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MEASUREMENT OF TURBINE INFLOW WITH A 3D WINDSCANNER SYSTEM AND A SPINNERLIDAR

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Summary

UniTTe is a research project coordinated by DTU aiming to develop measurement procedures with nacelle mounted lidars for wind turbine power performance and loads assessment based on the inflow close to the rotor, i.e., within the rotor induction zone. This paper is presenting the first measurement campaign of UniTTe. Detailed measurements of the inflow to a 500 kW Nordtank wind turbine, at the DTU Risø Campus, have been taken simultaneously with the DTU short-range WindScanner system and the SpinnerLidar. This is a unique measurement campaign, combining high spatial and temporal resolution of the SpinnerLidar measurements and the 3 dimensional measurements of the short-range WindScanner system. The measurements were first validated against a sonic anemometer mounted on a mast, at 31.5 m a.g.l. and 48.7 m from the turbine. A good agreement was found between the measurements and the CFD model of the wind velocity decrease due to the rotor blockage effect and the induction, thus validating the inflow model.

1. Introduction

Wind turbine power performance measurement are based on the relation between the free wind speed, i.e. the wind speed at the turbine location if there were no turbine, and the turbine response in terms of power or loads. Practically, this requires measuring the wind speed upstream of the induction zone of the turbine. However, as the size of wind turbines is increasing, the measurements need to be taken several hundreds of meters away from the turbine. The correlation between the wind measured upstream and the wind at the turbine location is therefore decreasing, especially for turbines installed in complex terrain.

The UniTTe (Unified Turbine Testing) project (<http://www.UniTTe.dk>) aims at developing new procedures for power curve and loads assessment based on wind measurements taken closer to the rotor plane – therefore inside the induction zone – in order to increase this correlation. One of the fundamental aspects of this project is therefore to get a better understanding of the turbine inflow from the location where the flow is free from the rotor influence up to the rotor position. This is done through CFD simulations of the inflow.

In order to compare CFD simulations to measurements, an experimental campaign has been set up at DTU Risø Campus test site. The short range WindScanner system provided 3-dimensional measurements of the inflow to the 500kW Nordtank turbine. Simultaneously, the SpinnerLidar, here used as a nacelle mounted lidar, was measuring at one rotor diameter upstream with a high temporal and spatial resolution.

The short-range WindScanner and the SpinnerLidar are remote sensing instruments developed in the Wind Energy department at the Technical University of Denmark (DTU) in the framework of the WindScanner.dk and the Integration of "Wind Lidar In Wind Turbines for Improved Productivity and Control" research projects respectively. Both instruments consist of two main components, a modified version of a commercial ZephIR wind lidar (ZephIR Ltd., UK) and a scanner head (IPU, DK). The modifications applied to the ZephIR had the

objective to provide a high streaming rate of laser Doppler spectra, as well as, to allow the synchronization of the data acquisition with the scanner head.



Figure 1 Picture of one of the three short range WindScanners (R2D3) deployed around the Nordtank turbine at DTU Risø Campus site.

2. Measurement set up

2.1. Wind turbine

The 500kW wind turbine used is located at the DTU Risø Campus test site in Roskilde, Denmark. It has a rotor diameter of 41.1m and a hub height of 36m. The terrain is flat with a maximum (downwards) slope of 3° towards the Roskilde fjord. The free undisturbed inflow is from the dominant westerly wind direction.

2.2. Meteorological masts

A meteorological mast (met mast) is placed at 92.4m from the wind turbine in the westerly direction, 283° from the geographical North. The mast is equipped for measurement of wind speed over the turbine rotor, wind direction, air temperature, air barometric pressure and humidity. There is also another shorter met mast between the turbine and the taller mast at 48.7m from the

turbine. The short met mast was equipped for this experiment with a 3D sonic anemometer on the top.

2.3. Short-range WindScanner system

The DTU short-range WindScanner system consists of three lidars with DTU developed dynamically steerable scanner heads [1]. The scanner head consists of two prisms of a 30° deflection angle. The prisms are driven separately to steer the lidar's line-of-sight within a cone with a full open opening angle of 120°. The three WindScanners are connected by optical fibre cables to the master computer that controls and synchronizes the movement of both the lidars' scanner heads and focus motors and gathers Doppler spectra and measurement positions from all three units.

For the needs of the experiment, three different scanning patterns were selected (see section 3.1). The physical positions of three units were determined based on the specifications of the different scanning patterns. The criteria used were:

- installing the instruments close to the scanning area to ensure as short as possible lidar probe lengths;
- the velocity and acceleration of the motors' motion should be lower than their upper limits.

The first unit (R2D1) was deployed 35m south of the turbine, the second (R2D2) 50m north of the turbine and the third (R2D3, shown in Figure 1) 78m in the 283° direction (Figure 2).

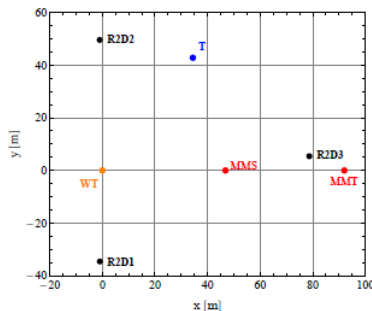


Figure 2 Relative positions of the three short range WindScanners (R2D1, R2D2, R2D3), wind turbine (WT), and two met masts (MMS, MMT).

To evaluate the alignment of the short-range WindScanners, a rotating ball (30 cm diameter) was temporarily installed on top of the short met mast. The rotating ball location was measured using a total station theodolite and it was found that it was located 30.6 m above the ground level at the wind turbine location. The rotating ball was scanned by the three WindScanners and was found to be at a height of 30.36 m, 30.37 m, 30.46 m by the WindScanners R2D1, R2D2 and R2D3 respectively. These heights indicate an offset of the tilt angle of the instruments of 0.18°, 0.16° and 0.12° respectively. These offsets were accounted for in the configuration of the scanning patterns (see section 3.1).

2.4. SpinnerLidar

The SpinnerLidar has been developed to scan the wind inflow towards a wind turbine rotor when installed either in the spinner of a wind turbine hub or on top of the nacelle [2]. Technologically, it is similar to the short-range WindScanners, except that it has only one motor driving the two prisms at a constant speed with a fix gear ratio (13/7) and that the deflection angle of the prisms is 15°.



Figure 3 Picture of the DTU SpinnerLidar installed on top of the nacelle behind the rotor (the system was protected from the rain with an aluminium enclosure)

When the measurement distance away from the instrument is fixed, the rotating prisms steer the laser beam in a scanning pattern similar to a rosette curve (see Figure 4). In this campaign the SpinnerLidar was focused at 47m.

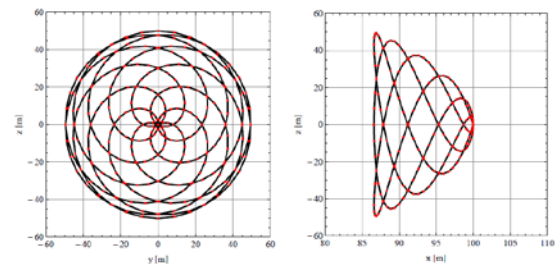


Figure 4 DTU high-resolution SpinnerLidar scanning pattern seen from the front (left); seen from the side (right). This figure is only illustrative and the dimensions are not those that have been used in this campaign.

The pointing accuracy of the laser beam was estimated by comparison to a red laser pointer installed 15cm below the prism. The offset between the red laser position and the center of the scanning pattern was measured indoors prior to the installation of the SpinnerLidar on the Nordtank turbine. Secondly, the position of the red laser beam was measured once the device was mounted on the turbine nacelle, which provided the actual position of the scanning pattern.

3. Short range WindScanner system

3.1. Scanning patterns

The short-range WindScanner system was configured to scan three different scanning patterns. Each scanning pattern was repeated for a duration of 30 minutes. Due to different requirements in the motion (velocity and acceleration) of the motors for

the realization of each pattern, the time of completion of one full scan pattern differs. The first scanning pattern consists of 11 lines in a horizontal plane, extending from the rotor plane up to 62 m away (Figure 5). The horizontal distance between each line is 4 m. The time of completion of one scan is approximately 15 seconds. The goal of this scan is to monitor the induction of the wind flow in a horizontal plane.

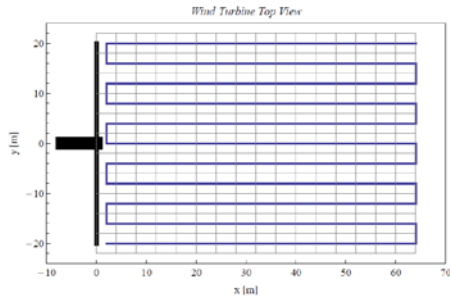


Figure 5 Scanning pattern number 1: 11 lines perpendicular to the rotor plane within a horizontal plane at 36m a.g.l. (hub height)

The second scanning pattern consists of 11 lines in a vertical plane, extending from the rotor plane up to 62 m away (Figure 6). The vertical distance between each line is 4 m. The time of completion of one scan is approximately 30 seconds. The goal of this scan is to monitor the induction of the wind flow in a vertical plane.

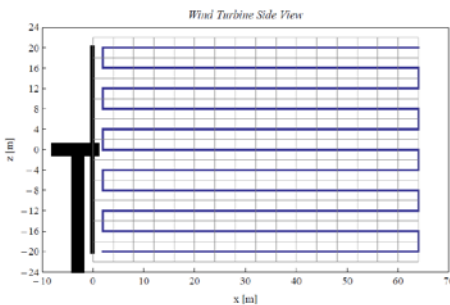


Figure 6 Scanning pattern number 2: 11 lines perpendicular to the middle of the rotor plane within a vertical plane

The third scanning pattern is within a vertical plane parallel to the rotor plane. The scan follows a rosette pattern which is confined within the 2/3 of the radius of the wind turbine rotor (Figure 7). The time of completion of one scan is approximately 6 seconds. The goal of this scan is to investigate the coherence of the wind flow in different parts of the wind turbine rotor when the flow is already affected by the induction zone.

3.2. Comparison to the sonic anemometer

First of all the time lag between the WindScanner measurements and the sonic anemometer was detected for each 30 minute time period by a cross-correlation method. In order to perform the cross-correlation, the length of the data for each 30-min period needs to be the same. Because the sonic anemometer measured at 35 Hz, block averaging of

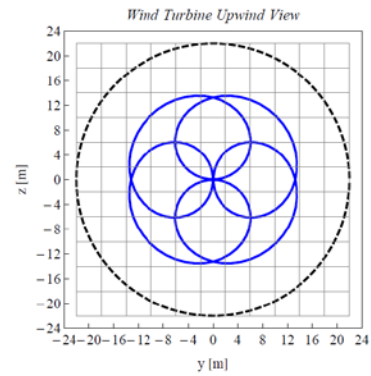


Figure 7 Scanning pattern number 3: the pattern (in blue) is within a vertical plane parallel to the rotor plane. The dashed black line represents the dimensions of the swept rotor area.

the sonic data was carried out that corresponded to the sampling frequency of the respective scanning patterns by the WindScanners. The estimated time lags were added to the time stamp of the WindScanners that resulted in selecting the same 30-min period as that of the sonic anemometer without any time lag.

Figure 8 shows the scatter plot of the 30 minute average longitudinal wind speed estimated by the WindScanners with that estimated by the sonic anemometer, for the point the closest to the sonic anemometer. It is clear that the WindScanners measure the 30-min mean wind speeds with very small systematic error (slope of 0.991) and uncertainty ($R^2 = 0.99809$).

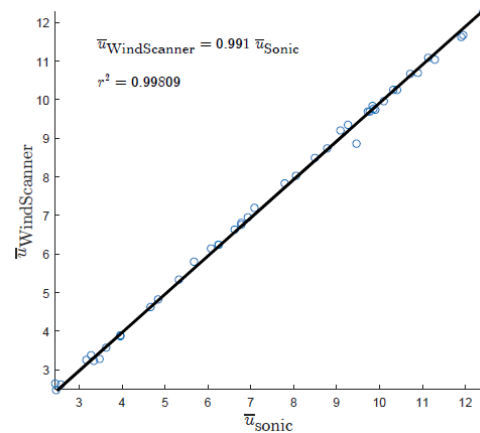


Figure 8 Comparison of the 30 min average longitudinal wind speed measured with the short range WindScanner system and the sonic anemometer.

3.3. Turbine inflow measurements

The measurements of the wind speed along a horizontal line in the middle of the rotor and orthogonal to the rotor plane were compared to CFD simulations (see Figure 9). The measured data were binned and averaged according to the free wind speed (bins of 1.9m/s) and position along the scanning pattern. Good agreement in wind speed variations, but with an offset, was obtained between

the measurements and the CFD simulations for wind speeds above 5m/s. The deviation observed between 0 and 0.2 is mainly due to the simulations performed without a nacelle.

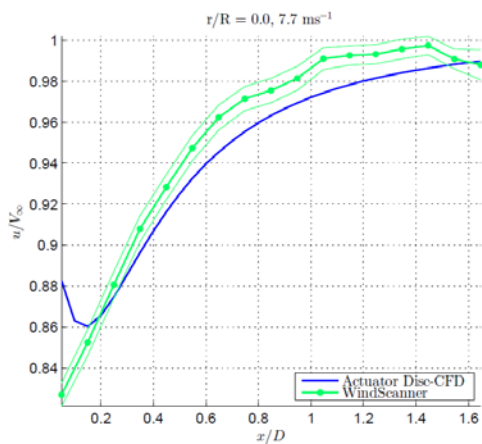


Figure 9 Wind speed normalised with the free wind speed as a function of the distance from the turbine rotor. WindScanner measurements (green) and CFD simulations (blue).

4. Spinner Lidar

One of the challenges with the spinner lidar was to distinguish the signal backscattered by the turbine rotor blades from the actual radial wind speed. As a first step, a simple approach was applied: radial wind speeds below 3.5m/s were excluded. This resulted in holes in the scanning pattern. Nevertheless, given the high spatial resolution, a large amount of measurements are still available after filtering.

4.1. Comparison to the sonic anemometer

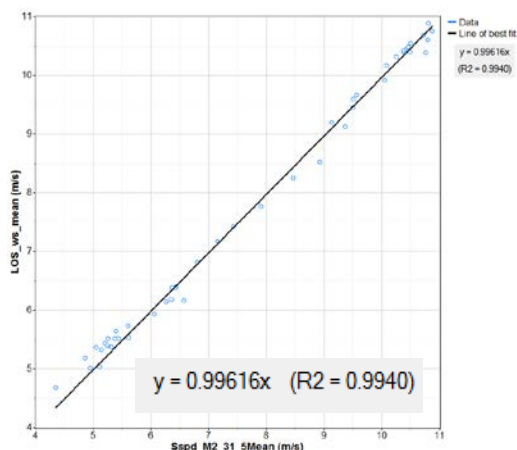


Figure 10 Comparison of the 30 min average longitudinal wind speed measured with SpinnerLidar and the sonic anemometer.

In order to get a first evaluation of the spinner lidar measurements, the radial wind speed at the center of the scanning pattern (measurements obtained within a square of 1m by 1m around the center) was assumed to be horizontal and always aligned with the wind direction (i.e. no yaw error from the

turbine). 30 minutes averages were compared to the horizontal wind speed measured by the sonic anemometer on the short met mast. The laser beam is then about 8m higher than the sonic anemometer. Results are shown for one day of measurements in Figure 10. During this day the turbine yaw has been varying between 220° and 270°.

4.2. Turbine inflow measurements

Figure 11 shows an example of radial wind speed measurement over one scan (completed in 4 seconds) from the SpinnerLidar. Some kind of instantaneous vertical wind shear can be observed.

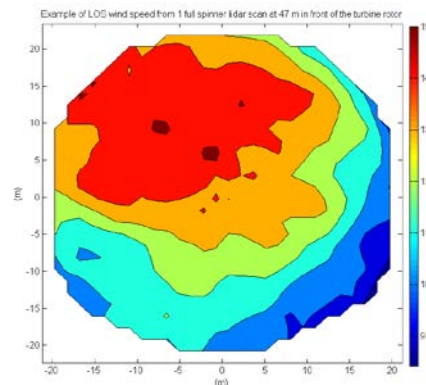


Figure 11 Interpolated radial wind speed measured over one scan (completed in about 4 seconds) of the SpinnerLidar.

5. Conclusions and future work

We have presented the setup of a unique measurement campaign combining the DTU short-range WindScanner system and the DTU high-resolution SpinnerLidar. This is also a unique opportunity to directly compare the measurements from those instruments to classic anemometry. The first results have shown very good agreement in terms of average wind speed.

Modelling of the inflow to the turbine rotor with CFD has been to some extent validated with the WindScanner measurements.

The next steps are to investigate the measurement of turbulence quantities such as spatial cross correlation over the rotor and their use to improve wind turbine loads assessment using measurements obtained with the third scanning pattern from the WindScanner and the SpinnerLidar.

6. References

- [1] Sjöholm M et al., Two-Dimensional Rotorcraft Downwash Flow Field Measurements by Lidar-Based Wind Scanners with Agile Beam Steering, J. Atmos. Oceanic Technol., 2014, **31**-4: 930-937
- [2] Sjöholm et al. Full two-dimensional rotor plane inflow measurements by a spinner-integrated wind lidar, EWEA2013

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