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An experimental study of the wake of a model wind turbine using phase-averaging

Pål Egil Eriksen, Per-Åge Krogstad*

Norwegian University of Science and Technology, Department of Energy and Process Engineering, Kolbjærn Hejes vei 2, 7491 Trondheim, Norway

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The wake of a model wind turbine with a rotor diameter of 0.9 m has been investigated at the design condition (tip speed ratio = 6) in a closed return wind tunnel with a cross-section of 1.8 by 2.7 m. The three bladed rotor was operated in a low turbulence intensity uniform flow. Velocity data were obtained in the wake using a four-wire hot-wire probe at 18 radial traverses from $x/D = 0.22$ to 5. All three components of the velocity vector were resolved instantaneously for a wide range of flow angles and velocity magnitudes. In addition to time averaged data, phase-averages with respect to rotor position have been used to extract periodic phase-averaged motions from the flow. In this way the downstream development of the tip vortices was extracted. The phase-averaging method allows the local phase-averaged and turbulent parts of the stresses associated with the vortical motion to be studied, as well as their production terms. The results show that the periodic phase-averaged structures initially contains most of the turbulent kinetic energy and dominate the edge of the wake. The helical vortex structures interact and pair-up, merge and finally breaks up within $x/D = 3$. From this point the phase-averaged motion is lost and the radial transport of momentum across the wake is seen to increase significantly. By $x/D = 5$ the large scale diffusion has removed the sharp edge of the wake that was characteristic in the initial region, and developed the approximately Gaussian velocity defect which is characteristic of bluff body wakes.

1. Introduction

Accurate prediction of wake losses is essential for estimating the overall production of a planned wind farm. If the wake losses are underestimated, the profit of the farm will be reduced compared to the predictions. And if the wake losses are overestimated, a potentially profitable wind farm may never be built. In a study by Walker et al. wake loss measurements from several wind farms were compared to predictions from industry standard tools. The goal of the study was to show that the uncertainty in wake loss predictions was within 25%. While the comparison confirmed the 25% estimate, it also indicated that there is significant room for improvement in the numerical models.

Development and validation of numerical models requires reliable experimental data. The NREL large scale wind tunnel tests, completed in 2000, and the following blind tests by a large number of calculation methods (Simms et al., 2001), demonstrated how important it is to have detailed data to validate predictions against. The comparison showed that there was large uncertainty in the prediction methods, which called for more refined computer codes. Discussions of some of the issues that surfaced after the tests were presented in the special issue of *Wind Energy*, which was published in 2002 (Schreck, 2002).

Since the NREL tests, significant improvements in turbine performance and wake development prediction methods have been achieved. The progress in wake predictions over a decade of research may e.g. be found by comparing the review papers by Crespo et al. (1999) from 1999 with that of Sanderse et al. (2011) published in 2011. From simple analytical wake models based on classical theories, the standard is now to solve transport equations for turbulence properties or solving the turbulent field in time and space using large eddy simulations. But even at these levels of sophistication the results obtained rely heavily on assumptions incorporated by the modeller. This was clearly demonstrated in the comparisons of wake predictions performed by Cabezón et al. (2011) using various turbulence transport equation models.

A number of investigations of the very near wake of the turbine exists, many of which aim to link the initial velocity field to the circulation shed from the rotor. E.g. Papaconstantinou and Bergeles (1988), Vermer and van Bussel (1990), Ebert and Wood (1997; 1999; 2001) and Haans et al. (2008). All of these studies used point

* Corresponding author.
E-mail address: per.a.krogstad@ntnu.no (P. Krogstad).

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measurements (hot-wire and hot-film), but none of them resolved the full velocity vector instantaneously.

Investigations of larger sections of the near wake and beyond into the transition region also exist. Examples of such investigation performed with cross-wires are the work of Talmon, Medici and Alfredsson (2005) and Chamorro and Porté-Agel (2009). Talmon (1985) used a rotor with a diameter of 0.36 m and investigated the wake in both uniform inflow and a boundary layer down to $x/D = 9.6$. Medici and Alfredsson (2005) investigated the wake of a small rotor with a diameter $D = 0.18$ meters down to $x/D = 9$ with and without yaw. All three velocity components were obtained by rotating the cross-wire probe. Chamorro and Porté-Agel (2009) used an even smaller rotor to investigate how the wake develops in a turbulent boundary layer down to $x/D = 15$. They focused on the added turbulence intensity in the wake.

PIV studies have also been performed to investigate the wake. One of the first PIV studies of a wind turbine wake was undertaken by Whale et al. (2000), who compared the measured vorticity to that predicted by a vortex lattice code down to $x/D = 2.9$. Grant and Parkin (2000) used PIV to measure the local velocity field induced by the vortices shed from a rotor operating in yaw conditions. Massouh and Dobrev investigated the near wake of a 0.5 m diameter rotor using a combination of PIV and cross-wires. The measurements with PIV covered an axial range of $x/D = 0$ to 1.6. Zhang et al. (2012) used the same rotor and a very similar setup to the one used by Chamorro and Porté-Agel (2009) and a combination of stereo-PIV (down to 5D) and cross-wires (down to 20D) to investigate the presence of tip vortices in the near wake from measurements of vorticity and power density spectra. The evolution of the flow in the far field was also investigated.

Few studies have been undertaken of the near wake of larger sized model rotors. In addition to the 10 m diameter NREL turbine (Schreck, 2001) already mentioned there was the MEXICO Schepers et al. (2012) experiment on a rotor with a diameters of 4.5 m. While the investigations of the NREL turbine focused on the rotor, the MEXICO project combines detailed investigations of both rotor performance (loads and pressure distributions) and the wake. The first set of tests on the MEXICO rotor was undertaken in 2007 and provided a large dataset which included flow investigations with PIV covering an axial range of $x/D = -0.96$ to 1.27. A stereoscopic PIV system was used which means all three velocity components where resolved. A second measurement campaign was undertaken during the summer of 2014, the “New MEXICO” test Boorsma and Schepers (2014). These measurements addressed some uncertainties of the initial tests and extended the test matrix with investigations of yawed flow, parked conditions, pitch misalignment, boundary layer manipulation etc.

One recent study performed at TU Delft is worth mentioning as it has many similarities with the current study. Lignarolo et al. (2014) used stereoscopic PIV to investigate the wake of a two bladed rotor with a diameter of 0.6 m down to a distance of $x/D = 5$. The rotor is therefore of similar size to the one used in the present experiment and the study concentrates on the same region of the wake as the current study. The turbine operated at the same design tip speed ratio, $TSR = 6$ and at very comparable Reynolds numbers ($Re_{tip} \approx 10^5$). The author also applied a very similar phase-averaging technique to extract information about the periodic structures in the wake. A PIV study can extract spatial information which cannot be found using single point measurements, but many quantities may also be compared, and some may only be extracted with the high temporal resolution of CTA. It is therefore interesting to compare the results from the current measurements with those of Lignarolo.

At NTNU (Norwegian University of Science and Technology), a series of four blind tests have been carried out to investigate the performance of various numerical methods for wind turbine performance and wake predictions. The test definitions and the details have been reported in Krogstad and Eriksen (2013), Pierella et al. (2014), Krogstad et al. (2015) and Bartl and Sætran (2016). In the first blind test (BT1), reported in Krogstad and Eriksen (2013), the wake of a single turbine operating in a uniform, low turbulence level inflow (Ti = 0.24%) was investigated. The size of the rotor ($D = 0.894$ m) allowed for an investigation which covered the first 5 diameters of the wake. Eight groups of modellers were invited to calculate the performance of the turbine over a range of operating conditions, as well as the development of the flow in the wake. The participants were only given the definitions of the test conditions and the geometry of the turbine model. The predictions, ranging from standard Blade Element Momentum methods to Large Eddy Simulations, were presented at a workshop in 2011 and compared to the measurements. The results showed that there was significant uncertainty in the results, both compared to the experimental data, as well as between the various prediction methods.

The second test case (BT2) used two turbines operating in-line and the task was to predict the performance of the two turbines, operating at the same rotational speed and separated by only 3 diameters, and to predict the wake development behind the downstream turbine. Hence, this was assumed to be a considerably more challenging test case. Again, the predictions of the downstream turbine performance showed considerable scatter. (Full documentation of these tests may be found in Pierella et al., 2014.)

Two more blind tests (BT3 and BT4) have been organised with the same turbines, where the effects of turbine lateral shifts (BT3) and high turbulence level atmospheric velocity profile inlet conditions (BT4) have been studied (see references Krogstad et al., 2015 and Bartl and Sætran, 2016). It was concluded from these tests that when it comes to wind farm planning, the estimates of wake development has still not reached the reliability that is necessary for accurate estimates of turbine interactions. However, it was found that when adding free stream turbulence and shear the agreement between measurements and predictions improved.

In order to help the modellers to understand the large discrepancies between the predictions and experimental data in BT1, there was a strong request to provide more detailed data that could be used to study the various terms in the model equations. The original wake dataset available from BT1 consisted of only the time averaged streamwise velocity component and turbulent kinetic energy profiles at three streamwise positions. The measurement campaign reported in this paper re-investigates the experiment from the first blind test in much more detail, using an improved measurement technique that allowed all three velocity components to be measured simultaneously and the velocity field to be separated into the phase-averaged and turbulent motions. Also, the number of streamwise locations has been increased to 18, giving improved details of the flow development.

2. Experimental setup

The measurements were carried out in the closed-loop wind tunnel used in the blind tests. It has an 11 m long, rectangular test section with a cross section of 1.8 m × 2.7 m at the inlet. The height was adjusted to compensate for boundary layer growth along the walls and was 1.82 m high where the model was located. An upstream honeycomb and screen section, fitted to a contraction with an area ratio of 4.3, provides an inlet velocity profile which is uniform to within ±1% and with a turbulence intensity $Ti_x = 100 \times \sqrt{\overline{u_x u_x}}/U_\infty = 0.24\%$. Here U_∞ is the freestream mean velocity and u_x its fluctuation. The three-bladed turbine (shown in Fig. 1) was positioned 4D from the test section inlet. The twisted and tapered blades are designed with the NREL S826 profile and operated at a tip Reynolds number of $Re_c = c_{tip}U_\infty/\nu \times TSR \approx 10^5$,