

Unsteady Aerodynamic Simulations of Floating Offshore Wind Turbines with Coupled Periodic Surge and Pitch motions

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ABSTRACT

Compared with bottom-fixed wind turbines, a floating offshore wind turbine (FOWT) has an extra level of complexity on aerodynamic performance because of the motions of the supporting platform. In this paper, the unsteady aerodynamic performance of the NREL-5MW Baseline wind turbine with coupled periodic surge and pitch motions of its supporting platform are investigated. The three-dimensional Reynolds Averaged Navier-Stokes equations are solved for the aerodynamic numerical simulation. The naoe-FOAM-os-SJTU solver, which is based on OpenFOAM and overset grid technique, is employed. From the simulation, the time series of the unsteady torque and thrust are obtained, together with detailed information of the wake flow field to clarify the detailed flow field information. The simulation results are compared both with those obtained from aerodynamic simulation of wind turbine with effects of platform's periodic surge motion, and with other approaches with different numerical methods.

KEY WORDS: coupled periodic surge and pitch motions; floating offshore wind turbine (FOWT); overset grid technology; naoe-FOAM-os-SJTU solver.

INTRODUCTION

As renewable and sustainable, wind energy is at the forefront of the world's shift away from the reliance on fossil fuels, especially for the coastal countries with enormous ocean wind energy resource. With special and strong advantages over fixed-bottom wind turbines, floating offshore wind turbines (FOWT) become more competitive. But the environmental loads on FOWTs have an extra level of complexity over that on fixed bottom wind turbines, among which the aerodynamic loads are of great significance.

Compared with onshore wind turbine or fixed offshore wind turbine, the floating offshore wind turbines (FOWTs) work in much more complex environment. With wave impacts, the floating platform, on which the wind turbine with tower is mounted, gets large oscillating motions in 6DOFs^[1]. When the floating platform's motion is considered, the aerodynamic performance of the floating offshore wind turbines becomes much more complex than that of bottom-fixed wind turbines. The aerodynamic forces on the wind turbine become unsteady, and the unsteady aerodynamic simulation of the FOWTs are even more important.

In particular, the oscillating motions, especially surge, pitch and yaw, can lead to sensitive effect on the relative velocity of the flow and the rotor-wake interaction, which would cause significant changes in the aerodynamic forces on blades as well as the power generation. Vaal, et al.^[2] studied the impact of an oscillating surge motion of floating platform on wind turbine using the blade element momentum with quasi-steady wake, as well as dynamic inflow

models, and the actuator disk model. Tran, et al. [3] illustrated the unsteady aerodynamics of a FOWT with prescribed sinusoidal pitch motion of the platform using overset grid technique with Star-CCM+. Li, et al. [4] conducted the unsteady simulation of the NREL 5-MW baseline wind turbine with sinusoidal surge motion and pitch motion of the platform respectively using the unsteady actuator line model (UALM).

In this paper, the unsteady aerodynamic performance of the NREL-5MW Baseline wind turbine with coupled periodic surge and pitch motions of its supporting platform is investigated. The three-dimensional Reynolds Averaged Navier-Stokes equations are solved for the aerodynamic numerical simulation. The naoe-FOAM-os-SJTU solver based on OpenFOAM and overset grid technology is employed. From the simulation, the time series of the unsteady torque and thrust are obtained, together with the detailed information of the wake flow field.

MATHEMATICAL MODEL AND NUMERICS

Overset Grid Technique

In this paper, our in-house code naoe-FOAM-os-SJTU^[5] is employed to do the complex aerodynamic simulation. The naoe-FOAM-os-SJTU is compiled by implementing the dynamic overset grid technique into naoe-FOAM-SJTU^[6-8] based on OpenFOAM, which provides a good platform for both aerodynamic and hydrodynamic numerical analysis^[9].

Overset grid technique provides a convenient way for simulation of large amplitude motion problems and independently moving multi-bodies problems, since the separate overlapping grids for each part with independent motions are permissible. And the connection among grids of each part is built by interpolation at appropriate cells or points using DCI (domain connectivity information) which is produced by SUGGAR++^[10,11]. There are four main steps when using DCI in the overset grid technique: (a) To mark the hole cells which are located outside the simulation domain or of no interest, and exclude them from computation. As shown in Fig.1, in each overset grid, there exist series of cells around hole cells named fringe cells, and for each fringe cell there are several donor cells which provide information from the donor grids. (b) To seek for the donor grids of each fringe cell and provide information from the donor grids. (c) To obtain the value of a variable ϕ of the fringe cell by interpolation using Eq.1 from the donor cells found in the second step.

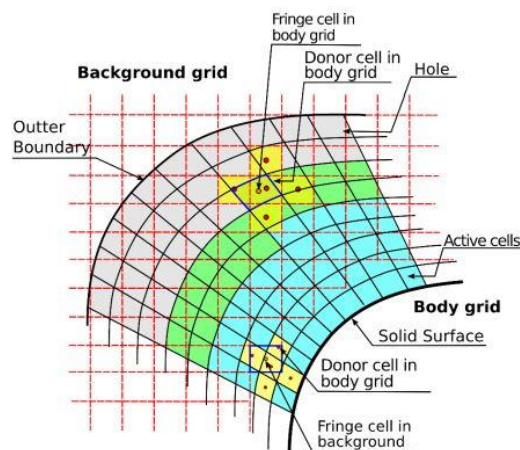


Fig. 1 Diagram of Overset Grid

$$\phi_I = \sum_{i=1}^n \omega_i \cdot \phi_i \quad (1)$$

Where ϕ_I is the value of a variable ϕ of the fringe cell, ϕ_i is the value for the i^{th} donor cell, ω_i is the weight coefficient, which is dimensionless and follows the condition shown in Eq.2:

$$\sum_{i=1}^n \omega_i = 1 \quad (2)$$

(d) To optimize the overlapping area and improve the accuracy of interpolation.

Governing Equations

The governing equation solved in this paper is the three dimensional incompressible Reynolds-Average Navier-Stokes (RANS) equations which can be written as:

$$\frac{\partial U_i}{\partial x_i} = 0 \quad (3)$$

$$\frac{\partial U_i}{\partial t} + \frac{\partial}{\partial x_j} (U_i U_j) = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left(\nu \frac{\partial U_i}{\partial x_j} - \overline{u_i u_j} \right) \quad (4)$$

Where U is the velocity of flow; ρ is the density of the fluid; p is the pressure; ν is the kinematic viscosity.

To solve the above governing equations, the k- ω SST turbulence model^[12] is employed. And the turbulent kinetic energy k and the turbulent dissipation rate ω used in k- ω SST turbulence model can be described as:

$$\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left(\Gamma_k \frac{\partial k}{\partial x_j} \right) + G_k - Y_k + S_k \quad (5)$$

$$\frac{\partial}{\partial t} (\rho \omega) + \frac{\partial}{\partial x_i} (\rho \omega u_i) = \frac{\partial}{\partial x_j} \left(\Gamma_\omega \frac{\partial \omega}{\partial x_j} \right) + G_\omega - Y_\omega + D_\omega + S_\omega \quad (6)$$

Where, Γ_k and Γ_ω represent for the effective diffusion coefficients for the turbulent kinetic energy k and dissipation rate ω respectively, G_k and G_ω represent for turbulence generation terms, Y_k and Y_ω represent for turbulent dissipation terms, D_ω is the cross-diffusion term for ω , S_k and S_ω are the source term.

SIMULATION SETUP

Geometry model and grids

Phase II of OC4 project involving modeling of NREL 5MW Baseline Wind Turbine^[13] and the semi-submersible floating offshore wind system^[14] is chosen in this paper, which is shown below in Fig.2. As shown in Fig.2, this FOWT consists of four main parts: the rotor with nacelle and hub in air above water, the tower mounted on the floating platform, the semi-submersible platform suffering hydrodynamic forces on the free surface, and the mooring system working under water. In this paper, effect of platform and mooring system is simplified as a periodic motion, and the aerodynamic performance of the former two parts in air are studied.

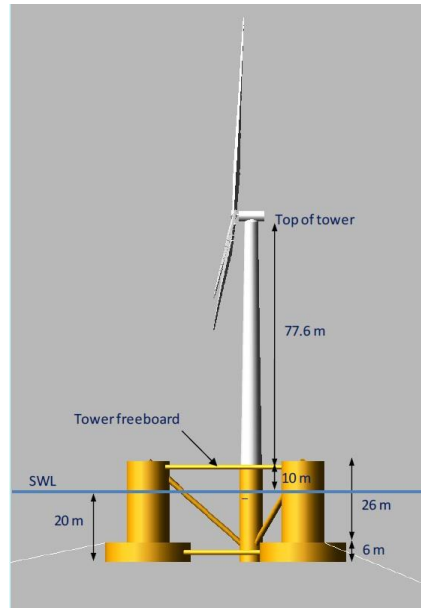
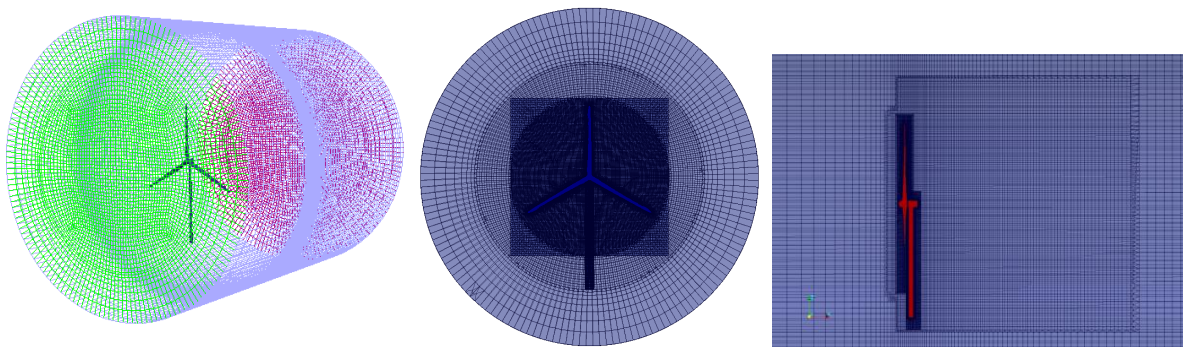


Fig. 2 The Phase II of OC4 Floating Wind Turbine

Rating	5MW
Rotor Orientation	Upwind
Rotor Diameter / Hub Diameter	126m / 3m
Hub Height	90m
Maximum Rotor / Generator Speed	12.1rpm / 1,173.7rpm
Length of Blade	61.5m
Height of Tower above Ground	87.6m

Table 1. Summary of Properties the NREL 5MW Baseline Wind Turbine and Tower

Table.1 gives some properties of the NREL 5MW Baseline Wind Turbine and tower. According to the structural properties and the detailed data of blade^[15], the structural model is built first. According to the structural properties listed in Table.1, the simulation domain is generated as a cylinder, which is shown in Fig.3. The radius the cylinder domain is about $2.5R$, where R is the radius of the rotor, and length of domain is 360m. The distance between the model and the inlet boundary is 120m, and the distance between the model and the outlet boundary is 240m. To improve the simulation accuracy, refinement of the mesh around turbine and tower is necessary, and proper mesh refinement in the wake flow field is also shown in Fig.3, which very important for capturing the flow information in the wake flow.



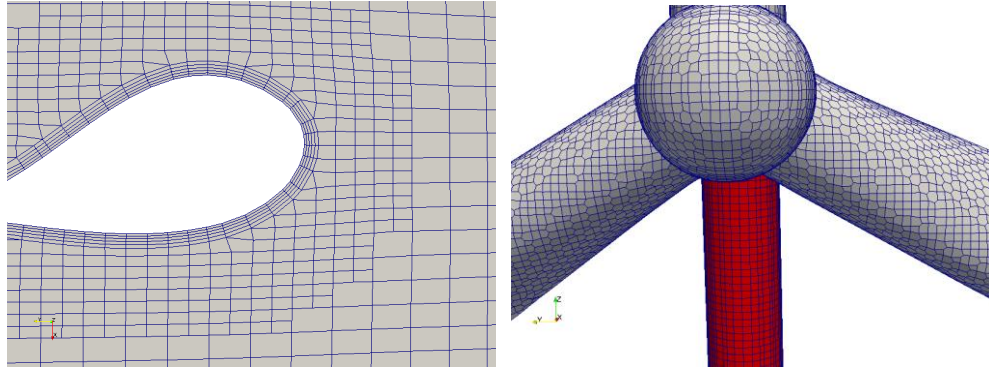


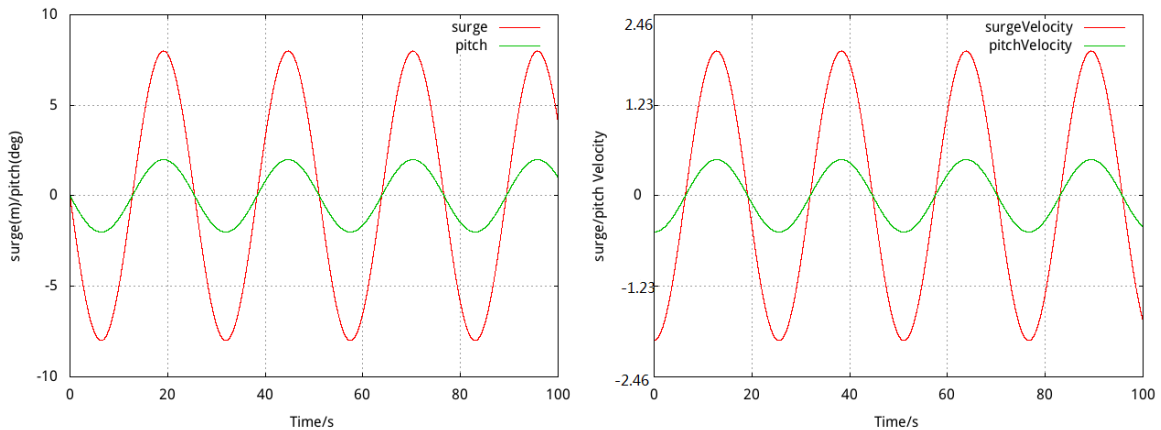
Fig. 3 Geometry Model and Grid Structure

To use the overset grid technique, three overlapping meshes are generated, which are the background mesh of the simulation domain generated with blockMesh and snappyHexMesh supplied with OpenFOAM, and the overlapping grids for the rotor and tower generated with snappyHexMesh respectively. Fig.3 also shows some detailed grid structure around blade and rotor.

Simulation Cases

Motion Direction	Motion	Velocity
Surge	$X_{\text{Surge}}=8\sin(0.246*t)$	$U_x=1.968\cos(0.246*t)$
Pitch	$\theta_{\text{Pitch}}=2\sin(0.246*t)$	$\omega_{\text{Pitch}}=0.492\cos(0.246*t)$

Table 2 simulation cases



(a) Displacement of Surge and Rotation angle of Pitch (b) Velocity of surge and Angular Velocity of Pitch

Fig.4 Periodic Motion Description

In this paper, the aerodynamic simulation of the wind turbine is conducted with the impact of predicted sinusoidal motion of the floating platform both in surge and pitch directions. To analyze the effect of coupled surge and pitch motion, a simulation with periodic surge motion alone is added, in which case the periodic surge motion is the same as the surge component in the coupled-motion case. The description of the periodic motion is listed in Table.2.

Fig.4 shows the motion description of both surge and pitch motion. From Table.2 and Fig.4, we can figure out that the period of the motion is $T=25.54s$, while the rotation speed of rotor is set to 12.1rpm, so the period of coupled surge and pitch motion is about 5 times of the rotor's rotation period. The periodic surge and pitch motion changes the relative velocity of

flow around blades. Eq.7 describes the relative velocity of flow near the blades' surface.

$$\mathbf{U}_{re} = \mathbf{U}_{inlet} - \mathbf{U}_{blade} = \mathbf{U}_{inlet} - \mathbf{U}_{rotate} - \mathbf{U}_{surge} - \mathbf{U}_{pitch} \quad (7)$$

Where, U_{inlet} represents the inlet wind speed ($U=11.4\text{m/s}$), and U_{blade} is the moving speed of pressure point on the surface of blades which including three parts: the rotation speed of rotor $U_{rotate}=r*\omega$, the moving speed caused by surge of floating platform $U_{surge}=1.968*\cos(0.246*t)$ and moving speed depends on the angular velocity of pitch motion $U_{pitch}=d*0.492\cos(0.246*t)$ (or $U_{pitch}=0$) (h is the distance from the pressure point to the rotational center of the whole floating wind turbine system).

RESULTS AND DISCUSSION

Rotor Thrust and Power Coefficient

From the simulation, the time history of unsteady thrust and torque of the wind turbine are obtained. Fig.5-6 show the time history of thrust coefficient and power coefficient respectively, where the right figures are the enlarged views of the left ones during one oscillation period.

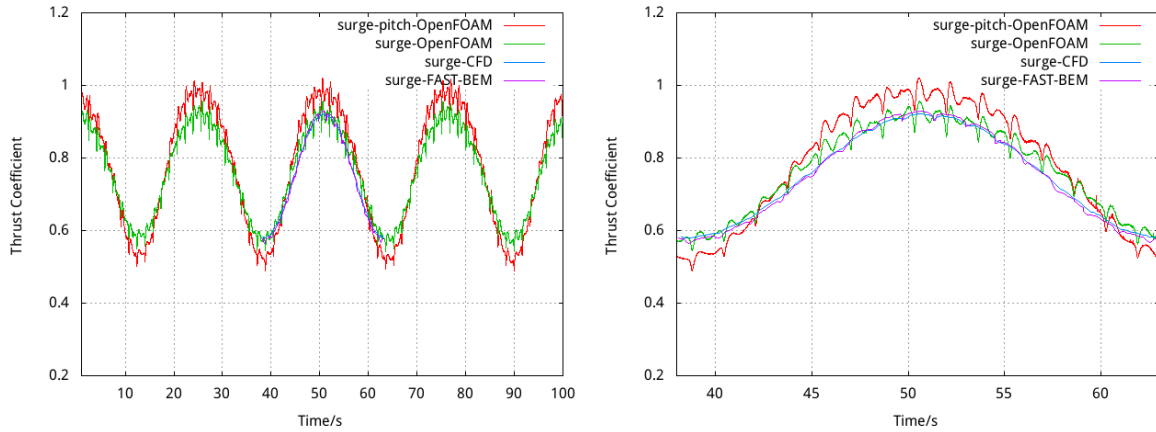


Fig.5 Time History of Thrust Coefficient

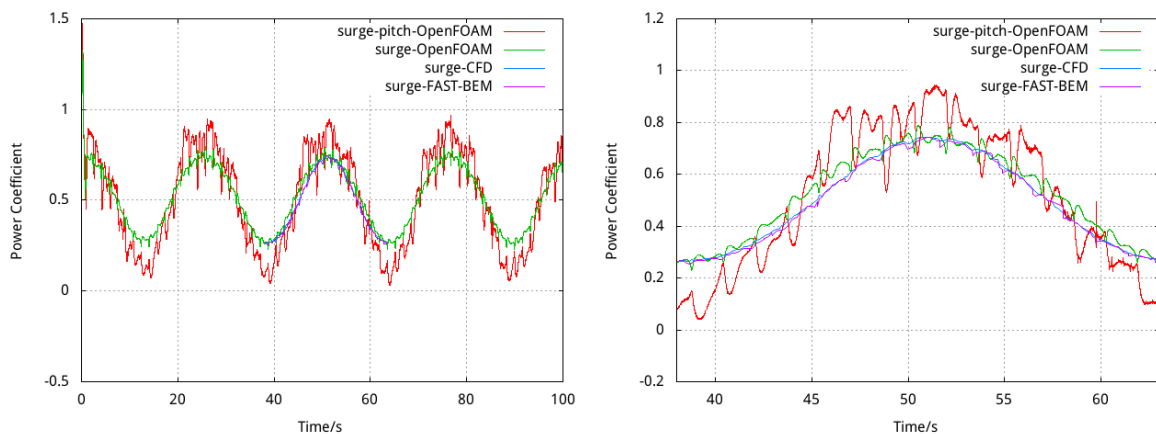


Fig.6 Time History of Power Coefficient

In Fig.5-6, the red line shows the results obtained from the simulation of the FOWT with coupled periodic surge and pitch motion. To analyze the effect of coupled surge and pitch motion, a simulation with periodic surge motion alone is added, the results of which are shown in Fig5-6 with green lines. The violet line named surge-FAST-BEM stands for the

numerical results obtained with BEM method^[16]. And the blue line surge-CFD represents for the simulation results using CFD^[17]. And in both the latter two cases (surge-FAST-BEM and surge-CFD), periodic surge motion is considered alone, just the same as case surge-OpenFOAM.

In Fig.5-6, both thrust and power coefficients in surge-motion alone case show quite good agreement with the violet and blue curves except some cyclical mutations, and all the four curves show sinusoidal oscillating regularities with the period equal to the period of surge and pitch motion. Combining the motion and velocity described in Fig.4, both the thrust and power decrease rapidly when the rotor moves upward to the flow (positive direction of inlet flow) and back to the original position, while increase rapidly when the rotor moves downward(negative direction of inlet flow) and then back to the original position. That's believed to be caused by the change of the relative velocity of flow around blades described in Eq.7, which affects the pressure distribution on the surface of blades as well as the thrust and torque obtained by integration of the pressure. In the first quarter of oscillation period when the turbine moves upwards, the moving speed is negative and decreases from the max negative peak to zero and the relative velocity increases at the same time, which causes the decline of the pressure on the blades. The thrust and power are both obtained with the integral of pressure on the blades' surface, so the both the thrust and power coefficients diminish with the relative velocity. Likewise, the thrust and power coefficients decrease with the relative velocity in the second quarter of the oscillating period and increase with the relative velocity in the second half period.

Compared with the results in periodic surge-motion alone case, the coupled surge and pitch motion shows much more significant effect on both thrust and power coefficient. Similar with impact of surge motion, the periodic pitch motion leads to cyclical changes in relative velocity around blades, which finally causes the cyclical changes of thrust and power. So when the platform surges and pitches with the same period, the effect of the combined motions should be larger than the effect by either single motion. The added pitch motion with amplitude of 2deg causes extra 30% of variation of thrust coefficient and 50% of variation of power coefficient over the surge-motion alone case.

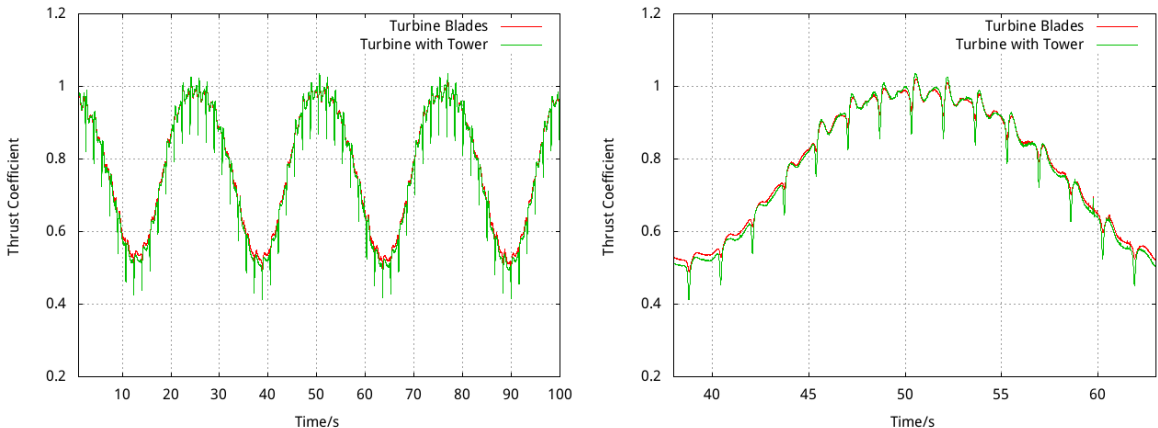


Fig.7 Time History of Thrust Coefficient with Tower Interaction

Besides the sine variation depending on the periodic surge and pitch motion, the cyclical mutations with much shorter period are observed on the green and red curves. The period of these the cyclical mutations is just one third of the rotating period. The cyclical variation is caused by the impact of the tower. During one cycle of rotation, there are three times for one

of the three blades rotates to the right upstream position of the tower, when the distribution of flow velocity and pressure is affected by the tower and both the thrust and torque changes significantly. In reality, the thrust on tower should also be added when analyzing the impacts of the turbine and tower on the platform, so the coupled thrust on blades and tower with coupled surge and pitch motions is plotted in Fig.7 with green lines. With the tower effect, the cyclical drop of thrust value increases obviously, while the average values of the two curves have tiny difference.

Wake Vortex

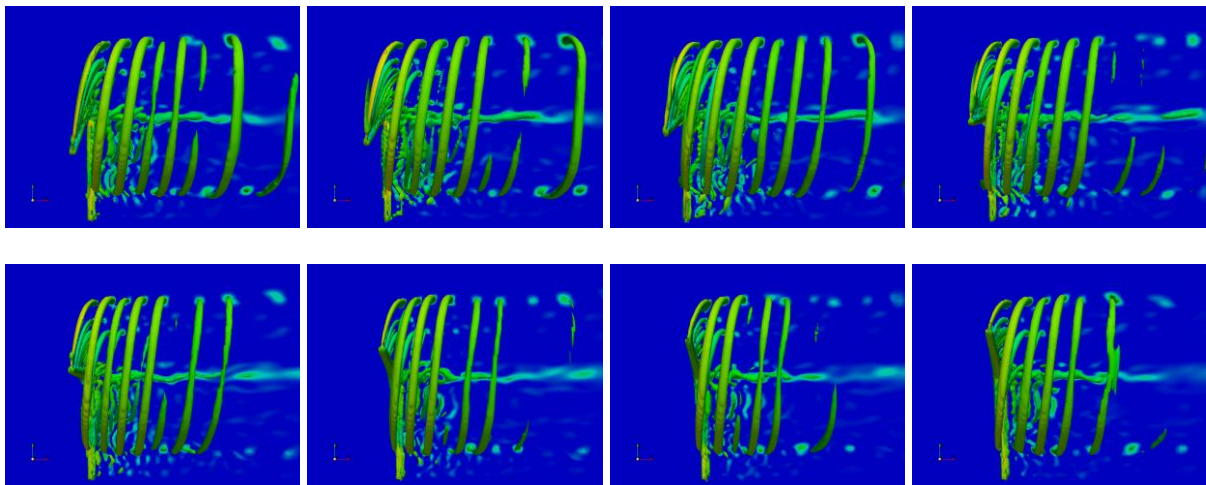
The wake vortex structure is a very important index in the aerodynamic analysis of wind turbine, because the wake vortex near the blades has great influence on the aerodynamic properties of the blades. To get a proper wake vortex visualization result, the second invariant of the velocity gradient tensor, $Q^{[18]}$, is used to capture the iso-surface of the vortex, which is:

$$Q = \frac{1}{2} (\Omega_{ij} \times \Omega_{ij} - S_{ij} \times S_{ij}) \quad (7)$$

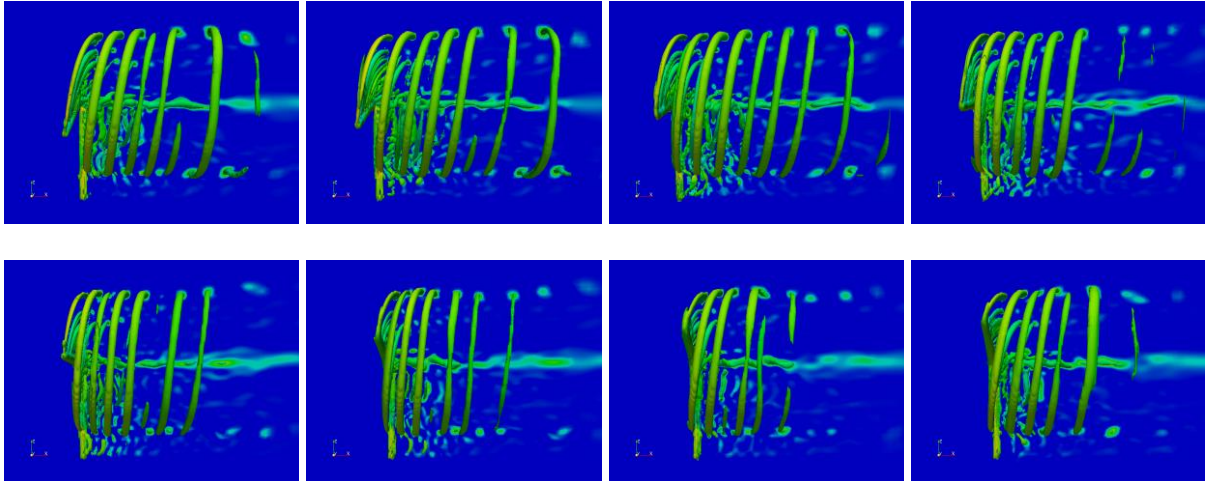
Where, the Ω_{ij} represents the strength of the vortex, and S_{ij} is the shear strain rate.

The global wake vortex with the vorticity distribution on the cross section across the rotor center at different time ($t=1/8T, 2/8T, 3/8T, 4/8T, 5/8T, 6/8T, 7/8T$ and T) of a motion period is illustrated in Fig. 7, in which (a) show the results in periodic surge motion alone case, and (b) demonstrates the flow information obtained in the coupled motion case.

The instantaneous vorticity distribution picture show the obvious variations of the gap distance of each two adjacent vortex tubes during one oscillating period. Combined with the motion description in Fig.4, it's obvious that the gap distance increases when the rotor moves upward to the flow, and decreases when the rotor moves downward to the flow. The vortices are generated with the disturbing of the blades tip, and moves downstream with flow, so when the blades move upwards the flow, the distance between two nearby iso-surfaces of the vortex increases to the maximum value as the blades moves upwards to the most upstream position. Likewise, gap distance decreases evidently while the blades move downwards the flow. Besides this regular change of the gap distance, a pitch motion of the global wake vortex structure is observed in Fig.7(b).



Periodic Surge Motion alone ($t=1/8T, 2/8T, 3/8T, 4/8T, 5/8T, 6/8T, 7/8T$ and T)



(b) Coupled Periodic Surge and Pitch Motion ($t=1/8T, 2/8T, 3/8T, 4/8T, 5/8T, 6/8T, 7/8T$ and T)
 Fig.7 Visualization of Instantaneous Iso-vorticity Contours

CONCLUSIONS

In this paper, the unsteady aerodynamic performance of the NREL-5MW Baseline wind turbine with coupled periodic surge and pitch motion of its supporting platform is investigated. The naoe-FOAM-os-SJTU solver is employed. The time series of the unsteady thrust and power coefficients are obtained, together with the detailed information of the wake flow field. The simulation results are compared with other approaches with different numerical methods. Proper discussions are made.

Periodic surge or coupled motions cause sinusoidal variation of relative velocity of flow near the blades, which causes the change of the pressure distributed on the surface of blades, so the oscillating regulation of the thrust and power coefficient with the same period is observed. And the coupled surge and pitch motion shows larger effect on both thrust and power coefficient. The average of both thrust coefficient and power coefficient in surge-motion alone case in this paper show good agreement with those approaches with other methods. The tower the tower effect is captured and the impact on the aerodynamic force and power coefficient is shown distinctly. When the rotor moves periodically, the differences of the gap distance of each two adjacent vortex tubes at each instantaneous moment are observed.

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