch responses may have adverse effects on the power output. Furthermore, the dramatic change of aerodynamic loads significantly alters the forces acting on the rotating blades with a result of rapidly increased fatigue loads. The oscillating amplitudes of axial and tangential bending moments at the rotating blade root with realistic platform pitch motion are both nearly 3 times of those with fixed platform. In the view of wake characteristics, the tip vortices are clearly captured and the wake filed maldistribution is more serious due to the influence of platform pitch motion, which leads to more complicated and unsteady inflow condition for the downstream FOWT. Thus, complicated control strategies are supposed to apply in the FOWT system to suppress the motion responses of floating platform. Moreover, the influence of other degree-of-freedom platform motions such as surge and yaw on the unsteady aerodynamic performance of the FOWT in operating wind-wave conditions will be discussed in the future.

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References

[1] Wang, X., Zeng, X., Li, J., Yang, X., and Wang, H. (2018) A review on recent advancements of substructures for offshore wind turbines, Energy Conversion and Management 158, 103-119.

[2] Lei, H., Zhou, D., Bao, Y., Chen, C., Ma, N., and Han, Z. (2017) Numerical simulations of the unsteady aerodynamics of a floating vertical axis wind turbine in surge motion, Energy, 127, 1-17.

[3] Rodrigues, S., Restrepo, C., Kontos, E., Pinto, R. T., and Bauer, P. (2015) Trends of offshore wind projects. Renewable and Sustainable Energy Reviews 49, 1114-1135.

[4] Sun, X., Huang, D., and Wu, G. (2012) The current state of offshore wind energy technology development, Energy 41(1), 298-312.
[5] Butterfield, S., Musial, W., Jonkman, J., and Sclavounos, P. (2007) Engineering challenges for floating offshore wind turbines (No. NREL/CP-500-38776), National Renewable Energy Lab.(NREL), Golden, CO (United States).
[6] Shen, X., Chen, J., Hu, P. (2018) Study of the unsteady aerodynamics of floating wind turbine, Energy 145, 793-809.
[7] Sebastian, T. The aerodynamics and near wake of an offshore floating horizontal axis wind turbine, PhD Thesis, University of Massachusetts, USA, 2012.
[8] Leble, V., and Barakos, G. (2017) 10-MW wind turbine performance under pitching and yawing motion, Journal of Solar Energy Engineering 139(4), 041003.
[9] Tran, T. T., and Kim, D. H. (2015) The platform pitching motion of floating offshore wind turbine: A preliminary unsteady aerodynamic analysis, Journal of Wind Engineering and Industrial Aerodynamics 142, 65-81.
[10] Tran, T., Kim, D., and Song, J. (2014) Computational fluid dynamic analysis of a floating offshore wind turbine experiencing platform pitching motion, Energies 7(8), 5011-5026.
[11] Tran, T. T., and Kim, D. H. (2015) The aerodynamic interference effects of a floating offshore wind turbine experiencing platform pitching and yawing motions, Journal of Mechanical Science and Technology 29(2), 549-561.
[12] Wen, B., Dong, X., Tian, X., Peng, Z., Zhang, W., and Wei, K. (2018) The power performance of an offshore floating wind turbine in platform pitching motion, Energy 154, 508-521.
[13] Wen, B., Tian, X., Zhang, Q., Dong, X., Peng, Z., Zhang, W., and Wei, K. (2019) Wind shear effect induced by the platform pitch motion of a spar-type floating wind turbine, Renewable Energy 135, 1186-1199.
[14] Hu, H., Khosravi, M., and Sarkar, P. (2016) An experimental investigation on the aeromechanic performance and wake characteristics of a wind turbine model subjected to pitch motions, In 34th Wind Energy Symposium (p. 1997).
[15] Rockel, S., Camp, E., Schmidt, J., Peinke, J., Cal, R., and Hölling, M. (2014), Experimental study on influence of pitch motion on the wake of a floating wind turbine model, Energies 7(4), 1954-1985.
[16] Huang, Y., Cheng, P., and Wan, D.C. (2019). Numerical analysis of a floating offshore wind turbine by coupled aero-hydrodynamic simulation. Journal of Marine Science and Application.
[17] Cheng, P., Huang, Y., and Wan, D.C. (2019) A numerical model for fully coupled aero-hydrodynamic analysis of floating offshore wind turbine, Ocean Engineering 173, 183-196.
[18] Sorensen, J. N., and Shen, W. Z. (2002) Numerical modeling of wind turbine wakes, Journal of Fluids Engineering 124(2), 393.
[19] Jonkman, J., Butterfield, S., Musial, W., and Scott, G. (2009) Definition of a 5-mw reference wind turbine for offshore system development, Office of Scientific & Technical Information Technical Reports, 1–75.
[20] Jonkman, J., and Musial, W. (2010) Offshore code comparison collaboration (oc3) for IEA wind task 23 offshore wind technology and deployment, Office of Scientific & Technical Information Technical Reports 303, 275-3000.