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To cite this article: F Massouh and I Dobrev 2007 J. Phys.: Conf. Ser. 75 012036

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Exploration of the vortex wake behind of wind turbine rotor

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Abstract. The present paper describes a wind tunnel study of flow downstream a small horizontal axis wind turbine (HAWT). The experimental investigations were carried out with the use of particle image velocimetry (PIV). To obtain the flow field in the rotating frame of reference, the phase-locked technique was applied. Explorations were carried out in azimuth planes with different angles. The 3D velocity field was reconstituted by processing the images resulting from the explored azimuth planes. In addition to PIV investigations, hot-wire measurements were also carried out immediately behind the wind turbine rotor at different radial and axial distances. The obtained results are very useful to analyze wind turbine wake and to constitute a reference for CFD computation.

1. Introduction

The study of wake behind horizontal axis wind turbine can be separated into two flow fields: the near wake and the far wake. The investigation of the far wake development is needed in the case of wind farm design. The near wake structure is relevant when the flow around the wind turbine is analyzed. The flow field immediately behind the rotor is altered by the blade geometry and the rotor angular velocity. The rotor decreases axial velocity and rotates the flow in the opposite direction. The viscous flow effects are responsible of the shear layer formed by the suction and pressure boundary layers and the flow detachments also. However the most important features appearing here are tip vortices generated by the blades. Not only the tip vortices influence significantly the flow behind the rotor, but they are also an important source of rotor noise and blade vibration.

Several studies were undertaken in order to reveal the development of wake behind a wind turbine and to obtain comprehensive results. One complete review of studies concerning wind turbine wakes is presented in [1]. The most comprehensive wake measurements are obtained using hot wire anemometry (HWA) or particle image velocimetry (PIV). Important results obtained by means of HWA are presented in [2]-[5]. In these studies the authors reveal clearly the axial and tangential velocities induced by the bounded vorticity and the tangential velocity peak caused by the blade shear layer. The researches with PIV technique to explore wind turbine wake are not frequent but their results are also very interesting. Here one can mention the papers [6]-[11], [16]. In these studies the authors track the tip vortices radial positions behind the rotor and study the vortex convection downstream. Also some details concerning vortex structure, mean velocity field and flow around the blade airfoils are presented. However, in the case of wind turbine, systematic studies of tip vortex structure like in the case of helicopter rotor flow [12], [13] are not presented.

The PIV technique enables to obtain some quantitative information on the wake behind the wind turbine rotor, which cannot be obtained by other techniques. Like laser Doppler velocimetry (LDV), PIV is non-intrusive and can give furthermore the full instantaneous velocity field in the investigated
plane. In this study, PIV exploration is used to obtain only axial and radial velocity components. This limitation is due to the planar PIV exploration and also to the non-favorable ratios between axial and tangential velocities, which makes it very difficult to take images of quality in planes normal to the rotor axis. Therefore, the use of HWA is needed to obtain the tangential velocity component.

The objective of this work is to obtain the quantitative information about rotor wake that can be used for testing of CFD codes. This information also permits to calculate tip vortex core radius, vortex velocity distribution, vortex decaying etc.

2. Description of experimental equipments

The Fluid Mechanics Laboratory at ENSAM-Paris has a closed circuit type of wind tunnel with a test section semi-opened to atmospheric pressure. The test section working dimensions are 1.35 m by 1.65 m and over 2.0 m of length. A settling chamber has a convergent (nozzle) with contraction ratio of 12. This contraction ratio ensures a homogeneous and low turbulences flow. Thus, in the convergent outlet the turbulent intensity is lower than 0.5% for a 35 m/s velocity. The presence of a three-coordinate computerized traverse system makes it possible to carry out 3D explorations of velocity field using HWA.

Wake measurements are carried out in the wind tunnel using a modified commercial wind turbine of Marlec Rutland 503. The original turbine had six blades but three blades were removed. This led to a three blades wind turbine like most wind turbines used in farms. Also this helped increasing the tip-speed ratio compared to the original turbine.

The wind turbine has a rotor diameter of 500 mm and a hub diameter of 135 mm. The blades are untwisted with a pitch angle of 10° and had a 45 mm chord at tip and 65 mm at root. The blade airfoil have concave pressure surface and is well adapted for flows with low Reynolds number. The rotational speed during the tests is 1050 rpm with a wind velocity of 9.3 m/s. Hence, the TSR is equal to 3, which is lower than the case of market wind turbines.

The wind turbine is mounted on a steel tube support of 37 mm of diameter ensuring a sufficient height that allows the lasers fixed above the transparent roof to illuminate the explored plane with a sufficient intensity, figure 1. A rheostat connected to the electrical generator incorporated in the wind turbine nacelle ensured the control of torque and rotational speed.

The PIV technique is applied to obtain the radial and axial velocity field in the wake of the rotor. A double cavity Quantel “Blue Sky” Nd:YAG pulsed laser (532 nm), which produces approximately 120 mJ per pulse, is installed above the transparent roof of the wind tunnel test section. A cylindrical
lens is used to create a thin vertical sheet of laser light, which is parallel to the flow. As the wind tunnel test section is semi-open and without sidewalls it is possible to place the CCD camera outside the tunnel. Hence PIV equipment cannot obstruct the flow. The ratio between blade swept area and semi-opened wind tunnel test section is about 0.224 and therefore the blockage factor may be neglected.

Olive oil droplets are introduced for seeding on the inlet of the wind tunnel diffuser. The test bench is equipped with an optical sensor of emitter/detector type, which tracks the light reflected from a mirror element fixed on the rotor hub. This sensor provides a trigger pulse of 5 V per revolution and thus indicates the angular position of the rotor. The emitted signal enables to control the lasers and the retrieval of images. To ensure the phase locked measurements of flow fields, the signal of the optical sensor is sent via a delay circuit. The time interval between two laser pulses is set to 150 µs. At each laser shot one raw image TIFF 1600 by 1200 pixels is acquired and stored on the PC hard disk, figure 2. As the tangential flow component is not zero it is probable that the tracked particles will be blown out of the illuminated surface between the laser pulses. As a consequence, it is needed to adjust the laser sheet thickness to nearly 3-4 mm.

The exploration of the flow downstream the rotor is carried out in four azimuth planes with the angles of 0°, 30°, 60° and 90°. Here, the plane at 0° corresponds to the vertical position of the reference blade, figure 1. Due to the laser power limitation and the camera resolution, it is not possible to obtain a velocity field larger than 300 mm. Thus to widen the explored area, the velocity field is divided into six windows (3 horizontal by 2 vertical) with a certain overlapping. These windows designated as h1, h2, h3, m1, m2 and m3 are presented in figure 3. For each window, the scale factor and the relative position to the rotor-based cylindrical coordinate system are defined using calibration markers placed inside the explored area. For this purpose, the images of the markers are taken after each series of tests.

![Figure 3. Flow map reconstruction](image)

![Figure 4. HWA test bench](image)

Due to relatively high rotational speed of the rotor (around 1050 rpm), the camera captures a pair of images every two turns. For each explored window the imagery is repeated 95 times in order to reproduce a temporal sequence of 12 seconds approximately which improves the precision of averaged velocity calculation. Hence, four series of 6 by 95 pairs of images, figure 3, are acquired for the planes with azimuth angles of 0°, 30°, 60° and 90°. The phase-locked measuring is carried out for yawed and non-yawed rotor. In the case of yaw the flow is unsteady even in the coordinate system relative to the rotor axis. Therefore the reconstruction of the three-dimensional velocity field like in non-yaw case is not possible.

To complete PIV velocity investigations with tangential velocity component, the hot-wire measurements are also carried out behind the wind turbine rotor at different radial and axial distances.
The velocities are measured with DANTEC “StreamLine” constant temperature anemometer CTA with 55CT90 modules equipped with X-probe with parallel stem orientation 55P61. The most appropriate technique for rotating wake exploration is applied: phase-locked, ensemble averaging, [14]. The data acquisition from CTA bridges is carried out with PCMCIA National Instrument DAQ 12-bit card 6020E. The constant sampling rate ensures at least two measurements per degree. Thanks to the reference trigger signal, radial and axial positions of the traverse system the velocity field is reconstructed in an appropriate cylindrical coordinate system, figure 4. In order to simplify the measurements, the radial component of velocity is neglected. However, near the blade suction surface and also in the viscous flow wake, this component may be important. To obtain unique relationship between HWA output signals ($E_1, E_2$) and tangential and axial velocity ($V_a, V_t$), the calibration method described in [14] is applied. Hence, before each test the hot wire probe is calibrated for yaw angles $\theta$ from -40° to 40° and for velocities between 1 m/s and 25 m/s. The calibrating is carried out on DANTEC 90H10 calibration system, equipped with computerized yaw manipulator. Then, the coefficients of King’s law $A$, $B$ and $n$, for each of the wires, are expressed as functions of yaw angle $\theta$. Lately, during the data reducing, these functions are interpolated in order to obtain iteratively the velocity components in tangential and axial directions. To avoid the errors caused by individual blade geometries, the performed ensemble averaging is based on a period equal to the time separating two marker pulses i.e. one revolution. In these measurements the ensemble averaging procedure is based on records comprising 300 revolutions.

Initially, the measurements are taken immediately behind the rotor at each 0.02D along the blade span, between the hub and the blade tip. Then the exploration is carried out behind the rotor in 11 planes perpendicular to the rotor axis located from 0.08D to 2.5D. In each plane the measurements are taken every 0.05D along the blade span. The measurements are not taken for the radii greater than the blade radius. Here the signal is strongly influenced by the tip vortices and also the angle between hot-wire probe and velocity vector is higher than an acceptable value. For the last reason the measurements behind the turbine nacelle are not taken.

![Figure 5. Contours and vectors of instantaneous velocity field - $h1$ window](image1)

![Figure 6. Contours and vectors of averaged velocity field – $h1$ window](image2)

### 3. Results and discussion

#### 3.1. PIV axial and radial velocity field

It is interesting to observe the vortex cores on the raw image presented on figure 2. Due to induced velocities by the tip vortices, the seeding particles are turned around the vortex core center and the centrifugal forces discard these particles outside the vortex centre. As a result the intersection of a vortex tube with the investigation plane appears on the images like a black spot due to deficiency in seeding particles in the core. Susset from R&D Vision carries out the statistical processing of the raw
images by means of the algorithm described in [15]. The interrogation sub-window in this study is equal to 16 by 16 pixels and for each pair of raw images 124 by 93 velocity vectors are obtained. The use of the calibration scale factors permits the velocity conversion from pixels per second to meters per second. In this manner the field of instantaneous velocity is calculated for each window. Furthermore, the processing of calibrating images makes it possible to find the position of each window relatively to the rotor.

The figure 5 shows the field of instantaneous velocity of h1 window, which results from the processing of the raw image shown on figure 2. Here, one can easily observe the intersection between the exploration plane and the helical vortex tubes emerging from blade tips. Also, we can see the effect of flow deceleration induced by the rotor, whose consequence appears as an increase of downstream flow tube diameter. Therefore, the flow tube is not cylindrical as the linear theory of the propellers assumes.

![Figure 7. Contours and vectors of the induced velocity; h1 window](image1)

![Figure 8. Contours and vectors of average velocity fields; h1, m1 windows](image2)

The instantaneous velocity fields resulting from each series of 95 captured images permit to obtain the average fields. On figure 6 this average field is presented for the window h1, positioned immediately behind the rotor. On this same figure the presence of large vortex structure detached from the nacelle can be observed. Note that the fluid reversal zone downstream the nacelle has a much greater diameter than it can be expected from the nacelle body only. It is to be mentioned that root vortex structures are present on the external boundary of the inner reversal flow. These structures are visible on the instantaneous vorticity field already presented in [16].

The spreading of reversal flow is similar to what is observed in the case of swirling jets. The expansion of inner flow downstream the turbine rotor may appear because the inboard blade sections are effective. In this case the induced axial velocity downstream the rotor is high and the flow loses its axial momentum. In the same time the induced tangential velocity is high and the swirling momentum increases. Beyond certain ratio between these momentums the flow expands and a zone of reverse flow is amplified. Due to the pressure gradient of swirling flow, this reversal zone has a diameter much greater than the wind turbine hub. It must be noted that the initial detachment is influenced also by the interaction between the negative pressure difference created by the rotor and the hub boundary layer. Obviously, the observed formation of hub vortices structures is not universal and may be different for other hub-blade configuration.
It is useful to mention here the PIV study of Whale et al [8], which deals with inboard vorticity. In this case the hub to rotor ratio is much smaller than in the present study but the measurements for high tip speed ratio $\lambda$ also reveal the large expanding of inner vorticity. The authors [8] affirm that the root vortices can be distinguished for $\lambda$ of 6 and 8 and they report that the inner vorticity expands and merges with the helical tip vortex system at around 1.0D downstream the rotor. However, they suppose that the inboard vorticity is due to the blockage caused by the high solidity of the blades, particularly when operating in high $\lambda$. It must be noted that the flow visualizations presented by Grant et al [9] also permits to observe the large expanding turbulent structures downstream the hub.

**Figure 9.** Contours of axial velocity $-z/D = 0.02$

**Figure 10.** Contours of tangential velocity $-z/D = 0.02$

The observation of the time series of the instantaneous velocity fields shows that beyond a distance of the order of 0.5D downstream the rotor, there is a fluctuation in the position of the cores of the tip vortices. For example on figure 5 relative to h1 window, the instantaneous velocity filed comprises three vortices whereas on figure 6 the averaged velocity field for the same window has only two vortices. So a problem arises when the average values are calculated from the instantaneous fields because vortex core wandering produces an artificial reduction of vortex intensity. Then, the averaged velocity field is not completely representative of the far wake development.

Contrarily of flow visualization presented in [9] and [17], in the present study the trailing edge vortex sheet and the blade shear layer are difficult to observe. Indeed, the accelerated rolling up allows seeing this vortex sheet only on certain instantaneous velocity fields.

The instantaneous velocity fields resulting from each series of 95 captured images permit to obtain the average fields. Then, to represent the explored area completely the six windows are assembled, by respecting the superposition in the zones of overlapping, figure 3.

To represent uniquely the induced velocity by the tip vortices, the axial velocity of the vortex cores is withdrawn from the velocity field and the results are presented on figure 7. In this manner, the vortex cores divide the flow into two domains: an internal domain with a slowed axial velocity and an external domain where velocity is increased. Finally, by use of velocity fields corresponding to the different explored azimuth planes a three-dimensional representation is obtained for the near wake, see figure 8. Thus one can determine the position of tip vortex tubes behind the rotor by observing the intersection between these tubes and each azimuth plane.

As the images were captured in azimuth planes, one cannot obtain the tangential component of velocity. The exploration, undertaken by the authors using a hot-wire anemometer, indicated that this velocity is between 0.20 and 0.6 times the axial velocity and that it would be difficult to measure it with the planar PIV measurement equipment, which was used during the testing campaign.
3.2. HOT WIRE MEASUREMENT
To complete PIV measurements, the explorations with a hot-wire anemometer are carried out firstly in the plane perpendicular to the rotor axis and situated 10 mm immediately behind the rotor. In radial direction the measurements are taken from 0.3D to 0.96D each 0.02D. For these measurements the two-component hot-wire probe is used and the radial velocity component is neglected. The hot-wire signals are reduced to velocity using the procedure mentioned in paragraph 2. Then, the ensemble averaged velocities and the ensemble rms fluctuations are obtained on the base of 300 rotor revolutions. The applied sampling rate permits to take more than two samples per degree. In all figures the velocities are normalized with the free stream velocity, which is 9.3 m/s.

![Figure 11. Contours of near wake axial velocity](image)

![Figure 12. Contours of near wake tangential velocity](image)

The results for axial and tangential velocities in the plane z/D=0.02 are shown on figure 9 and figure 10. It can be observed that the rotor decelerates the flow and it begins to rotate in direction opposite to rotor. Here it can be distinguished the axial and tangential velocity induced by the blade bound vortices. The axial velocity induced by the bound vortices is observed as negative and positive peaks with the same amplitude about the mean axial velocity. The tangential velocity induced by the bound vortices may be distinguished as negative peak in direction opposite to rotor. The blade viscous wake perturbs slightly the axial velocity, but its influence on tangential velocity is more important. Tangential velocity induced by the viscous wake is in the same direction as the rotor rotation, which diminishes the power. It must be noted that velocities induced by the bound vortices are more regular compared to velocity induced by the blade shear layer. Additional measurements are taken downstream the rotor in eleven planes perpendicular to rotation axis and located at axial distances z/D = 0.08, 0.125, 0.25, 0.375, 0.5, 0.75, 1.0, 1.25, 1.5, 2.0 and 2.5. At each plane the measurements are taken at radiuses r/D = 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45 and 0.48. The results of wake exploration are shown for axial velocity on figure 11 and for tangential velocity on figure 12. Here the presented results are only for the first six planes. After a distance of one diameter the presence of individual blades disappears and the velocities are averaged circumferentially. Only tip vortices can be observed farther than 2D. It is interesting to observe how the wake is developed. It can be distinguished that the viscous vortex wake deviates azimuthally, but the velocity induced by bounded circulation stays always in the same azimuth position. Also it must be noted that the tip vortices has greater influence on axial than on tangential velocity.
The rms fluctuations of axial and tangential velocity and the ensemble-averaged velocities are shown on figure 13. The viscous wake is very instable and is highly turbulent, and the rms fluctuation values calculated from experimental data are greater than 35% of upstream velocity.

Contrarily, the bounded vortices induced velocities are stable and their rms fluctuations are lower than 4% of upstream velocity. Earlier, the same observations were reported in [2].

Because the radial velocity is not measured, it is impossible to detect the presence of hub vortices similarly to [4]. However it is possible to show the expanding of axisymmetric hub vortices sheet. On figure 14 this is presented by the expanding of the lines of constant $rV_r/RV_\infty$ values downstream the rotor.

4. Conclusion

This paper describes PIV and HWA measurements in the near wake of a wind turbine model. The horizontal axis wind turbine has three constant-pitch blades and relatively high hub to rotor ratio. The synchronization of the laser pulses and the images retrieval with azimuth position of the blades permits to visualize the flow in a rotating reference frame.

To widen the PIV measured field, the plane of exploration is divided into 6 windows with an overlap. The carried out superposition of these windows after measurements makes it possible to obtain the velocity field in the complete plane. Thus, the helical pitch and the radial position of the tip vortices cores could be localized. The results show that the tip vortices issued from the blade tips are not located on a cylindrical surface as it is assumed in linear propeller theory; they expands in radial direction and thus increase the diameter of the flow tube. The analyses of the obtained results permit to show the induced velocity due to the tip vortices.

The measurements revealed the presence of an important sheet vortex structure downstream the hub. Due to interaction between the rotor and the hub boundary layer and also the ratio between swirl and axial momentums the reversal zone expands much than in the case of flow around an isolated hub.

The PIV measurements are completed with phase locked hot-wire measurements. These measurements show that the individual presence of blade downstream the rotor disappears beyond a distance of one rotor; however the tip vortices stay present. The comparison between axial and tangential velocity and rotor position permits to distinguish the viscous wake from the bounded vortex induced velocities. The velocity field induced by the bounded vortex has always the same azimuth position; however the viscous wake rotates azimuthally.
Generally the measurement carried out downstream the wind turbine permits to reveal the near wake structure. Obviously, this structure may be different for different turbine.

However, new measurements are previewed for a wind turbine with smaller hub and narrow blades. Also more detailed vortex core measurements are envisaged.

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