Wind-tunnel study of the wake behind a vertical axis wind turbine in a boundary layer flow using stereoscopic particle image velocimetry

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Abstract. Stereo particle image velocimetry is used in a wind-tunnel to study boundary layer effects in the wake behind a vertical axis wind turbine. The turbine is a three-bladed giromill with a solidity of 1.18. The wake is studied for a tip speed ratio of 2 and an average chord Reynolds number of $1.6 \times 10^4$. The velocity deficit and turbulence levels in the horizontal plane are observed to be strongly asymmetrical with two strong peaks corresponding to the two halves of the rotor where blades move either towards the oncoming flow or away from it. The stronger peak is measured behind the blades moving upstream, however this region also benefits from a greater rate of re-energization. Due to the incoming boundary layer profile, momentum is also entrained downwards into the wake from above and aids with the recovery of the core of the wake.

1. Introduction
In response to the growing need for renewable energy, vertical axis wind turbines are enjoying a period of renewed interest. Horizontal axis wind turbines (HAWTs) have benefited from a larger volume of research than vertical axis wind turbines (VAWTs). Nonetheless, VAWTs offer some advantages over HAWTs which merit further investigation of the technology. For instance, the generator of a VAWT is placed at ground level, as opposed to in the nacelle of a HAWT which is placed at the rotor hub-height. This reduces the loads on the structure, thereby diminishing capital and maintenance costs, and simplifying the construction of the turbine making it an attractive option for off-shore wind arrays [1]. These turbines are also insensitive to the direction of the incoming wind and therefore require no yaw equipment [2]. The simpler design of the VAWT has also been shown to reduce the noise produced which is an important commercial advantage [3].

Due to the fact that a VAWT rotates about an axis perpendicular to the incoming wind, the blades are subjected to a flow with continuously changing magnitude and direction. This behavior introduces some phenomena unique to VAWTs: the thrust and torque forces produced by the rotor oscillate as a function of the azimuthal position of the blades, the downstream half of the rotor will be subjected to the wake of the upstream half, and the high angles of attack encountered when the blade is perpendicular to the incoming flow can lead to dynamic stall conditions and induce vortex shedding. These effects have been shown not only to alter the flow downstream of the turbine but also to influence its performance. Many studies have been...
conducted using a variety of numerical and experimental techniques to examine this unsteady behavior. [4–7]

Possibly the first wake measurement behind a VAWT was performed by Muraca and Guillote (1976) [8], who profiled the wake velocity upstream and downstream of the turbine at different elevations. Bergeles et al. (1988) [9] carried out a more comprehensive study by using two-component hot-wire measurements to observe the velocity vectors and turbulence intensity in the wake at various downstream locations and tip speed ratios. They reported an easily identifiable wake, characterized by an abrupt change in velocity between the wake and unperturbed flow, and high turbulence intensities near the edges of the wake. They also reported a deflection of the wake in the direction of rotation and generally stronger wake characteristics behind the blades moving upwind at low tip speed ratios. More recently, Battisti et al. (2011) [10] performed a similar investigation using hot-wire probes over a vertical plane behind the VAWT. Battisti reported behavior similar to what has been previously observed, but by phase-locking the measurements, they related some of the asymmetrical characteristics of the wake to the unsteady behavior of the VAWT. The present study will aim to get a better picture of the wake and its re-energization by increasing the spatial resolution of measurements and reporting three-component statistics using PIV techniques. A key difference between the current study and those discussed in the literature, however, is that the present examination is conducted in a boundary layer flow, whereas previously they had been performed exclusively in uniform flows.

If VAWTs are to be deployed in an array, whether onshore or offshore, it is vital to understand and characterize the behavior of their wakes. Turbine-wake interaction in arrays dramatically reduces the effectiveness of the array, and increases the need for maintenance due to vibrational loading [11]. The atmospheric boundary layer plays an important role in wake flow, altering the rate of re-energization and entrainment of momentum. Many studies have been carried out in order to understand the interaction between the boundary layer and the wake of a HAWT. Chamorro and Porté-Agel (2009) [12] carried out a comprehensive examination of the wake behind a HAWT in boundary layer flow using hot wire measurements. Their findings indicate that turbulent mixing effects are stronger around the upper edges of HAWT wakes, where velocity gradients are steeper, and more momentum is entrained downwards from the faster moving winds of the unperturbed flow. At the time of writing there is little to no literature regarding a similar characterization of VAWT wakes in boundary layer flow.

The present study intends to analyze the interaction between the turbine and the boundary layer flow and to understand how it influences the structure of the wake. Stereoscopic particle image velocimetry (S-PIV) is deployed in the WIRE wind tunnel at the EPFL to observe the time-averaged wake behind a scaled-down model VAWT immersed in a boundary layer flow. The velocity deficit, turbulence kinetic energy (TKE), and the crosswind and vertical turbulent fluxes of momentum are quantified to characterize the wake and the entrainment of momentum.

2. Experimental setup

2.1. Model vertical axis wind turbine

The turbine used in this experiment is a three-bladed giromill, shown in figure 1. The blade profile is a 5% thick plate with a 5% circular arc camber, shown in figure 2. This shape has been shown to have better lift-to-drag ratios and delayed stall at low Reynolds numbers compared to the more conventional NACA profiles used at larger scales [13–15]. The turbine is designed with a blade span of 15.24 cm (6 in) in order to maintain a realistic scale relative to the height of boundary layer, which will be quantified in the following section. A 12 W Maxon EC 45 motor is used in order to maintain a tip speed ratio of 2. The geometry of the turbine is summarized in table 1.
Figure 1. A graphical representation of the model turbine used in the experiment.  
Figure 2. Thin plate with 5% circular arc camber.

Table 1. List of important rotor and airfoil design parameters

| Parameter                   | Symbol | Value          |
|-----------------------------|--------|----------------|
| Blade chord                 | C      | 5 cm           |
| Rotor radius                | R      | 7.62 cm        |
| Rotor height                | H      | 15.24 cm       |
| Midspan height              | H_m   | 12.7 cm        |
| Number of blades            | N      | 3              |
| Rotor solidity              | σ = NC/R | 1.18          |
| Velocity at midspan         | U_∞    | 4 ms^{-1}      |
| Rotational velocity         | ω      | 1,000 RPM      |
| Tip speed ratio             | λ = ωR/U_∞ | 2            |
| Average chord Reynolds number| Re = ρλU_∞C/µ | 1.60 × 10^4  |

2.2. Wind tunnel

The EPFL boundary layer wind tunnel is a closed-looped facility at the WIRE Laboratory. The test section is 28 m long with a 2.57 m × 2 m cross section. The facility is equipped with a 130 kW fan. Ahead of the test section the flow passes through a contraction with a 5:1 area ratio. The turbulence intensity in the center of the wind tunnel, or freestream, is approximately 0.5%. A turbulent boundary layer develops naturally over the long test section. This experiment is performed within the boundary layer approximately 22 m from the inlet of the test section. The boundary layer velocity and turbulence intensity profiles are shown in figure 3. The boundary layer has a total height of roughly 40 cm surface roughness, z_0, of 2.1612 × 10^{-2} mm, and friction velocity, u*, of 0.1319 ms^{-1}. The power density spectra of the incoming flow is plotted for varying heights in figure 4. The steeper slope of spectra at large wave-numbers is due to the greater dissipation of energy near the wind tunnel floor. The incoming wind at the midspan height of
Figure 3. Normalized mean velocity (left) and turbulence intensity of the incoming wind as a function of distance from the wind tunnel floor, $z$. $U_\infty$ denotes the wind velocity of the incoming wind at the midspan height. The dashed line represents the midspan height.

Figure 4. Normalized power density spectra of the incoming wind at various heights with respect to the wind tunnel floor.

the turbine, has a speed, $U_\infty$, of 4.0 ms$^{-1}$, and a turbulence intensity, $I$, of 7.71%.

2.3. Stereo-PIV configuration

The flow was continuously seeded with olive oil particles on the order of one micrometer in diameter. The particles were illuminated by a thin horizontal laser sheet at the equatorial height of the rotor. The laser sheet was produced by a dual head 435 mJ ND:YAG laser. A high-resolution stereoscopic PIV system developed by LaVision was used to measure the three velocity components in the illuminated plane. The imaging system comprised two 29MP 12-bit CCD cameras (6600 × 440 pixels) each with a 105 mm lens installed on scheimpflug adapters to improve the focus quality over the field-of-view (FOV). The imaging system was installed above the wind tunnel, in a forward-backward configuration, such that the cameras are oriented
Figure 5. Schematic representation of the PIV set-up as seen from downwind of the turbine.

perpendicular to the direction of flow. A schematic illustration of the set-up is shown in figure 5.

This allows the FOV to approach the back edge of the rotor. Due to the large distance between the measurement plane and the camera, as well as the low photo-sensitivity of the CCD array, the image captured is dimly illuminated. This is especially egregious in the case of the backwards camera, which receives mostly backscatter laser radiation. To compensate, this camera is moved so that it is directly perpendicular to the measurement plane, as in a 2D PIV configuration.

The captured image has an area of 676 mm × 451 mm, with a resolution of approximately 0.1 mm. This corresponds to 4.4 × 3.0 rotor diameters. In order to capture a larger region of the wake, two sets of measurements are taken by keeping the PIV system stationary and changing the streamwise position of the turbine. The time delay between exposures was set such that particles in the core of the wake region were displaced by roughly five pixels. Exactly 1,200 samples were acquired for each streamwise location. Images were processed using 32-pixel interrogation windows with 50% overlap.

3. Experimental results
Due to the turbulent nature of the wake, a statistical approach is adopted in this analysis. From this perspective, the wind is considered as a stochastic quantity composed of a mean and a fluctuating quantity. By convention the following notation is implemented:

$$ U = \overline{U} + u'. $$

In equation 1, $U$ represents the total velocity, $\overline{U}$ denotes the mean velocity, and $u'$ represents the fluctuating velocity. This representation is used for streamwise, crosswind, and vertical velocity, which are denoted as $U$, $V$, and $W$, respectively. The figures presented in this section illustrate the horizontal plane at the midspan of the rotor as seen from above. The rotor is centered at the origin and rotates counter-clockwise in this reference frame. Note that some figures have regions which have been cut; this is done to remove numerical inaccuracies on the edges of the image in the out-of-plane measurements.

3.1. Velocity deficit
Two clear minima can be observed in the wake velocity shown in figure 6. The profiles of
Figure 6. Contours of normalized time-averaged streamwise velocity \( (\overline{U}/U_\infty) \) of the wake in the symmetry plane behind the VAWT.

Figure 7. Crosswind profiles of normalized streamwise velocity deficit in the wake \( (1 - \overline{U}/U_\infty) \) at various downstream locations

The velocity deficit at various downstream locations, shown in figure 7, show that the wake of the blades moving upwind is significantly stronger than that of those moving downwind. This is due to the greater difference between the incoming wind speed and the tangential velocity of the blades as they move upwind. These peak regions will hereinafter be referred to as the stronger and weaker sides of the wake, respectively. The profiles also show that the wake on the stronger side tends to spread and diffuse into the unperturbed flow to a greater extent than on the weaker side. This indicates a faster recovery of the wake due to turbulent mixing related to the mechanical production of TKE, given by \(-\overline{u_iu_j}\frac{\partial \overline{u_i}}{\partial x_j}\) [16]. The mechanical production of TKE represents the contribution to the TKE produced by the wind large shears near solid objects. From this term, it is understood that the steeper velocity gradient on the stronger side of the wake is associated with higher levels of TKE in that region.

The crosswind velocity presented in figure 8 reveals motion tangential to the rear edge of the rotor. This suggests that the rotation of the turbine imparts some momentum to the wake. This may also play a role in the expansion of the wake on the stronger side into the unperturbed flow, as the crosswind momentum convects the wake turbulence outwards.
Figure 8. Contours of normalized time-averaged crosswind velocity ($\bar{V}/U_\infty$) of the wake in the symmetry plane behind the VAWT.

Figure 9. Normalized contours of turbulence kinetic energy ($e/U_{\infty}^2 = \frac{1}{2} \left( \overline{u'^2}/U_{\infty}^2 + \overline{v'^2}/U_{\infty}^2 + \overline{w'^2}/U_{\infty}^2 \right)$) in the symmetry plane in the wake of the VAWT.

Figure 10. Normalized contours of the streamwise component of turbulence intensity ($\sqrt{\overline{u'^2}}/U_{\infty}$) in the symmetry plane in the wake of the VAWT.

3.2. Wake Turbulence
Examining the turbulence kinetic energy in figure 9 reveals a highly turbulent region in the core of the wake. This core turbulence may be due to the large periodic blockage of the center of the rotor as a blade turns perpendicular to the incoming wind. By decomposing the turbulence kinetic energy into streamwise, crosswind, and vertical components of turbulence intensity shown in figures 10, 11, and 12, respectively, it is clear that the fluctuations in the core of the wake are largely due to fluctuations in vertical velocity. This result is somewhat puzzling. Typically
entrainment is strongest where the velocity gradients are greatest. However, in the core of the wake, where the vertical entrainment seems significant, the momentum is greater than in the surrounding wake. The presence of vertical entrainment is a sign of boundary layer effects. In a uniform flow, it would be expected that the momentum entrained downwards would be equivalent to that entrained upwards, and that vertical motion would not be observable at the rotor midspan.

In order to understand why vertical momentum is entrained into the core of the wake, an investigation of vertical planes is required. We can, however, provide some hypotheses; one possible explanation could be attributed to vortex shedding. In HAWTs, tip-vortices tend to shield the wake from entrainment and turbulent mixing. Similarly, it is possible that tip-vortices shed from the top and bottom of the VAWT rotor act as a barrier against vertical entrainment in the stronger and weaker sides of the wake, and instead allow entrainment only in the core of the wake. Another possibility is that the rotor exerts some crosswind force on the flow, and causes the flow to diverge in the wake. Due to continuity, this would induce out-of-plane motion to conserve mass within the wake. This idea is reinforced by the contours of crosswind velocity, which indicate motion in both the positive and negative $y$ direction in the core of the wake. These theories will require more investigation.

As mentioned previously, the mechanical production of turbulence kinetic energy is the product of the velocity gradient and turbulent flux of momentum. The turbulence flux of momentum represents the momentum transported by turbulent motion. Of particular interest are the crosswind and vertical components of turbulent flux of streamwise momentum, denoted as $u'v'$ and $u'w'$, respectively. The crosswind turbulent flux of momentum in figure 13 shows a
higher level of entrainment on the stronger side of the wake than the weaker one. It also shows some entrainment between the two sides with momentum being transferred from the weaker to the stronger side of the wake. This result is expected due to the previously observed shear on the stronger side of the wake which is associated with turbulent fluxes. The vertical turbulent flux of momentum in figure 14 shows entrainment downwards into the wake in agreement with the vertical fluctuations previously observed in figure 12. The stronger downwards entrainment of momentum is likely due to the higher momentum present above the rotor in the boundary layer. It remains unclear, however, why this momentum should be entrained directly into the core of the wake, rather than into the stronger and weaker sides of the wake where the velocity deficit is greater.

4. Summary

The wake behind a VAWT is complex and unique. In this study, the wake behind a VAWT in a turbulent boundary layer flow at low Reynolds numbers and a low tip speed ratio is examined. Two important regions of the wake can be distinguished: one behind the blades of the rotor as they move upwind, and the other as they move downwind. These two regions are termed the stronger and weaker side, respectively. The stronger side of the wake is associated with a significantly larger velocity deficit and a higher level of turbulence than the weaker side. The stronger side of the wake also tends to expand and diffuse into the unperturbed flow to a greater extent than the weaker one. This is primarily the result of the higher levels of turbulence produced by large wind shear on the stronger side, but may be due in part to the crosswind momentum imparted on the flow by the rotation of the turbine. In the core of the wake,
momentum is transferred from the weaker side of the wake to the stronger side, such that far downstream the wake becomes more symmetric.

The effect of the boundary layer in the core is also evident as it re-energizes this region with momentum entrained downwards. If instead the flow were uniform, the wake would be symmetric about the midspan plane of the rotor and no vertical momentum would be evident. The boundary layer effects may be responsible for the lower velocity deficit in the core of the wake. It remains unclear why vertical entrainment is almost exclusive to the core of the wake. Typically, entrainment should be greatest where there are larger velocity deficits, such as in the stronger and weaker sides of the wake. It is possible that blade-tip vortices at the top and bottom edges of the rotor are shielding the outer perimeter of the wake from vertical entrainment, or that aerodynamic forces produced by the rotor cause the flow to diverge in the wake and induce out-of-plane motion. This phenomenon will require investigation of the wake at different heights to be better understood.

A comprehensive understanding of the behavior of the wake and how it is influenced by the rotor geometry and operating conditions is also crucial for the successful planning and deployment of VAWT arrays and will be the target of future studies.

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