Wind Tunnel Investigation of the Near-wake Flow Dynamics of a Horizontal Axis Wind Turbine

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Abstract. Experiments conducted in a large wind tunnel set-up investigate the 3D flow dynamics within the near-wake region of a horizontal axis wind turbine. Particle Image Velocimetry (PIV) measurements quantify the mean and turbulent components of the flow field. Measurements are performed in multiple adjacent horizontal planes in order to cover the area behind the rotor in a large radial interval, at several locations downstream of the rotor. The measurements were phase-locked in order to facilitate the reconstruction of the three-dimensional flow field. The mean velocity and turbulence characteristics clearly correlate with the near-wake vortex dynamics and in particular with the helical structure of the flow, formed immediately behind the turbine rotor. Due to the tip and root vortices, the mean and turbulent characteristics of the flow are highly dependent on the azimuth angle in regions close to the rotor and close to the blade tip and root. Further from the rotor, the characteristics of the flow become phase independent. This can be attributed to the breakdown of the vortical structure of the flow, resulting from the turbulent diffusion. In general, the highest levels of turbulence are observed in shear layer around the tip of the blades, which decrease rapidly downstream. The shear zone grows in the radial direction as the wake moves axially, resulting in velocity recovery toward the centre of the rotor due to momentum transport.

1. Introduction

The rotating wake of a Horizontal Axis Wind Turbine (HAWT) can be divided into two separate regions: near wake and far wake. The near wake region, which is the subject of the present study, is approximately one to three diameters downstream of the turbine [1]. Further downstream the far wake region presents a flow structure that can be considered independent from the blade geometry and therefore independent of the Reynolds number [1]. The near wake flow field, however, is influenced by the rotor angular velocity and the geometry of the blade.

A number of experimental investigations have been previously carried out to quantify the flow field within the wake region including field tests and wind tunnel experiments. Wind tunnel measurements have the advantage of repeatability with experiments being performed under controlled test conditions.

The overall drawback of wind tunnel experiments is that they are mostly conducted at relatively low Reynolds numbers compared to the full scale phenomena which consequently results in scaling effects [1-2]. Given the high uncertainties in full scale measurements and the scaling effects associated with small experimental set-ups, experiments in large wind tunnel facilities are critically important. To
date only two such experiments have been conducted to measure the wake flow region. National Renewable Energy Laboratories (NREL) conducted experiments at the NASA-Ames wind tunnel [3], and the MEXICO project experiments were conducted at the German-Dutch wind tunnel [4]. The rotor diameter of generic wind turbines used in both cases was larger than 4m. The NREL measurements, performed on a real two bladed rotor, were mainly restricted to determine blade aerodynamic load and blade pressure distribution with no emphasis on the wake measurements. The MEXICO measurements were considered as a complementary experiment for the NREL in the sense that a three bladed rotor was used. The MEXICO project included measurements of blade loading as well as the pressure distribution over the blade. In addition, near wake measurements were carried out using PIV technique in order to quantify the flow characteristics in the near-wake region. The results of the MEXICO project have been only partially analyzed and are mostly presented in the form of mean velocity profiles with no insight yet in the turbulence characteristics [5]. Therefore, a comprehensive investigation of rotational wakes of full scale models including investigation of the turbulent behavior of the flow in the near-wake region is still needed.

Herein we employ phase-locked Particle Image Velocimetry (PIV) technique in a large wind tunnel set-up to measure both mean and turbulent flow fields in horizontal planes at two downstream locations behind a 2.2 meter diameter horizontal axis wind turbine in the near-wake region. The data acquired provides useful insight into the physics of the flow in a rotating wake, in particular the downstream convection and dissipation of the tip vortex structure.

2. Experimental setup

The experiments were conducted in the low-speed test section of the closed circuit Boundary Layer Wind Tunnel II (BLWTL II) at the University of Western Ontario. This section is 4 m high, 5 m wide and 52 m in length. The maximum achievable wind speed in this section is 36 km h\(^{-1}\) (10 m/sec). An upwind, three-bladed small HAWT rotor of 2.2 m in diameter was used for this study. The blade airfoils are approximated by NACA 6515 and FX 63 137 for the root and tip regions, respectively. This rotor resulted in a geometric blockage ratio of 1 to 5.3. The experiments were conducted at the average wind speed of 4.1 m/sec. The turbine rotor was installed 11 meter downstream of the test section. The distance between the turbine post and lateral walls were 2.5 meter. The freestream turbulence intensity was approximately 2% at the height of the rotor hub. The tip speed ratio was 5.65 and the local chord Reynolds number was 93,000 at 0.6R.

The PIV system consists of a YAG laser and a CCD camera with the resolution of 1600×1200 pixels. The camera was connected to a PC equipped with a frame grabber acquiring 8 bit images at a rate of 30 Hz. Except the camera, all the equipment was kept outside the tunnel in order to avoid any disturbances within the flow. The PIV measurements were performed in horizontal planes, behind the rotor at a vertical position corresponding to the center of the rotor (170 cm from the tunnel floor) were both the mean and the turbulence characteristics of the inflow were quasi-uniform. Measurements were performed at two downstream locations (X=1.02R and X=2.02R), where X was measured from the rotor.

A phase-locking technique was employed using a photo emitter/detector (E/D) device. The device was mounted at a fixed location on the top of the turbine nacelle immediately behind the rotor. A small mirror was installed at the back of one of the blades. Every time the corresponding blade passed the E/D device, it provided a trigger signal for the PIV system (laser and camera) to acquire PIV images. Measurements at different blade phase angle were made by defining an appropriate time delay between the trigger signal from the device and the signal provided by the synchronizer to trigger the laser and camera. Eight angular positions of the blade between 0 and 105 degrees with an increment of 15 degrees were covered at each measurement window for the two axial locations.

The region of interest for the flow measurements at each downstream location, X=1.02R and X=2.02R, was 77 cm × 15.5 cm and 88 cm × 15.5 cm, respectively. Due to camera resolution and spatial restrictions, a row of four radially distributed measurement windows (tiles) were used to cover the region of interest (see figure 1). The overlap between the windows was set equal to 10% of the
radial length of each window to acquire continuous flow field at boundaries of the two adjacent PIV measurement planes. A total of 4000 images (2000 velocity fields) were acquired for each run at each measurement window location for a certain angular position of the blade.

Figure 1. Schematic of the measurement fields behind the turbine rotor.

3. The mean field
The axial and radial velocity components are extracted in horizontal planes that cover the radial extent of 0.4<r/R<1.1 and 0.4<r/R<1.3 for two axial intervals for -1.1<X/R<-0.96 and -2.1<X/R<-1.96, respectively. The mean velocity was obtained at each grid point by time averaging. A technique similar to the one used by Dobrev et al. [6] and Xiao et al. [7] was applied to patch the windows.

Figures 2(a) and (b) present radial profiles of the normalized axial velocity deficit for eight different phase angles at the two axial positions, X=R and X=2R downstream of the rotor plane, respectively. It can be seen that the velocity magnitude increases closer to the blade tip; however, the complete recovery of the axial velocity component only occurs at r/R>1, which is consistent with Vermeulen [8] and Vermeer et al. [1]. This shows the expansion of the rotating wake. It can be seen that in accordance with previous investigations [9-11], at X=R, the maximum axial velocity deficit (-0.7~0.75) occurs in the range 0.55<r/R<0.9. This velocity deficit is directly related to the power extraction from the wind and hence it can be concluded that the maximum power extraction from the wind occurs in the mid-to-tip section of the blade. At X=2R downstream of the rotor, the maximum velocity deficit occurs at 0.4<r/R<0.8 closer to the center of the wake compared to that at the X=R position. This is due to the entrainment of the outer fluid towards the central wake region which results in the further wake development [9,11]. As the wake develops downstream, it expands in the crosswind direction and the wake expansion can be determined by tracing the radial location at which the axial velocity reaches the free stream wind speed. While this happens at r/R~1.1 for X=R, it shifts to r/R~1.2 for X=2R. The shear zone is the zone in which maximum velocity gradients occur. The approximate radial position of this location is displayed in figure 2 by an arrow. It can be observed that at X=R, the shear zone is located at 0.85<r/R<1.1, while it expands to 0.75<r/R<1.2 further downstream at X=2R.

In terms of phase dependency, it can be observed that at X=R, the axial velocity deficit is phase dependent for r/R>0.85 and almost independent of phase for r/R<0.85 (see figure 2(a)), which is in
agreement with observations by Schepers et al. [5]. Further downstream, at X=2R, the axial velocity is independent of the phase angle at any radial location. Close to the rotor, at X=R, the flow structure is dominated by the tip vortex dynamics while further downstream, at X=2R, the tip vortex structure starts to dissipate.

\[ \frac{\partial U}{\partial r} \approx 0 \]

**Figure 2.** Radial profiles of streamwise velocity deficit for eight phase angles of the blade at, a) X=R, b) X=2R. The vertical arrow presents the approximate radial location of the maximum velocity gradient.

Similar to the behavior of the axial velocity, the radial velocity (not shown here) is found to be strongly dependent on the phase angle near the rotor at X=R, while it becomes independent of the phase angle further downstream at X=2R. The phase dependency at X=R is very pronounced for r/R >0.85 which is likely due to the passage of the tip vortex in the axial direction. For 0.6 <r/R< 0.85, the radial velocity magnitude is very small and independent of the phase angle. For r/R<0.6, the velocity magnitude increases with small variation due to root vortices.
4. The turbulent field

Figure 3(a) displays the radial profiles of the normalized $u_{rms}$ at $X=R$ for different phase angles. As expected, the turbulence intensity varies with the phase angle at $r/R>0.85$. The largest value of the streamwise turbulent intensity (0.43) at $r=1.05R$, occurs at 15 degrees phase angle which corresponds to the location of the core of the tip vortex exactly at $X=R$. The location of the tip vortex core was estimated using simple wake convection velocity approximation combined with the rotational velocity of the rotor. The streamwise turbulent intensity decreases at higher phase angles since the vortex moves both in the axial and circumferential directions, i.e. while moving downstream, it also moves out of the measurement plane. Similar to the behavior of the mean component of velocity, the turbulence intensity is almost independent of the phase angle at $0.6 < r/R < 0.85$; However, at $r/R < 0.6$, it changes with respect to the phase angle due to the root vortices. Although $u_{rms}$ values are increasing in the root region (for $r/R < 0.6$) they are still lower compared to the turbulence intensity attributed to the tip vortex.

![Figure 3(a)](image)

**Figure 3.** Radial profiles of normalized $u_{rms}$ at a) $X=R$ b) $X=2R$ for different phase angles of the blade.
Figure 4. Radial profiles of normalized a) $v_{rms}$, b) Reynolds shear stress $\langle u'v' \rangle$, c) TKE at $X=R$ downstream the turbine for eight different phase angles of the blade.
Figure 3(b) shows the radial profiles of the normalized $u_{rms}$ at $X=2R$ downstream of the turbine. Similar to the mean velocity field, the results show that at $X=2R$, the streamwise turbulence intensity is independent of the phase angle. The magnitude of $u_{rms}$ is also reduced at larger distances from the rotor, which is consistent with Vermeer et al. [1]. Nevertheless, large values of streamwise turbulence intensity are found in the shear layer, $r/R>0.75$, with a maximum value of 0.18 at $r=1.05R$. Comparison between figure 3(a) and figure 3(b) indicates that the shear layer shifts from $r/R>0.85$ at $X=R$ to $r/R>0.75$ at $X=2R$, while the turbulence intensity is still larger than 10% within the layer. This confirms the development of the shear layer in the axial direction resulting in the momentum transport towards the center of the rotor. It can be concluded that as the flow convects downstream in the wake, the turbulence acts as the mixing mechanism, transporting the momentum toward the centre of the wake while its magnitude decreases. The normalized radial profiles of the rms radial turbulent velocity ($v_{rms}$), Reynolds stress ($<u'v'>$) and Turbulent Kinetic Energy (TKE) at $X=R$ for different phase angles are displayed in figure 4. The radial turbulent intensity (figure 4(a)) shows general trends similar to the streamwise turbulent intensity i.e. the peak magnitudes in the vicinity of the blade tip, which is due to the presence of the tip vortex. It is also observed that at a given phase angle, the radial turbulent intensity magnitudes are slightly lower than the streamwise turbulent intensity. The results also show that the maximum radial turbulent intensity occurs at phase angles range 15-30°, which is relatively similar to that of the streamwise turbulent intensity (figure 3(a)).

The Reynolds shear stress $<u'v'>$ and (TKE) also show similar trends as expected. The peak magnitudes of both occur at the phase angle of 15° with the magnitude of 0.045 and 0.26, respectively (see figure 4(b) and (c)). For $\Theta<90^\circ$, the magnitudes of all turbulent properties decrease as the phase angle increase beyond the peak magnitude position. These magnitudes start increasing again for $\Theta\geq90^\circ$ which corresponds to the tip vortex generated from the next blade. Figure 4(b) shows that for $0.45<r/R<0.9$, the Reynolds shear stress becomes almost zero but shows a slight increase for $r/R<0.45$. It should be noted that the normal and shear components of Reynolds stress, are the main sources of the production of the TKE. In the present experiments, the results corresponding to the Reynolds Stresses indicate that the turbulence production occurs mostly in the tip region of the blade ($r/R>0.9$) within the near-wake region.

5. Conclusions

The flow structure within the near-wake region of a horizontal axis wind turbine is experimentally studied in a large wind tunnel set-up. Using PIV technique, the mean and turbulent flow components are characterized. The measurements are phase-locked in order to extract phase information and compute phase-averaged characteristics.

The mean velocity field shows that the maximum power extraction from the wind by the turbine, as indicated by the maximum axial velocity deficit, occurs in the radial interval of $0.7<r/R<0.9$. The axial velocity reaches its maximum value at $r/R>1$ (a radial position larger than the physical radius of the turbine), which indicates the expansion of the wake downstream of the rotor. Close to the rotor, in the very near wake influenced by the rotor angular velocity and the geometry of the blade (at $X=R$) the mean velocity components and turbulent characteristics vary considerably with respect to the blade phase angle, particularly in the regions affected by the tip and root vortices (i.e. $r/R>0.9$ and $r/R<0.6$, respectively). The results indicate that the maximum values of turbulent components occur in the annular high-shear zone, located at $r/R>0.85$, which represents the region affected by the tip vortex. Farther downstream, (at $X=2R$) the wake region starts showing a flow structure becoming independent from the blade tip and root regions. Here, while the highest values of turbulence characteristics still occur within the shear layer, the magnitudes of turbulent components reduce rapidly. In addition, at $X=2R$ downstream of the rotor, the mean and turbulent velocity components become independent of the phase angle of the blade. This behavior can be regarded as an evidence that the helical vortex structure of the wake breaks down because of the turbulent diffusion.
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