ON THE WAKE CHARACTERISTICS OF THE NREL PHASE VI WIND TURBINE UNDER TURBULENT INFLOW CONDITIONS

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ABSTRACT

Wind turbines often work under turbulent inflow conditions due to the random and the continuously changing wind motion in both time and space. Turbulence affects wind turbines in several ways, including power output, aerodynamic loads, fatigue, wake effects and noise emissions. The wake effect is the biggest challenge when locating downwind turbines in wind farms which imposes large separation distances between individual turbines. In this paper, an overview of the effect of atmospheric turbulence on the wake characteristics of wind turbines is introduced. The reference NREL Phase VI wind turbine was chosen for the present examination. For this purpose, the Lifting Line Free-Vortex Wake (LLFVW) modelling is employed using the Qblade code. This approach relies on a more realistic representation of the wind turbine aerodynamics especially for dynamic wake effects unlike the Blade Element Momentum (BEM) approach which is based on several empirical correction models. The LLFVW results are validated against CFD and NREL/NASA Ames wind tunnel measurements. Ambient turbulence is imposed in the LLFVW simulations with different values of turbulence intensity (TI) ranging from 2% to 15%, which is the typical range for wind turbines.

KEYWORDS

TURBULENCE, NREL PHASE VI, COMPUTATIONAL FLUID DYNAMICS (CFD), LIFTING LINE THEORY (LLT), FREE-WAKE VORTEX (FWV)

NOMENCLATURE

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<tr>
<th>Symbol</th>
<th>Description</th>
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<tr>
<td>r</td>
<td>Radial position [m]</td>
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<tr>
<td>R</td>
<td>Blade length [m]</td>
<td>Greek symbols</td>
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<td>TI</td>
<td>Turbulence intensity [%]</td>
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<td>Δt</td>
<td>Time marching step [s]</td>
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<td>Δθ</td>
<td>Azimuthal marching step [°]</td>
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<td>Ω</td>
<td>Rotational speed [rpm]</td>
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<td>ω</td>
<td>Specific turbulence dissipation [1/s]</td>
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<td>UΓ</td>
<td>Induced velocity [m/s]</td>
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<td>α</td>
<td>Angle of attack [°]</td>
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<tr>
<td>Utotal</td>
<td>Total velocity [m/s]</td>
<td>Abbreviations</td>
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<td>Ux</td>
<td>Streamwise velocity [m/s]</td>
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<tr>
<td>U∞</td>
<td>Incoming wind speed [m/s]</td>
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<td>Umotion</td>
<td>Velocity due to motion [m/s]</td>
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<tr>
<td>y*</td>
<td>Normalized wall distance [m]</td>
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<tr>
<td>t</td>
<td>Time [s]</td>
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<tr>
<td>f</td>
<td>Frequency [Hz]</td>
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INTRODUCTION

Wind farms (onshore and offshore) consist of set of wind turbines operate in the atmospheric boundary layer, where turbulent inflow conditions are experienced. Some characteristics of the atmospheric boundary layer such as incoming wind speed, background turbulence, wind shear, atmospheric stability and complex terrains affect the loads on the individual wind turbines and, ultimately, shorten their lifespan (Vermeer et al., 2003; Barthelmie et al., 2009; Chamorro and Porté-Agel, 2009). Indeed, downstream wind turbines often work in the wakes of the upstream wind turbines in the wind farm. Even if the first row of wind turbines in the array is exposed to non-turbulent inflow, wind turbines themselves impose turbulence into their wakes increasing the fatigue loads on the downstream wind turbines. The quantification of wind turbine wakes can be divided into two main parts: near wake and far wake (Vermeer et al., 2003). The near wake is characterized by significant velocity deficit which results in lower power extraction from the individual wind turbines. Vermeer et al. (2003) and Sandser (2009) defined the near wake to dissipate at around $x/R = 2$, whereas Gómez-Elivra et al. (2005) suggested that the near wake ends somewhere between $x/R = 4 – 10$. The far wake is more concerned with the wake effects on the downstream wind turbines and the surrounding environment Marmidis et al. (2003).

Several studies have been carried out to examine the essence of the wake behind a wind turbine under turbulent inflow conditions. Advanced wake models relying on high-fidelity CFD simulations have been intensively reported in the recent years. Kim et al. (2016) conducted DDES simulations to predict the development of the near wake of the 10 MW AVATAR wind turbine in ambient turbulence with different scales generated by the Mann box model (Mann, 1994). Kabir and Ng (2018) performed full rotor URANS simulations of the NREL Phase VI wind turbine to investigate the effect of the different atmospheric boundary layers on its wake. More complex wake models have been suggested by incorporating analytical methods such as actuator-line or actuator-disk models into LES. The CFD approach is considered to be a practical tool for the prediction of the wake characteristics of a wind turbine. However, a wind farm is a cluster of wind turbines and indeed the employment of the CFD approach became not practical for the wind farm market. Such a method requires high computational resources and time, which does not suit the market needs for an efficient wind farm layout. The increased interest of the industry towards efficient wind farms, highlights the need for fast and sufficiently accurate wake models for wind turbines. Unlike the computationally expensive CFD approach, engineering models such as blade element-momentum theory and lifting-line theory have been developed to consider the interaction of the rotor blade with the wake as well as the flow nature in the boundary layer attached to the blade. Additionally, these engineering models demonstrated their effectiveness in predicting the aerodynamic loads of wind turbines under turbulent inflow conditions (Bangga et al., 2018; Marten et al., 2019; Ramos-García et al., 2018).

In this paper, the wake characteristics of the reference NREL Phase VI is investigated under incoming turbulence using a simplified approach, namely the Lifting Line Free-Vortex Wake (LLFVV) model. The LLFVV computations are carried out using the open-source Qblade code (Marten et al., 2013). Comparisons against high-fidelity CFD simulations and experimental NREL data are carried out to ensure the reliability of the LLFVV model in predicting the underlying complex wake flow behind a wind turbine. In the field of wind energy, ambient turbulence is usually quantified with an indicator called turbulence intensity ($TI$). The Veers Sandia method (Veers, 1988) based on an inflow velocity of 7 m/s is employed to generate a turbulent windfield with scaled magnitude of the fluctuations at hub height of 12.192 m to obtain 4 $TI$ cases of 2%, 5%, 10%, and 15%.

METHODOLOGY

For this study, the two-bladed, NREL Phase VI wind turbine is chosen since experimental database from the NREL for the UAE Phase VI are available (Hand et al., 2001). This full-scale reference wind turbine has been used extensively in several research studies. The following
subsections briefly discuss the different methods used for load predictions of the NREL Phase VI wind turbine.

**NREL/NASA Ames Wind Tunnel Measurements**

The two-bladed upwind wind turbine was tested in a 24.4 m × 36.6 m wind tunnel equipped with 15 bladed fans at the NASA Ames under different inflow conditions, with wind velocities ranging from 5 to 25 m/s with step of 1 m/s (See Figure 1(a)). The 19.8 kW NREL Phase VI turbine consists of two linearly tapered, non-linearly twisted blades with radius $R = 5.029$ m. The single NREL S809 airfoil was chosen to form the cross-section profile of the NREL Phase VI rotor blades. For sequence-S setup, the blade tip pitch angle was set to 3°, the rotational speed to 72 rpm, the yaw angle to 0° and the cone angle to 0°. A typical digital photograph of the turbine wake taken with a digital still camera in the NASA Ames research center is shown in Figure 1(b). More details about the NREL Phase VI rotor geometry and its technical specifications are available in (Hand *et al.*, 2001).

![Figure 1](a) NREL Phase VI wind turbine in NASA Ames research center’s wind tunnel. (b) A typical photo of wake flow visualization of the operating turbine in the wind tunnel. The images are taken from Hand *et al.* (2001).

**CFD Model**

For validation purposes, time-accurate CFD simulations in 180° (1/2) model are conducted to assess the ability of the LLFWV model to predict loads on the NREL Phase VI wind turbine. The commercial software Simcenter STAR-CCM+ is employed for the 3D CFD simulations in this study. Turbulence closure of the URANS is provided by the eddy-viscosity, two-equation Shear Stress Transport (SST) $k-\omega$ model due to its capability in predicting fluid flows experiencing adverse pressure gradients. Figure 2 illustrates the computational grid used for the 3D CFD simulations. By making use of the commercial grid generator Pointwise®, a structured grid of O-type is generated for the blade with an automated script developed at Institute of Aerodynamic and Gas Dynamics (IAG) of University of Stuttgart. The grid of the blade consists of 256×128×200 cells in circumferential, normal and radial directions, respectively. This ends up to $\approx 8.8$ million cells for the NREL Phase VI rotor blade. The first cell layer on the blade wall is set to meet our $y^+$ criteria ($y^+ < 1$) to avoid the use of wall models. The boundary layer of the blade is discretized by 32 cells around the airfoil to directly resolve the viscous sub-layer. The overset “Chimera” method is adopted to avoid the complex grid construction. The simulations were performed using the time step size of $\Delta t = 2.32 \times 10^{-3}$ s, which is equivalent to $\Delta \theta = 1^\circ$ rotor revolution. The nacelle as well as the tower are not modelled in these simulations for simplification.
Figure 2: Computational grid of the NREL Phase VI blade \((R = 5.029 \, \text{m})\): (a) Surface grid and (b) Detailed cross-section grid at \(r/R=0.95\).

Lifting Line Free–Wake Vortex Model

The lifting line free-vortex wake (LLFVW) calculations are conducted for the NREL Phase VI wind turbine using the simulation tool Qblade (Marten et al., 2010; Marten et al., 2013). The LLFVW model is based on the lifting line theory (LLT) as developed by van Garrel (Van Garrel, 2003). Relying on potential “inviscid” flow assumption, rotor blade is divided into panels represented by ring of bound vortices. The bound vortices are concentrated to the location of the quarter chord and their summation forms a lifting line. The Kutta-Joukowski theorem and the airfoil polar data calculated with XFOIL at each spanwise station are used to calculate the circulation of the bound vortices:

\[
\Gamma = \frac{F_l}{U_{\text{total}}} \cdot \rho = C_l(a) \frac{1}{2} |U_{\text{total}}| \cdot c
\]  

(1)

Where \(\Gamma\) is the filament circulation, \(F_l\) is the lifting force per unit length, \(U_{\text{total}}\) is the total velocity, \(\rho\) is the density, \(C_l\) is the lifting coefficient, \(a\) is the angle of attack and \(c\) is the chord. The total velocity \((U_{\text{total}})\) is the summation of the inflow velocity \((U_{\infty})\), the velocity due to blade motion \((U_{\text{motion}})\) and the induced velocity from the wake \((U_{\Gamma})\):

\[
U_{\text{total}} = U_{\infty} + U_{\text{motion}} + U_{\Gamma}
\]  

(2)

The induced velocity \((U_{\Gamma})\) of all wake filaments is calculated by making use of the Biot-Savart law at each blade panel:

\[
U_{\Gamma}(x_p) = -\frac{1}{4\pi} \frac{1}{|x_p-x|^3} \int \Gamma \frac{(x_p-x) \times \Delta l}{|x_p-x|^3} dx
\]  

(3)

Where \(x_p\) is the position of the point where the Biot-Savart law is applied, (i.e., the blade panel), \(x\) is the position of the wake vortices and \(\Delta l\) is the vectorized length.

An iterative procedure is derived for equations (1 - 3) to solve for the circulation at each blade spanwise station. According to Kelvin’s circulation theorem, the circulation is shed to the wake
resulting in trailing and shed vortices at each time step. The trailing vortices arise from the variations in spanwise circulation and the shed vortices from the shed circulation. By applying Biot-Savart law (equation (3)) to the wake vortices, the induced velocity ($U_i$) of each vortex filament can be determined. The effect of flow retardation downstream the rotor can be modeled by summing the effect of all vortex filaments lie in the wake. By calculating the velocity at all wake points, the free convection of the wake can be predicted. Figure 3 illustrates the wake rollup of the NREL Phase VI rotor blade during the LLFVW simulation. It includes the theory discussed in this section.

![Diagram](image)

**Figure 3:** Illustration of the LLFVW method on the NREL Phase VI rotor blade.

The rotor blade is discretized with 30 sinusoidally distributed panels. The azimuthal discretization is set to 10 deg. which is equivalent to a time step size of 0.0232 s. The initial vortex core size is set to 0.1819 m and the turbulent vortex viscosity coefficient (Xu and Ryckaert, 1990) is set to 40. The LLFVW simulation is calculated for 60 full rotor revolutions, whereas the wake is truncated after 15 full rotor revolutions, resulting in a maximum of ~70,000 vortex filaments at a time. It should be emphasized that the 2D polar are used without any 3D correction. The 3D correction models are not included in the present study. On a standard PC (2.30 GHz Intel Core i7-10510U, 12.0 GB RAM) the wall clock-time required for each simulation was 18 hours, which reduces the runtime of the LLFVW computation by more than 14 orders of magnitude over that of the URANS-CFD simulation.

**CODE VALIDATION**

To assess the accuracy of the LLFVW code in predicting wake characteristics of the NREL Phase VI rotor, a validation study should be conducted by comparing our results against the documented data in the Unsteady Aerodynamics Experiment (UAE) NREL Phase VI experiment Hand et al. (2001). For this validation study, wind speeds of 5, 7, 10, 13, 5, 20 and 25 m/s from the UAE NREL Phase VI experiment (sequence S) were considered, and the results for the power curve ($P$) and thrust force ($F_{th}$) are presented in Figure 4. As shown in Figure 4(a), the LLFW method of Qblade showed an over-prediction in the power ($P$) at wind speeds of 10, 13 and 15 m/s, which means that prediction accuracy of the output power decreased when the blade exposed to partly separated flows. The same behavior is noticed for the power results calculated by CFD method. However, the LLFVW method predicts the deep stall much better than the CFD method and overall shows very good agreement for both high and low wind speeds. Figure 4(b) shows that LLFVW model significantly under predict thrust ($F_{th}$) especially at high wind speeds while a very good agreement is achieved in case of the calculated thrust by CFD techniques throughout the whole operational range.
RESULTS AND DISCUSSIONS

In the following, the analysis of the effect of the ambient turbulence on the wake characteristics of the NREL Phase VI rotor is presented. A correlated, three-dimensional, turbulent windfield is generated with the Veers Sandia method (Veers, 1988). Typically, four different cases with turbulence intensity ($T_I$) ranging from 2% to 15% are modeled through LLFVW simulations with Qblade software. The turbulent windfield is imposed to the LLFVW simulations as a set of planes with a velocity distribution, whereas each plane represents the windfield at certain point in certain time. Then, the turbulent windfield is interpolated in between its spatial and temporal points. The turbulent windfield is allowed to be run for about $t = 50$ s with time step size of $\Delta t = 0.0232$ s. In all cases, the incoming wind speed ($U_\infty$) is set to be 7 m/s at rotational speed of $\Omega = 72$ rpm. In order to isolate the turbulent inflow conditions, the ground effects and the tower shadow effects are not included in the LLFVW simulations. The time evolution of power fluctuations (Figure 5(a)) and thrust fluctuations (Figure 5(b)) of the NREL Phase VI rotor for each turbulence level ($T_I = 2\%$, 5\%, 10\%, and 15\%) is illustrated. As the $T_I$ increases, the fluctuation amplitude increases gradually, as shown in Figure 5(a). For high turbulence levels, the power and thrust fluctuations are much stronger. This is closely related to the tip-vortex shedding and wake mixing therein. In the wake area, the strength of vortices and turbulent mixing enhance with the increase of $T_I$, as shown in Figure 7 and 9. Maximum amplitude occurs in the case $T_I = 15\%$, which is $3 \text{ kW}$ and $300 \text{ N}$ for power and thrust, respectively. In contrast, for $T_I = 2\%$, the time response of power and thrust is relatively stable. Power and thrust fluctuations in case of $T_I = 5\%$ can also be observed, but they are really slight in comparison with higher turbulence intensity (i.e., $T_I = 10\%$, and 15\%).
Figure 5: Time evolution of (a) power and (b) thrust fluctuations for different turbulence levels.
The Fast Fourier Transform (FFT) is used to analyze the frequency domain of power and thrust fluctuations of the NREL Phase VI rotor. Figure 6 shows the power spectrum of power and thrust fluctuations for each turbulence level $TI = 2\%, 5\%, 10\%$, and $15\%$. According to the results of power spectrum density (PSD), the dominant frequencies of $TI = 2\%, 5\%, 10\%$, and $15\%$ are 2.41 Hz, 2.51 Hz, 2.55 Hz, and 2.36 Hz, respectively. In this work, the resolved scales of spatial spectrum are asymptotic to $f^{-5/3}$ scaling, which can be deduced according to the Kolmogorov's theory of turbulence. These results reveal that present LLFVW simulation can capture the isotropy turbulence spectrum within the inertial subrange.
Figure 6: Power spectrum of (a) power and (b) thrust fluctuations for different turbulence levels.

Figure 7 shows a visualization of the wake structure behind the NREL Phase VI rotor at $U_\infty = 7$ m/s immersed in ambient turbulent inflow with $TI = 2\%$, 5\%, 10\% and 15\%. The $\lambda_2$-criterion are adopted to create the vorticity iso-contours which are colored by the magnitude of the total velocity ($U_{\text{total}}$). It can be observed that cases with high $TI$ showed earlier breakdown of the coherent wake structure, so the wake recovers more rapidly. As depicted in Figure 7, the enhancement of the wake velocity fluctuations increases by increasing the turbulence intensity ($TI$). This leads to more turbulent mixing in the wake area, changing the magnitude and the direction of the incoming wind for the downstream wind turbines in arrays. A big care should be paid to the fluctuations responsible for the severe vibration that acts on the downstream turbines, putting their structures at risk.

The velocity within the wake area is often expressed in terms of a non-dimensional velocity deficit, which is function of the velocity in the wake ($U_w$) and the incoming wind speed ($U_\infty$). The streamwise velocity deficit normalized by the incoming wind speed ($1-U_x/U_\infty$) at downstream location of 25 m ($x/R = 5$) for different turbulence levels is presented in Figure 8. Velocity vectors are projected onto the extracted $y$-$z$ planes. It can be seen that cases of high ambient turbulence level showed low wake velocity deficit. Comparing the velocity deficit for the 4 $TI$ cases indicated that increasing the turbulence intensity ($TI$) speeds up the wake recovery. This means that downstream turbines in a wind farm have a faster wake recovery as compared to wind turbines located in the first row. Accordingly, the downstream wind turbines could produce more output power due to the added ambient turbulence from the upstream wind turbines. In that case, a compromise could be made between the amount of power produced and the load fluctuations by means of a suitable active control system.
Figure 7: Wake structure from LLFVW simulations visualized by $\lambda_2$-criterion of -0.1 s$^{-2}$, colored by total velocity ($U_{total}$). Variables $x$, $y$ and $z$ represent local coordinates in the rotating reference frame.

Figure 8: Contours of streamwise velocity deficit normalized by the incoming wind speed ($1 - U_x/U_\infty$) at downstream location of 25 m ($x/R = 5$).

A snapshot of the streamwise velocity ($U_x$) field downstream the NREL Phase VI rotor along the wake is depicted in Figure 9 for all 4 $TI$ cases. As the higher turbulent flow past the rotor, the tip-
vortices are more broken with more unevenly distributed streamwise velocity ($U_x$) particularly at the rear part of the wake area. In-plane velocity vectors at different downstream locations, namely $x/R = -2, 4, 6, 10, 14$ and $20$ are overlaid in Figure 9. It is clear from the velocity vectors distributed along the wake that the higher the turbulence intensity ($TI$), the faster is the recovery of the boundary layer towards its basic shape.

![Figure 9: Contours of streamwise velocity ($U_x$) downstream the rotor exposed to different ambient turbulence levels in the $y/R = 0$ plane.](image)

**CONCLUSIONS**

The wake characteristics of the reference NREL Phase VI wind turbine has been investigated under turbulence inflow conditions using an engineering model, namely the Lifting Line Free-Vortex Wake (LLFVW) approach. A wide range of turbulence levels has been considered, varying the turbulence intensity from $TI = 2\%$ up to $TI = 15\%$. Additional URANS CFD simulations have been performed using Simcenter STAR-CCM+ code to assess the accuracy of the LLFVW model of Qblade, where a very good agreement is found for the whole operational range. The time evolution and the power spectra for the NREL Phase VI rotor have been illustrated for different values of turbulence intensity ($TI$). The results revealed that the fluctuation amplitude increases as the $TI$ increases. The resolved scales of spatial spectrum of the power and thrust fluctuations are asymptotic to $f^{-5/3}$. In this work, it is indicated that the tip-vortices become stronger and the turbulent mixing is enhanced when the rotor exposed to high turbulence intensity. Cases with high $TI$ exhibited an earlier breakdown of the coherent wake structure leading to a faster wake recovery. On the one hand, the rapid recovery of velocity deficits in a wind turbine wake may benefit the downstream turbines to
produce more output power, on the other hand the stronger fluctuations of the wake velocity change significantly the magnitude and direction of the approaching wind to the downstream turbines. A trade-off between these two factors should be considered in designing a wind farm to avoid excessive stresses and vibrations that may act on the downstream wind turbines at high TI.

REFERENCES


