Detecting wind turbine wakes with nacelle lidars

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Abstract.
Because the horizontal homogeneity assumption is violated in wakes flows, lidars face difficulties when reconstructing wind fields. Further, small-scale turbulence which is prevalent in wake flows causes Doppler spectrum widths to be broader than in the free stream. In this study the Doppler peak variance is used as a detection parameter for wakes. A one month long measurement campaign, where a continuous-wave lidar on a turbine has been exposed to multiple wake situations, is used to test the detection capabilities. The results show that it is possible to identify situation where a downstream turbine is in wake by comparing the peak widths. The used lidar is inexpensive and brings instalments on every turbine within economical reach. Thus, the information gathered by the lidars can be used for improved control at wind farm level.

1. Introduction

Within a wind farm wakes from neighbouring turbines cannot be avoided; optimal wind farm design can minimize these effects but never completely avoid them. Much effort has been put into wake models as wind farm design tools (for an overview see [1]) and their validation, while significant interest in measuring wake with the use of remote sensing devices originates from optimal wind farm operation using wake redirection.

In this paper we want to present a novel method of detecting wakes by using a forward-looking nacelle lidar. Information of the detection can be applied as input to wind farm based yaw steering.

A very straight-forward approach to detect wakes was introduced by [2] of merely using wind farm SCADA data. Aim was to reduce turbine fault activations that are caused by wakes. Based on turbine data a wake pattern for each turbine was measured and used to decide in real time whether a power reduction was due to a wake or an actual fault.

An alternative method to detect wakes was presented in [3]. The local wind speed and turbulence intensity are derived from strain gauges or optical fibres. It was shown that this method is capable of detecting differences of these quantities on the two sides of the rotor and thus detect wakes. These theoretical methods have more recently been studied on scaled wind turbines in a wind tunnel showing similar success of detecting the lateral position of upstream wakes [4]. One drawback of this method is that to estimate wind speeds from blade bending moments requires an aerodynamic model of the turbine. Wind farm operators often do not have access to this kind of information.

Remote sensing devices have shown potential at measuring wakes. Studies have shown application to detecting aircraft tip vortex using ground-based [5] and on-board devices [6]. Further lidar ship wake detection has been studied in [7].

Most recently, interest has grown in the application of lidar systems to wind energy. [8, 9] have used a scanning lidars to track the wake behind a turbine and measured wake deficit, width and centre. In [10] two lidar systems were used to measure a wake immediately behind a turbine. The study was extended in [11] to investigate the influence of the stability of the atmosphere on wake recovery. However, these lidar systems are very complex and expensive and are not realizable as commercial products for employment of several turbines within a wind farm.

Here we are presenting wake detection capabilities of an inexpensive, commercial lidar. It is mounted on the nacelle and measures the incoming wind field and thus our interest lies in detecting wakes in the inflow.

2. Experimental Setup and Motivation

The data analysed here have been gather during a one month long period in late 2015. A WindEYE lidar by Windar Photonics A/S was mounted on a Vestas V52 at the Risø test site. A schematic of the setup is shown in figure 1. The Vestas turbine, where the WindEYE was mounted, was exposed to a wake of a smaller Nordtank 500kW turbine, see figure 2.

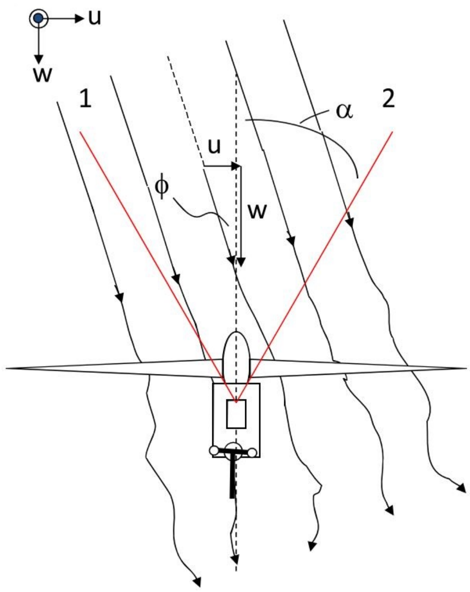

Figure 1. Setup schematic of the WindEYE lidar on a wind turbine ($\alpha = 30$ deg).

Figure 2. Overview of the Ris test site.

The lidar is mounted on the nacelle of a wind turbine and is looking upwind to measure the incoming wind field. From the two measured line-of-sight velocities ($v_{\mathrm{LOS},1}$ and $v_{\mathrm{LOS},2}$) the horizontal components (U and W) of the wind can be estimated. In the process it is necessary to make the following assumptions about the incoming wind field:

(i) The wind field is horizontally homogeneous and
(ii) no vertical components.

In situations where the turbine is exposed to a wake of an upstream turbine, assumption (i) is heavily violated and thus the derived wind field information will be invalid. Thus a wake detection algorithm is necessary to identify conditions where the applied assumptions are not valid.

3. Approach

The approach is based on the assumption that the lidar can detect enhanced turbulence, and that this enables the system to determine whether one or more beams of the system are measuring inside wakes. However, turbulence measured with a lidar is affected by the relatively long effective measurement volume. The lidar effectively averages the wind speeds within the volume [12].

Small-scale turbulence manifests itself in the width of the Doppler peak of the lidar, so that the width is a measure of the small-scale turbulence [13, 14]. Specifically, it has been shown that the width of the Doppler spectrum of a continuous-wave lidar is proportional to the turbulence intensity within the probe volume of the instrument [15]. At the same time, it is known that small-scale turbulence, which would be particularly responsible for increasing the Doppler spectrum width, is prevalent in wakes [16, 15].

As a measure of the Doppler spectrum width we use the 2nd central statistical moment of the peak. The first moment is defined as the centroid. In order to reduce noise in the width estimation a running average filter with a size of 600s has been used.

4. Results

In this section two periods are presented: one with a wake situation and one without a wake situation.

The results for the first period are shown in figure 3. The top panel shows the difference in peak variance between beam 1 and 2. Two vertical lines at 20 and -20 are also plotted. Large differences indicate enhanced turbulence levels, and thus a wake, in one of the beams. The centre panel shows the yaw position of the two turbines including an indication of the wake sector. The bottom panel shows the power production of the wake-emitting turbine.

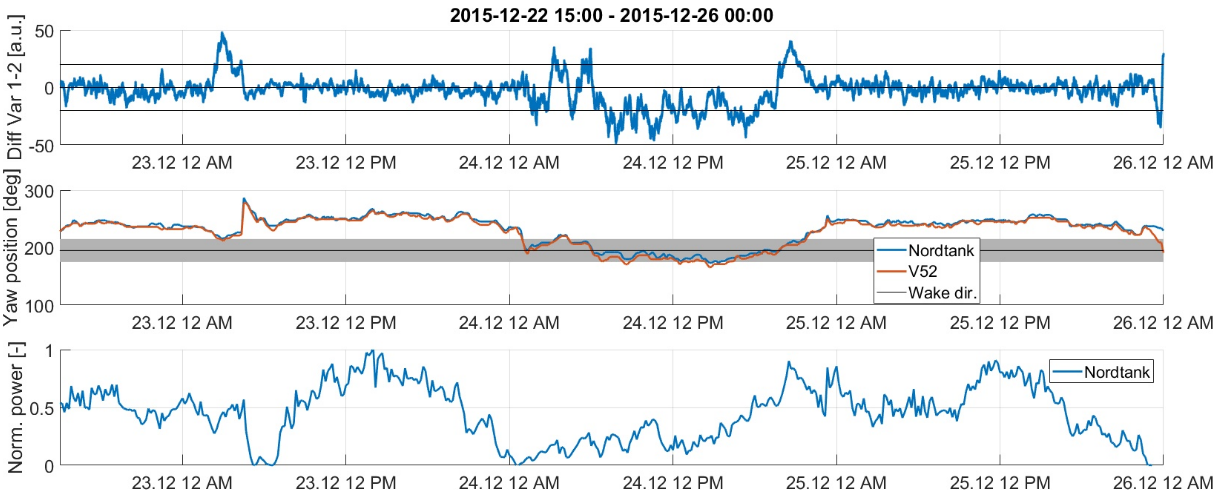

Figure 3. Top: difference of peak variance between beam 1 and 2. Centre: yaw position of both turbines. Bottom: Power production of Nordtank turbine.

It can be seen that as soon as the upstream turbine is expected to emit a wake on the downstream turbine (based on their yaw positions), there is a sudden jump in the difference of the peak variances. This is shown especially after Dec 23rd 12AM, where a negative spike in variance difference can be seen as soon as a wake position is entered. This means that a wake on the left half of the rotor is detected, which agrees with the yaw position showing higher values than the wake direction (195 deg). Similarly, the period around the Dec 24th 12AM shows a wake on the right half of the rotor (positive difference in peak variance), which is also confirmed by the turbine yaw position. Hence, the sign of the peak variance difference can detect a wake situation and show which half of the rotor is affected.

Figure 4 shows the results for a period where according to the yaw positions no wake situation is expected. When looking at the difference in peak variance, it can be seen that at all time the values fluctuate around zero. Contrarily to the wake situation no sudden deviation in peak variance difference can be seen and so no wakes are predicted by the lidar.

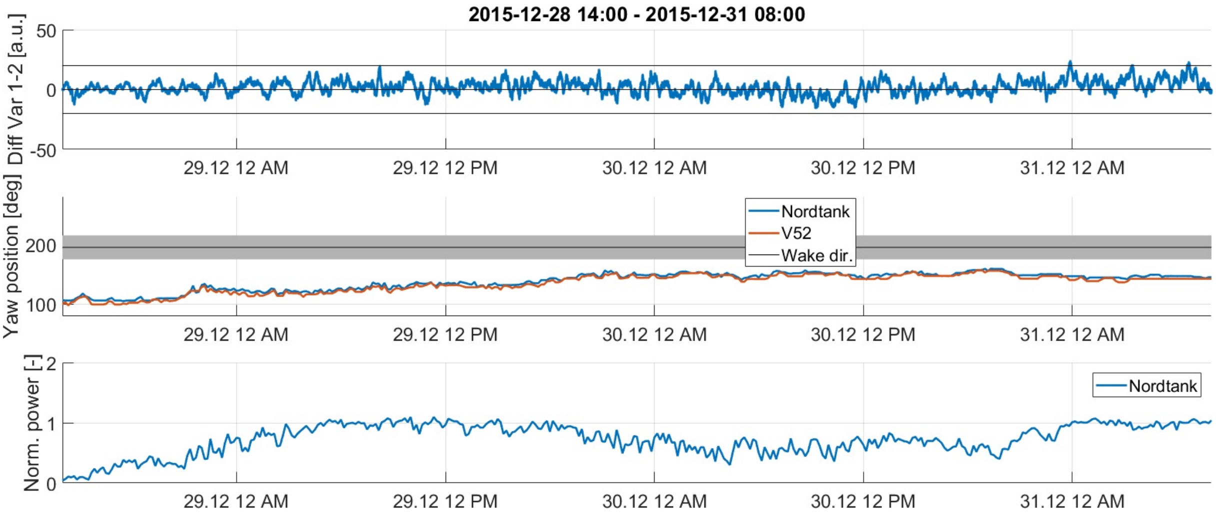

Figure 4. Top: difference of peak variance between beam 1 and 2. Centre: yaw position of both turbines. Bottom: Power production of Nordtank turbine.

5. Conclusion

This study investigated the wake detection possibilities of a nacelle lidar. It was shown that by comparing the Doppler peak width of the two line-of-sight velocities wake situations can be predicted. A suitable measure of the peak width is the 2nd central statistical moment. The sign of the peak width difference indicates which side of the turbine is exposed to a wake. A challenge remains in setting appropriate thresholds for the difference of peak variances. Such a limit is probably dependent on ambient turbulence levels and future experiments will be conducted to test the algorithm in different turbulence levels.

Wake detection is necessary to identify where the assumption used for wind field reconstruction are violated. Further, information about the position of wakes is very valuable information and can be exploited for wind farm control.

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