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Detailed analysis of a waked turbine using a high-resolution scanning lidar

T G Herges[1], J C Berg[1], J T Bryant[1], J R White[1], J A Paquette[1] and B T Naughton[1]

[1]Sandia National Laboratories, Albuquerque, NM, 87185, United States of America

Abstract. Sandia National Laboratories and the National Renewable Energy Laboratory conducted a wake-steering field campaign at the Scaled Wind Farm Technology facility. The campaign included the use of two highly instrumented V27 wind turbines, an upstream met tower, and high-resolution wake measurements of the upstream wind turbine using a customized scanning lidar from the Technical University of Denmark (DTU). The present work investigates the impact of the upstream wake on the downstream turbine power, blade loads, and nacelle accelerations as the wake sweeps across the rotor in various waked conditions. The wake position was tracked using the DTU SpinnerLidar and synchronized to the met tower and turbine sensors. Initial analysis shows a power increase when the wake was located next to the rotor edge, accompanied with an increased mean blade root flap moment, and a large power decrease in the fully waked condition.

1. Introduction

Wind turbine wakes significantly influence both the power output and loading of wind turbines within farms, due to the disturbed inflow experienced by downstream turbines. Atmospheric conditions primarily determine the wake propagation to downstream turbines, with stable atmospheric conditions generating more resilient wakes that persist farther downstream [1]. The IEC 61400-1 Annex D standard accounts for fatigue loading of waked turbines by adding extra turbulence using a method developed by Frandsen [2]. However, detailed field campaigns that provide data from highly instrumented wind turbines in various waked conditions along with simultaneous high spatial and temporal resolution wake tracking and velocity deficit measurements are scarce.

In this paper, data from the Sandia National Laboratories (SNL)/US Department of Energy (DOE) SWiFT wind turbines [3] were analyzed to identify the differences in turbine power output and blade loads between fully-waked, partially-waked, and adjacently-waked turbines. The SWiFT facility has well-instrumented meteorological towers and research turbines that include root-bending strain, rotor azimuth position, and nacelle accelerometer measurements all synchronised in time. The upstream wind turbine wake tracking and velocity deficit measurements were coordinated with the downstream turbine sensors using the Technical University of Denmark (DTU) Wind Energy Department custom-built SpinnerLidar [4]. The DTU SpinnerLidar was uniquely capable of measuring the wake at the temporal and spatial resolution required for the experiment. The analysis focused on stable atmospheric conditions in the partial load (Region II) of the production controller, where maximum coefficient of thrust (Ct) occurs.

The analysis in this work will help to quantify the impact of the waked condition on wind turbines. The contribution will improve both high-fidelity modelling and help facilitate future wind turbine design. The study will include the mean flap root bending moment, root fatigue loading, nacelle acceleration, and power measurements corresponding to upstream wake position and velocity deficit at the downstream rotor plane. The investigation will include a loads analysis of the downstream rotor corresponding to different wake conditions [5]. This work will provide insights to assess the cost and turbine-life trade-off between power and loads for different waked cases. The data used in this two-turbine waked condition analysis will be made publicly available through the DOE Atmosphere to electron (A2e) Data Archive and Portal (DAP) to support further work by the international community.

2. Experimental Setup

Sandia National Laboratories operates the Scaled Wind Farm Technology (SWiFT) facility located in Lubbock, Texas. The baseline site instrumentation includes three research wind turbines (WTG) and two meteorological towers (MET) as shown in figure 1.

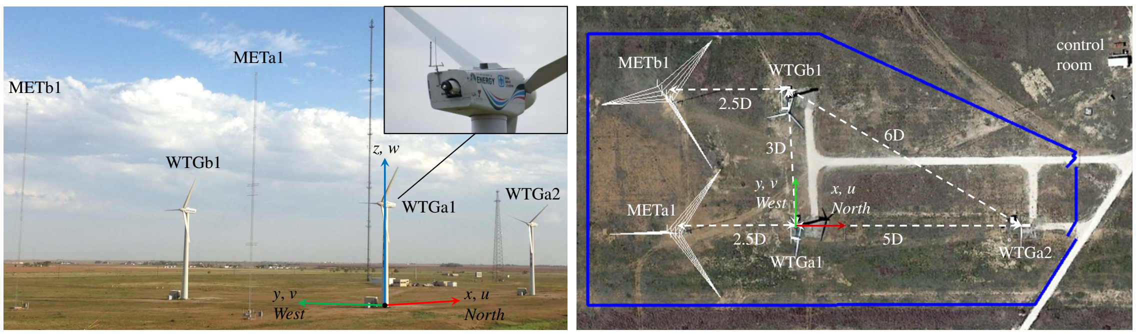

Figure 1. SWiFT site layout and coordinate system with the DTU SpinnerLidar installed in WTGa1 including a top view of the facility layout [3].

The layout of the SWiFT facility is seen from an overhead view in figure 1. The met tower and the two turbines used in this campaign (METa1, WTGa1, and WTGa2) are all aligned with the predominant wind direction at the site, 180 degrees (north is 0 degrees). This configuration allows measurement of the atmospheric inflow with the met tower and measurement of the wake of the WTGa1 turbine using the nacelle-mounted DTU SpinnerLidar. The SWiFT turbines are highly-modified, variable speed, variable collective pitch Vestas V27 machines with a hub height of 32.1 meters, a rotor diameter of 27 meters, and a maximum power output of 192 kW [3]. The meteorological towers are 59 m tall with a suite of atmospheric sensors as described in Ref. [4]. The entire site is on a fiber optic data acquisition and control network and each WTG and MET are individually synchronised to GPS.

DTU developed the SpinnerLidar to be a turbine mounted lidar for rapid scanning of the wind field in a two-dimensional plane. For this experiment, the SpinnerLidar was mounted as shown in figure 1 to point out of the rear of the upwind SWiFT turbine nacelle (WTGa1), optimally positioned to capture the full wind turbine wake primarily at five rotor diameters downstream (D = 27 m), near WTGa2. The SpinnerLidar scans the two-dimensional surface of a sphere with an approximately 30° half angle in a fixed rosette pattern, acquiring 984 line-of-sight velocity measurements in 2 seconds (see Ref. [4] for an example scan capturing the wake of WTGa1).

Both wind turbines have data acquisition systems mounted in the hub for recording GPS synchronized rotor measurements. For this campaign blade root edge and flap optical Fiber Bragg Grating strain sensors were installed and measured by Micron Optics fiber optic interrogators. As built airfoil profile measurements were taken and precise blade pitch and rotor azimuth calibrations were conducted on the mounted rotor to reduce uncertainty in the orientation of the blade loading. During this campaign, valid data were recorded for one of the blades on WTGa1 and for two of the blades on WTGa2.

3. Results

Throughout the wake-steering campaign at the SWiFT site, 12.9 hours of data were collected where WTGa2 operated with the WTGa1 wake within a lateral distance of 2D. The DTU SpinnerLidar acquired velocity measurements with a focus distance of 5D and root strain data were acquired on two of the WTGa2 blades. Throughout this time, different yaw offsets were prescribed to analyze the effect of the upstream WTGa1 wake across the downstream WTGa2 rotor. Thus, the yaw offset set points were not always set to increase power output of the array, but sometimes included steering the wake into the downstream turbine in order to create various waked conditions on WTGa2.

Figure 2 shows WTGa2 behavior with a DTU-SpinnerLidar measured WTGa1 wake center within a lateral distance of 2D using 1-minute time bins. Figure 2a displays the measured WTGa1 wake center positions colored with the normalized power output of WTGa2. The normalization values for power and blade root flap moments were calculated from the average WTGa2 measurements during non-waked periods for a corresponding met tower hub-height wind speed. The locations of the wake center created an arc in the SWiFT coordinate system because of a fixed SpinnerLidar focus distance with different WTGa1 yaw headings. The bin-averaged normalized power and blade root flap moments versus the position of the WTGa1 wake center are plotted in Figures 2b and 2c, respectively. The results show a power increase in WTGa2 when the upstream wake edge was located just off the edge of the rotor. The expected power decrease during the fully waked condition was also present. However, the average flap moment also increased with the upstream wake located adjacent to the downstream rotor edge and decreased when WTGa2 was fully waked.

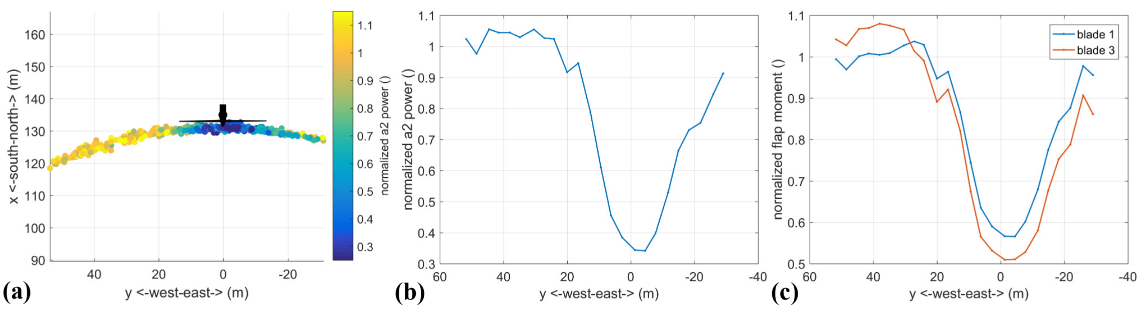

Figure 2. WTGa2 behavior with a DTU SpinnerLidar measured WTGa1 wake center within a lateral distance of 2D using 1-minute time bins: (a) measured wake center colored with normalized power, (b) bin-averaged normalized power vs spanwise position of WTGa1 wake, and (c) bin-averaged normalized blade root flap moments vs position of WTGa1 wake.

4. Conclusion

The detailed analysis and data in this study will help to quantify the impact of the waked condition on wind turbines. Initial results quantify the impact of the upstream wake on WTGa2 power output and average blade root flap moments in various waked conditions. A power increase was observed when the wake was located next to the rotor edge with an increased average root flap moment. A large power decrease also occurs in the fully waked condition. The final study will include the average flap root bending moment, root fatigue loading, nacelle acceleration, and power measurements as quantities of interest. This work will help assess the trade-offs between power and loads for a turbine in various waked conditions.

5. References

[1] Nygaard N G 2014 Wakes in very large wind farms and the effect of neighbouring wind farms *Journal of Physics: Conference Series* **524** 012162.

[2] Frandsen S T 2007 Turbulence and turbulence-generated structural loading in wind turbine clusters. Risø-R-1188(EN).

[3] Berg J, Bryant J, LeBlanc B, Maniaci D C, Naughton B, Paquette J A, Resor B R, White J and Kroeker D 2014 *32nd ASME Wind Energy Symposium*: American Institute of Aeronautics and Astronautics.

[4] Herges T G, Maniaci D C, Naughton B T, Mikkelsen T and Sjöholm M 2017 High resolution wind turbine wake measurements with a scanning lidar *Journal of Physics: Conference Series* **854.**

[5] White J R, Ennis B L and Herges T G 2018 Estimation of Rotor Loades Due to Wake Steering. In: *AIAA SciTech Wind Energy Symposium.*

Acknowledgments

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