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Numerical Simulations of Complex Aerodynamic Flows around NREL Offshore 5-MW Baseline Wind Turbine

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Abstract: For further design and development of wind turbines, accurate prediction of aerodynamic performance is of great significance. The aerodynamic performances of large-scale floating offshore wind turbine blades NREL 5-MW of OC4 are simulated with the effect of tower, the transient solver pimpleDyMFoam in open-source software OpenFOAM is employed, the sliding mesh method is used, and the simulation under different wind speeds are conducted. The time history of thrust and torque are obtained, the wake vortexes are available. Discussions about tower-blade interaction, rotation effects are done in this research work.

Keywords: aerodynamic simulation; offshore wind turbine; OC4; the NREL offshore 5-MW baseline wind turbine; pimpleDyMFOAM.

1 Introduction

Wind energy, which is renewable and sustainable, represents a potential to solve the energy crisis and environment crisis. With a lot of special and strong advantages over onshore wind turbines, offshore wind turbines become more and more attractive. With the development of the offshore wind turbine technology, floating offshore wind turbines with higher capacity will be a key trend. And horizontal axis wind turbines appear to be the most feasible choice. The existence of the tower makes the flow around a horizontal axis wind turbine more complex. So accuracy prediction of the aerodynamic performance of the wind turbine rotor and blades with the existence of the tower is of great significance.

The blades-tower interaction is a key issue that must be taken into account in prediction of the aerodynamic performance. Some authors have studied the tower effect in horizontal axis configuration. Duque et al. (1999) first performed the simulation of the unsteady flowfield of a downwind configuration, the NASA-Ames Phase II experiment. CFD method was used to solve the unsteady compressible thin-layer Navier-Stokes equations, and the overset grids were employed to capture the interface between the tower and rotor. However, the simulation of the blade-tower interaction was not good. Zahle and Johanson (2009) did the prediction of the downwind blade-tower interaction using the EllipSs3D solver. The prediction agreed with the experimental results very well with some key features captured. However, in high wind speed cases, the simulation results showed poor agreement with the experiment results. A few authors have predicted the upwind configuration. Gomez-Iradi and Steijl (2009) used the WMB (Wind MultiBlock), a CFD code solving compressible Navier-Stokes equations, to simulate the aerodynamic performance of the NREL phase VI wind turbine. The simulations agreed with the experimental results quite well. Li et al. (2012) used CFDIowa-ship v4.5, an incompressible RANS and DES solver, with overset grids to compute the aerodynamic performance of the NREL phase VI wind turbine. The computational results showed good agreement with the experimental ones. Wang et al. (2012) used pimpleDyMFoam, a solver in OpenFOAM tools, with AMI (Arbitrary Mesh Interface) method to study the blade-tower interaction of the NREL phase VI wind turbine in upwind configuration. Detailed flow information of the complex flowfield was obtained, key features showing strong interaction between tower and rotor were observed. Zhou and Wan (2015) used the pimpleDyMFoam coupled with the AMI method to study the difference between the aerodynamic performances of downwind configuration and upwind configuration of the NREL phase VI wind turbine. it was proved that the configuration of the wind turbine had significant impact on the blade-tower interaction.

2 Numerical Method

The transient solver pimpleDyMFoam in open-source software OpenFOAM(Jasak, 2009; Jasak et al, 2013) is employed in in the simulation of all the cases in this paper.

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PimpleDyMFoam is a reliable code to solve unsteady incompressible problems, which has been validated for the aerodynamic simulation of wind turbines by Wang et al. (2012), Zhou and Wan (2015).

2.1 Governing Equations

Because of the low wind velocity around and the small Mach number (Ma<0.3), the flow around wind turbines is essentially incompressible. And the gravity can be neglected because the small air density. So the governing equations can be written as:

$$\frac{\partial \mathrm{U}_i}{\partial x_i}=0 \tag{1}$$

$$\frac{\partial U_i}{\partial t}+\frac{\partial}{\partial x_j}(U_iU_j)=-\frac{1}{\rho}\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\nu\frac{\partial U_i}{\partial x_j}-\overline{u_i u_j}\right) \tag{2}$$

where (1) is the continuity equation and (2) is the momentum equation, U_i is the time-averaged velocity and P is the time-averaged pressure.

2.2 Turbulence Modeling

In order to solve the governing equations, the two-equation k-ω SST (Shear Stress Transport) turbulence model (Menter, 1994; Menter, 2009) is used in this paper. The turbulence kinetic energy k and the specific dissipation rate ω are determined as:

$$\frac{\partial}{\partial \mathrm{t}}(\rho k)+\frac{\partial}{\partial x_i}(\rho k\,\mathrm{u}_i)=\frac{\partial}{\partial x_j}(\Gamma_k\frac{\partial k}{\partial x_j})+\mathrm{G}_k-Y_k+S_k \tag{3}$$

$$\frac{\partial}{\partial \mathrm{t}}(\rho\omega)+\frac{\partial}{\partial x_i}(\rho\omega\,\mathrm{u}_i)=\frac{\partial}{\partial x_j}(\Gamma_\omega\frac{\partial \omega}{\partial x_j})+\mathrm{G}_\omega-Y_\omega+D_\omega+S_\omega \tag{4}$$

Where Γ_k and Γ_ω represent for the effective diffusivity of the turbulence kinetic energy k and the specific dissipation rate ω respectively, G_k and are the production terms for k and ω, Y_k and Y_ω are the dissipative terms for k and ω, D_ω is the cross-diffusion term, S_k and S_ω are the source terms for k and ω.

As a combination of the standard k-ω turbulence model and the k-ε turbulence model, the cross-diffusion term D_ω is added:

$$D_\omega=2(1-\mathrm{F}_1)\rho\sigma_{\omega,2}\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial\omega}{\partial x_j} \tag{5}$$

where,

$$F_1=\tanh(\Phi_1^4) \tag{6}$$

$$\Phi_1=\min\left[\max\left(\frac{\sqrt{k}}{0.09\omega y},\frac{500\mu}{\rho y^2\omega}\right),\frac{4\rho k}{\sigma_{\omega,2}D_w^+y^2}\right] \tag{7}$$

$$D_\omega^+=\max\left[2\rho\frac{1}{\sigma_{\omega,2}}\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial\omega}{\partial x_j},10^{-20}\right] \tag{8}$$

3 Simulation Model

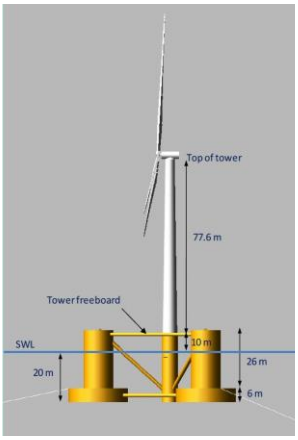


Fig.1 The Phase II of OC4 floating wind turbine

The NREL-5MW baseline wind turbine (Jonkman et al. 2009) is chosen as the simulation model, which is shown in Fig.1. Geometry properties of the simulation model are listed in Table.1~ Table.1, more detailed information can refer to related paper (Jonkman et al. 2009).

Table 1 Summary of the NREL 5MW Baseline Wind Turbine properties

Rating	5MW
Wind Regime	IEC 61400-3 (Offshore) Class 1B / Class 6 winds
Rotor Orientation	Upwind
Control	Variable Speed, Collective Pitch
Rotor Diameter / Hub Diameter	126m / 3m
Hub Height	90m
Maximum Rotor / Generator Speed	12.1rpm / 1,173.7rpm
Maximum Tip Speed	80m/s
Overhang / Shaft Tilt / Precone	5m / 5 º/ 2.5 º

Table 2 Summary of the Blade Structural Properties

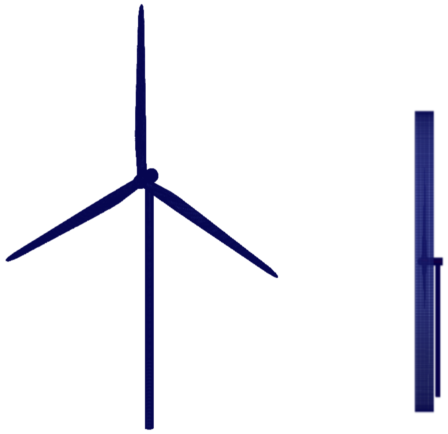
Length (w.r.t. Root along Preconed Axis)	61.5m
Mass Scaling Factor	4.536%
Overall (Integrated) Mass	17,740 kg
Second Mass Moment of Inertia (w.r.t. Root)	11,776,047 kg-m^2
First Mass Moment of Inertia (w.r.t. Root)	363,231 kg-m
c.g. Location (w.r.t. Root Along Preconed Axis)	20.475m
Structural Damping Ratio (All Modes)	0.477465%

Table 3 Tower Properties

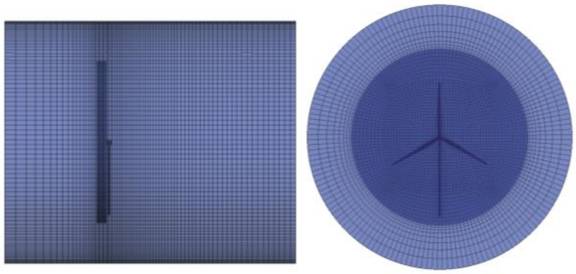
Height above Ground	61.5m
Overall (Integrated) Mass	347,467 kg
CM Location (w.r.t. Ground along Tower Centerline)	20.475m
Structural Damping Ratio (All Modes)	1%

With the all the geometry properties, the simulation model

(Fig.2 (a)) is built with CATIA, and the simulation grids are generated with snappyHexMesh utility in OpenFOAM. Before using snappyHexMesh, a background mesh which fills the entire simulation domain is created with ICEM, a mesh generation tool. The grids structure of the whole simulation domain is shown in Fig.2 (c).



(a) the simulation model (b) AMI interface



(c) the side view and front view of simulation domain

Fig.2 Simulation Model and Grids

In this paper, the AMI (Arbitrary Mesh Interface) method is conducted to deal with the grids. The key step for the AMI method is to define the AMI interface to separate the rotating part and the fixed part of the simulation domain. In this paper, the AMI interface (Fig.2 (b)) is created to separate the rotor and the fixed part including the tower. This can be done using two utilities in OpenFOAM, creatAMIFaces and createBafflesDict.

4 Results and Discussion

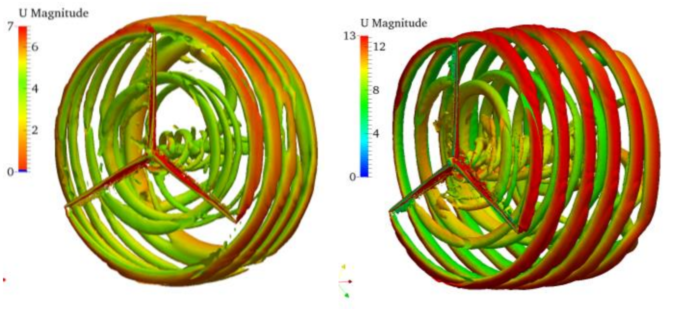
To analyze the tower-blade interaction, the aerodynamic performance of the wind turbine with tower is simulated under different wind speeds, and so is the aerodynamic performance of the wind turbine without tower. The simulation cases are listed in Table 4.

Table 4 Simulation Cases

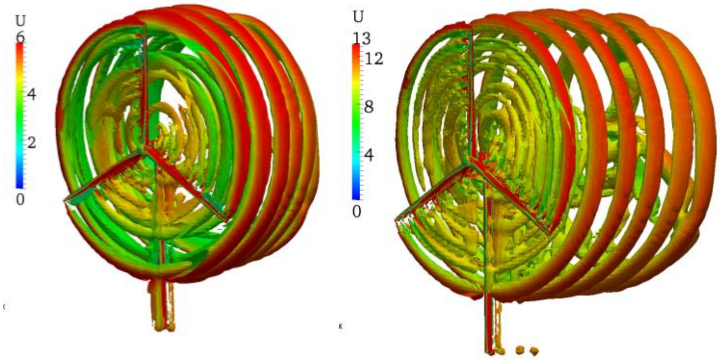
Case	Wind Speed (m/s)	Rotation Speed (r/min)
1	5	7.39
2	8	9.16
3	11.4	12.1

4.1 Wake Vortex Structure

After the simulation the wake vortex structures are obtained, which are very helpful to analyze the flow field around the wind turbine. Fig.3 shows the wake vortexes around the wind turbine in different cases. Fig.3 (a) and (b) show the wake vortex structures around the NREL-5MW baseline wind turbine without tower with the wind speed U=5m/s and U=11.4m/s respectively; Fig.3 (c) and (d) show the wake vortex structures around the NREL-5MW baseline wind turbine with tower under the wind speed U=5m/s and U=11.4m/s respectively.



(a) wind turbine without tower at U=5m/s (b) wind turbine without tower at U=11.4m/s



(c) wind turbine with tower at U=5m/s (d) wind turbine with tower at U=11.4m/s

Fig.3 Wake Vortex Structures

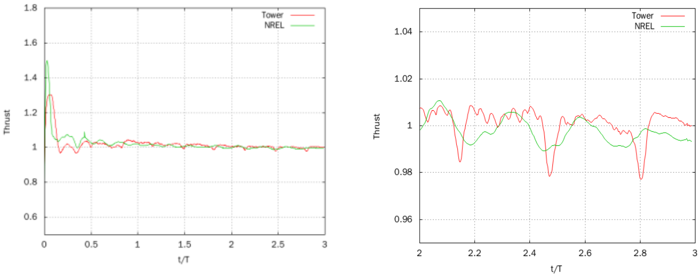
Comparing Fig.3 (a) with (c) and Fig.3 (b) with (d), the tower-blade interaction becomes noticeable. Fig.3 (a) shows a neat wake vortex structure, while the wake vortex structure in Fig.3 (c) is more complex and the flow separation is more obvious. The existence of the tower makes the flow field more complex not only near the tower but the whole field around the wind turbine. The same phenomenon can be seen in Fig.3 (b) with (d). As the wind speed increases, the effect of the existence of tower becomes stronger.

4.2 Time Histories of Thrust and Torque

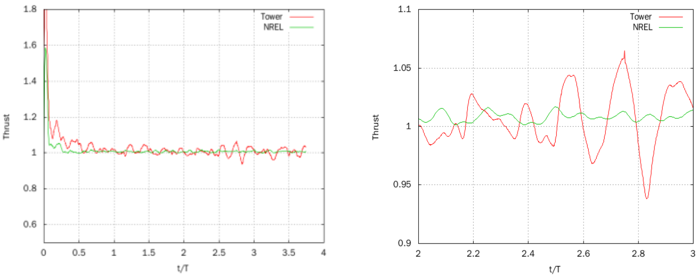
The pimpleDyMFoam is a transient solver, the time history of unsteady thrust and torque of the wind turbine are obtained after the simulation. Fig.3 and Fig.4 shows the time history of the thrust and torque respectively. For all the cases in this paper, the simulations are conducted over three periods of time to ensure the reliable of the results.

To analyze the effect of the existence of tower, the non-dimensional treatment of thrust and torque are done. The mean value of thrust and torque of each case are gained from the simulation results, then divide the results data by this mean value. The same non-dimensional treatment is done on time data. For each different wind speed case, the time data is divided by its own rotating period.

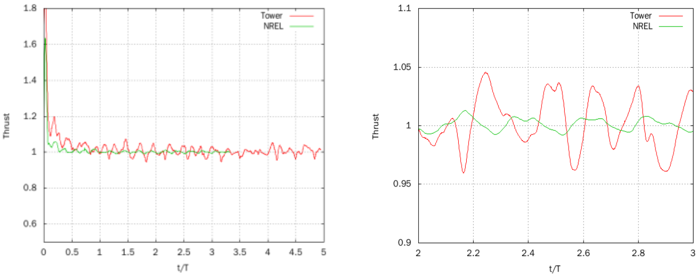
Fig.4 shows the time history of the thrust in three different cases. In each case, there exist two figures: the left is the time history of the thrust during all the whole simulation progress, and the right one shows the time history of the thrust during one period. In each figure of Fig.4, the red line named Tower presents for the thrust get from the simulation of the wind turbine with tower, and the green line named NREL represents for the simulation results without tower. It can be seen clearly from the left figures that the red lines are much more stable than the green line. To make a deep analysis, the time history of the thrust during the third period is expanded in the right figure. In the right figure of Fig.4 (a), it is clearly to be seen that there are three valleys during one period (t/T=2.14, t/T=2.47, t/T=2.8), which appear when one of the three blades overlaps the tower. When the wind speed increases, the thrust becomes more unsteady and more than three valleys appear during one period, but the valley still appears when one of the three blades overlaps the tower.



(a) U=5m/s



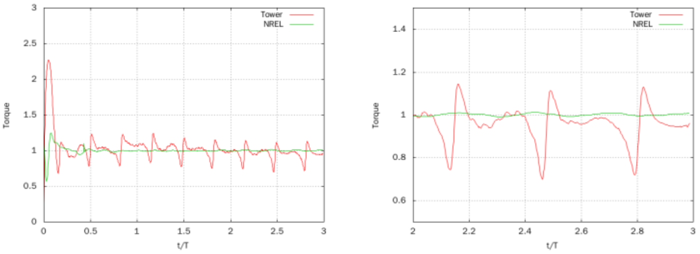
(b) U=8m/s



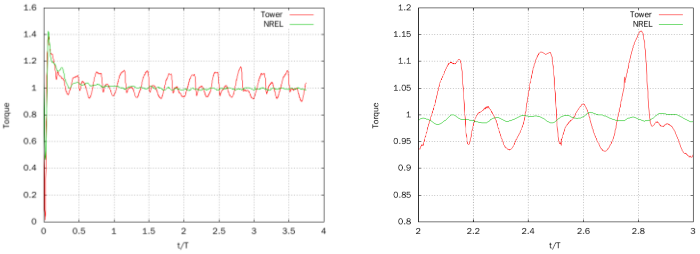
(c) U=11.4m/s

Fig.4 Time History of Thrust

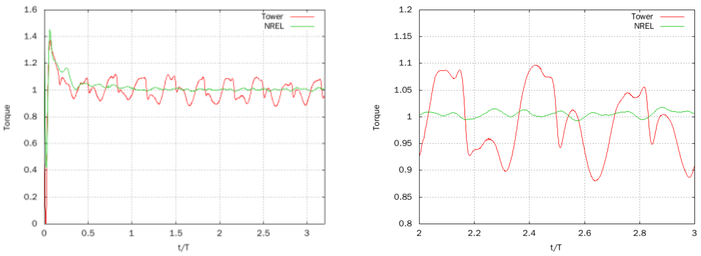
Fig.5 shows the time history of the torque in three different cases. Similar as Fig.4, the left figures are the time history of the torque during all the whole simulation progress, and the right ones show the time history of the torque during one period. In all the three cases, three significant valleys appear during one period when one of the three blades overlaps the tower. With the increasing of the wind speed, more other valleys appear.



(a) U=5m/s



(b) U=8m/s



(c) U=11.4m/s

Fig.5 Time History of Torque

5 Conclusions

The aerodynamic performance of the wind turbine with tower is simulated under three different wind speeds, and so is the aerodynamic performance of the wind turbine without tower. After simulation, the time history of thrust and torque at each case are obtained, and the wake vortex structures are available too.

Analyzing the wake vortex structures around the wind turbine, it is clearly to be seen that the wake vortex structure becomes more complex and the flow separation is more obvious with the effect of the existence of tower. And this effect becomes more obvious when the wind speed increases.

The time history of thrust and torque has supported this conclusion. In the low wind speed case, the time history of thrust and torque both exist three valleys appear during one period when one of the three blades overlaps the tower. When wind speed increases, there are still three significant valleys during one period, besides several valleys added.

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