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Numerical Simulation of Wind Turbine Aerodynamic Characteristics under Wind Shear Based on Lattice-Boltzmann Method

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Abstract: In order to study the influence of wind shear on the aerodynamic characteristics of large wind turbines, taking the 5MW wind turbine blade model published by NREL as the research object, large eddy simulation (LES) of wind turbines was carried out by using XFlow fluid simulation software based on Lattice-Boltzmann method (LBM). WALE turbulence model was used to study wind shear at 3, 11.2 and 25m/s wind speeds. The effect of factors on the axial thrust and torque of wind turbines is compared with the data published by NREL. The results show that the XFlow software based on LBM and LES method has good capturing ability for the eddy wake of wind turbine; wind shear causes the airfoil section of each section of blade to deviate from the best designed attack angle in theory and results in a decrease in torque applied to the wind turbine.

1 Introduction

Under the trend of large-scale development of wind turbines, it becomes particularly important to accurately analyze the aerodynamic performance of large wind turbines. According to the aerodynamic loads of wind turbines obtained from the analysis, the aerodynamic layout optimization design of wind turbines is carried out, which ensures the structural strength and at the same time obtains a higher wind energy utilization coefficient [1].At present, experimental and numerical simulation methods are mainly used to study the aerodynamic performance of wind turbines. The numerical simulation methods mainly include Blade-element Theory (BEM), eddy current theory and computational fluid dynamics method (CFD) [2]. With the improvement of computer performance, large commercial CFD software has been more and more widely used and has become a sharp tool for wind turbine aerodynamic performance research [3]. This paper takes 5MW wind turbine of National Renewable Energy Laboratory (NREL) as the research object, large eddy simulation (LES) of wind turbine was carried out by XFlow fluid simulation software, and studies the influence of wind shear factor on axial thrust and torque of wind turbine at 3, 11.2 and 25 m/s wind speeds, and verifies the reliability of simulation software by comparing it with published data of NREL.

2 Geometric models and computational domains

2.1 Three-dimensional model of wind turbine

This paper takes NREL 5 MW wind turbine as the research object. The wind turbine is a horizontal axis, three-blade and windward wind power unit [4]. Its main parameters are shown in Table 1.

Table 1. Main parameters of NREL5 MW wind turbine

Parameters	Numerical value	Parameters	Numerical value
Rating	5 MW	Cut-in wind speed	3 m/s
The number of blades	3	Cut-out wind speed	25 m/s
Wind turbine diameter	123 m	Rated wind speed	11.4 m/s
Hub diameter	3 m	Cut-in rotor speed	6.9 r/min
Hub height	90 m	Rated rotor speed	12.1 r/min
Shaft tilt	5 °	Cone angle	2.5 °

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In this paper, the numerical simulation calculation model only considers the wind turbine part, without considering the influence of engine compartment and tower. The wind turbine has elevation and cone angle. The wind turbine model is shown in Figure 1.

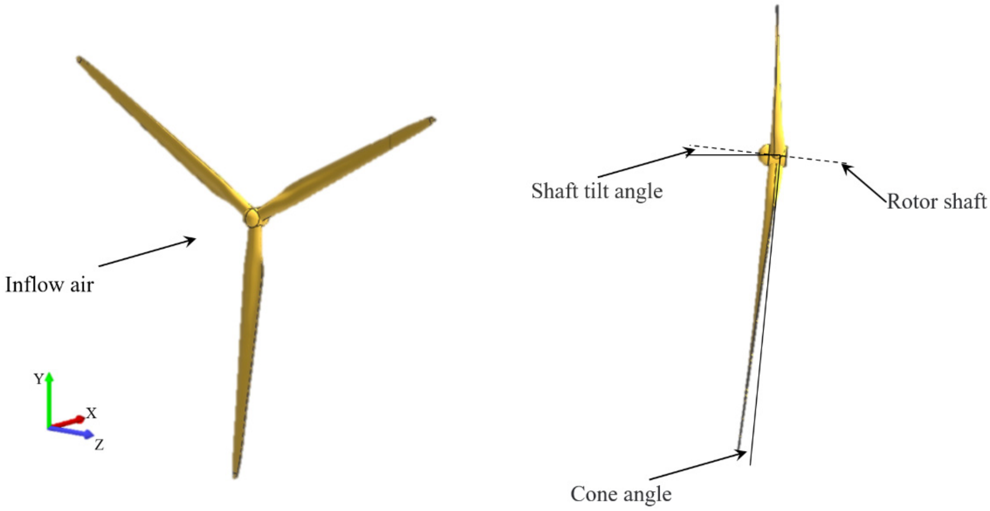

Figure 1. Geometric model of wind turbine

2.2 Wind field modeling and meshing

After verification of irrelevance of wind field size, the selected wind field size is 600 m x 290 m x 400 m. Considering the influence of ground, the height of wind wheel center from ground is 90 m, and the distance from inlet of inflow is 200 m. Both left and right boundary and upper boundary of calculation area are 200 m, as shown in Figure 2.

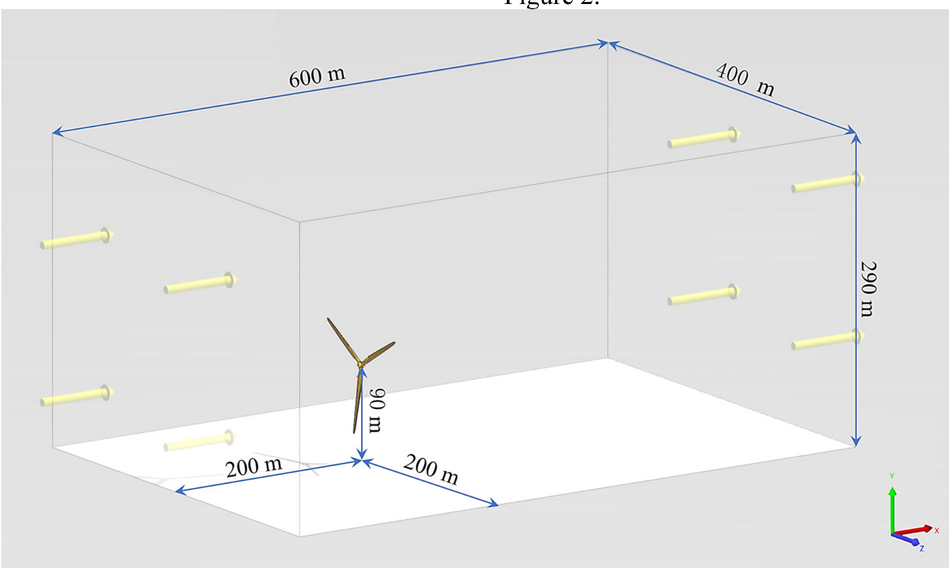

Figure 2. calculation domain of wind field

3 CFD software principles and numerical methods

3.1 Introduction to XFlow software

XFlow is a new generation of fluid dynamics simulation analysis software based on Lattice-Boltzmann method (LBM). It uses particle-based and complete Lagrange function method, has advanced large eddy simulation (LES) model and uses uniform non-equilibrium wall function to simulate boundary layer.

3.2 LBM Method

The LBM method is to discrete the Boltzmann-BGK equation in space, time and velocity [5]. The Boltzmann transport equation is as follows:

$$f_i\left(r+c_i\Delta t, t+\Delta t\right)=f_i\left(r,t\right)+\Omega_i^B\left(f_1,\ldots,f_b\right) \quad (1)$$

Where f_i is the distribution function in the direction; Ω_i^B is the collision operator; t is the discrete time, s; c_i is the velocity in the i direction, m/s; r is the

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position on the lattice.

The lattice Boltzmann method (LBM) defines a simplified operator under the Bhatnagar-Gross-Krook (BGK) [6] approximation as follows:

$$\Omega_i^{BGK} = \frac{1}{\tau}\left(f_i^{eq} - f_i\right) \tag{2}$$

Where f_i^{eq} is a local equilibrium function; τ is a relaxation characteristic time.

Typically, the balanced distribution function expression is as follows:

$$f_i^{eq}\left(r,t\right) = t_i \rho\left(1 + \frac{c_{ia}v_a}{c_s^2} + \frac{v_\alpha v_\beta}{2c_s^2}\left(\frac{c_{i\alpha}c_{i\beta}}{c_s^2} - \delta_{\alpha\beta}\right)\right) \tag{3}$$

Where c^s is the sound velocity, m/s; v_α and v_β are the macro-viscosities, Pa.s; $\delta_{\alpha\beta}$ is the Croneker function; t_i is the parameter to ensure spatial isotropy; ρ is the macro-density, kg/m3.

3.3 large eddy simulation Method

Large eddy simulation method (LES) filters continuity equation and N-S equation, filters subgrid vortices smaller than filter scale, decomposes control equation describing the motion of large eddy, and introduces subgrid stress term into the equation to consider the influence of momentum and energy of subgrid vortices on large eddy [7]. The subgrid turbulence model used in XFlow software is a wall-adaptive local eddy viscosity model (WALE), which has good characteristics in both laminar and turbulent flows, whether close to the wall or far from the wall. The model restores the asymmetric characteristics of the turbulent boundary layer without adding artificial turbulent viscosity to the wake shear zone, which can be directly solved. The WALE model [8] is represented as follows:

$$\mu_{\mathrm{t}} = \rho L_{\mathrm{s}}^{\ 2}\frac{\left(S_{ij}^d \cdot S_{ij}^d\right)^{3/2}}{\left(\overline{S}_{ij}^d \cdot \overline{S}_{ij}^d\right)^{5/2} + \left(S_{ij}^d \cdot S_{ij}^d\right)^{5/4}} \tag{4}$$

$$L_s = \min\left(\kappa d, C_w V^{1/3}\right) \tag{5}$$

$$S_{ij}^d = \frac{1}{2}\left(\overline{g}_{ij}^2 + \overline{g}_{iji}^2\right) \tag{6}$$

Where WALE constant C_w is usually 0.2; S_{ij}^d is the strain rate tensor, which reflects not only the function of the symmetric part of the velocity gradient tensor, but also the effect of the asymmetric part.

3.4 Wind shear model

The NREL 5 MW large wind turbine is 123 m in diameter and the effects of wind shear must be taken into account. Changes in wind speed perpendicular to the wind plane are called wind shear or wind speed profiles, where an exponential law distribution is used, as shown in the Equation (8):

$$U = U_{\mathrm{ref}}\left(\frac{y}{y_{\mathrm{ref}}}\right)^\alpha \tag{7}$$

In the formula, *U* is the average wind speed at *y* above ground level, m/s; y_{ref} is the reference height, taking the hub center height of 90 m; U_{ref} is the average wind speed at the hub center height, m/s; α is the wind speed profile index, and here take 1/7.

4 Numerical simulation results and analysis

Under three wind speeds of 3 m/s, 11.2 m/s and 25 m/s, the wind turbine is simulated under two conditions of wind shear and no wind shear, and the axial thrust and torque changes of the wind turbine are monitored. The lattice analytical scale of calculation domain is 4 m for far-field solution, 0.25 m for near-wall solution and 0.25 m for eddy wake solution. Dynamic adaptive tracking encryption control is used for eddy wake. At this time, the number of grids is about 19.32 million and the calculation time is about 15 hours. The calculation accuracy and cost of eddy wake simulation are relatively balanced. The lattice analytical scale is shown in Figure 3 and the three-dimensional volume field cloud of vorticity is shown in Figure 4.

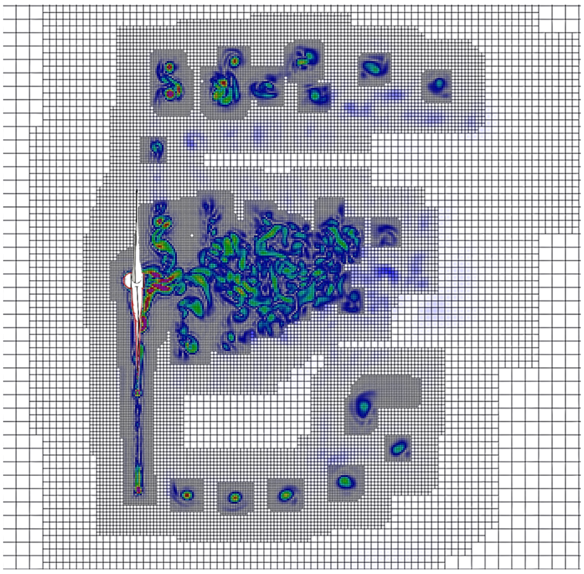

Figure 3. The lattice analytical scale

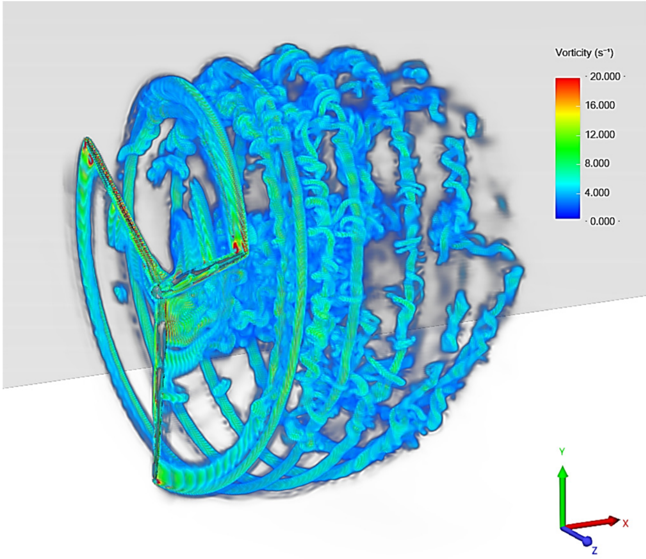

Figure 4. The 3D volume field cloud of vorticity

It can be seen from Figure 3 that obvious vortex wake is formed behind the blade, and the grid analytical scale in the wake area is automatically adjusted. From Figure 4, it can be seen that the spiral vortex wake is formed in the wind field due to the rotation of the wind turbine, and vortices of different sizes are generated in the wake, which can well simulate the flow state of subgrid vortex. In other words, XFlow software can automatically detect and capture the large and sub-grid vortices in the wake area, update and encrypt the grid analytical scale of the wake area in real time, accurately simulate the vortex wake of wind turbine, and effectively save computing resources.

The data of numerical simulation results select the average load value within 5 rotation cycles after stabilization and compare with NREL published data, as shown in Table 2, where F_{XB} is the axial thrust of the wind turbine, and M_{XB} is the torque of the wind turbine.

Table 2. Comparison of simulation data and NREL data

Operating conditions		Wind turbine load					
Wind speed (m/s)	Wind shear	F_{XB} (kN)	F_{XB} of NREL (kN)	Error (%)	M_{XB} (kN·m)	M_{XB} of NREL (kN·m)	Error (%)
3	Yes	149	168	11%	58	56	4%
	No	155	168	8%	61	56	9%
11.4	Yes	760	794	4%	4318	4181	3%
	No	766	794	4%	4362	4181	4%
25	Yes	345	373	8%	4320	4181	3%
	No	350	373	6%	4370	4181	5%

According to the data comparison in Table 2, under all working conditions, the axial thrust of the wind turbine is slightly less than the NREL open value, and the wind turbine torque is slightly greater than the NREL open value, and the error at cut-in wind speed is relatively large, and the error at rated wind speed is relatively small. The results show that the relative errors between the numerical simulation results and NREL open results of the axial force and the torque of the wind turbine are within a reasonable range, which shows that the XFlow software based on Lattice-Boltzmann method and large eddy simulation has high accuracy for the simulation of wind turbine vortex wake. In addition, compared with the effect of wind shear, it is found that the thrust and torque of the rotor shaft under the action of wind shear are relatively less than the value of no wind shear under the corresponding wind speed. This is because the wind shear causes the wind speed of the wind turbine blade to be larger when it is at the high position in the rotation cycle, and the wind speed is small when it is at the low position, and the incoming wind speed of the blade presents periodic fluctuations, which deviates from the theoretical design wind speed. The results show that the angle of attack of each airfoil periodically deviates from the optimal design angle of attack, resulting in the reduction of wind turbine torque, which is less than the value without wind shear.

5 Conclusion

(1) The XFlow software based on LBM and LES method has good capture ability and high simulation accuracy for large eddy and subgrid vortices in the wake area of wind turbine.

(2) Wind shear makes the attack angle of each section of the blade periodically deviate from the theoretical optimal design angle of attack, which leads to the decrease of wind turbine torque.

Acknowledgments

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