Research on the Influence of Shear Turbulence on the Aerodynamic Loads Characteristics of Wind Turbine

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Abstract. In order to accurately analysis the aerodynamic loads characteristics of the wind turbine under different turbulent wind conditions, the horizontal homogeneity in the flow field without a wind turbine and the numerical accuracy of the homogeneous flow field with a wind turbine were validated against the experimental results. The aerodynamic loads of the wind turbine were studied under the conditions of the uniform wind with a uniform turbulence intensity, the uniform wind with a shear turbulence intensity, the shear wind with a uniform turbulence intensity and the shear wind with a shear turbulence intensity. The results show that the increasing turbulence intensity leads to a small reduction in the torque of the wind turbine. Compared with uniform wind, shear inflow leads to a sine or cosine variation in the aerodynamic performance of the wind turbine and a reduction in the wind turbine’s thrust and torque. Compared with uniform turbulence intensity, shear turbulence intensity leads to a reduction in the wind turbine's thrust and torque, and a more obvious phase lag effect, but it has little influence on the yawing moment and pitching moment.

1. Introduction

Wind turbines operate in the near-ground atmospheric boundary layer. From the perspective of wind energy utilization, the neutral atmospheric boundary layer is the wind condition that needs to be considered most in the aerodynamic calculation of wind turbines. Zheng et al. [1], Gao et al. [2-3] and Li et al. [4] conducted outstanding numerical research and experimental analysis of wind turbines under atmospheric conditions. When the atmosphere stratification is neutral, the average wind speed in the boundary layer exhibits the characteristics of wind shear in space, and its turbulence intensity also decreases with the increase of altitude. Therefore, the key to aerodynamic calculation of wind turbines is to adopt accurate incoming flow conditions according to the characteristics of the neutral atmospheric boundary layer. At the same time, the boundary layer air flow should meet the horizontal uniformity, that is, the physical quantities in the flow field remain unchanged along the flow direction. Blocken et al. [5], Hargreaves et al. [6] have confirmed that the horizontal uniformity of the atmospheric boundary layer will have a significant impact on the numerical calculation results. Therefore, before the numerical simulation of the wind turbine, the empty flow field simulation without a wind turbine should be carried out to meet the boundary layer horizontal uniformity condition.

In this work, the exponential wind shear model was used to correct the longitudinal turbulence of the incoming flow in combination with the empirical formula obtained from the Engineering Scientific Data Unit (ESDU), which verifies the horizontal uniformity of the flow field in the numerical domain of the empty flow field without a wind turbine. Then, the aerodynamic loads of a two-blade horizontal axis wind turbine under four incoming flow conditions were calculated, and the results were analysed.
2. Numerical model

2.1. Wind speed model

The wind shear of the average wind speed varying with height is usually described by the exponential law or the logarithmic law. In this work, the exponential model was used as follows

\[ u(z) = u(z_0) \left( \frac{z}{z_0} \right)^\alpha \]  

(1)

where \( u(z) \) is the average wind speed at the height of \( z \); \( u(z_0) \) is the wind speed at the reference height \( z_0 \), usually the \( z_0 \) is the hub height; \( \alpha \) is the wind shear exponent, which is set to 0.3 in this work.

The formula for calculating the streamwise turbulence intensity, \( I_u \), is

\[ I_u = \frac{\sigma_u}{u^*} \frac{u^*}{u(z)} \]  

(2)

where \( u^* \) is the friction speed, and there is

\[ \frac{\sigma_u}{u^*} = \frac{7.5\eta [0.538 + 0.09 \ln (z / z_0)]^\nu}{1 + 0.156 \ln (u^* / (f z_0))} \]

\[ \frac{u^*}{u(z)} = \frac{k_\eta}{\ln (z / z_0) + \psi} \]

\[ \nu = \frac{34.5 f z}{u^*} \]

\[ \eta = 1 - \frac{6 f z}{u} \]

\[ p = \eta^{16} \]

\[ f = 2\Omega \sin(|\lambda|) \]

where \( k_\eta \) is the Von Karman constant value (approximately 0.4), \( f \) is the Coriolis force parameter, \( \Omega \) is the angular velocity of the earth rotation, and \( \lambda \) is the latitude.

2.2 Turbulence field simulation method

The incompressible Navier-Stokes equation based on the three-dimensional Reynolds averaging was used, and the \( k-w \) SST turbulence model was used to model the turbulence. The change of the turbulent flow intensity, \( I_u \), in the streamwise direction at the inlet should be converted into turbulent kinetic energy, \( k \), and the specific dissipation rate, \( w \), which is

\[ k = \frac{3}{2} (u(z) \cdot I_u) \]

\[ \varepsilon = C_{\mu}^{3/4} \frac{k^{3/2}}{l} \]  

(4)

\[ w = \frac{\varepsilon}{k} \]

where \( C_{\mu} = 0.09 \), and \( l \) is the turbulent flow length scale, which was set to 87.318 m.

3. Validation

Figure 1 shows the distribution of three characteristic quantities of the wind speed (\( u \)), the turbulent kinetic energy (\( k \)), and the specific dissipation rate (\( w \)) at the inlet, 35m and 70m from the inlet, and the outlet. The comparison shows that the three flow characteristic quantities maintain good horizontal
uniformity at heights above 5 meters. There is an error at a height below 5 meters near the ground. The reason is that the definition of the turbulence boundary condition at the inlet is an empirical formula, and the momentum equation is not considered, so there is a defect. In addition, the vertical span of the wind turbine in our work was 8 ~ 22.8 m, and the horizontal uniformity of the flow field is maintained within this vertical range.

Fig. 1. Comparison of these four flow characteristics.

For the NREL Phase VI wind turbine, the $k$-$\omega$ SST turbulence model is used to simulate the wind turbine under the condition of a uniform incoming wind speed of 7 m/s and a rotor speed of 72 rpm. Took the pressure coefficient curve at the 30%$R$ section of the blade root zone and 80%$R$ section of the blade heavy load zone, and compared them with the experimental values. The results are shown in Figure 2. The surface pressure coefficient curve is in good agreement with the experimental value. In summary, the numerical calculation method used in this work can ensure the horizontal uniformity of the flow characteristics in the air flow field and the accuracy of the calculation of the wind turbine flow field.
4. Results
This work used 4 Sugon CB65-G dual-path blades for calculation. Each blade computing node was configured with two AMD Opteron 6272 2.3GHz sixteen-core processors and 32G DDR3 memory. The computing platform used 40Gb QDR InfiniBand network interconnection. Taking an empty flow field without a wind wheel as an example, a grid cell of 13.85 million full hexahedrons was divided and 128-core computing resources were used for calculation.

Figure 3 shows the change curve and trend line of the axial thrust, torque, yaw moment and pitching moment of the wind turbine when the turbulence intensity is 0 ~ 30% under the uniform flow of 11m/s. It can be seen from the figure that as the degree of turbulence intensity increases, the aerodynamic loads generally show a downward trend. Affected by the numerical truncation error, the slight differences of the specific value of each aerodynamic load with the degree of turbulence intensity are related to the number of iteration steps, so the points in the curve are randomly arranged in a narrow range of the ordinate. The correlation analysis of the obtained aerodynamic loads values is carried out to determine the influence of turbulence on each aerodynamic load. The coefficient of variation and relative range of the yaw moment and the pitching moment are relatively large, and the correlation coefficient is low-degree negative correlation. This shows that there is no significant correlation between yaw moment, pitching moment and turbulence, but there are certain numerical fluctuations affected by the number of iteration steps. At 11m/s wind speed, turbulence intensity greater than 20.145% is an extreme wind condition. At this time, the impact of high turbulence and fluctuating wind speed on the safety of the wind turbine should be mainly considered.
Fig. 3. Aerodynamic loads in the uniform wind and turbulence intensity.

Figure 4 Figure 7 shows the three types of shear wind and shear turbulence (WS.IS.), uniform wind and shear turbulence (WU.IS.), shear wind and uniform turbulence (WS.IU.). Under flow conditions, the change curve of the axial thrust, torque, yaw moment, and pitching moment of the wind turbine. The wind shear effect will make the aerodynamic loads of the wind turbine show a sine and cosine change law, while the shear turbulence has little effect. The average wind speed changes with the height, and each blade element on the rotor undergoes a process from low wind speed to high wind speed with the change of height during a rotation of the wind turbine, which causes periodic changes in aerodynamic loads. Wind shear will reduce the average axial thrust of the rotor by 3.06% and the average torque by 5.51%. The degree of shear turbulence will reduce the average axial thrust of the
rotor by 2.60%, and the average torque by 4.03%, but has little effect on the yaw moment and pitching moment of the rotor. At the same time, the degree of shear turbulence will increase the axial thrust and torque by approximately 6.25° and 4.00° phase lag, respectively. The more fluctuating shear turbulence will cause: 1. Stronger dissipation effect reduces aerodynamic performance; 2. Stronger turbulence mixing effect strengthens the induction effect of the rotating wind turbine on the incoming flow, thereby increasing the phase lag effect.
5. Conclusion

This work first verified the horizontal uniformity of the flow characteristics in the empty flow field and the accuracy of the calculation of the wind turbine flow field. On this basis, the aerodynamic loads of the wind turbine under four incoming flow conditions was studied. The main conclusions are as follows:

1. Under uniform wind and uniform turbulence wind conditions, the increase of turbulence intensity will increase the turbulent kinetic energy, turbulence dissipation rate and specific dissipation rate, and increase the dissipation effect, which will cause the rotor torque to slightly decrease. Therefore, the safety of the wind turbine should be mainly considered under high turbulence wind conditions.

2. Wind shear will cause the aerodynamic loads of the wind turbine to show a sine and cosine change law; compared with uniform wind, wind shear flow will reduce the axial thrust and torque of the wind turbine.

3. Compared with the uniform turbulence, the shear turbulence will cause the axial thrust and torque of the rotor to decrease, the phase lag is more obvious, and the influence on the yaw moment and pitching moment is less.

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