A numerical model for fully coupled aero-hydrodynamic analysis of floating offshore wind turbine

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ARTICLE INFO

Keywords:
- Unsteady actuator line model
- Coupled aero-hydrodynamics
- FOWT-UALM-SJTU solver
- naoe-FOAM-SJTU solver
- Floating offshore wind turbine

ABSTRACT

Designing floating offshore wind turbine system is a quite challenging task because of the complex environmental loading and complicated coupling effects. In the present study, the fully coupled aero-hydrodynamic model for numerical simulation of floating offshore wind turbine (FOWT) is established with open source tool OpenFOAM. The coupled FOWT-UALM-SJTU solver is developed using the open source CFD package OpenFOAM, in which the unsteady actuator line model (UALM) is introduced into OpenFOAM for the aerodynamic simulation of wind turbine, while the hydrodynamic computation of floating platform is carried out with a two-phase CFD solver naoe-FOAM-SJTU. In the coupled model, the three-dimensional Reynolds-Averaged Navier-Stokes (RANS) equations are solved with the turbulence model k-ω SST employed for closure of RANS equations, and the Pressure-Implicit with Splitting of Operations (PISO) algorithm is applied to solve the pressure-velocity coupling equations. The coupled responses of a FOWT with NREL-5MW baseline wind turbine mounted on a semi-submersible platform are investigated. From the simulation, aerodynamic forces including the unsteady aerodynamic power and thrust can be obtained, and hydrodynamic responses such as the six-degree-of-freedom motions of the floating platform and the mooring tensions are also available. The impact of dynamic motions of floating platform on the aerodynamic performance of wind turbine is analyzed, and the effect of the aerodynamic forces on the hydrodynamic response of the floating platform is also studied.

1. Introduction

Excessive exploitation of conventional fossil fuels has intensified the energy crisis and environmental pollution problem, which makes it an immediate issue to find clean and renewable energy resource to replace the traditional energy. As one of the most promising non-polluting renewable energy sources, wind energy has shown great potential and attracted the global attention. Exploitation of wind energy has experienced rapid growth since last few decades. According to the statistics, the global reserves of wind energy is up to 2.74 × 10^9MW and 2 × 10^7MW are utilizable (Zhang et al., 2010), which is about 10 times of the available water energy. The offshore wind resource has lots of particular advantages over onshore wind energy. For instance, the average speed of offshore wind is about 90% larger than that of onshore wind (Archer and Jacobson, 2005). Wind turbines, as wind energy harvesting devices, has developed from onshore to offshore wind farms in recent years.

Installing wind turbines in offshore wind farms far away from land can reduce the visual pollution and noise compared with those onshore or near land offshore ones (Bae et al., 2011). Water depth increases rapidly with the distance from the land, while cost of the traditional gravity-based or jacket type foundations grow sharply with water depth. Floating offshore wind turbines (Sørensen and Shen, 2002) are more cost effective choice for offshore wind farms with water depth exceeding 50m (Butterfield et al., 2005). In June 2009, the first multi-megawatt FOWT in the world, Hywind Demo equipped with a 2.3-MW wind turbine, was installed at the west coast of Norway, and its power production has been quite promising (Skare et al., 2015). And the success of Hywind Demo has inspired the development on FOWT. The Scottish government granted installation of a floating offshore wind farm with five 6-MW FOWTs in the North Sea off the Peterhead coast (BBC, 2015; Liu et al., 2017), where the water depth is over 100m.

However, designing FOWT system is a quite challenging task due to the complicated structure, the complex environmental loading and the coupling effects (Liu et al., 2012). Compared with conventional onshore wind turbine or fixed-bottom wind turbine working in shallow water, a FOWT suffers much more complicated environmental loads: the aerodynamic forces on turbine rotor, the hydrodynamic loads on
floating support platform and the mooring forces, etc. Furthermore, the aerodynamic forces on turbine rotor transmitted to the floating support platform via the tower, which affects the dynamic responses of the platform; the mooring lines provide restoring forces on supporting platform to restrict the movement of the system; and on the other round, the motion of platform influences the aerodynamic performance of the turbine blades by changing the relative flow velocity experienced by turbine blades. Complex interaction between the components makes coupling prediction of FOWT a quite challenging task.

Experimental test, as an indispensable tool for research, plays an important role in study on FOWT. A couple of intermediate-scale FOWT models have been deployed on ocean coast (Viselli et al., 2015). Experiencing the offshore wind-wave environment, the intermediate-scale experiments provide reliable reference data for further design of commercial-scale devices. However, the high cost and the difficulties in operational control make intermediate-scale experiment an inadvisable choice. Meanwhile, a number of scaled-down FOWT with different designing concepts have been carried out in wave basin under various experimental conditions (Martin, 2011; Koo et al., 2014; Myhr ANyggaard, 2014; Sandner et al., 2015). These scaled-down experiments also show practical results and reference data for validation and designing of FOWT. But there still underlies a problem that the Froude scaling law and the Reynolds similarity law cannot be guaranteed at the same time.

To meet the requirement of predicting coupled aerodynamic performances of a FOWT system, the numerical method stands out, which is much more economical than experimental tests either in intermediate-scale or scaled-down models and without limitation of the scaling laws. Since onshore wind turbines have developed for decades, there exist a couple of numerical tools for aerodynamic analysis. The most commonly used numerical methods are the blade element momentum (BEM) method (Glauert, 1963), the vortex methods (Voutsinas et al., 1995), the potential flow theory (Van Bussel, 1995), the actuator line model (Shen and Sørensen, 2002), the computational fluid dynamics (CFD) methods (Zhou and Wan, 2015), etc. BEM method is simple and very time-saving during computing, and most of the commercial numerical tools are developed based on BEM method (Jonkman, 2007). However, the assumptions in this model and the dependency on 2D aerodynamic experimental data of airfoils exposed the limitation and the inaccuracy of BEM model. To gain the description of 3D flow information around turbine blades, the vortex methods and potential flow theory are developed. As is known to all, these two methods are based on the inviscid flow assumption, so the viscous effects are neglected, which may result in significant inaccuracy. Besides, the vortex method has a potential risk for stability while vortex elements getting close to each other (Hansen et al., 2006). With rapid development of computational technology, the CFD method is becoming popular in aerodynamics study (Cheng et al., 2016). With direct calculation by solving Navier-Stokes (N-S) equations, CFD simulations provide much more precise results including detailed flow information for in-depth discuss on the physical mechanism. On the other side, the direct calculation method requires higher computing performance and takes much longer time. Using the actuator line model (ALM) is an effective way to reduce computational cost by replacing the real blade structure with virtual actuator lines, and guarantee considerable precision by solving the Navier-Stokes equations in flow field (Troldborg et al., 2007).

However, the aerodynamics analysis of FOWTs is significantly different from the conventional fixed wind turbines due to the additional motion caused by platform dynamic responses (Sebastian and Lackner, 2012). In some previous research works, the unsteady aerodynamics of FOWT blades is investigated by considering the typical motions of support platform. Tran (Tran and Dong, 2015; Tran and Kim, 2016a) has done a series of calculations on unsteady aerodynamic predictions of turbine blades by considering platform motion with periodic surge, pitch or yaw using unsteady CFD methods with a dynamic moving grid technique. Besides the oscillating regularity of both aerodynamic thrust and power, the flow interaction phenomena between the turbine blades with oscillating motions and the generated blade-tip vortices were observed. Wu (Wu and Nguyen, 2017) has developed a CFD model for unsteady and non-linear aerodynamic simulations of rotor under floating platform-induced motions with arbitrary mesh interface (AMI).

Recently, fully coupled aero-hydrodynamic simulations of FOWTs have been conducted under combined wind-wave conditions, and the coupling effects between the aerodynamics of wind turbine and the hydrodynamics of floating platform are studied. The National Renewable Energy Laboratory (NREL) developed a fully coupled aero-hydro-servo-elastic tool named FAST (Jonkman, 2009), which is based on BEM and potential flow theory, to implement the coupled simulation of FOWTs. However, utility of FAST is dependent on data-inputting from an external potential-flow-based hydrodynamic solver, such as WAMIT, which restricts its usage for more accurate predictions as the viscous effect is ignored in potential flow theories. There are other numerical tools for coupling simulation of FOWT based on BEM method, such as HAWC2, 3Dfloat, bladed, etc. (Cordle, 2010). As BEM is an empirical method with various correction models (such as Glauert correction, skewed wake correction, etc.), Sebastian (Sebastian and Lackner, 2013) indicated that the BEM is still questionable in unsteady aerodynamic prediction for FOWTs. Therefore, benefitting from the rapid development of high-performance computing (HPC) technique, the CFD method has shown great potential for accurate numerical simulation for FOWT. In recent years, studies on fully coupled analysis of FOWTs have been conducted with CFD method. Tran conducted the fully coupled aero-hydrodynamic analysis of a semi-submersible FOWT using a dynamic fluid body interaction approach (Tran and Kim, 2016b). Liu (Liu et al., 2017) established a fully coupled CFD analysis tool for FOWTs based on OpenFOAM package and the coupling effect of the OC4 DeepCWind semi-submersible FOWT was studied. CFD simulations achieve accurate results and enable detailed quantitative analysis of flow field. However, a full structure CFD simulation is quite computational costly.

Based on the open source platform OpenFOAM, our research team developed the CFD solver naoe-FOAM-SJTU to investigate hydrodynamic problems in the field of ship and ocean engineering, and the unsteady actuator line model (UALM) (Li et al., 2015) was introduced into OpenFOAM for aerodynamic simulation of wind turbine. By combining these two solvers, the fully coupled aero-hydrodynamic model for simulation of a floating offshore wind turbine is established. By using the solver, the validation of unsteady aerodynamic loads was conducted compared to different numerical methods. Moreover, the coupled aero-hydrodynamic simulation for a FOWT was also completed compared to the simplified method (Karimirad and Moan, 2012). In the present study, the coupled aero-hydrodynamic responses of Phase II of OC4, which is a semisubmersible-supported wind turbine system, are investigated. The three-dimensional Reynolds-Averaged Navier-Stokes (RANS) equations coupled with the k-ω SST turbulence model are solved. The Pressure-Implicit with Splitting of Operations algorithm (PISO) is employed to solve the pressure-velocity coupling equations. The effect of turbine aerodynamics on floating platform response is investigated with proper comparison between the fully coupled simulation of FOWT system and the hydrodynamic results of pure platform. Similarly, the influence of platform hydrodynamics on turbine dynamics is examined by comparing the fully coupled simulation of FOWT system and the aerodynamic results of pure wind turbine. In addition, the impact of incoming wave condition on the system performance is analyzed by varying the wave conditions.

In this paper, the numerical model utilized in this present work is introduced firstly; validations for both aerodynamic and hydrodynamic models are conducted and presented in the following part; and the descriptions of the physical model employed in the present study, the Phase II of OC4 floating offshore wind turbine system, are shown; simulation results and discussions are interpreted; and finally, proper
conclusions are stated.

2. Numerical method

2.1. Governing equations

In the fully coupled numerical simulation model for FOWT system, the three-dimensional (3D) Reynolds-Averaged Navier-Stokes (RANS) equations for transient, incompressible and viscous Newtonian fluid are solved, which contain the continuity and momentum equations:

\[ \nabla \cdot \mathbf{U} = 0 \]

\[ \frac{\partial (\rho \mathbf{U})}{\partial t} + \nabla \cdot (\rho (\mathbf{U} \mathbf{U})) = -\nabla p + \mathbf{g} \times \mathbf{r} + \nabla \cdot (\mu_{eff} \nabla \mathbf{U}) + (\mathbf{U} \nabla \mathbf{U}) \]

(1)

Where, \( \mathbf{U} \) represents velocity of flow field; \( \mathbf{U}_b \) is the velocity of grid nodes; \( \rho \) is the density pressure by subtracting hydrostatic component \( \rho g \mathbf{x} \) from total pressure; \( \mathbf{g} \) is the acceleration vector of gravity; \( \rho \) is the mixture density with two phases (water and air); \( \mu_{eff} = \rho (\mu + \nu) \) is the effective dynamic viscosity, in which \( \nu \) and \( \nu_t \) are the kinematic viscosity and eddy viscosity respectively; \( \mathbf{f} \) is the source term. With introduction of the time-averaged terms, the above RANS equations are not closed as they contain more variables than equations. In order to meet the closure requirement and solve RANS equations, the two-equation turbulence model \( k-\omega \) SST (Menter, 1994) is employed, where the turbulent kinetic energy \( k \) and the turbulent dissipation terms for \( \omega \) are described as:

\[ \frac{\partial k}{\partial t} + \nabla \cdot (k \mathbf{U}) = \nabla \cdot (h_k \nabla k) + G_k - Y_k + S_k \]

(2)

\[ \frac{\partial \omega}{\partial t} + \nabla \cdot (\omega \mathbf{U}) = \nabla \cdot (h_\omega \nabla \omega) + G_\omega - Y_\omega + D_\omega + S_\omega \]

(3)

Where, \( h_k \) and \( h_\omega \) are the effective diffusion coefficients for the turbulent kinetic energy \( k \) and the turbulent dissipation rate \( \omega \) respectively; \( G_k \) and \( G_\omega \) are generation terms for \( k \) and \( \omega \); \( Y_k \) and \( Y_\omega \) are dissipation terms for \( k \) and \( \omega \); \( S_k \) and \( S_\omega \) are the source terms for \( k \) and \( \omega \). \( D_\omega \) is the cross-diffusion terms for \( \omega \).

2.2. Unsteady actuator line model

In this present study, the actuator line model (ALM) is utilized to implement the aerodynamic prediction of FOWT. The ALM is an effective way to reduce computational cost by displacing the real blades surfaces with virtual actuator lines and not being required to solve the blade geometry layer. The wind turbine blades are simplified into actuator lines withstand body forces in ALM, which are divided into a series of discrete actuator points (Sørensen and Shen, 2002).

In this study, modifications are made to the initial ALM so that it can be used to simulate the FOWT. This is accomplished by accounting for the influence of the platform motion on the blades. When the ALM is applied to the simulation of the FOWTs, the velocity vector \( \mathbf{U}_{b} \) induced by the motions of the floating platform is added into the velocity triangle (as shown in Fig. 1), which will lead to complex interactions between the rotor and its wake. So the ALM needs to be modified to solve the unsteady problem caused by the dynamic motion responses of floating platform. The unsteady actuator line model considering the effect of six-degree-of-freedom motions is used in this paper.

In order to determine the aerodynamic forces acting on rotor blades, a blade element method combined with two-dimensional (2D) airfoil characteristics is used. Fig. 1 shows a cross-sectional element at radius \( r \) which defines the airfoil in the xOy plane. The figure shows the integral velocity vectors relationship described as:

\[ \mathbf{U}_{total} = \mathbf{U}_{in} + \mathbf{r} \times \mathbf{r} + \mathbf{U}_{rot} + \mathbf{U}_{M} \]

(5)

Where, \( \mathbf{U}_{in} \) represents the inflow velocity vector, \( \mathbf{U}_{rot} \) is the flow velocity induced by the rotating blade, \( \mathbf{r} \times \mathbf{r} \) is the speed of airfoil causes by the blades rotation, \( \mathbf{U}_{M} \) is the additional airfoil velocity vector induced by the motions of the floating platform. And the magnitude of the local velocity relative to the rotating blade is given as:

\[ |\mathbf{U}_{tot}| = \sqrt{(\mathbf{U}_{in} - \mathbf{U}_{M})^2 + (\mathbf{r} \times \mathbf{r} - \mathbf{U}_{rot} + \mathbf{U}_{M})^2} \]

(6)

The angle of attack \( \alpha \) which determines the airfoil aerodynamic data is defined as:

\[ \alpha = \phi - \phi_0, \phi = \tan^{-1}\left(\frac{\mathbf{U}_{in} - \mathbf{U}_{M}}{\mathbf{r} \times \mathbf{r} - \mathbf{U}_{rot} + \mathbf{U}_{M}}\right) \]

(7)

Where, \( \phi \) is the inflow angle; \( \phi_0 \) is the local airfoil twist angle; and the aerodynamic lift and drag forces can be given by the following equation:

\[ \mathbf{f} = (\mathbf{L}, \mathbf{D}) = \frac{\rho |\mathbf{U}_{tot}|^2}{2\chi_{0}} \left( C_L \mathbf{e}_L + C_D \mathbf{e}_D \right) \]

(8)

Where, \( c \) is the chord length of the airfoil, \( N_0 \) is the total number of blades; \( C_L \) and \( C_D \) are the lift and drag coefficient respectively, \( \mathbf{e}_L \) and \( \mathbf{e}_D \) denote the unit vectors in the directions of the lift and the drag respectively. The lift and drag coefficient are determined from measured or computed 2D airfoil data which are corrected with 3D effects.

The aerodynamic lift and drag forces are acting as body force in the flow field after smooth treatment to avoid singular behavior.

\[ \mathbf{f}_i = \mathbf{f} \otimes \mathbf{n}_i \]

(9)

and,

\[ \eta_i(d) = \frac{1}{e^{2\pi d^2/\chi_{0}^2} + \left(\frac{d}{\chi_{0}}\right)^2} \]

(10)

Here, \( d \) is the distance between the measured point in flow field and the actuator points on the rotor. \( \chi \) is a constant width parameter to adjust the strength of regularization function, and the parameter \( \chi_0 \) is suggested to be determined according to the length of grid near turbine blades or the chord length of airfoil (Sørensen et al., 1998). And the body force added onto the right side of the momentum equations as a source term can be written as:

\[ \mathbf{f}_i(x, y, z, t) = \sum_{i=1}^{N} f(x_i, y_i, z_i, t) \frac{1}{e^{2\pi d^2/\chi_{0}^2} + \left(\frac{d}{\chi_{0}}\right)^2} \]

(11)

Then the UALM is programmed as a C++ class based on the OpenFOAM.

2.3. Six-degree-of-freedom (6DOF) motions

The fully coupled aero-hydrodynamic solver is established by combining the aerodynamic UALM module and the hydrodynamic code. And the hydrodynamic solver employed in this paper is our in-house code naeo-FOAM-SJTU (Shen et al., 2012a). naeo-FOAM-SJTU is developed based on the OpenFOAM, which is an open source tool package. In this solver, the two-phase incompressible RANS equations are solved, which are discretized by the finite volume method (FVM), and the volume of fluid (VOF) method is utilized to capture the free surface and the dynamic deformation mesh approach is employed to handle structure motions (Shen et al., 2012b). Based on fundamental codes in OpenFOAM, several modules are developed: a numerical tank system including the wave generation and damping module, the six-Degree of Freedom (6DOF) motion module and the mooring system module. As validations, hydrodynamic simulation of floating platform coupled with mooring system was conducted by Cao using naeo-FOAM-SJTU (Cao et al., 2013), and some verification was made in previous work (Zhao and Wan, 2015), which proved that naeo-FOAM-SJTU is a good choice to deal with this kind of problems.

With establishment of the 6DOF motion module, the naeo-FOAM-
SJTU solver is able to predict the motion responses of floating structures. Two coordinate systems (as shown in Fig. 2) are set up in the procedure of solving 6DOF motion equations: the body-fixed coordinate system and the earth-fixed coordinate system. At each time step simulation, the motion equations are solved in platform-fixed coordinate system while the forces are calculated in earth-fixed coordinate system. Therefore, a transformation between the data in these two systems is essential. The added velocity induced by the dynamic motions of the supporting platform is updated by the following equation:

\[ \mathbf{U}_{\text{motion}} = [\mathbf{J}](\mathbf{U}_C + \omega_C \times (\mathbf{x}_c - \mathbf{x}_c)) \]  

Where, \([\mathbf{J}]\) represents the transformation matrix defined from the body-fixed coordinate to earth-fixed coordinate; \(\mathbf{U}_C\) and \(\omega_C\) donate the translational velocity and the angular velocity of the rotating center; \(\mathbf{x}_c\) is the location the rotating center.

2.4. Volume of fluid (VOF) method

For capturing the free surface, the VOF method (Hirt and Nichols, 1981) with bounded compression technique (Rusche, 2003) is applied in our solver. The VOF transport equation is defined as:

\[
\frac{\partial \alpha}{\partial t} + \nabla \cdot \left( \mathbf{U} \alpha \right) - \nabla \cdot \left( \alpha \mathbf{U}_g \right) = 0
\]  

(13)

Where, \(\mathbf{U}\) is the velocity of flow field, \(\mathbf{U}_g\) is the velocity of grid nodes, and \(\alpha\) is the volume fraction representing the relative proportion of fluid in each cell which is defined as:

\[
\alpha = \begin{cases} 
0 & \text{air} \\
1 & \text{water} \\
0 < \alpha < 1 & \text{interface}
\end{cases}
\]  

(14)

And the fluid density \(\rho\) and the dynamic viscosity \(\mu\) can be described with the volume fraction as:

\[
\rho = \alpha \rho_l + (1 - \alpha) \rho_g
\]  

(15)

\[
\mu = \alpha \mu_l + (1 - \alpha) \mu_g
\]  

(16)

Where, \(\rho_l\) and \(\mu_l\) are the density and dynamic viscosity of the liquid (water), while \(\rho_g\) and \(\mu_g\) are the density and dynamic viscosity of the gas (air).

2.5. Wave generation and absorption module

For hydrodynamic simulation of a floating platform, the work of wave generation must be implemented. In naoe-FOAM-SJTU solver, the wave generation and absorption module is capable of generating various types of waves such as linear wave, high order (2nd to 5th) Stokes waves, irregular waves (Shen and Wan, 2016), focusing waves (Cao and Wan, 2014), etc. The linear regular waves will be adopted in the following paper. The surface elevation for the linear regular wave and the horizontal and vertical components of fluid velocity distribution are described as:

\[
\eta = A \cos(kx - \omega t)
\]  

(17)

\[
\begin{align*}
\mathbf{u} &= \frac{AH}{2} \frac{\cosh k(z + d)}{\sinh kd} \cos(kx - \omega t) \\
\mathbf{w} &= \frac{AH}{2} \frac{\sinh k(z + d)}{\sinh kd} \sin(kx - \omega t)
\end{align*}
\]  

(18)

Where, \(A\) and \(H=2A\) denote the wave amplitude and wave height; \(k\) and \(\omega\) are wave number and wave circular frequency; \(z\) is the vertical coordinate and \(d\) represents the water depth.

Once the wave is generated and propagates from inlet towards outlet boundary, reflection is non-negligible which travels in an opposite direction and may interfere with the incident wave, so that the wave damping module is developed (Larsen and Dancy, 1983). In the wave damping module, sponge layer takes effect by adding an additional artificial viscous term as a source term on the right side of the momentum equation in RANS. The new term is expressed as:
where the aerodynamic simulations are conducted with the UALM, and the subscript i represents the ith node lies on the ith segment.

Where, \( \mu_s \) is the artificial viscosity determined by the following equation:

\[
\mu_s(x) = \begin{cases} 
\alpha_s \left( \frac{x-x_0}{x_0} \right)^2, & x > x_0 \\
0, & x \leq x_0 
\end{cases}
\]

Where, \( \alpha_s \) is a dimensionless quantity defining damping strength for the sponge layer. \( L_s \) represents the length of sponge layer, and \( x_0 \) is the start of the sponge layer (see Fig. 3).

### 2.6. Mooring system modelling

To simulate the interaction between the mooring lines and floating platform, the code of mooring system module (Liu, 2014) is developed. Here, the piecewise extrapolating method (PEM) which is a quasi-static solution is conducted (Li, 2016). Fig. 7 illustrates the thrust and power comparisons of the numerical results and the experimental ones. Both the numerical power and thrust show quite good agreement with the test data, which confirms ALM a powerful and reliable tool in aerodynamic simulation.

The UALM module is employed for the aerodynamic simulation of NREL-5MW baseline wind turbine (detailed description can be found in the following section). The aerodynamic forces and powers on the NREL-5MW wind turbine with various steady uniform wind speed are first obtained with ALM model. The results of power and thrust are compared with results obtained with previous results in Fig. 8, which shows quite good agreement with other results and certifies that the FOWT-UALM-SJTU solver is reliable in basic aerodynamic simulation.

Considering the wind turbine in the whole FOWT system experiences 6DOF motion, the unsteady aerodynamic simulation for turbine rotor experiencing periodic surge motion is also conducted for validation of UALM module. The surge motion is determined with a sinusoidal function \( s = 8 \sin(0.246t) \), where the amplitude and the circular frequency of oscillating surge motion are 8m and 0.246, respectively. The periodic surge motion causes the variation of the relative wind speed nearby the turbine blades, and brings about the oscillation of the aerodynamic forces on turbine. The aerodynamic thrust and power are compared with those calculated with overset grid technique (Tran and Kim, 2016a), and the curves in Fig. 9 show good agreement in both thrust and power of the wind turbine. The range between the maximum and the minimum of both the aerodynamic power and thrust resulted from UALM are a little smaller than that from simulations using full-structured CFD method with overset grid technique but the difference is no more than 7%. It is also well proved that the FOWT-UALM-SJTU solver is a reliable solver for both unsteady aerodynamic calculations.

### 3. Validation for the numerical models

#### 3.1. Validation for aerodynamics with UALM module

In our previous study with ALM, the validation against “Blind Test 1” is conducted (Li, 2016). Fig. 7 illustrates the thrust and power comparisons of the numerical results and the experimental ones. Both the numerical power and thrust show quite good agreement with the test data, which confirms ALM a powerful and reliable tool in aerodynamic simulation.

The 3D numerical wave tank including wave generation and absorption module is also considered as a source term \( f_s \) on the right side of the momentum equations. In addition, the effect of sponge layer is also considered as a source term \( f_s \). So the momentum equation in RANS is modified as:

\[
\frac{\partial(\rho U)}{\partial t} + \nabla \cdot (\rho U U) = -\nabla p - g \rho \mathbf{V} + \nabla \cdot (\mu_s \nabla U) + (\rho U \mathbf{V})
\]

Where, \( f_s \) is the surface tension term in two phases model and takes effect only on the liquid free surface.

The solving procedure of coupled aero-hydrodynamic simulation for the FOWTs is shown in Fig. 6. The main program loop is based on naoe-FOAM-SJTU. At the start of the simulation for each time step, the aerodynamics, hydrodynamics, and the mooring systems are calculated simultaneously with corresponding modules since the mesh grid and fluid field information are updated according to the motions calculated in last time step. Then the volume forces calculated with the UALM module are transferred to the main program to solve the RANS equations (Eqn. (22)) with PISO loops for the whole fluid field, where 2–6 PISO loops are required to reach convergence of the fluid field simulation. And when the 6DOF motion equations are solved, the turbine aerodynamic forces calculated with UALM module, as well as the mooring forces simulated with the mooring module are transferred to the main program, so the motion of FOWT is calculated and the mesh deforming information is updated.

#### 3.2. Validation for wave generation and absorption module

The 3D numerical wave tank including wave generation and absorption is employed. The wave properties used for validation and the following coupled simulation in the present work are listed in Table 1.
Fig. 5. Coupled analysis modules.

Fig. 6. Solving procedure of coupled simulation.

Fig. 7. Comparison of numerical thrust and power coefficient with “Blind test 1” result (Krogstad and Lund, 2012; Li, 2016).
The simulation domain is set as a rectangular region with longitude range of $-150m$–$300m$ which is about three times of the wave length, a range of $-150m$–$150m$ in landscape direction, and the distance from bottom to the initial water surface is $100m$ to guarantee the linear wave condition requirement. To validate the wave generation and absorbing, four wave gauges are set along wave propagating direction in the numerical wave tank ($x = -50m$, $0m$, $100m$, $279m$) to monitor wave elevation at different position.

The numerical results are compared with the theoretical data. The first three pictures in Fig. 10 show the comparison results of wave elevation at the position of the three wave gauges, and the fourth shows result at the end of the damping area. The figures indicate that the numerical simulation results agree quite well with the theoretical solutions. In the last figure, the wave height has been significantly reduced over $90\%$ with the sponge layer effect, in which case the wave reflection effect is neglected. Therefore, the wave generation and absorbing module for naoe-FOAM-SJTU solver utilized in this paper is accurate and reliable.

3.3. Validation for naoe-FOAM-SJTU with hydrodynamic response of platform in regular wave

The hydrodynamic response of the semi-submersible floating platform is also investigated under a regular heading wave condition as introduced above. Three main degrees of freedoms of the floating platform with the most significant responses in heading wave conditions, surge, heave and pitch, are analyzed. Fig. 11 shows the Response Amplitude Operators (RAOs) for surge, pitch and heave motions of the floating platform. The numerical results of this present work are compared with the experimental data and numerical results with FAST (Coulling et al., 2013) and other CFD solvers (Liu et al., 2017; Tran and Kim, 2016b). To get the RAOs of the platform motions, the motion amplitudes of surge, pitch and heave are normalized by the amplitude of the regular wave ($3.79m$). Fig. 11 shows that the hydrodynamic prediction of the platform motion in this regular heading wave condition agrees quite well with the experimental data as well as the numerical results using other simulation solvers.

3.4. Validation for naoe-FOAM-SJTU solver with free-decay motion of the platform

Free-decay test is an efficient way to predict the natural frequency of a floating structure, which is one of the main hydrodynamic coefficients. Since the surging, pitching, heaving motion responses are more significant than others in heading waves, the free-decay motion analysis of the OC4 DeepCWind semi-submersible floating platform utilized in the present study is performed for each of the three DOFs (surge, heave, pitch) using naoe-FOAM-SJTU solver. The platform model and simulation domain are shown in Fig. 12, while detailed structural parameters are described in the following section. Free-decay tests are carried out in calm water without wind/wave/current. Herein, the platform is initially perturbed with a prescribed displacement, and released to move freely as oscillating back to the equilibrium position. The perturbed displacements in the numerical simulation are determined with experimental data. Table 2 presents the natural periods for these three DOFs compared with experimental and numerical results. The natural period obtained in the present simulations show good agreement with those from other numerical tools with potential-flow panel method or CFD method, and matches quite well with the experimental results by MARIN (Coulling et al., 2013). Fig. 13 illustrates the dynamic responses of free-decay surge and pitch motions. The dynamic motion results are compared with the previous studies (Tran and Kim, 2015; Luan et al., 2013; Krogstad and Lund, 2012) in both CFD method and potential-flow method.

Table 1

<table>
<thead>
<tr>
<th>Wave properties</th>
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<tbody>
<tr>
<td>Wave Length</td>
</tr>
<tr>
<td>Wave Period</td>
</tr>
<tr>
<td>Wave Height</td>
</tr>
</tbody>
</table>

Fig. 8. Aerodynamic simulation results with different numerical methods.

Fig. 9. Aerodynamic thrust and power of the NREL-5MW wind turbine with periodic surge motion ($s = 8\sin(0.246t)$) of platform.

Fig. 10. The aerodynamic simulation results with different numerical methods.

Table 2

<table>
<thead>
<tr>
<th>Platform DOFs</th>
<th>Natural Period (T) (s)</th>
<th>Experimental</th>
<th>Numerical (naoe-FOAM)</th>
<th>Numerical (FAST)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surge</td>
<td>10.3</td>
<td>10.2</td>
<td>10.1</td>
<td>10.4</td>
</tr>
<tr>
<td>Pitch</td>
<td>10.3</td>
<td>10.2</td>
<td>10.1</td>
<td>10.4</td>
</tr>
<tr>
<td>Heave</td>
<td>10.3</td>
<td>10.2</td>
<td>10.1</td>
<td>10.4</td>
</tr>
</tbody>
</table>
4. Description of Geometry Model

4.1. Phase II of OC4 floating offshore wind turbine system

In the present simulation work, a semi-submersible floating offshore wind turbine (FOWT) system, Phase II of OC4 project (Robertson et al., 2012), is adopted. The Offshore Code Comparison Collaboration Continuation (OC4) project, which was formed in 2010 under the International Energy Agency Wind Task 30, is a project to verify the accuracy of the simulation tools and codes for offshore wind turbines (Robertson et al., 2013). The FOWT contains several main parts: a wind turbine (the NREL-5MW baseline wind turbine), a tower supporting the turbine, a supporting floating platform (the semi-submersible platform) on which the tower is mounted, and the mooring system to restrict the motion of platform. Fig. 14 shows the sketch of this FOWT system.

4.2. NREL-5MW baseline wind turbine

The wind turbine in Phase II of OC4 FOWT system is NREL-5MW baseline line wind turbine, which is a conventional three-bladed, upwind, variable-speed and blade-pitch-to-feather controlled wind turbine. This 5-MW wind turbine is a large scaled turbine with blade length of 63m, and the center of rotor is 90m above the still water level (SWL). The specification of the prototype is listed in Table 3 (Jonkman et al., 2009).

4.3. The semi-submersible platform

As shown in Fig. 15, the semi-submersible floating system consists of a main column attached to the tower, three offset columns covering significant portion of buoyancy, a couple of smaller diameter pontoons and cross braces to link the main column and offset columns and to strengthen the structure. Detailed properties are listed in Table 4.

Table 2

<table>
<thead>
<tr>
<th>DOF</th>
<th>Experiment (Coulling et al., 2013)</th>
<th>FAST (Coulling et al., 2013)</th>
<th>Simo/Riflex + TDH/MILL (Lian et al., 2015)</th>
<th>AQWA (Tran and Kim, 2015)</th>
<th>Unsteady CFD (Krogstad and Lund, 2012)</th>
<th>naoe-FOAM-SJTU (present work)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surge</td>
<td>107.0</td>
<td>107.0</td>
<td>115.9</td>
<td>112.5</td>
<td>108.1</td>
<td>108.3</td>
</tr>
<tr>
<td>Heave</td>
<td>17.5</td>
<td>17.3</td>
<td>17.1</td>
<td>17.3</td>
<td>17.8</td>
<td>17.58</td>
</tr>
<tr>
<td>Pitch</td>
<td>26.8</td>
<td>26.8</td>
<td>25.8</td>
<td>25.4</td>
<td>25.2</td>
<td>25.8</td>
</tr>
</tbody>
</table>

method. The present CFD approach (black solid curve) is capable to consider the viscous effect of floating platform, which shows improved hydrodynamic damping of CFD results than those potential based approach.
4.4. Mooring system

The semi-submersible floating system for Phase II of OC4 is moored with three catenary lines spread symmetrically about the platform center (Robertson et al., 2012). Fig. 16 shows the arrangement of the mooring system. Table .5 lists the mooring system properties used in this paper.

4.5. Determination of the rotating center

The Phase II of OC4 Floating Wind Turbine System is shown in Fig. 14. Besides the floating support platform, the FOWT system also contains the wind turbine and the tower above the supporting system. So the wind turbine and the tower should be counted when analyzing the mass distribution and the inertia of the whole system. The mass distribution and the structural of the whole system are listed in Table .6 and Table .7.

4.6. Simulation domain and grid structure

The entire hexahedral simulation domain is set as $750(x) \times 320(y) \times 400(z)$, as shown in Fig. 17. In Fig. 17, the parameter $\lambda$ represents for the wave length which changes in the cases, so the length of simulation domain is not set exactly according to the wave 

---

**Table 3**

Specification of NERL 5-MW turbine.

<table>
<thead>
<tr>
<th>Rating</th>
<th>5 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor Orientation, Configuration</td>
<td>Upwind, 3 Blades</td>
</tr>
<tr>
<td>Control</td>
<td>Variable Speed, Collective Pitch</td>
</tr>
<tr>
<td>Drivetrain</td>
<td>High Speed, Multiple-Stage Gearbox</td>
</tr>
<tr>
<td>Rotor, Hub Diameter</td>
<td>126 m, 3 m</td>
</tr>
<tr>
<td>Hub Height</td>
<td>90 m</td>
</tr>
<tr>
<td>Cut-in, Rated, Cut-out Wind Speed</td>
<td>3 m/s, 11.4 m/s, 25 m/s</td>
</tr>
<tr>
<td>Cut-in, Rated Rotor Speed</td>
<td>6.9 rpm, 12.1 rpm</td>
</tr>
<tr>
<td>Rated Tip Speed</td>
<td>80 m/s</td>
</tr>
<tr>
<td>Overhang, Shaft Tilt, Precone Angle</td>
<td>5 m, 5°, 2.5°</td>
</tr>
<tr>
<td>Rotor Mass</td>
<td>110,000 kg</td>
</tr>
<tr>
<td>Nacelle Mass</td>
<td>240,000 kg</td>
</tr>
<tr>
<td>Tower Mass</td>
<td>347,460 kg</td>
</tr>
<tr>
<td>Coordinate Location of Overall CM</td>
<td>$(−0.2 m, 0.0 m, 64.0 m)$</td>
</tr>
</tbody>
</table>
length. The distance between the inlet boundary and the center the floating offshore wind turbine system is 200m, and a sponge layer region with 180m length is set for wave absorption near the outlet boundary. Here, the water depth is set as 200m, and the distance between the bottom of the computational domain and the initial still water surface is 10m, where $d$ is the water depth. And the height of domain above the water surface is set as $4D \approx 260$m, where $D$ is the diameter of rotating turbine. The right figure shows the grid structure on a cross section. The refine region around the platform and the wake flow area with second-order refinement is illustrated in the right figure in Fig. 17.

As ALM is an efficiency model with simplified actuator model instead of the real blades structure in the aerodynamic simulation, much higher level refinement along the blades surface layer is saved. Thus the total number of grid cells in this simulation is about 3.5M. Both simulations are running in parallel with 40 processors, and time consumption for each time step with 6 inner PISO loops is about 20s.

5. Results and discussions

5.1. Aerodynamics of NREL-5MW wind turbine

The fully coupled aero-hydrodynamic numerical simulations of the phase II of OC4 semi-submersible FOWT are conducted with two different regular incoming waves under same inflow wind condition. As listed in Table 8, the inflow wind speed for both fully coupled simulations are set as the rated wind speed 11.4 m/s, while regular incoming waves with different wave period and wave height are adopted. In CASE#1, the wave period is 9.7s and the wave height which is two times of the wave amplitude is 3.66m, while the wave period and wave height in CASE#2 are 12.1s and 7.58m, respectively.

Aerodynamic forces and power of the FOWT are recorded during simulation, and time history of aerodynamic thrust and power are plotted in Fig. 18. Different from the conventional steady aerodynamic simulations for centre fixed wind turbines, both aerodynamic thrust and power of FOWT show significantly unsteady characteristics with the coupling interaction between aerodynamic loads on turbine and the hydrodynamic responses of floating platform. The time history of thrust curves of CASE#1 and CASE#2 both fluctuate periodically, while the periods of differs from each other. Due to the computational start-up fluctuation, the quasi-static periodic results are achieved since $t \approx 200$s, and curves in Fig. 18 are drawn with data in time range of (340s–356s), which covers fluctuation periods of both cases.

The fluctuation periods of both thrust and power in CASE#1 are about 9.7s, which is the same with the wave period adopted in CASE#1. Similarly, the fluctuation period of aerodynamic loads in CASE#2 are about 12.1s same with the wave period in CASE#2. Wave does not act on the turbine blades directly but on the floating platform, which causes periodic hydrodynamic motion responses of the platform. Here in the present work, the platform, wind turbine and tower are all regarded as rigid bodies. Mounted on the floating platform through rigid tower, the wind turbine gains an additional motion from the platform’s hydrodynamic response.

Compared with the thrust and power data obtained from steady aerodynamic simulations conducted in the above Validation section, the averaged value of both thrust and power of FOWT are decreased. The difference between the averaged values of CASE#1 and CASE#2 is negligible, but the oscillating amplitude of both thrust and power in CASE#2 is significantly larger than that in CASE#1. Thus a preliminary conclusion indicates that the growth of incoming wave amplitude

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**Table 4**

Floating platform geometry.

| Depth of platform base below SWL (total draft) | 20m |
| Elevation of main column (tower base) above SWL | 10m |
| Elevation of offset columns above SWL | 12m |
| Spacing between offset columns | 50m |
| Length of upper columns | 25m |
| Length of base columns | 6m |
| Depth to top of base columns below SWL | 14m |
| Diameter of main column | 6.5m |
| Diameter of offset (upper) columns | 12m |
| Diameter of base columns | 24m |
| Diameter of pontoons and cross braces | 1.6m |

---

**Table 5**

Mooring system properties.

| Number of Mooring Lines | 3 |
| Angle Between Adjacent Lines | 120° |
| Depth to Anchors Below SWL(Water Depth) | 200m |
| Depth to Fairleads Below SWL | 14m |
| Radius to Anchors from Platform Centerline | 837.6m |
| Radius to Fairleads from Platform Centerline | 40.866m |
| Unstretched Mooring Line Length | 835.5m |
| Mooring Line Diameter | 0.0766m |
| Equivalent Mooring Line Mass Density | 113.35 kg/m³ |
| Equivalent Mooring Line Mass in Water | 108.63 kg/m³ |
| Equivalent Mooring Line Extensional Stiffness | 7.536E+8 N/m |
| Hydrodynamic Drag Coefficient for Mooring Lines | 1.1 |
| Hydrodynamic Added-Mass Coefficient for Mooring Lines | 1.0 |

---

**Table 6**

Mass distribution of the FOWT system.

<table>
<thead>
<tr>
<th>Mass(kg)</th>
<th>CM Location above SWL (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor</td>
<td>1.1E5</td>
</tr>
<tr>
<td>Nacelle</td>
<td>2.4E5</td>
</tr>
<tr>
<td>Tower</td>
<td>2.497E5</td>
</tr>
<tr>
<td>Platform</td>
<td>1.347E7</td>
</tr>
<tr>
<td>Total</td>
<td>1.407E7</td>
</tr>
</tbody>
</table>

---

**Table 7**

Structural properties of the system.

| Structural mass | 1.407E7kg |
| CM location below SWL | 9.9376m |
| Total structure roll inertia about CM | 1.1E10 kg*m² |
| Total structure pitch inertia about CM | 1.1E10 kg*m² |
| Total structure yaw inertia about CM | 1.226E10 kg*m² |

---

Fig. 16. Arrangement of the mooring system.
causes the increase of fluctuation amplitude, but has tiny influence on the averaged value of the turbine aerodynamic loads.

5.2. Hydrodynamic responses of the semi-submersible platform

As is well known, an incoming regular wave induces periodic motion responses of the structures floating on the free surface (Cheng and Wan, 2015), where the first-order wave force causes the periodic motion around the initial position with the same period as incoming wave, while the higher-order hydrodynamic wave load drives the structure towards the wave marching direction. With restriction of mooring system, the floating structure will finally oscillates around an equilibrium position after a period of evolution. A FOWT naturally is a moored floating structure with additional wind turbine, so the basic oscillating regulation is observed in the hydrodynamic motions recorded during fully coupled simulation. And the motions time history of three main DOFs in heading waves (surge, heave and pitch) are plotted in Fig. 19.

The impact of wind turbine on platform is equivalent to external dynamic forces transformed through tower. Since the tower is ignored in the structure model, the force approximates to the aerodynamic forces by integrating the aerodynamic forces on actuator points along turbine blades, and the moments is determined as cross product of the aerodynamic forces and the moment arm vector pointing from turbine rotating centre to the FOWT rotating centre. Previous studies (Cheng and Wan, 2015) indicated that the distance from equilibrium position of hydrodynamic oscillating motion to the initial centre is no more than 0.5m with same wave condition as CASE#1, while the equilibrium position for coupled system in CASE#1 is about 14.2m as shown as surge motion in Fig. 19 (a), which is significantly increased with the aerodynamic impacts of the wind turbine. With growth of wave amplitude and wave length, the averaged surge motion is increased from CASE#1 to CASE#2. The averaged surge motion is driven by two main factors: high-order drift forces with incoming wave and the external forces from the wind turbine. As discussed above, the aerodynamic forces of wind turbine in CASE#1 and CASE#2 have similar averaged value, so it can be demonstrated preliminarily that the increase of averaged surge motion from CASE#1 to CASE#2 is mainly resulted from the growth of drift forces. On the other hand, the oscillating amplitudes of the motions are quite similar to that from previous calculation (Cheng and Wan, 2015). However, as larger-amplitude wave in CASE#2 causes stronger oscillating forces which induces greater periodic motion, the increase of oscillating amplitude is observed for all three DOFs in Fig. 19.

5.3. Coupled aero-hydrodynamic analysis

As discussed above, the oscillating motion of floating platform has significant influence on the aerodynamic loading of the wind turbine, and the aerodynamic forces also strongly affects the hydrodynamic responses of supporting platform. Eqn. (8) illustrates that the determining factor for the aerodynamic loads is the relative velocity near the actuator points, which has taken the platform motion into account. When rotor blade moves towards inflow wind marching direction, the relative velocity of air flow is lower compared to the fixed rotating...
only the surging motion but also pitching motion. Comparing Fig. 19(a) with Fig. 19(c), the platform surging motion has an opposite variation law with pitching motion. Namely, when the platform surge motion drives the rotor blade towards the Ox direction, the blade motion caused by the platform pitching motion points to the -Ox direction. There is another notable phenomenon, the aerodynamic forces of CASE#1 and CASE#2 meet the maximum value at the same time about $t = 342.2s$ in Fig. 18, but both surge and pitch in these two cases change on the opposite way at $t = 342.2s$. This is comprehensible by combining the surging effect and the pitching effect on the blades motion. In CASE#1, the oscillating amplitude of surge is 0.7m while the oscillating amplitude of pitch is about 0.8deg. Multiplying pitch angle with the distance between blade points to the rotational centre of whole FOWT system (100m), the amplitude of equilibrium motion induced by platform pitching motion is up to 1.4m, so the pitching motion plays the leading role in affecting the relative flow velocity at turbine blade. The platform motion speed is determined with the time derivative of surge displacement or pitch angle, and it's clear to see that pitching motion meets the minus maximum speed around $t = 342.2s$, therefore the relative flow speed achieve the maximum value, and so does the aerodynamic loads. The same principle applies to CASE#2 with surge oscillating amplitude 2.3m and pitch oscillating amplitude 1.05deg, in which case the surging motion acts as the leading factor. Thus CASE#2 meets the maximum aerodynamic forces when platform surging with the minus maximum surging speed.

The aerodynamic forces also cause significant increase of averaged surge and pitch motion on hydrodynamic responses of floating platform, and the fluctuation of aerodynamic forces also influences the oscillating amplitude of surge and pitch. Nevertheless, the aerodynamic forces and moments transmitted to floating platform are negligibly small compared with the hydrodynamic loads.

With the coupling interaction, the wake flow is also disturbed. The evolution of wake vortex structure of CASE#1 is illustrated during a representative period in Fig. 20. The wake vortex of the rotor is visualized with the iso-surface of the second-order invariant of velocity gradient $Q$ (Digraskar, 2010), and the wave free surface is contoured by surface elevation. Three clear and stable spiral vortexes are generated at the tip of the blades then march downstream with positive speeds of air flow. With additional motions transmitted from platform, the rotor blades moves into and out of its wake flow, which results the differences of the distance between two neighbour vortex tubes. And this additional motion also disturbs the wake flow and results in the quick dissipation of vortexes.

6. Conclusions

The actuator line model (ALM) is introduced into OpenFOAM for aerodynamic simulation of wind turbine. To take the platform motion into consideration in the aerodynamic simulation of wind turbine, the unsteady actuator line model (UALM) is established. By implementing the UALM as an aerodynamic simulation module into our in-house CFD code naoe-FOAM-SJTU, the fully coupled aero-hydrodynamic model FOWT-UALM-SJTU is developed for the fully coupled aero-hydrodynamic analysis of FOWTs. Since the complex blades structures are simplified as actuator line model and only structured background grids are requested for aerodynamic simulations, this numerical model is quite time-saving comparing with other conventional CFD tools. Besides, by solving the N-S equations in the entire flow filed, this simulation model provides more detailed and more accurate flow information over traditional BEM and potential flow theory.

Proper fundamental validations for the FOWT-UALM-SJTU solver are carried out, which shows good capability and reliability on both aerodynamic prediction of wind turbine and the hydrodynamic calculation of floating platform. Then fully coupled aero-hydrodynamic simulation of Phase II of OC4 semi-submersible FOWT is conducted with this coupled model.

Compared with aerodynamic loads in fixed centre simulations, both aerodynamic thrust and power decrease in fully coupled FOWT system. From the coupled aero-hydrodynamic simulation results, oscillating regularity on aerodynamic loads of wind turbine is observed with the same oscillating period as the incoming wave. With growth of the wave amplitude, the fluctuation amplitude of aerodynamic loads increases obviously, but wave condition has tiny influence on the averaged value of the turbine aerodynamic loads. The fluctuation of aerodynamic load results from the oscillation of platform motions, and meets the maximum value when the blade actuator points moves with the maximum speed in the opposite direction with inflow wind. Both surging and pitching motions play important roles in the influence on the relative flow velocity, and the maximum of aerodynamic loads are achieved when the leading motion reaches the minus maximum speed. With effect of turbine aerodynamics as an external load on the supporting platform, the platform motion shows significant increase on the averaged value, while the influence of turbine loads on the fluctuation of
platform is negligible. Nevertheless, the wave amplitude affects the fluctuation amplitude of platform a lot. Besides, the oscillating motion of the FOWT disturbs the flow wake of turbine and speeds up the dissipation of wake vortex.

The coupling interactions between the turbine aerodynamics and the platform hydrodynamics is much more complicated, and more research work need to be done for further study on the complex coupled floating offshore wind turbine system. In the preliminary stage, the model studies herein limited in steady wind and regular wave conditions with rigid blade structures, where the flexibility of the structures, the pitch-control effect, as well as the tower-blades interaction are omitted. Thus in our near future work, the numerical model will be improved to take these practical factors. This numerical model shows great potential in aero-hydrodynamic simulations of floating offshore wind turbines.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (51879159, 51490675, 11432009, 51579145), Chang Jiang Scholars Program (T2014099), Shanghai Excellent Academic Leaders Program (17XD1402300), Program for Professor of Special Appointment (Eastern Scholar) at Shanghai Institutions of Higher Learning (2013022), Innovative Special Project of Numerical Tank of Ministry of Industry and Information Technology of China (2016-23/09) and Lloyd’s Register Foundation for doctoral student, to which the authors are most grateful.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.oceaneng.2018.12.021.

References