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Research on the Loads of NREL 5MW Wind Turbine under Stable Atmospheric Conditions

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Abstract. To study how the atmospheric turbulence affects the wind turbine, blade element momentum theory coupled with harmony superposition method was used to study the loads of NREL 5MW wind turbine based on the standard Von Karman spectrum and NWTC measured spectra with different atmospheric stability. The results show that the standard Von Karman spectrum overestimates power and thrust relative to NWTC spectrum. From a frequency domain perspective, there is a critical frequency linearly related to the tip speed ratio, which determines the range of turbulence scales that can affect the wind turbine. The wind-turbine loads are mainly affected by the low-frequency turbulent structure in the flow below the critical frequency and decoupled from the flow above the critical frequency. From an intuitive perspective, the low-frequency turbulence structure can't be effectively absorbed by the rotor, but is transformed into fatigue loads by the structure.

1. Introduction

Large-scale wind turbines operate in the stable atmospheric boundary layer (SABL), where they are subjected to strong wind shear and high turbulence levels relative to wind tunnel experiments [1]. These incoming flow characteristics affect the stability of wind-turbine loads and can't be effectively studied based on the standard Von Karman spectrum, so it is necessary to carry out studies based on a measured spectrum [2]. Time averaged theory can only predict statistical characteristics of turbulence rather than unsteady fluctuation characteristics which are important in large-scale wind turbines [3]. Some studies have shown that the combination of harmony superposition method (HSM) and blade element momentum (BEM) theory is effective and simple [4]. Therefore, based on the National Wind Technology Center (NWTC) wind speed spectra, this paper studies the effects of atmospheric turbulence on the aerodynamic loads of wind turbines under stable atmospheric conditions. We used HSM to generate atmospheric wind speed and BEM to calculate wind-turbine loads, and verified our algorithm by comparing it with experiment.

2. Numerical methods

2.1. The NWTC velocity spectra

For stable and neutral conditions ($Ri \geq 0$), the NWTC model velocity spectra $S_K(f)$ for the three wind components, K, are given by adding scaled versions of the $S_T(f)$:

$$S_K\left(f\right)=p_{1,K}S_T\left(F_{1,K}f\right)+p_{2,K}S_T\left(F_{2,K}f\right) \tag{1}$$

where f is the frequency, $p_{1,K}$, $p_{2,K}$, $F_{1,K}$ and $F_{2,K}$ are functions of the Gradient Richardson number, Ri, and $S_T(f)$ is the Risø smooth-terrain model [5], which is defined by

$$\frac{S_T\left(f\right)}{u_*^2}=\frac{A\left(\frac{z}{\bar{u}\phi_M}\right)\left(\frac{\phi_E}{\phi_M}\right)^{2/3}}{1.0+B\left(\frac{fz}{\bar{u}\phi_M}\right)^{5/3}} \tag{2}$$

where the input parameter, u_*, is the friction velocity, $\bar{u}$ is the mean velocity at height z, and ϕ_E and ϕ_M are functions of the stability parameter. The two scaling factors, A and B, are defined as follows:

$$\left\langle A,B\right\rangle=\begin{cases}\left\langle 79.0,263.0\right\rangle, & \text{for } u.\\ \left\langle 13.0,32.0\right\rangle, & \text{for } v.\\ \left\langle 3.5,8.6\right\rangle, & \text{for } w.\end{cases} \tag{3}$$

2.2. HSM and BEM theory

We used the HSM to generate fluctuating wind speed and BEM to calculate aerodynamic loads on the turbine. In the BEM theory, the blade tip and hub loss correction model, Glauert correction, skewed wake correction and 3D stall-delay model are considered [6, 7]. Since the purpose of this paper is to study the effects of different wind speed spectra on the aerodynamic loads of wind turbines, the spectral model is mainly introduced, and the HSM and BEM are not described again.

3. Validation

Figure 1 shows the numerical results of the power and thrust of the NREL 5MW wind turbine. The line marked with a red square represents theoretical values, and the line with the blue right triangle represents the numerical values. The results show that below the 11.4m/s, the numerical results are accurate compared with the theoretical values; above 11.4m/s, the numerical values are larger than the corresponding theoretical value. This is because, as the wind speed increases, although the pitch control of the blades can reduce the occurrence of the stall zone, localized stalls still occur in parts of the rotor blades. Compared with the theoretical values, the power error is less than 7.37%, and the thrust error is within 9.63%, which satisfies the accuracy requirements of engineering calculation.

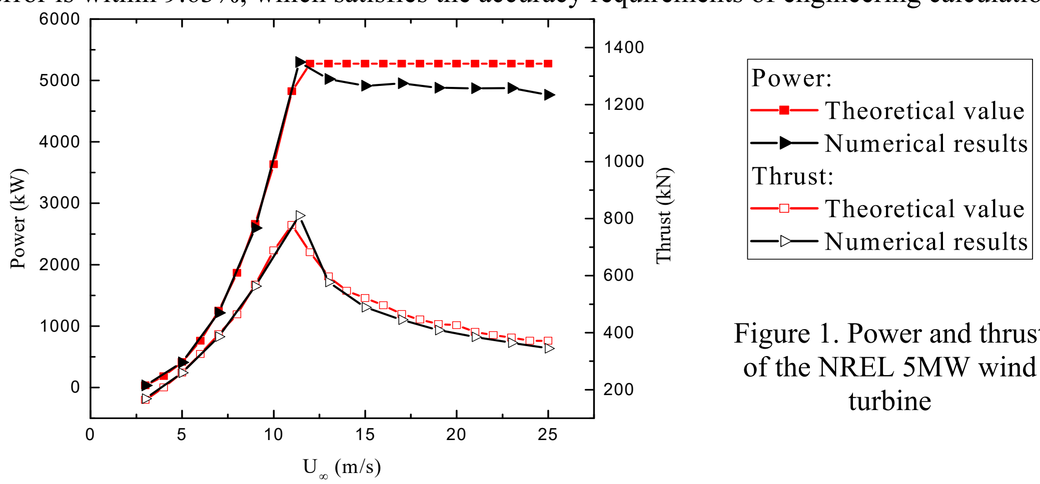

Figure 1. Power and thrust of the NREL 5MW wind turbine

4. Results and discussions

In the simulations, the total simulation time is 900s, the time step is 0.02s, and the surface roughness is 0.01m. As can be seen from figure 1, the numerical results are closer to the experimental values below

11.4m/s. Therefore, under different stable atmospheric conditions, the mean velocity used in our simulations is always 7m/s, the rotor speed is 8.48rpm and the pitch angle is 10°. **Figure 2** shows the turbulence characteristics in the flow and wind-turbine loads under different stable atmospheric conditions (Von Karman spectrum and NWTC spectra with *Ri* is 0.00, +0.20, +0.40, +0.60, +0.80, respectively). The first row are the mean turbulent kinetic energy ($\overline{TKE}$) and mean coherent turbulence kinetic energy ($\overline{CTKE}$), the second row are the mean power coefficient ($\overline{C}_P$) and the mean thrust coefficient ($\overline{C}_T$), and the last row are the standard deviation of the two coefficients. Taking neutral conditions as an example, compared with NWTC spectra, the wind speed field generated by the standard Von Karman spectrum has lower $\overline{TKE}$ and $\overline{CTKE}$, and its power coefficient and thrust coefficient are predicted to be 15.9% and 9.2% higher, respectively. Under stable atmospheric conditions (*Ri* = 0.2~0.8), as the atmospheric stability increases, the power and thrust coefficients increase, but the change is not obvious.

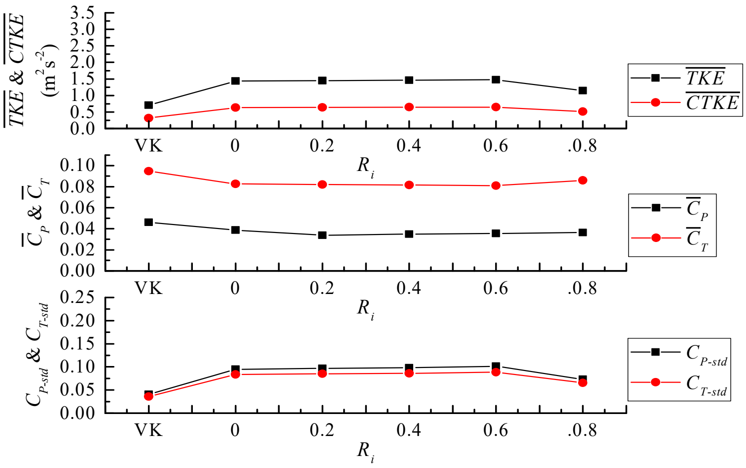

Figure 2. Turbulence characteristics of inflow and loads response of the wind turbine

In this section, we used the standard Von Karman spectrum and the NWTCUP spectrum at Ri=0.00 as a comparison. Figure 3a shows the fluctuating velocity spectra generated by these two models in the *u*-direction. It can be seen that the wind speed spectra of both models show a -5/3 power law region, which is related to the inertial sub-region in the Kolmogorov turbulence stratification theory. A longer -1 power law region relative to the Von Karman spectrum appears in the NWTC fluctuating velocity spectrum. The -1 power law region in the atmospheric wind speed spectrum is related to the large-scale low-frequency turbulence structure, which may disappear when using the standard Von Karman spectrum to calculate the wind-turbine dynamic loads. Further, we set the wind-turbine rotation frequency to f_T. Figure 3b shows the corresponding power and thrust spectra for the two inflow conditions. It can be seen from the figure that the low-frequency region of the aerodynamic loads spectra is only related to the low frequency characteristics of the incoming wind speed spectrum (-1 power law zone and part of the -5 /3 power law zone), which indicates that the low-frequency region of the power and thrust spectra is strongly influenced by the energy cascade. In the high-frequency region of the aerodynamic load spectrum, high-order harmonics related to the multiple of the rotation frequency appear, but there is no obvious interaction with the turbulent structures in the flow.

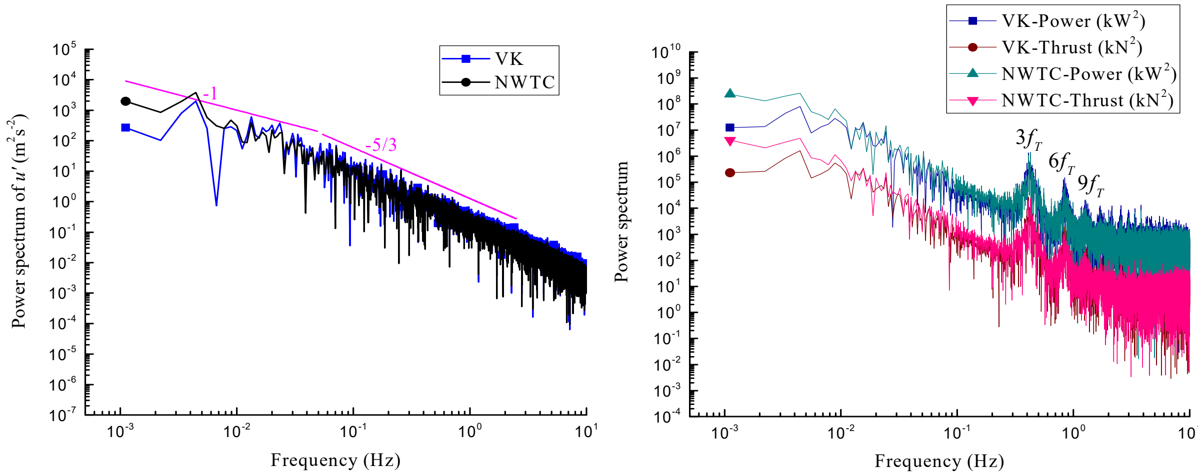

Figure 3. The *u*-direction fluctuating velocity spectra, the spectra of wind-turbines power and thrust

5. Conclusion

To study how the atmospheric turbulence affects the wind turbine, based on the NWTC measured spectrum model, we verify the accuracy of the algorithm used in the wind-turbine loads calculation, and the aerodynamic response of the NREL 5MW wind turbine under the standard Von Karman spectrum and the NWTC measured spectra with different stable atmospheric conditions were studied. The results show that the standard Von Karman spectrum results in a higher value of power and thrust than the measured velocity spectrum. In the low-frequency region, the measured velocity spectrum has higher turbulent energy than the standard Von Karman spectrum. In order to further study the influence of this turbulent structures on the wind turbine, we analyzed the power spectrum of the wind turbine's power and thrust, and found that on the one hand, low-frequency region of the power and thrust spectra is strongly influenced by the energy cascade in the flow; on the other hand, the high-frequency region is mainly affected by the dynamic characteristics of the wind turbine itself.

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