Investigation of the Wind Turbine Vortex Structure

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Abstract This paper describes the investigation of vortex wake flow downstream of a three blades rotor of a horizontal- axis wind turbine (HAWT) with 0.5 m diameter, placed in a semi-closed return wind tunnel. The phase-locked measurements are carried out by means of particle image velocimetry in several azimuth planes. In order to widen the explored area, the investigated velocity field is divided into several windows with some overlapping. Therefore, it was possible to reconstruct completely the 3D averaged velocity field and to keep track of the tip vortices emitted by blades. The obtained results show the effect of flow deceleration caused by the wind turbine rotor through the increase of the downstream wake diameter. An algorithm based on circulation calculation permits to find the vortex core centers and to extract velocity, vorticity and circulation in respect to these vortex centers. After the subtraction of mean flow effect, the net vortex induced velocity is extracted and the characteristics of the tip vortices trailing from consecutive blades are evaluated. The obtained results for the tangential velocity are analyzed and coefficients of Vatistas vortex model are evaluated. These coefficients are found to be different from the case of helicopter tip vortices. Finally, velocity field analysis shows how trailing vortex circulation, vortex core diameter and peak tangential velocity vary as a function of the vortex age. These characteristics are important for realistic viscous correction of the free vortex methods and accounting for them permits a significant improvement of results.

1. Introduction

The investigation of the wake development downstream wind turbines is required for the design of wind farms. The tip vortices present in the wake play an important role in wind turbine aerodynamics. Emitted from blade tips, they stay close to the rotor and produce a very complex velocity field with strong gradients. These vortices are also a major source of unsteadiness, aerodynamic noise and aerodynamic interactions. The free wake method is often used to analyze unsteady flow around the wind turbine. To improve this method we need to replace the potential vortex line with a real vortex tube, Leishman et al. (2002). Therefore it is important to investigate the vortex issued from blade tip in order to gather comprehensive information about vortex intensity, swirl velocity distribution and vortex diffusion depending on vortex age.

The wake flow behind a wind turbine is very complex and it is very difficult to obtain the velocity field downstream the rotor. Some experiments in-situ permit to understand the wake structure, see Vermeer et al. (2003). However, in the case of large-scale experiments and due to the sensors used for velocity measurements, it is difficult to acquire with sufficient spatial and temporal resolution the development of the wake. As a result, the usefulness of the obtained velocity field to serve as reference for wind farm modeling or rotor aerodynamic calculations is limited. Fortunately, there are investigations of wake flows realized in wind tunnel. These measurements are carried out in controlled flow conditions and are more accurate for velocity measurements.
Numerous studies were performed in wind tunnels in order to reveal the development of wake behind a wind turbine and to obtain accurate results. These studies presented by Ebert et al. (1997, 2000), Vermeer (2003) and Mast et al. (2004) were carried out with hot wire anemometry (HWA). The main limitation of these experiments is the one-point measurement capability of used sensors. Thus it is not possible to obtain instantaneous velocity simultaneously in the entire field of investigation. Also, due to limited directional sensibility, it is not possible to obtain the velocities of core vortices generated by blade tip. However, the particle image velocimetry (PIV) is a non-intrusive method that can measure the instantaneous velocity vectors field in a plane. But few researchers used PIV technique for the exploration of wind turbine wakes and they have obtained rather qualitative results. Here we might mention the papers presented by Smith et al. (1991), Whale et al. (1996), Grant et al. (1997, 2000, 2000), Maeda et al. (2005) and Massouh et al. (2007). The most comprehensive study is presented by Snel et al. (2007) concerning the flow downstream a 10m-rotor of a horizontal axis wind turbine. Unfortunately, detailed analysis of the results is not available for the moment.

The aim of this study is to present the quantitative information about the wake downstream of a model wind turbine. This information is acquired by means of the PIV technique and cannot be obtained by techniques like HWA or pneumatic sensors. The possibility of obtaining numerical data on velocity field around the tip vortices is of great interest. Moreover, the quality of data obtained allows the use of these results as a reference for CFD computing of flow around the model wind turbine.

Fig. 1. Test bench.

2. Experimental results

The Fluid Mechanics Laboratory at ENSAM Paris has a closed circuit wind tunnel with a semi-open test section. A settling chamber is equipped with a convergent nozzle, which has a contraction ratio of 12. This contraction ratio ensures a uniform flow and the turbulence intensity does not exceed 0.5% for a velocity of 35 m/s. The test section has working dimensions of 1.35 m by 1.65 m.
and 2 m of length. The investigation is carried out in wind tunnel using a modified commercial wind turbine Rutland 503. This horizontal axis wind turbine has a three blades rotor with a diameter of 500 mm and a hub diameter of 135 mm. The blades are tapered and untwisted. They have a pitch angle of 10° and a chord of 45 mm at tip and 65 mm at root. The rotational speed is 1000 rpm with a free-stream velocity of 9.3 m/s. Hence, the tip to speed ratio (TSR) is equal to 3, which is lower than the case of market wind turbines. The wind turbine is mounted on a support tube of 37 mm of diameter ensuring a sufficient height in order to allow the lasers fixed above the transparent roof to illuminate the explored plane with a adequate intensity, Fig. 1.

The PIV technique is applied to obtain the velocity field in the wake downstream the turbine rotor. Here, a double cavity Quantel “Blue Sky” Nd:YAG pulsed laser (532 nm) producing 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 passes through the center of the rotor. As the test section is semi-open and without sidewalls, it is possible to place the camera outside the tunnel, Fig. 1. Olive oil droplets are introduced for seeding on the inlet of the wind tunnel diffuser.

In order to carry out the phase-locked measurements, the test bench is equipped with an optical sensor. This sensor synchronizes the laser pulses and a reference angular position of the blade. The sensor tracks a reflecting target fixed on the rotor hub and emits a signal each time the target passes. Then the emitted signal is sent via a delay circuit. The change of delay time permits to change accordingly the angular distance between the reference position of the blade and the plane of exploration.

As the plane of exploration passes through the rotor axis and given that the PIV used in this study is planar, then it is only possible to obtain radial and axial velocities. Time interval between two laser pulses is set to 150 µs. Therefore, given that the tangential velocity of the flow downstream the rotor is not equal to zero, it is likely that the tracked particles will be blown out of the illuminated volume. Hence the laser sheet thickness was adjusted to nearly 3-4 mm.

Exploration of flow downstream the rotor is carried out in four azimuth planes with angles 0°, 30°, 60° and 90°. Here, the plane of 0° corresponds to the vertical position of the reference blade. Because of the laser output power limitation and the camera resolution of 1600x1200 pixels, it is not possible to obtain with sufficient precision a velocity field larger than 300 mm. As a consequence of widening the explored area, the investigated velocity field is divided into six windows (3 horizontal by 2 vertical) with some overlapping, Fig. 2. The scale of windows and their

![Fig. 2. Flow map reconstruction.](image-url)
relative positions are defined using calibration markers placed in known positions inside the interrogation area. For this purpose, the images of these markers are taken after each series of tests.

For each explored window, the imagery is repeated 95 times synchronously with rotor rotation. Hence temporal sequence is acquired during approximately 12 seconds in order to improve the precision of averaged velocity calculation.

In total, four series of 6 by 95 pairs of images were acquired for different planes with azimuth angles of 0°, 30°, 60° and 90°, with zero degree corresponding to the vertical position of the reference blade.

![Fig. 3. Raw image taken immediately behind the rotor in the h1 window.](image)

The raw images have a resolution of 1600x1200 pixels and 12 bits of grayscale resolution. Thanks to the synchronization between the laser pulse and the rotor position detected by the optical sensor, we can distinguish a blade frozen in vertical position, on the left. The cores of vortex tubes emitted from the tips of other blades can also be seen, Fig. 3. Due to velocities induced by tip vortices, the seeding particles are turned around the vortex core center and the centrifugal forces carry out these particles outside of the vortex center. As a result the vortex tube core appears on the images like a black spot because the quantity of the seeding particles decreases inside.

Statistical processing of the raw images is carried out by means of MatPIV ver.1.6.1 developed by Sveen (2004). The “multi-pass” algorithm with 3 passes is applied, the final size of interrogation window is 32x32 pixels and the overlapping is 75%. The obtained results are filtered by means of signal-to-noise (SNR), median and mean filter, then all vectors marked as “spurious” are discarded and new values are obtained by interpolation from nearest points. The criterion for discarding is the quality of velocity and vorticity fields. If the level of cut-off SNR is too high the flow is smoothed and some vorticity structures disappear, but if the SNR is too low then vorticity field is very noisy.

The instantaneous velocity fields resulting from each time series of 95 captured images are used to obtain the average fields in each of the investigated windows. Also, the processing of the calibrating images makes it possible to obtain the scale constants, the true velocity and the position of each window relative to the rotor. In this manner the fields of instantaneous and averaged velocity are calculated for each window.

Some uncertainty on the velocity measurement in the vicinity of the blade comes from the specific difficulties of the PIV technique to explore flow field close to the walls due to reflection. It must be noted also that the high levels of the tangential velocities can take place just a few millimeters from the blades. This does not permit that the same seeding particles remain in the laser sheet between
consecutive laser pulses. Therefore the cross-correlation algorithm used in PIV image analysis fails to obtain the instantaneous velocity field.

The Fig. 4 shows the velocity field resulting from averaged velocity fields for windows $h_1$. Here, we can observe the intersection between the plane of exploration defined by the laser sheet and the helical vortex tubes emanating from blade tips. Also we can see the effect of flow deceleration created by the wind turbine rotor whose consequence is shown by the increase of the downstream flow tube diameter. It must be noted that the flow tube is not cylindrical as assumed in the linear theory of propellers. We clearly see the deformation of flow tube surface due to the presence of tip vortices. It should be noted that there is a large vortex structure, which results from a detachment behind the hub. In the vicinity of the blade, the flow field is not well resolved because of the presence of reflecting surfaces.

Fig. 4. Contours and vectors of average velocity in window $h_1$.

The analysis of near rotor wake shows that the hub is a major source of disturbances and unsteady aerodynamic effects. This is due to the bluff shape of the rotor hub, which contains the electric generator. The flow detachment from the hub is intensified due to the highly loaded root blade sections. For this reason high axial velocities are induced; the flow on the hub surface is decelerated and then separated in the vicinity of the blade attachment to the hub. The results of this phenomenon are visible in Fig. 4 where we note a return flow up to approximately 40% of the rotor diameter.

It is helpful to reconstruct the 3-D velocity field by means the results for azimuth planes close to the rotor. Thanks to the synchronization of measurements it is possible to observe the intersection of these planes with the tip vortices emitted by blade tips. The obtained data also make it possible to track the helical tip vortices in the wake downstream of the rotor, Fig. 5.

The investigation of the time series of instantaneous vorticity fields, Fig. 6, shows that there is a fluctuation in the position of the cores of tip vortices. These fluctuations, known as vortex wandering, produce an artificial reduction of vortex intensity when the average values are calculated from the instantaneous fields. The fluctuation of vortex center behind the rotor is shown on Fig. 7. It can be observed that the amplitude of the fluctuations increases downstream the rotor. In reality, in spite of vortex position instability, the vortex intensity does not decrease as rapidly as the averaged velocity field predicts. Consequently, the average velocity field is not completely

Fig. 5. 3-D average velocity field for azimuth planes $h_1$ of 0°, 30°, 60° and 90°.
representative for comparison with CFD numerical simulations.

Fig. 6. Instantaneous vorticity in window h1.  
Fig. 7. Vortex wandering in h1 window.

3. Analysis of vortex characteristics

The objective of this analysis is to find the vortex core characteristics as a function of vortex wake. The presence of tip vortices is inevitable when fixed or rotating lifting surfaces are present. Vortices are the source of drag, noise and unsteadiness. Often, for the analysis of unsteady flow around a wind turbine, the free wake method is used. To improve this method, the potential vortex line needs to be replaced by a real vortex tube. Therefore it is important to investigate the vortex issued from blade tip and to gather comprehensive information about the most important characteristics of tip vortex. These characteristics are vortex intensity, swirl velocity distribution and vortex diffusion as a function of vortex age.

Regardless of their origins, strong vortices are similar. Usually, despite their very complex nature, vortices may be represented by very simple yet effective models. These models are specified in terms of 2-D tangential velocity profiles. Usually, radial and axial velocities are small compared to tangential velocity and therefore they may be neglected. The vortex is divided into two parts: inner and outer. The inner part, where viscous forces are predominant, is rotated as a rigid body, and at the vortex center the tangential velocity tends to zero. In the outer part, the velocity distribution decreases hyperbolically with radius and thus is similar to the flow induced by the potential vortex. The radius where the tangential velocity reaches a maximum and where the velocity distribution is changed is known as vortex core radius $r_c$.

The laminar vortices are studied extensively and there are different vortex models based on the simplified solutions of Navier-Stokes equations for laminar flow, like the solutions proposed by Rankine, Lamb, Oseen or Burgers. Compared with real tip vortices encountered in rotor aerodynamics, where flows are very turbulent, there are some discrepancies. In case of turbulent flow, for the same vortex core radius and for the same peak tangential velocity, the decreasing velocity gradient is smaller compared than in laminar flow. To get a better match, Vatistas (2006) recently proposed the following velocity distribution:

$$V_{\theta}(\bar{r}/r_c) = V_{\theta \text{max}} \frac{\bar{r}}{r_c} \left[ \frac{\alpha + 1}{\alpha + (\bar{r}/r_c)^{\beta}} \right]^m,$$
where \( m = (\alpha + 1)/4 \). Studying the experimental data obtained for helicopters rotors, Vatistas concluded that \( \alpha = 0.75 \) represents the best turbulent tip vortices. However, the flow downstream a wind turbine rotor is quite different from the flow downstream a helicopter rotor and we expected a different value of \( \alpha \). Therefore, we need to obtain data about vortex parameters and vortex decaying in the case of wind turbine.

There are different methods of obtaining the vortex core centers in the investigated velocity field. The simplest method is to calculate vorticity and then to identify the nodes with maximum vorticity as the vortex core centers. Vorticity calculation is usually needed to evaluate velocity derivatives. Unfortunately the use of vorticity field to detect the position of vortex core centers is not satisfactory. Due to centrifugal forces in the vicinity of vortex core, the quantity of seeding particles is not sufficient and the obtained velocity field is noisy. The use of derivatives to calculate vorticity amplifies the noise in the data and decreases the accuracy of results. To illustrate this problem, the contours of vorticity and circulatory part of velocity are shown in Fig. 8 for a vortex of 60° age. We can only observe few vorticity peaks, thus it is very difficult to find the vortex center. To circumvent this problem and to improve the vortex center detection, we prefer to use a detection based on circulation calculation. Thus, around each node of velocity field the circulation is calculated. The path of integration is a circle with a radius slightly greater then the vortex core radius. When the center of the integration curve coincides with a vortex core, the integral reaches a maximum. Thus, to obtain the vortex center we just need to find the point where circulation is maximal. To show the advantages of this method, we used the same velocity field as for the previous calculation. The results are shown in Fig. 9 where we can see that the obtained maximum circulation is close to vortex center compared with the previous case. Also it must be noted that the negative influence of spurious vectors is less pronounced and it is easier to find the vortex center for all exploration windows, Fig. 10.

Using the proposed method, the vortex centers were obtained for all velocity fields. The calculation results for all windows are presented in Fig. 11. Here we can see that vortex wandering increases significantly downstream the rotor. It must be noted that the vortex wandering is greater than in the wing case. This is due to helical vortex instability; see Okulov et al. (2007). Moreover, wind turbine
blades operate at high angles of attack. Therefore the flow is close to stall or completely stalled. In this case the blade section lift varies and therefore circulation varies permanently along the blades. As a result of bounded vorticity variation, the free vorticity varies too. Hence tip vortices intensity and vortex cores positions are changed permanently. The vortex wandering was already observed in the case of helicopter and wind turbine rotor, see Bhagwat et al (2000) and Grant et al. (2000). In this study, the vortex wandering effect is eliminated by means of conditional averaging according to vortex center.

![Fig. 10. Circulation distribution colored by axial velocity.](image1)

![Fig. 11. Vortex center positions.](image2)

It is very difficult to compare the blade trailing vortex directly with Vatistas model. The circulatory part of velocity is not symmetric around the vortex center, because blade vortices are helical whereas wing trailing vortices are linear. The additional distortion is created by significant axial velocity deceleration of the wake-like flow downstream the wind turbine rotor. For this reason the tangential velocity in Vatistas formula is presented by related averaged tangential velocity, expressed by the following equation:

\[ \Gamma(\bar{\tau}/r_c) = 2\pi\bar{\tau}/r_c V_{\theta\text{avg}} \]

![Fig. 12. Normalized tangential velocity induced by the tip vortex.](image3)

![Fig. 13. Coefficient \(a\) in Vatistas vortex model as a function of vortex age.](image4)
To generalize the velocity profile, the averaged tangential velocity is presented in dimensionless form. The tangential velocity is divided by the corresponding peak tangential velocity and the presented results vary as a function of dimensionless radius \( r/r_c \). The obtained velocity profiles are presented on Fig. 12 and show a good similitude.

The value of the coefficient \( \alpha \) in Vatistas equation is found by means of least square method and results are shown in Fig. 13, where we can see the variations of \( \alpha \) as a function of vortex age. Overall, the value of \( \alpha \) is lower than the value obtained by Vatistas. Thus, in the case of wind turbine rotor, the tangential velocity decreases slowly compared to helicopter case.

Fig. 14. Tip vortex circulation as a function of vortex age.

Fig. 15. Peak tangential velocity as a function of vortex age.

Other important characteristics of vortex are circulation decay and peak tangential velocity decrease as a function of vortex age. They are presented in Fig. 14 and Fig. 15 respectively. The tangential velocity is presented in dimensionless form by dividing with blade tip velocity \( \Omega R \) and the circulation by dividing with \( \Omega R^2 \), where \( \Omega \) is the angular velocity and \( R \) is the rotor radius. It must be noted that for two turns, peak velocity and circulation decrease by more than 20% but contrarily to results presented by Bhagwat et al. (2000) the vortex core radius varies insignificantly with vortex age.

3. Conclusion

This paper describes PIV measurements in the near wake of a model wind turbine. The synchronization of the laser pulses along with the retrieval of images with the azimuth position of blades permit the visualization of flow in a reference frame relative to the rotor.

To widen the measured field, the plane of investigation is divided into 6 windows with some overlap. Analysis carried out after measurements make it possible to obtain the velocity field in the full plane. Hence, the helical pitch and the radial position of the tip vortices core could be localized.

The results show that the tip vortices resulting from the blade tips are not located on a cylindrical surface as it is assumed in the linear propeller theory; they expand in the radial direction and thus the diameter of the flow tube increases. The analysis of the obtained results permits to find the induced velocity due to the tip vortices.

The positions of the vortex cores are obtained by an in-house developed program based on circulation integration. As in the other studies, the vortex wandering has been observed and vortex cores positions were changing permanently. The wandering effect is eliminated by conditional averaging and comprehensive information about the most important characteristics of the tip vortex were obtained.
The analysis of vortex characteristics permits to express the vortex core diameter, the swirl velocity distribution and the vortex diffusion as functions of the vortex age. It has been found that the obtained data are quite different from those of a helicopter rotor. In this study, the vortex core radius remains constant with the vortex age and the tangential velocity decreases slowly compared to helicopter rotor.

Finally, it must be noted that the quality of the obtained results permits their use as a reference for CFD flow computing around the model wind turbine. Also, they can be helpful for viscous corrections, when needed, in free vortex methods.

References