Wake Meandering – An Analysis of Instantaneous 2d Laser Measurements

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Abstract. The vast majority of wind turbines are today erected in wind farms. As a consequence, wake generated loads are becoming more and more important. We present a new experimental technique to measure the instantaneous wake deficit directly, thus allowing us to quantify the wake meandering as well as the instantaneous wake expansion expressed in a meandering frame of reference. The experimental results are subsequently used in a preliminary verification of the basic conjecture of a wake meandering model that essentially considers the wake as a passive tracer.

1. Introduction
The vast majority of wind turbines are today erected in wind farms. As a consequence, wake generated loads are becoming more and more important. While the average wake has been studied extensively in the past due to its implications for energy production, studies of the dynamics of the wake, which is of crucial importance for turbine loadings, are more rare. We present a new experimental technique to measure the instantaneous wake deficit directly, thus allowing us to quantify the wake meandering as well as the instantaneous wake expansion expressed in a meandering frame of reference.

The experiment was designed and conducted with the primary aim of verifying the basic conjecture in the Dynamic Wake Meandering (DWM) model complex i.e. that the lateral- and vertical wake deficit transport (i.e. meandering) basically act as if the wake (deficit) was a passive tracer driven by the large-scale turbulence eddies in the atmospheric boundary layer [1]. However, also the study the shape, widening and attenuation of the wake deficit are of interest.

In order to achieve the goal put forward above, it has been necessary to develop a measuring technique that allow for an instantaneous recording of the wake deficit at a specified down stream position. The key instrument in this respect is a LiDAR (Light Detecting and Ranging) system based on measurement of the Doppler shift between emitted- and reflected laser signals from aerosols assumed to follow the flow in question (Figure 1).

2. Test Site
The test site is a relatively flat and homogeneous terrain located near Risø National Laboratory/DTU Roskilde, Denmark, and it is being used simultaneously also for other experiments. The site’s average yearly wind direction is 289°. The experimental setup consists of the LiDAR system mounted on a test turbine along with two meteorological masts dedicated to wind field reference measurements.
The test turbine is a Tellus 95 kW. Hub height is 29.3 m, and rotor diameter is 19 m. The primary reference mast is the MM2 situated 36 m from the test turbine in a westerly direction. This mast is 33 m high and equipped with wind speed and wind direction sensors in various heights to supply mean wind speed data as well as wind direction data that can be suitably averaged to filter away that fast fluctuating part of the wind direction signal associated with the small scale turbulence. The secondary reference mast, MM1, is situated 114 m from the test turbine in a north-western direction. This reference mast is likewise equipped with wind speed and wind direction sensors in various heights and in additional with temperature, pressure and rain sensors. A second turbine, Nordtank 500 kW, is erected 70 m approximately north of the test turbine. Hub height is 36 m and rotor diameter is 41 m. This turbine is not a part of this experiment, but excludes wake investigations for mean wind directions from a certain wind sector. The positions of the turbines and meteorological masts at the site are shown in Figure 2. The details of the available sensor signals appear from Table 1.

Table 1. Available data in the database.

| T/M       | Channel | Height |
|-----------|---------|--------|
| MM1       | WS      | 35 m   |
|           | WD      | 36 m   |
|           | Temperature | 3 m   |
|           | Pressure | 3 m    |
|           | Rain     | -      |
| MM2       | WS      | 29.3 m |
|           | WD      | 19.7 m |
|           | WD      | 29.3 m |
|           | WD      | 35 m   |
| Tellus    | WSN     | 35 m   |
|           | WDN     | 35 m   |
|           | Power   | -      |
|           | YM      | -      |
| Nordtank  | WSN     | 29 m   |
|           | Power   | -      |
|           | RPM     | -      |
|           | Status  | -      |

Figure 1. ZephIR Prototype is being used at Risø since 2004. (a) Original QinetiQ design conical scanning mode ZephIR, at operation at Risø Høvsøre Test center, a homogenous flat terrain. (b) Risø adaptation of ZephIR, operational at Risø Roskilde Test Center for fast laser wake

Figure 2. Shown are the positions of the two masts and two wind turbines. Light blue area denotes the selected wind direction sector. All represented data in this paper are from this sector while the Tellus nacelle position is in the same direction. The sector is 30° wide between from 274° to 304°; thus centering the primary reference mast, MM2. The red area behind the Tellus is the possible wake width up to 70 m downstream according to the N.O. Jensen wake model [2] likewise for the Nordtank wake. Green is the example swept area of the LiDAR Line Scan measurement.
3. ZephIR Prototype
Risø has possessed a prototype model of the QinetiQ ZephIR LiDAR instrument since 2004. The original design of the ZephIR Prototype was as a vertical scanning tool facilitating focusing of the laser beam at different focus distances (heights). At the given altitude it scans a circular pattern with a cone angle of 30.6° by means of an optical wedge from which the horizontal wind speed can be derived. More information about the original design mode of ZephIR can be found in reference [3].

The first tests to assess the quality of the instrument have been performed at Risø Høvsøre Test Centre in Denmark at the end of 2004 and beginning of 2005 [4]. This and other studies show very good correlation with Risø cup anemometer [5] and SODAR measurements [6]. Since then the instrument has been used in various experiments at Risø and will be used in the future with new adaptations.

3.1. Adaptation
The available systems showed up to have some shortcomings in respect to the present application. First of all, the data processing time in the supplied software showed up to have an unacceptable performance. Rewriting the data processing software in C and replacing the existing FFT algorithm with the Fastest Fourier Transform in the West (FFTW - www.fftw.org) has increased the processing speed significantly thus increasing the scanning rate to 136 measurements per second. This gives the possibility of scanning the wake behind the turbine fast enough before the wake changes its form or position significantly. The modified software is developed at Risø in cooperation with QinetiQ.

Secondly, the conventional conical scanning mode is designed for measurements of spatial averaged wind characteristics, whereas the desire here is to record instantaneous wind speeds in many points. To solve this problem, the wedge has been taken off. This makes the LiDAR device a straight shooter which measure the wind speed in the direction it is pointed. A tilt and pan head which is originally designed for security cameras has been modified, and the ZephIR has been mounted on it. The head can move between ±35° in pan and ±15° in tilt. However, only the pan movement has been utilized in the present experiment, and tilt is adjusted to align the laser beam with the surface. The recording process is controlled by a PC. The data from pan movement has been synchronized with the velocity measurements by simply measuring the pan position exactly the same time of measuring the wind speed. Time stamp for each measurement is also recorded.

The modified instrument has been mounted on the Tellus wind turbine looking downwind (Figure 3). The LiDAR head is nearly at 29 m a.g.l. which is the hub height. Various scanning modes have been developed and will be explained in the next subsection. The second part of the ZephIR – i.e. the laser source and process computer - is located in a shelter at the foot of the turbine and can be remotely controlled over a local area network.

Figure 3. Adaptation in three steps; 1) Tilt and pan head is modified with a holder. 2) The LiDAR head is mounted on it. 3) Mounted behind the Tellus turbine looking downstream.
Figure 4. (a) Line Scan Mode focuses to a single distance, the red dot, while panning between points $p_1$ and $p_2$. (b) Deep Line Scan Mode focuses to programmed distances while panning. (c) A sample of the Sphere Scan Mode pattern. Focus distance is 58m. Horizontal axis is the lateral deflection (in meters) associated with the pan position ($\pm 25^\circ$) and vertical axis is the vertical deflection (in meters) associated with the wedge rotation ($45^\circ$). Each full 2D pattern scan might end up with different point positions, but they will always be within the same boundaries.

3.2. Working Modes
After adaptation of the prototype three working modes have been developed including configurations with as well as without the wedge (Figure 4). The modes are named as follows:

3.2.1. Line Scan Mode
In this mode the LiDAR focuses to a single distance, and pans between $\pm 30^\circ$ generating an arc scan behind the wind turbine. Since the measurement focus distance is constant we name the mode “Line Scan”. Each line scan takes 1.3 seconds, while the wind speed is measured nearly 180 times on different positions along the arc. See Figure 4a.

3.2.2. Deep Line Scan Mode
As an additional operation to the previous mode, the focus distance is changed every other line scan. Each focus distance thus includes nearly 360 wind measurement points. The focus is changed so that the instrument roughly follows the same air parcel downstream. The focus limit of the ZephIR is 200 m, so when it reaches this limit, focus distance is changed to 20 m to start the operation all over again. We have tried the Deep Line Scan Mode in the range from 1 diameter to 10 diameter distance with 4-5 stations which takes between 18 and 24 seconds for one cycle (Figure 4b).

3.2.3. Sphere Scan Mode
Unlike the two modes described above the “Sphere Scan” mode uses the wedge. We have designed a special wedge mechanism to move it in a range of $45^\circ$ in total, moving back and forth instead of making full rounds. With the wedge properly mounted this result basically in a vertical-like beam direction which, together with the mechanically generated horizontal panning movement of the head, results in the requested 2D scanning pattern. The LiDAR is focused to one single distance, and the pan movement is between $\pm 25^\circ$. This scans a small 2D area of a sphere behind the wind turbine. One cycle of the wedge takes one quarter of a second. An example of a scan pattern is shown in Figure 4c.
3.3. Data Processing and Database
The data from turbines and meteorological masts are collected into one single synchronized MySQL database to facilitate data analysis. The combined database includes 17 channels of data originating from three different measuring campaigns in May 2005, November 2005 and February 2006, respectively. The signals are recorded using up to four synchronized measurement PC’s.

Table 2 Measurement Calendar

| Setup | Scanning Mode                   | Start    | End      |
|-------|---------------------------------|----------|----------|
| 1     | Line Scan & Deep Line Scan      | 2004-09-15 | 2005-05-01 |
| 2     | Deep Line Scan                  | 2005-10-14 | 2005-10-29 |
| 2     | Line Scan                       | 2005-10-29 | 2005-11-21 |
| 3     | Sphere Line Scan                | 2006-04-26 | 2006-05-11 |
| 3     | Sphere Line Scan                | 2006-06-06 | 2006-07-12 |

4. Results
The first data of Line and Deep Line Scanning mode has been collected in 2004. The wake behind the wind turbine is observed as in Figure 5. Four focus distances have been selected, and from each station nearly 300 data points are collected. In the closest focus distance all measurements are in the wake, but further downstream the wake as well as undisturbed wind on the sides of the wake can be seen. At the end of 2005, mast MM2 is erected and measurements are repeated.

As for the line scan measurements, blocks consisting of 10 minutes of data are analyzed. Each scanned arc of velocities are included in a plot side-by-side with a gray scale indicating the measured wind speed (cf. Figure 6), thus resulting in a depiction of the wake deficit displacement at the particular focus distance as a function of time. The light areas in the figure symbolize high wind speeds, whereas dark areas symbolize low wind speeds. The red symbolizes model predictions of the wake deficit positions (meandering) based on the spatially averaged (instantaneous) direction evaluated from the three wind vanes on the reference MM2 mast, corrected for the measured yaw position of the Tellus nacelle as well as for the advection time (MM2 to focus distance).

With the selected representation of data and model, it is easy to see the measured wake width and wake movements as well as the correlation between the predicted instantaneous wake position and measured instantaneous wake position. The model of the wake dynamics assumes the wake deficit to be advected in the mean wind direction with the mean wind speed and advected in the lateral direction with the large scale lateral turbulence component [1]. Assuming Taylor’s hypothesis, the “driving” lateral velocities are perfectly correlated with the filtered wind direction measurements at the reference meteorological mast, however, delayed with the transportation time from the mast to the downstream point of interest. Thus for the present case, where the meteorological mast is 36 m upstream the turbine, the requested delay is the time for an air particle to move 36 m plus the focus distance with the mean wind speed. In general, the predicted wake movements show a convincing correlation with the measured wake movements, thus supporting the wake meandering hypothesis stated in the introduction.

One of the problems in understanding the data in Figure 6 is that the wake width is often smaller than anticipated. The Tellus turbine has rotor diameter of 19 m, and focus points are 3 diameters downstream. The wake width can be estimated to approximately 12° to 18° in pan, corresponding to a
wake diameter of the order 12 m to 18 m, which is even smaller than the rotor diameter. According to the currently available wake models, the width should be larger. Currently we do not fully understand this discrepancy, which also contradicts the measurements from the first measuring campaign. In second quarter of 2006, the LiDAR is physically updated with a new wedge mechanism. However, most likely we cut the wake horizontally not in the middle but closer to the top or the bottom.

The problem with interpretation of the observed wake widths from the line scan measurements can be studied more in detail if based on Sphere Scan recordings, which resolves both the lateral- and the vertical wake position at a prescribed downstream distance.

An provisional example of a 2D scan of the instantaneous wake deficit is shown in Figure 7. In this experiment, with a focus distance of 58m, a wake width of nearly 28 m has been observed which is as expected. This result supports our idea of cutting the wake in the upper or lower part in line scan mode. If this is the case, a reasonable explanation would be that the LiDAR is not perfectly horizontally aligned with the surface for the line scan recordings but is rather aligned with a small degree in tilt.

Figure 5. Deep Line Scan; data is collected from four different focus distances from 1 diameter to 9 diameter (19 m, 76 m, 130 m and 176 m). The initial wake is of the same size as the rotor and widens gradually downstream.
Figure 6. Line Scan data plotted in gray scale as function of time. Low wind speed is shown as black and higher wind speed is shown as white. Focus distance is 3 diameters (58 m).
5. Conclusion
For the first time ever instantaneous wakes deficits of wind turbines have been measured directly in one- (1D) and two dimensions (2D). This feature has enabled a detailed experimental investigation of the wake meandering phenomenon as well of the shape, widening and attenuation of the wake deficit. Resolving the wake meandering dynamics has allowed us to investigate the basic assumption in the Dynamic Wake Meandering model - i.e. that the wake deficit is advected passively by the larger than rotor size eddies in the inflow. The performed experimental analysis seems to support fully this hypothesis for the investigated full scale turbine located in the atmospheric boundary layer.

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References
[1] G.C Larsen, H.Aa. Madsen, K Thomsen and T.J. Larsen. Wake meandering - a pragmatic approach. Submitted for publication in Wind Energy.
[2] N.O. Jensen. A note on wind generator interaction. Technical Report Risø-M-2411, Risø National Laboratory, 1984.
[3] Ferhat Bingöl. Adapting a Doppler laser anemometer to wind energy. Master’s thesis, Technical University of Denmark, 2005.
[4] David A. Smith, Michael Harris, Adrian S. Coffey, Torben Mikkelsen, Hans E. Jørgensen, Jakob Mann, and Régis Danielian. Wind Lidar evaluation at the Danish wind test site Høvsøre. Wind Energy, 9(1–2):87–93, 2006.
[5] I. Antoniou, H. E. Jørgensen, T. Mikkelsen, T. F. Pedersen, G. Warmbier, and D. Smith. Comparison of wind speed and power curve measurements using a cup anemometer, a lidar and a sodar. European Wind Energy Conference and Exhibition, pages 47–51, November 2004.
[6] I. Antoniou, H. E. Jørgensen, T. Mikkelsen, S. Frandsen, R. J. Barthelmie, C. Perstrup, and M. Hurtig. Offshore wind profile measurements from remote sensing instruments. European Wind Energy Conference and Exhibition, February 2006.