Aerodynamic Analysis of the Wind Turbine by Two Different Numerical Methods

Ruicheng Zhang, Decheng Wan*

State Key Laboratory of Ocean Engineering, School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration, Shanghai 200240, China

*Corresponding author: dcwan@sjtu.edu.cn

Abstract

With the rapid development of wind power industry in recent years, the aerodynamic performance of wind turbines has attracted more attention, on account of its significant effects on the power generating capacity. Two of numerical simulation methods are selected in the present work to study aerodynamic performance of wind turbine. One is the actuator line model (ALM), the other is the overset grid method. In this study, the aerodynamic performance of a NREL 5-MW baseline wind turbine under rated wind speed of 11.4m/s is studied with these two methods. The time history of aerodynamic power and thrust, contours of axial direction wind velocity and vorticity, and wake vortex structures can be obtained and analyzed. Both methods can obtain relatively accurate simulation results. ALM method can reduce the number of grids and calculation time effectively. Overset grid method can obtain more accurate power and thrust forecasting due to simulation of real blades and hub. In addition, detailed flow field characteristics including the pressure distribution on the blade surface can be obtained with overset grid method.

Keywords: Aerodynamic loads, Wake field characteristics; Actuator line model; Overset grid method.

Introduction

The rapid development of global economic has led to increasing demand for energy in each country. The situation of the energy crisis is becoming more and more serious. As a kind of clean and renewable energy with huge reserves, wind energy has great potential for development and utilization. Wind energy has become one of the fastest growing renewable energy sources in the world, and wind energy technology has received extensive attention of many countries. Wind power is mainly used by converting wind energy into electric energy through wind turbines. Accurate prediction of wind turbine aerodynamic performance and wake field characteristics is very important for the early economic evaluation of wind farms.

In the past few years, many researchers have studied on the aerodynamic performance of wind turbines and proposed several methods, including the Blade Element Momentum theory (BEM), potential flow theory and CFD numerical simulation methods. The Blade Element Momentum theory (BEM) is one of the most classical methods for calculating the aerodynamic load of a wind turbine [1]. The Blade Element Momentum theory divides the wind turbine blade into a number of micro-segments that do not interfere with each other. The three-dimensional aerodynamic characteristics of the wind wheel can be obtained by integrating the aerodynamic characteristics of the blade elements in the radial direction. The numerical simulation results based on BEM theory have basically met the needs of practical engineering applications. BEM has the advantages of simplicity and ease of application, but it cannot study the details of the flow field, nor can it explain the three-dimensional effect of the blade and the stall delay effect [2]. The potential low theory introduces the aerodynamic model of the three-dimensional potential flow into the calculation of the wind turbine [3]. Although more detailed aerodynamic performance of the wind turbine is obtained, the viscosity of the flow field around the blade and the phenomenon of flow separation are not considered.

Computational Fluid Dynamics (CFD) is a technique developed by the rapid development of computers. It numerically solves the Navier-Stokes equations describing the conservation of viscous incompressible fluid momentum, which can accurately describe the complex flow field around the wind turbine, simulate the actual motion of the fluid in the field and obtain more complete flow field information. Choi et al. [4][5] used the CFD to numerically simulate the wind farm of two and three wind turbines, and studied the influence of the distance between the wind turbines on the power output and wake field characteristics of the wind farm. Yuwei et al. [6] used the DES method combined with dynamic overlapping grid technology to simulate the aerodynamic performance of wind turbines. Churchfield et al. [7][8] used SOWFA software to analyze the wake characteristics of the wind turbine using the large eddy simulation method.

However, the CFD method has disadvantages of the difficulty of meshing, long calculation time and high hardware requirements. Reducing the amount of calculation is a key issue in applying the CFD method. Therefore, the actuator line model (ALM), which combines BEM theory and CFD method, has been proposed. ALM do not need to establish the real rotor geometry model. ALM uses the virtual actuator line to replace the real blade structure, which can avoid solving the boundary layer of the blade surface and further reduce the calculation time. The ALM is very research-worthy and has attracted the attention of many researchers. Troldbrg and Sørensen [9] used the actuation line model to numerically simulate a three-blade wind turbine, obtained detailed information on the wake region, and fond a good agreement after comparing the power output curve with the experimental data. Mikkelsen et al. [10] used ALM combined with CFD technology to study the aerodynamic power output and wake characteristics of a wind farm with three wind turbines and obtained satisfactory simulation results.

Another widely used method of simulating the aerodynamic performance of wind turbines is the overset grid method. The overset grid method allows unconstrained relative displacement between multiple independent grids, and can achieve unconstrained six-degree-of-freedom motion of the object, so it is suitable for solving dynamic problems [11][12]. Naoe-FOAM-os-SJTU is a CFD numerical solver for marine and offshore engineering based on open source toolbox OpenFOAM combined with overset grid technology. The solver introduces the overlay overlap mesh technology to solve the topology constraint relationship between the object and the mesh, and can realize the six-degree-of-freedom unconstrained motion between multi-level objects that cannot be processed by the traditional dynamic mesh technology.

In this study, the ALM based on the OpenFOAM is used to study the aerodynamic performance of a NREL 5-MW baseline wind turbine. The overset grid method is also applied to investigate the aerodynamics of full-scale wind turbine model by naoe-FOAM-os-SJTU slover. The simulation results obtained from these two different numerical methods are compared to illustrate the advantages of different numerical methods.

Numerical Method

Actuator line model (ALM)

The actuating line model was first proposed by Sørensen and Shen [13][14]. Its main idea is to replace the real blade with a virtual, volumetric actuating line to avoid solving the boundary layer of the blade surface, thus reducing the difficulty of the meshing and the computation time. The actuator line model discretizes the blades in the radial direction into micro-segments that do not interfere with each other, called blade elements. The lift force and drag force of each blade element can be calculated as:

$$L = \frac{1}{2} C_l(\alpha) \rho U_{rel}^2 c dr \quad (1)$$

$$D = \frac{1}{2} C_d(\alpha) \rho U_{rel}^2 c dr \quad (2)$$

Where, $C_l(\alpha)$ is the lift coefficient, $C_d(\alpha)$ is the drag coefficient, α is the local angle of attack, ρ is the density, U_{rel} is the air flow rate relative to the blade, c is the chord length, and dr is the blade element width.

The relative velocity can be calculated by the local velocity vector relationship of the rotating blades. According to the velocity triangle in the figure1, the relative velocity can be expressed by the following formula:

$$U_{rel} = \sqrt{U_z^2 + (\Omega r - U_\theta)^2} \quad (3)$$

Where, U_z is the axial velocity, U_θ is the tangential velocity, and Ω is the rotational velocity of the blade.

The angle of attack is calculated from the geometric relationship:

$$\alpha = \phi - \gamma \quad (4)$$

Where, $\varphi = tan^{-1}((U_z/(\Omega r - U_\theta))$, γ is the blade pitch angle.

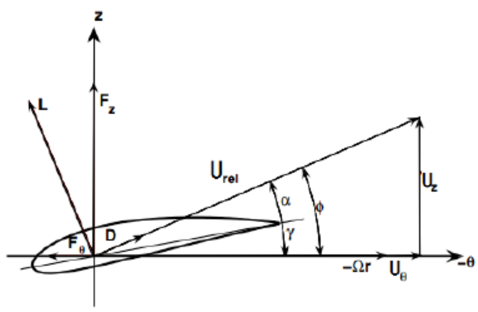


Figure1. Cross-sectional aero foil element

After obtaining the relative velocity and the attack angle, the lift force and drag force of each blade element can be calculated by:

$$f = (L, D) = \frac{1}{2}\rho U_{rel}^2 c(C_i\overrightarrow{eL} + C_d\overrightarrow{eD}) \tag{5}$$

The volume force generated by each actuator element is discrete and cannot directly act on the flow field, otherwise it will cause numerical oscillations, so it needs to be smoothed. The expression of the Gaussian smoothing function is as follows:

$$\eta_\epsilon(d) = \frac{1}{\varepsilon^3\pi^{3/2}} exp\left[-\left(\frac{d_i}{\epsilon}\right)^2\right] \tag{6}$$

After smoothing, the volume force at a point (x, y, z) in the flow field can be calculated by:

$$f_{\epsilon,i}(x, y, z, i) = f \otimes \eta_\varepsilon = \sum_{i=1}^{N} f(x_i, y_i, z_i, i)\frac{1}{\varepsilon^3\pi^{3/2}} exp\left[-\left(\frac{d_i}{\epsilon}\right)^2\right] \tag{7}$$

Where, d_i is the distance from the point (x, y, z) in the calculation domain to the *i*th actuator point(x_i, y_i, z_i), and ε is the Gaussian smoothing parameter.

Overset grid method

The overset grid method is to mesh each part of the object separately, then embed them in another set of grids. After the overlapping areas between the meshes are subjected to pre-processing such as tunneling, the mesh outside the calculation domain (such as the mesh cells located inside the surface of the object) will be dug out and excluded from the calculation, and the interpolation relationship is established in the remaining overlapping area. The interpolation relationship is calculated by the DCI data obtained by the SUGGAR program, and allows data exchange between overset grid to achieve the overall calculation of the flow field.

The process of solving DCI can be divided into four steps. The first step is to mark the grid outside the calculation domain as hole cells and exclude them from the calculation. The second step is to search for the donor cell and provide interpolation information for the interpolated cell. The third step is to calculate the interpolation coefficient (weight coefficient). The fourth step is to optimize the overlap area.

$$\phi_I = \sum_{i=1}^{n} \omega_i \cdot \phi_i \tag{8}$$

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.

Governing Equation

The governing equation used in the ALM and AMI is the RANS equations. The RANS algorithm treats the turbulence with irregular random pulsation characteristics as laminar flow, introduces the concept of pulsation that reflects the turbulence characteristics in the NS equation, and averages it over time to get the RANS equation whose expression is:

$$\frac{\partial U}{\partial X_i} = 0 \tag{9}$$

$$\frac{\partial U_i}{\partial t} + \frac{\partial(U_iU_j)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(v\frac{\partial U_i}{\partial x_j} - \overrightarrow{u_i'u_j'}\right) + \frac{1}{\rho}f_\epsilon \tag{10}$$

Where, *U* is the flow field velocity, ρ is the fluid density, p is the flow field pressure, v is the kinematic viscosity, and f_ϵ is the volumetric force in the actuator line model.

Solving the governing equation requires the use of a turbulence model to close the equation to achieve the numerical solution of the flow field. The k-ω SST turbulence model which is suitable for simulating the aerodynamic performance of wind turbines is used in this paper.

Simulation Setup

The wind turbine model used in this paper is NERL-5MW wind turbine. The main specifications of NERL-5MW turbine are given in the Table 1.

Table 1 Specifications of NERL-5MW turbine

Rating	5MW
Rotor Orientation, Configuration	Upwind, 3 Blades
Control	Variable Speed, Collective Pitch
Drivetrain	High Speed, Multiple-Stage Gearbox
Rotor, Hub Diameter	126m, 3m
Hub Height	90m
Cut-in, Rated, Cut-out Wind Speed	3m/s, 11.4m/s, 25m/s
Cut-in, Rated Rotor Speed	6.9rpm, 12.1rpm
Rated Tip Speed	80m/s
Overhang, Shaft Tilt, Precone Angle	5m, 5°, 2.5°

The computation domain is sketched in Figure 2. The height and width of the whole computation domain are both 400m. The length of the domain is 1000m.The distance from the inlet to the wind turbine is 300m. The height of hub is 200m.

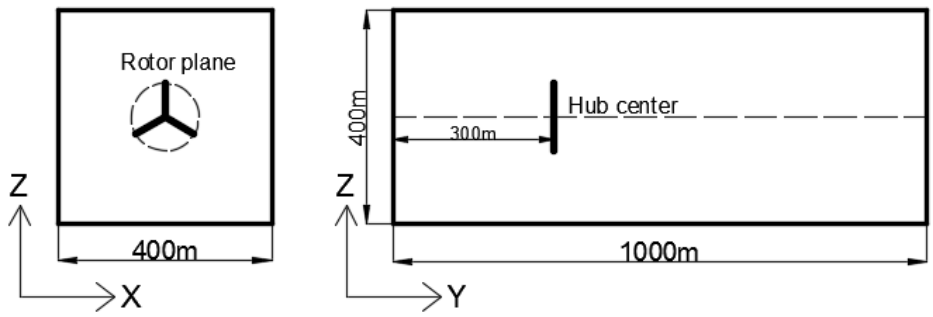
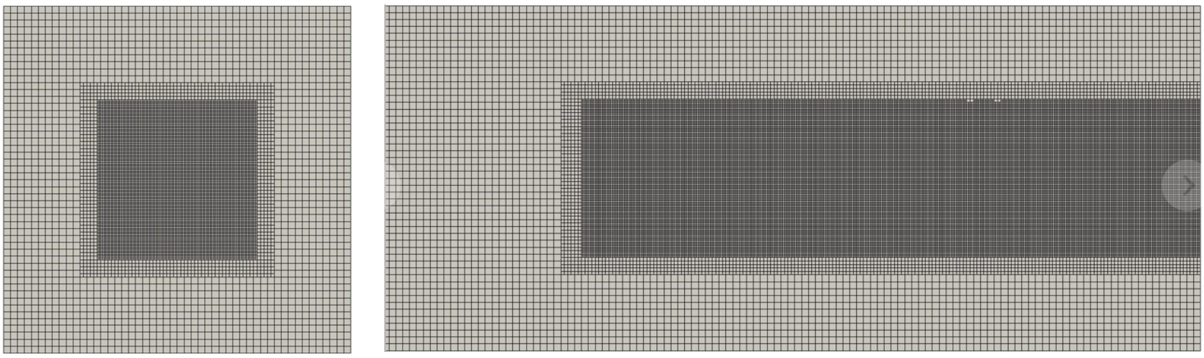


Figure 2. Computational domain

In this paper, the simulations conducted with ALM method and Overset Grid method share same background mesh. In simulation with ALM, a refined region covered the wind turbine blades and wake field with three levels refinement is provided as sketched in Figure 3. The total number of mesh is about 350 million. In simulation with overset grid method, the impeller of wind turbine is meshed and put into cylindrical background grid, and then embedded in the whole computational domain, as sketched in Figure 4. The total number of mesh is about 390 million.



(a)cross section **(b)lengthwise section**

Figure 3. Grid Structure with ALM method

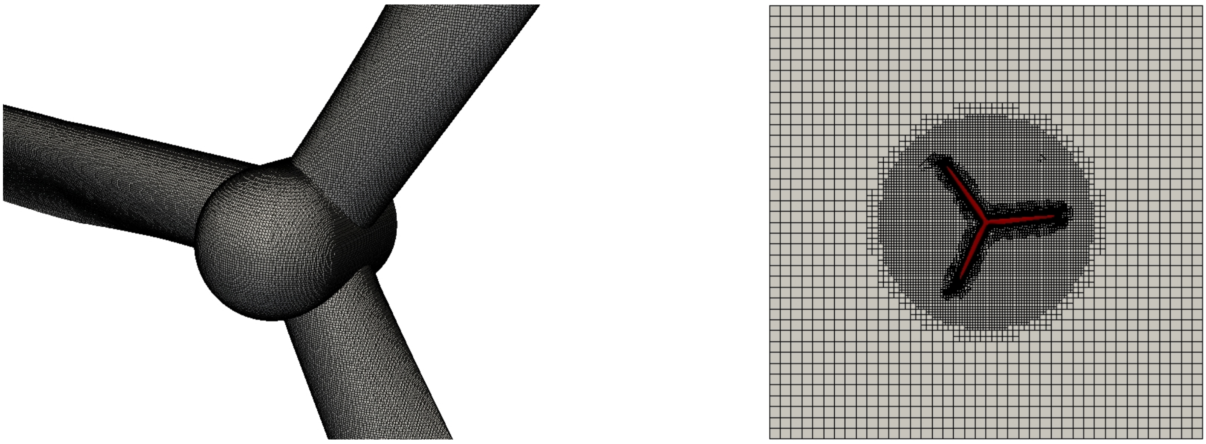


Figure 4. Grid structure with overset grid method

The inlet boundary adopts free flow boundary conditions, the wind speed is 11.4m/s constantly. The outlet boundary is applied to Dirichlet pressure condition, the pressure is equal to the atmospheric pressure. The top boundary and the bottom boundary are applied to the sliding conditions. The symmetric boundary conditions are set on the left boundary and the right boundary.

Results and Discussions

Aerodynamic power and thrust

The aerodynamic power and thrust of the wind turbine can be obtained by using both two simulation methods. Figure 5 shows the time history of aerodynamic power of turbine rotor in two simulations. The aerodynamic power of turbine is over predicted with ALM method than that with overset grid method. This is because the effect of the flow analysis phenomenon on the blade surface on aerodynamic power is not considered with ALM method. Figure 6 shows the time history of aerodynamic thrust of turbine rotor in two simulations. The aerodynamic power of thrust is underestimate with ALM method than that with overset grid method. This results from the presence of turbine hub accounted in overset grid method. In addition, data fluctuations over time can be observed on the curves of overset grid in both Figure 5 and Figure 6, and the period of the fluctuations equals to 1/3 of the rotating period of turbine rotor. This is because the three blades alternately cut in the area with higher wind speed under the effect of wind shear.

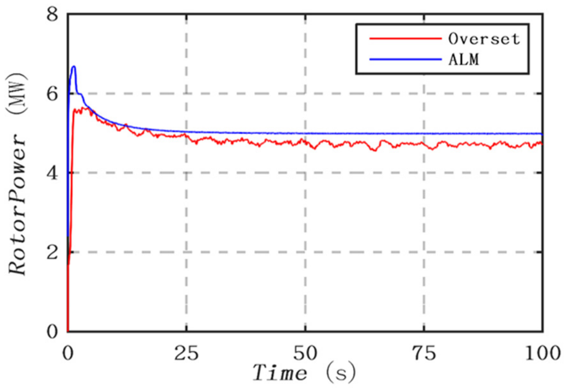


Figure 5. Aerodynamic power

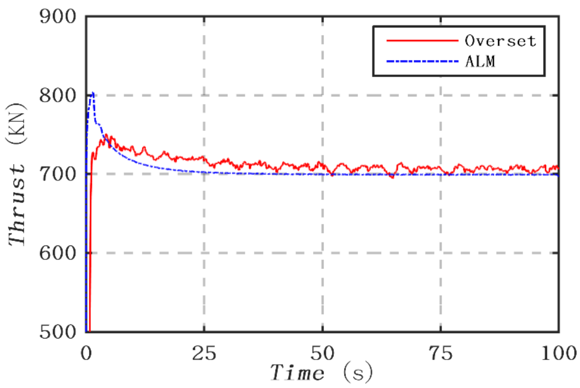
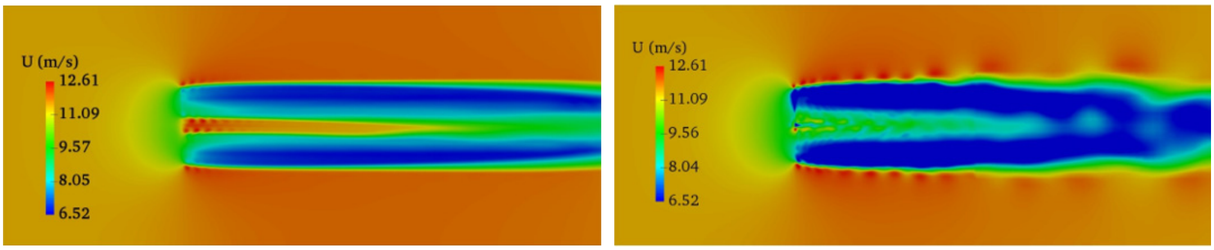


Figure 6. Aerodynamic thrust

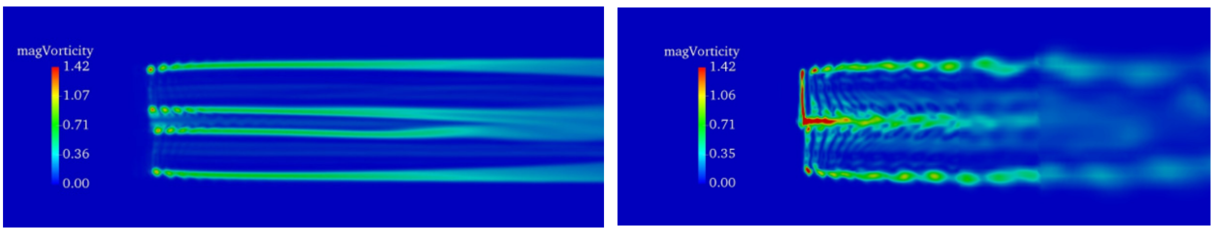
Wake Field

Through the post-processing software Paraview for visual processing, both simulation methods can clearly show the wake field information of wind turbine. Figure 7 shows axial direction wind velocity counters at the height of the center of rotor in horizontal plane. Figure 8 shows Vorticity at height z=0 with two simulation methods. Since the overset grid method meshes the real blades and hub of turbine, the wake information obtained is more abundant. It can seen wake velocity decrease greatly after wind passes through the turbine. In the Figure 7(a), along the direction of the inflow, at the 600m behind the hub(about 5 times the diameter of the turbine rotor), the wake velocity has recovered and the color there shows green. While in the Figure 7(b), there is still significant velocity speed loss. This is because overset grid method takes the effect of the hub into account.



(a) ALM **(b)Overset grid**

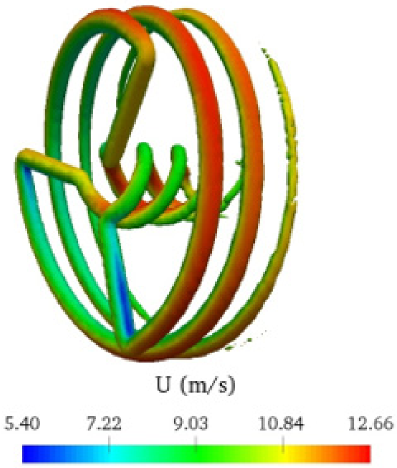
Figure 7. Contours of axial direction wind velocity in horizontal plane at z=0

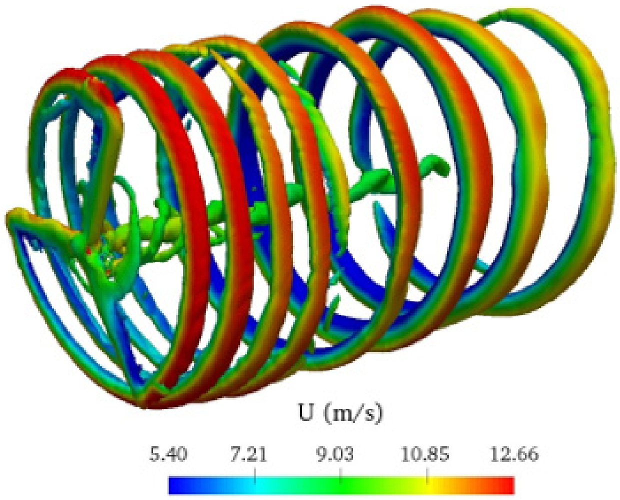


(a) ALM **(b)Overset grid**

Figure 8. Contours of vorticity in horizontal plane at height z=0

Figure 9 shows the wake vortex structure of wind turbine at moment of 100s with two simulation methods. The wake vortex structure is visualized by the contour of the second invariant of the velocity gradient tensor Q. Distinct blade tip vortices and root vortices are observed with both simulations. The wake vortex structure dissipates faster with ALM method than that with overset grid method, and three cycles of tip vortex can be observed in the Figure 9(a), while eight cycles of tip vortex can be observed in the Figure 9(b).



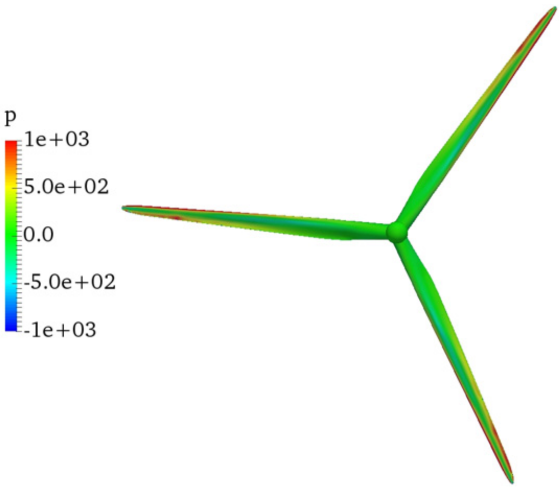


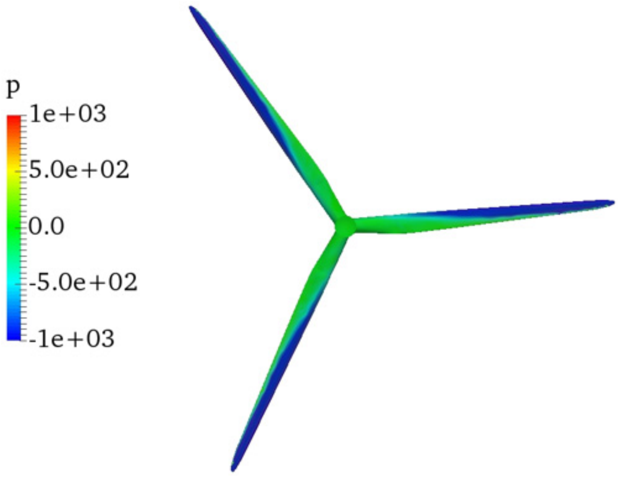
(a) ALM **(b) Overset grid**

Figure 9. Wake vortex structure with two simulation methods

Pressure Distribution

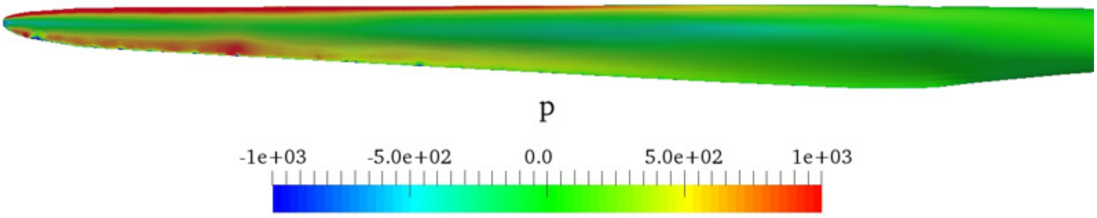
Overset grid method can provide more detailed flow information near the blades surface due to the simulation of real blades and hub of wind turbine. Figure 10 shows variation of pressure distribution on the blades surface at moment of 100s. In the Figure 11, the pressure distribution on tip sections are enlarged for better observation. The pressure distribution on the blades is mainly concentrated on the tips, and the pressure on the windward side is larger than the leeward side.



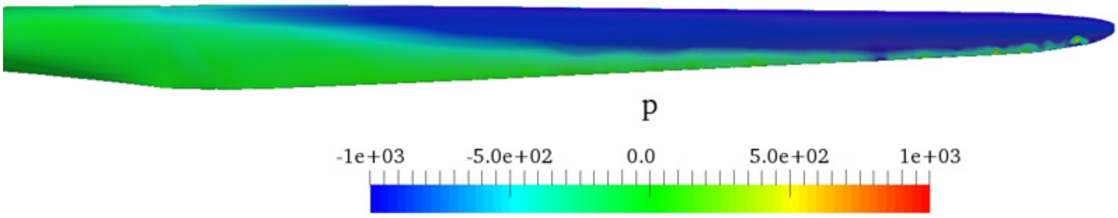


(a) Front **(b) Back**

Figure 10. Variation of pressure distribution on the blades surface



(a) Front



(b) Back

Figure 11. Variation of pressure distribution on the tip section

Conclusions

In this study, aerodynamic and wake field simulations of the NREL 5MW wind turbine are conducted with ALM method and overset grid method. With these two methods, the time history of aerodynamic power and thrust, contours of axial direction wind velocity and vorticity, and wake vortex structures are obtained and compared. Both methods can obtain relatively accurate simulation results to analyze of aerodynamic characteristics and wake characteristics of wind turbine. The ALM method replaces the real blades with actuator elements, which can reduce the number of grids and calculation time effectively. Compared with overset grid method, the aerodynamic power of turbine is over predicted, and the aerodynamic thrust of turbine is underestimate with ALM method. In addition, overset grid method can reflect fluctuations in aerodynamic power and thrust output with time. This indicates that more accurate power and thrust forecasting still needs to consider the effect of the blades and hub. Overset grid method simulates real blades of wind turbine, therefore it can provide more detailed flow information near the blades surface, such as variation of pressure distribution on the blades surface, which is helpful to further understand the complex flow phenomena around the wind turbine and optimal design for the wind turbine.

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.

References

[1] Lanzafame, R., and M. Messina. "Fluid dynamics wind turbine design: Critical analysis, optimization and

application of BEM theory." Renewable energy 32.14 (2007): 2291-2305.
[2]Shen, Wen Zhong, et al. "Tip loss corrections for wind turbine computations." *Wind Energy: An International Journal for Progress and Applications in Wind Power Conversion Technology* 8.4 (2005): 457-475.
[3]WHALE J, FISICHELLA C, SELIG M. Correcting inflow measurements from J3 AWTS using a lifting-surface code[J]. Urbana, 1999, 51:61
[4] Choi, Nak, et al. "CFD Study on Aerodynamic Power Output Changes with Inter-Turbine Spacing Variation for a 6 MW Offshore Wind Farm." *Energies* 7.11 (2014): 7483-7498.
[5] Choi, Nak Joon, et al. "Numerical study on the horizontal axis turbines arrangement in a wind farm: Effect of separation distance on the turbine aerodynamic power output." *Journal of Wind Engineering and Industrial Aerodynamics* 117 (2013): 11-17.
[6] Li, Yuwei, et al. "Dynamic overset CFD simulations of wind turbine aerodynamics." Renewable Energy 37.1 (2012): 285-298.
[7] Churchfield, Matthew, et al. "A large-eddy simulation of wind-plant aerodynamics." *50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*. 2012.
[8] Churchfield, Matthew J., et al. "A numerical study of the effects of atmospheric and wake turbulence on wind turbine dynamics." *Journal of turbulence* 13 (2012): N14.
[9] Sørensen J N, Shen W Z. Computation of wind turbine wakes using combined Navier-Stokes/actuator-line Methodology[C]//1999 European Wind Energy Conference and Exhibition. 1999: 156-159.
[10] Mikkelsen, Robert, et al. "Analysis of power enhancement for a row of wind turbines using the actuator line technique." *Journal of Physics: Conference Series*. Vol. 75. No. 1. IOP Publishing, 2007.
[11] SUGGAR: a general capability for moving body overset grid assembly." *17th AIAA computational fluid dynamics conference*. 2005.
[12] Carrica, P. M., et al. "Large-scale DES computations of the forward speed diffraction and pitch and heave problems for a surface combatant." *Computers & Fluids* 39.7 (2010): 1095-1111.
[13] Sørensen J N, Shen W Z. Numerical modeling of wind turbine wakes[J]. Journal of fluids engineering, 2002, 124(2): 393-399.
[14] Troldborg, Niels, Jens N. Sørensen, and Robert Mikkelsen. "Actuator line simulation of wake of wind turbine operating in turbulent inflow." *Journal of physics: conference series*. Vol. 75. No. 1. IOP Publishing, 2007.