COUPLED AERO-HYDRODYNAMIC SIMULATIONS OF TWO FLOATING OFFSHORE WIND TURBINES

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INTRODUCTION

The floating offshore wind turbines (FOWTs) play a vital role in the development of offshore wind power. It is necessary to study the coupled aero-hydrodynamic characteristics of FOWT in the floating wind farms. However, the complicated environment loads and the coupling effects between wind turbine and floating platform make it difficult to accurately predict the FOWT's coupled aero-hydrodynamic responses under variable wind and wave conditions. Along with the success of the emerging offshore wind industry, floating wind farms are planned for huge amount of clean electricity. In wind farms, wind turbines are usually clustered to decrease the overall installation and maintenance expenses, causing an adverse effect that the wind turbines generally experience a significant increased turbulence because of wake interaction from surrounding wind turbines [1]. Considering the fact that the wake interaction between FOWTs has significant effect on the power output, system dynamic responses and structural loadings, the wake interaction phenomenon in floating wind farms should be paid enough attention.

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) is developed to study the unsteady aerodynamic characteristics of FOWTs. To achieve coupled aero-hydrodynamic simulations of FOWTs, the UALM is embedded into the naoe-FOAM-SJTU to establish a fully coupled CFD analysis tool named FOWT-UALM-SJTU. By using the solver, the validation of unsteady aerodynamic loads is conducted compared to different numerical methods. Moreover, Coupled aero-hydrodynamic simulations of two OC3 Hywindspar FOWT models in tandem layout under shear wind and regular wave conditions are performed.

NUMERICAL METHOD

The actuator line model (ALM) [2] is an effective way to displace the real blade surfaces with virtual actuator lines. In consequence, it acquires a benefit of not requiring to solve the blade geometry layer. In the present work, the unsteady actuator line model (UALM) is used to simulate the unsteady aerodynamics of FOWTs, which is accomplished by modifying the initial ALM to consider the influence of the platform motions on the blades.

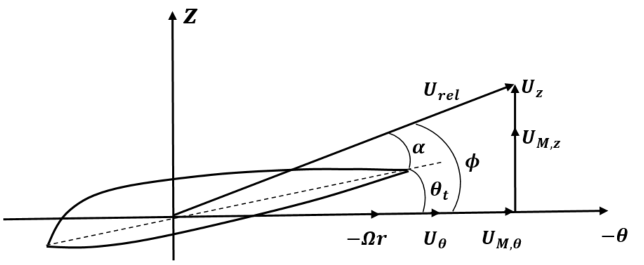


Figure 1: Velocity triangle seen locally on a blade section

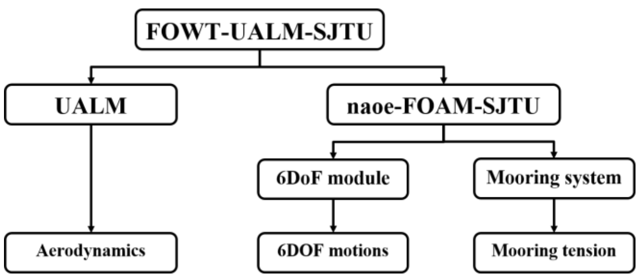


Figure 2: Frame diagram of FOWT-UALM-SJTU

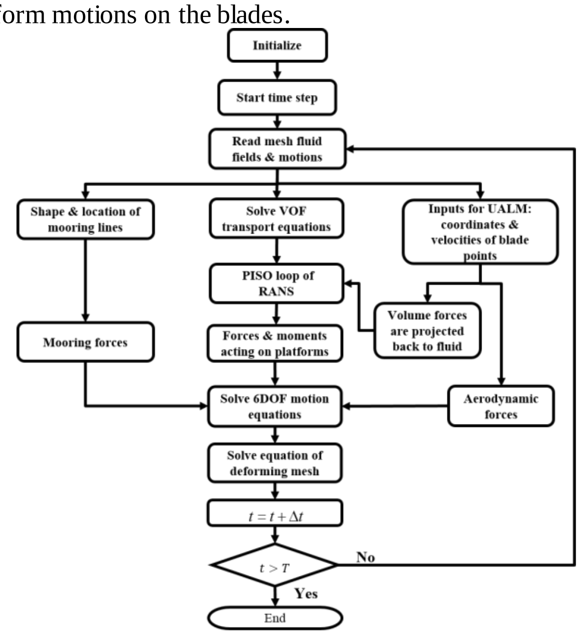


Figure 3: Solving procedure of coupled simulation

To determine the body forces distributed along the actuator lines, a blade element approach combined with two-dimensional airfoil characteristics is used. In Fig.1, 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 relative wind velocity $\vec{U}_{rel}$ seen from the blade section is determined as follows.

$$\boldsymbol{U_{rel}} = \boldsymbol{U_\theta} - \boldsymbol{\Omega r} + \boldsymbol{U_z} + \boldsymbol{U_M} \tag{1}$$

Where $\boldsymbol{\Omega}$ is the angular velocity of the rotor, $\boldsymbol{U_M}$ is the six degree of freedoms (DOFs) motion velocity of the actuator point induced by the platform motions.
The attack angle is defined as:

$$\alpha = \varphi - \gamma \tag{2}$$

Where $\varphi = \tan^{-1}\left(\frac{U_z + U_{M,z}}{U_\theta - \Omega r + U_{M,\theta}}\right)$ is the inflow angle with respect to rotor plane. θ_t is the local twist angle. $U_{M,\theta}$ and $U_{M,Z}$ are the projections of $\boldsymbol{U_M}$ on (θ, z) plane. After getting the attack angle, the body forces distributed along the actuator lines are calculated from the local attack angle and a look-up table of airfoil data. And the calculated body forces need to be distributed smoothly on the mesh points near the actuator point by using a 3D Gaussian function, which is the same as the traditional actuator line model.
The frame diagram of FOWT-UALM-SJTU is shown in Fig. 2. The aerodynamic forces can be got by the UALM. And the hydrodynamic responses including six-degree-of-freedom motions and mooring tensions are predicted by the naoe-FOAM-SJTU. In the coupled aero-hydrodynamics simulation code, the governing equations need some modification: a source term f_ε is added on the right side of the N-S equations for the flow field simulation (shown in Eqn (3)). And the solving procedure of coupled aero-hydro simulation for the FOWT system is shown in Fig. 3.

$$\frac{\partial \rho U}{\partial t} + \nabla \cdot (\rho U U) = -\nabla p - g \cdot \boldsymbol{x} \nabla \rho + \nabla \cdot \left(\mu_{eff} \nabla U\right) + (\nabla U) \cdot \nabla \mu_{eff} + f_\sigma + f_\varepsilon \tag{3}$$

RESULTS AND DISCUSSIONS

Aerodynamic Validation

The FOWT-UALM-SJTU solver is employed for the aerodynamic validation. And the results of power and thrust are compared with results obtained with FAST-BEM by Jonkman and OVERFLOW2. In Fig. 3, thrust and power results from aerodynamic numerical with FOWT-UALM-SJTU solver show good agreement with other results, which certifies that the FOWT-UALM-SJTU solver is reliable in aerodynamic simulation. Considering the wind turbine in the whole FOWT system experiences six DOF motion , another aerodynamic simulation for turbine rotor with periodic surge motion is conducted for validation . The results are compared with those calculated with overset grid technique [3], and the curves in Fig. 4 show good agreement in both thrust and power of the wind turbine, and the difference between the two curves is no more than 7%. With these validations above, the FOWT-UALM-SJTU solver is proved to be a reliable solver for both steady aerodynamic simulation and unsteady aerodynamic calculations.

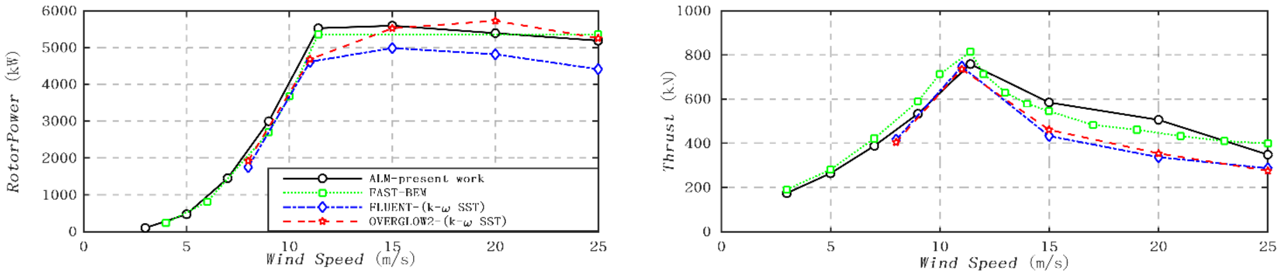


Figure 4: Aerodynamic Simulation Results with Different Numerical Methods

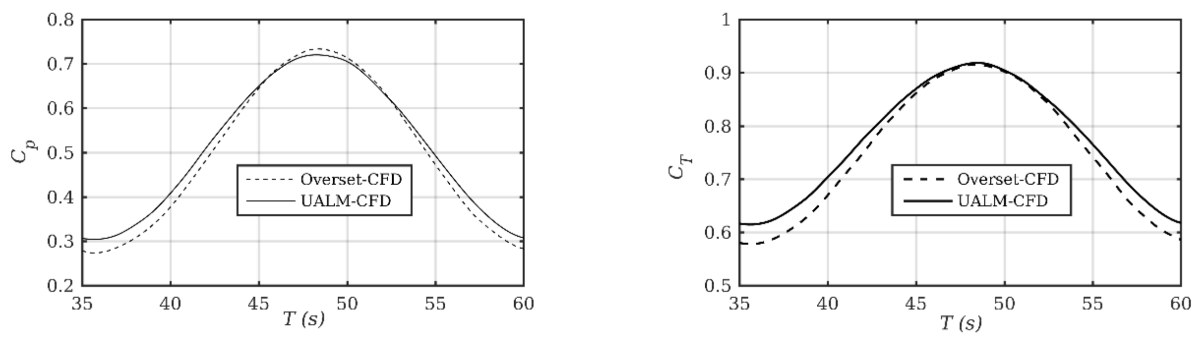


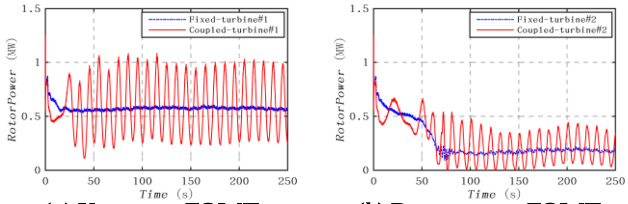
Figure 5: aerodynamic thrust and power of the NREL-5MW baseline wind turbine with periodic surge motion ($s = 8sin(0.246t)$) of platform.

Coupled Aero-hydrodynamic Simulation

Coupled aero-hydrodynamic simulations for two OC3 Hywindspar FOWT models in tandem layout under shear wind and regular wave conditions are carried out based on in-house CFD solver FOWT-UALM-SJTU. To investigate the influence of motion response of floating support platform on the wake interaction, both the platforms are fixed and the platforms are free to move are taken into consideration: *a*) Fixed case: the platforms are fixed; *b*) Coupled case: the platforms are free to move. Wind and wave conditions are kept in the same in these two cases. Steady wind velocity U=5m/s is adopted. The rotating speed is a fixed value 7.45rpm. Wave period and wave length are T = 10s and λ = 156m, respectively. And the wave height is H = 4m.

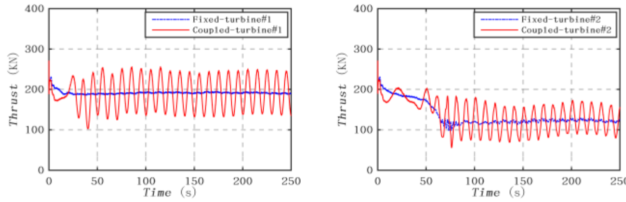
The time history curves of the rotor power and the thrust under different simulation conditions are shown in Fig. 6 and Fig. 7. The unsteady aerodynamic loads including the rotor power and thrust of the FOWTs in coupled case both fluctuate greatly and change periodically. The oscillation is believed to be caused by the motion of platform shown in Fig. 8, which makes the relative wind speed changes with the platform motion. Compared with aerodynamic loads in coupled case, the rotor power and thrust in parked case change little over time. It suggests that the aerodynamic loads of the FOWT are greatly influenced by the motions of floating support platform.

Affected by the wake from upstream FOWT, the incoming wind velocity for downstream FOWT is lower than that for upstream FOWT, which leads to the aerodynamic loads of downstream FOWT are much smaller than those of upstream FOWT. The rotor power and the thrust of the downstream FOWTs in fixed case are 94% and 99% compared with those in coupled case, respectively. And the rotor power and the thrust of the upstream FOWTs in fixed case are 85% and 97% compared with those in coupled case, respectively. It indicates that the rotor power and the thrust of FOWTs in coupled case are slightly larger than those of FOWTs in fixed case, which indicates that the motions of floating support platform may have beneficial effects on the aerodynamic loads of the FOWTs. And the influence of platform motions on rotor power is more significant than that on the thrust.



(*a*) Upstream FOWT (*b*) Downstream FOWT

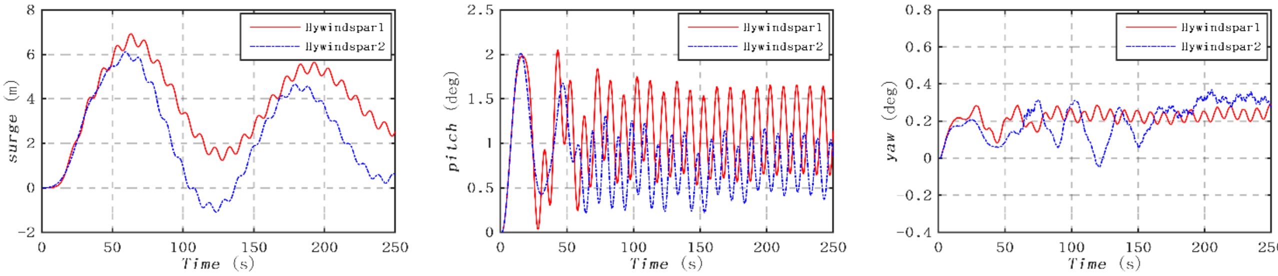
Figure 6: Power output of the FOWTs



(*a*) Upstream FOWT (*b*) Downstream FOWT

Figure 7: Thrust of the FOWTs

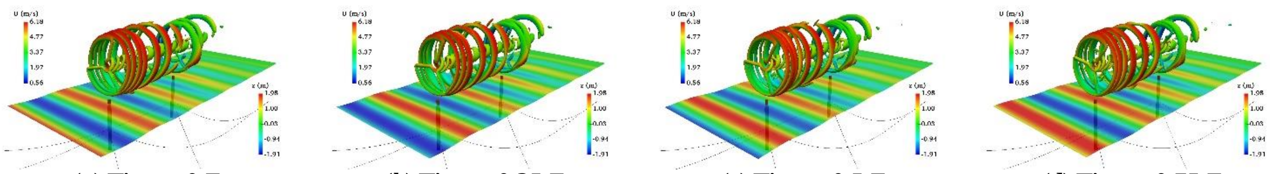
The motion responses of floating support platform in coupled case are presented in Fig. 8. The amplitude of surge motion of the upstream platform is larger than that of the downstream platform, resulted from the aerodynamic loads of upstream FOWT are larger than those of downstream FOWT. And the average value of pitch motion of upstream platform is greater than that of downstream platform for the same reason. In addition, the heave motion amplitudes of two platforms are almost the same. It suggests that the aerodynamic loads derived from the wind turbine have remarkable impact on the motion responses of floating support platform, especially for surge motion and pitch motion. While the heave motion is much less influenced by the aerodynamic loads.



(*a*) Upstream FOWT (*b*) Downstream FOWT (*a*) Upstream FOWT

Figure 8: Platform motion responses in coupled case

The evolution of wake vortex at different times of an entire wave circle in coupled case is illustrated in Fig. 8. The wake vortex of the rotor is visualized by the second-order invariant of velocity gradient, Q, and the free surface is contoured by elevation. Clearly spiral tip vortex from the upstream FOWT is captured, while this vorticity is quickly diffused in the downstream. While the tip vortex of downstream FOWT is not clear. The vorticity diffuses more quickly, and the vortex distance is much smaller compared with that of vortex from upstream FOWT. Due to the wake effect of the upstream FOWT, the axial direction incoming wind speed to the downstream FOWT decreases and the instability of flow field increases. This leads to the instability of the vortex from the downstream FOWT. Moreover, the vortices structures lean backward obviously resulting from the motions of floating support platform.



(*a*) Time = 0 ***T*** (*b*) Time = 0.25 ***T*** (c) Time = 0.5 ***T*** (*d*) Time = 0.75 ***T***

Figure 9: Instantaneous vortex structure of the rotor and wave height counter in coupled case

CONCLUSIONS

The unsteady actuator line model (UALM) is built up by modifying the traditional ALM based on OpenFOAM. By implementing the UALM into naoe-FOAM-SJTU, the fully coupled aero-hydrodynamic solver named FOWT-UALM-SJTU for the whole FOWT system is developed. Proper fundamental validations for the FOWT-UALM-SJTU solver are carried out, which show that it is reliable on unsteady aerodynamic performance research of wind turbine and on coupled aero-hydrodynamic simulation for the whole FOWT system containing the wind turbine, platform and mooring system respectively. Coupled aero-hydrodynamic simulations of two OC3 Hywindspar FOWT models in tandem layout under shear wind and regular wave conditions are performed with FOWT-UALM-SJTU. Both the platforms are fixed and the platforms are free to move are considered in the simulations. It can be found that the aerodynamic loads of downstream FOWT are much smaller than those of upstream FOWT due to wake interaction. And the platform motions have a bigger effect on the rotor power than that on the thrust. The blade tip vortex from the downstream FOWT become more unsteady owing to the wake interaction. And the platform motions increase the instability of the vortices in the wake. Furthermore, the aerodynamic loads affected greatly by the wake interaction have remarkable impact on the platform motion responses, especially for surge motion and pitch motion. The motion responses of floating support platform increase with the aerodynamic loads.

Acknowledgements
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