Full-Scale Field Test of Wake Steering

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Abstract. Wind farm control, in which turbine controllers are coordinated to improve farmwide performance, is an active field of research. One form of wind farm control is wake steering, in which a turbine is yawed to the inflow to redirect its wake away from downstream turbines. Wake steering has been studied in depth in simulations as well as in wind tunnels and scaled test facilities. This work performs a field test of wake steering on a full-scale turbine. In the campaign, the yaw controller of the turbine has been set to track different yaw misalignment set points while a nacelle-mounted lidar scans the wake at several ranges downwind. The lidar measurements are combined with turbine data, as well as measurements of the inflow made by a highly instrumented meteorological mast. These measurements are then compared to the predictions of a wind farm control-oriented model of wakes.

1. Introduction

Wind farm (or plant) control is a field of research in which the controller of individual wind turbines located within a farm are coordinated. The objective of this coordination is to improve global power production by accounting for wake interactions, or similarly improved loads, or the provision of grid frequency support services such as inertia response or active power control. We refer to [1] for an in-depth overview of the current activities and research questions in wind farm control. Among the implementations of wind farm control gaining interest, yaw-based wake steering has shown promise as a method of improving wind plant power output by reducing wake losses. In this method, wakes are steered away from downwind turbines through deliberate yaw misalignment of upwind turbines [2].

Simulation studies using computational fluid dynamics (CFD) simulations of wind farms demonstrated this wake steering effect when turbines are yawed ([3, 4]), and that although the upwind turbine is expected to lose power by being yawed, the net power can go up based on the increased power of downwind turbines now out of the wake [5]. Later work expanded on these findings by using engineering models of wakes [6] coupled to system-engineering tools [7], revealing that a meaningful impact on a wind farm's annual energy production could be achieved [8].

There is a need for experimental field testing of wake steering to determine if the observed and predicted benefits of simulation can be realized. There have been tests conducted in wind tunnels that have thus far aligned with simulation predictions [9, 10]. Also, tests have been conducted at scaled wind farm facilities [2]. Finally, there are some preliminary results from test campaigns at commercial wind farms [11]. However, a critical need is filled by a detailed full-scale test in which a utility-scale turbine operates at various yaw offsets while its wake is measured. In this paper, we describe such a campaign and how it can be used to validate simulation results.

In this paper, lidar measurement results from the field-test campaign are compared with the predictions of a control-oriented engineering model of wind turbine wakes. The model is not tuned to the field-test data, but was instead tuned beforehand to CFD data [6]. A first contribution of the paper is a validation of important aspects of engineering models of wake control. We note here that, at this time, this is a preliminary validation of the larger-scale effects, and that detailed validation using rigorous practices, such as uncertainty quantification, is the subject of future work.

Additionally, recent research using CFD has suggested that the wake shape and relationship to atmospheric stability ([12, 13]) can be critical in ensuring the correct implementation of wake steering. A second contribution of this paper is a first comparison of wake shape versus atmospheric conditions and yaw setting.

Finally, it has been proposed that some potential difficulties in wake steering, such as model uncertainties and disturbances, can be overcome by making use of a lidar system and feedback controller. The lidar system provides wake position information and a closed-loop wake redirection controller sets the yaw for the turbines [14]. A final contribution of this paper is to demonstrate the ability of a rear-facing, nacelle-mounted lidar (as would be used in wind farm control) to detect and characterize wakes for use in a control system.

This paper is structured as follows. Section 2 briefly describes the wake steering models for comparison. The test setup is described in Section 3. Section 4 describes data processing. Finally, Section 5 covers the results and discussion and conclusions are provided in Section 6.

2. Models of wind farm control

In the literature, there are many models of wind farms used to understand turbine wake interactions. One category of these models is known as "control-oriented modeling," and these models are meant to be computationally inexpensive, such that they can be used inside a controller or optimization routine. These models contain descriptions of wakes, including the effect of changes of turbine control and atmospheric conditions on the wake behavior. Examples of models like this include that of [15], [16], and [6]. The latter model, known as FLOw Redirection and Induction Steady State (FLORIS), was developed by the National Renewable Energy Laboratory (NREL) and the Delft University of Technology. This model will be used in this paper to provide insights into the lidar data in yawed and nonyawed conditions.

The FLORIS model is an augmentation of the Jensen model [17], with the model of wake steering provided by [3] and the division of the wake into zones. It predicts the average steady-state behavior of wakes, and accounts for the impact in changes in yaw as well as pitch and torque control. More recently, the model was updated to include the impact of certain atmospheric stability [13], and improvements to the model are still ongoing, based on field campaigns discussed here, as well as being informed by recent results from other institutes (for example, [12] and [15].)

The FLORIS model is tuned to match the simulation results performed in CFD simulations of wind farms, particularly NREL's Simulator fOr Wind Farm Applications (SOWFA) wind farm simulation tool [18]. Later, comparisons will be made between field-test data and the FLORIS model, wherein the FLORIS model has not been retuned to match the experimental data).

3. Experimental setup

In this field-test campaign, a utility-scale turbine is run with a yaw misalignment while a nacelle-mounted lidar continually scans the wake. This campaign began in September 2016 and is ongoing. In this section, we describe the turbine, nearby meteorological mast, and the lidar system employed. Finally, we describe the testing procedure.

Figure 1: The U.S. Department of Energy (DOE) 1.5 turbine at the National Wind Technology Center is shown with the University of Stuttgart lidar being installed. Photo by Dennis Schroeder, NREL 38271

3.1. General setup of field testing

The test turbine and meteorological (met) tower are located at the National Wind Technology Center in Boulder, Colorado. The site is located near and to the east of the Rocky Mountains, where flow from the mountains to the west is the predominant wind direction.

The turbine used in this test campaign is the DOE 1.5, a GE 1.5 SLE owned by the U.S. Department of Energy (DOE) and operated by NREL (shown in Figure 1). Details of the turbine are provided in Table 1.

Rated Power (kW)	1500
Hub Height (m)	80
Nominal Rotor Diameter (m)	77
Rated Wind Speed (m/s)	14

Table 1: Test Turbine Details.

The met tower is located 161 m in the predominant upwind direction of the turbine at a bearing of 276° relative to true north. It was instrumented in accordance with International Electrotechnical Commission 61400-12-1. Table 2 lists some of the met tower instrumentation by tower elevation. All booms are pointing in the 278° direction. In addition to the met tower, the turbine nacelle wind speed and wind direction are time-synchronously measured and recorded with the met tower instruments.

In this work, test data are limited to a cone of directions in which the met tower is relatively upwind with respect to the turbine. We use the hub-height wind speed and direction measurements to describe mean wind speed, direction, and turbulence intensity, whereas veer will be described using the 38 m and 87 m wind directions.

Instrument	Elevations (m)
Precipitation	1
Wind Speed	38, 55, 80, 87, 90, 92
Wind Direction	38, 87
Humidity	90
Temperature	38, 90
Barometric Pressure	90

Table 2: Met Tower Instrumentation Details.

3.2. Lidar specification

Figure 2: The University of Stuttgart lidar installed on the DOE 1.5 turbine. Photo by Andrew Scholbrock, NREL

The Stuttgart scanning lidar system was developed in 2008 for nacelle measurement campaigns to redirect the laser beam of a standard Windcube lidar system [19]. The complete system consists of two parts: a Windcube V1 from Leosphere and a scanner unit developed at the University of Stuttgart. A picture of the lidar from the University of Stuttgart is shown in Figure 2. Because the original Windcube was designed for site assessment with its beam pointing upwards, a two-degree-of-freedom mirror for redirecting the beam in any position within the mirror's range was installed in a second casing. The accessible area is a 0.75 D-by-0.75 D square in 1 D distance. The modified software allows up to 49 measurement positions and 5 scan distances to be used. Further, the scan rate depends on the number of pulses used for each measurement position. The lidar system has been successfully used for several inflow measurements for lidar-assisted control and wake measurements.

The lidar performs a grid measurement pattern to record the wake with a 1 Hz sampling frequency. In five different distances (1 D to 2.8 D), the wind flow is measured (as depicted in Figure 3). At each measurement point, the lidar uses $10,000$ laser pulses to measure the line-of-sight wind speed, v_{los}, that is a projection of the three wind vector components $[u, v, w]$ onto the laser beam.

The complete scan pattern consists of 49 points in each scan plane, and the five planes are

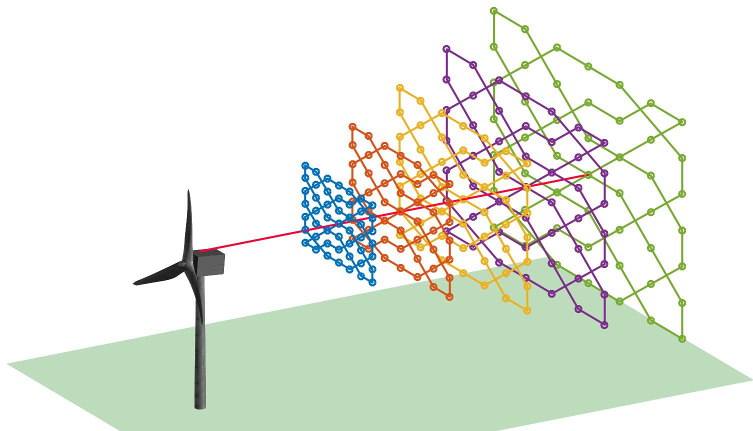

Figure 3: Visualization of the lidar scan pattern that is used to measure the wake behind the wind turbine. The lidar is measuring with a sampling frequency of 1 Hz simultaneously in five distances from 1 to 2.8 times the rotor diameter (D).

measured simultaneously. One scan takes an average of 48 s to complete. In this work, we refer to one scan, as one of these 48 s scans. In the upcoming analysis, scans of similar characteristics are aggregated to produce a mean or median scan for some conditions.

3.3. Field-testing procedure
The field test of wake steering was accomplished by implementing an outer control system above the built-in turbine control system. This control system would cause the turbine yaw control to track misaligned positions or offsets. These offset positions were changed every hour, and always included the baseline of zero offset in regular rotation. This practice helps ensure that for post-processing, each offset position can be compared with baseline operation in similar inflow conditions. Note that as Figure 4 shows, this target is tracked, but not perfectly, given wind direction variability and the limitation of the yaw controller. Therefore, analysis in this paper will be limited to periods when the target and actual yaw angles are close.

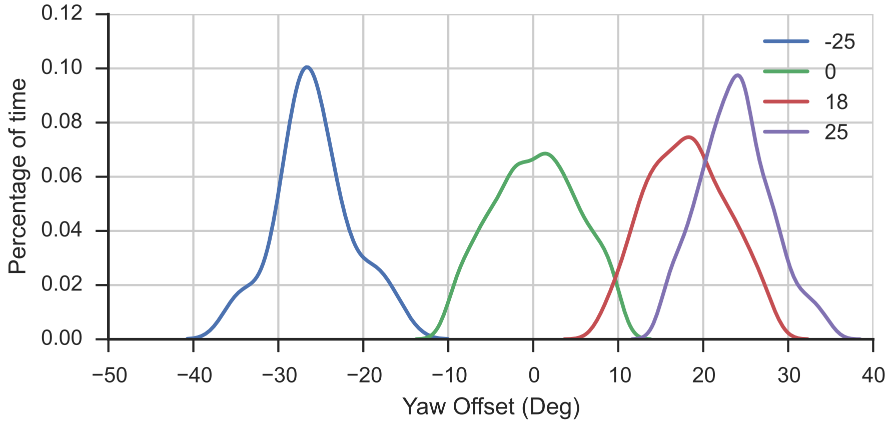

Figure 4: Percentage of actual time at a given yaw position grouped by the target yaw position.

Additionally, the lidar, located at the back of the GE1.5 SLE turbine facing downwind, is mounted on a rotational frame, which is motorized with a linear actuator. The same outer control system pivots the lidar opposite the yaw offset target. This setup allows the lidar to be directed downwind while the wind turbine is yawed.

4. Data processing

Processing of the recorded data is important to this work, which is briefly reviewed in this section. First, the recorded lidar measurement data are processed to filter out implausible data. Several methods are applied to check for hard target measurements, filter out lidar data with a bad carrier-to-noise ratio, and check for plausibility of the measurement data. All processed lidar data are grouped into scans, and combined with statistics of turbine and met mast sensor data, such as mean and standard deviation, over the period in which the scan is collected.

Finally, the data are filtered to include only certain conditions, including periods in which the met tower is nominally upwind of the turbine; periods in which the turbine is producing at least 100 kW, to eliminate faults and idling; and periods in which the target and realized offset are close.

At the time of this writing, there were approximately 15k scans completed, and the above filtering process reduces this to a set of approximately 1.5k scans to be used in this analysis, of which approximately half are aligned and half are yawed. For the analysis, all lidar scans belonging to a group (for example, scans of 8 m/s inflow while yawed) are aggregated, by finding the median velocity of each point. Median was used, and not mean, in order to diminish the impact of outliers.

5. Results

As described earlier, the results in this paper will be presented in comparison with predictions from the FLORIS model of wind farm control. The comparisons will be made with respect to the following key model properties: wake deflection, wake deficit and recovery, power loss from yaw offset, and atmospheric influence and wake shape.

5.1. Wake deflection

We first compare the wake deflection predicted by FLORIS with what is observed by the lidar. As stated earlier, the FLORIS model of deflection is based on [3], and predicts deflection at a given distance downstream as a function of coefficient of thrust and yaw angle.

In Figure 5, the median scan at 8 m/s wind for the first four ranges (with blue indicating low wind speed, and red faster wind speed) is compared with the deflection predicted by FLORIS (indicated by a green disk of the size of the turbine rotor). The model and test data show relatively good agreement. Note,for example, that FLORIS predicts nonzero deflection in the aligned case, which is observed in the lidar data. Also, the model predictions and observations are in agreement, showing that significant deflection has occurred by 1.5 D. Note that at the 1D range, the lidar scan is largely within the wake. However, a difference in deflection between aligned and offset operation can be observed on the left edge of wake.

5.2. Recovery and deficit

A second analysis can be made with predictions of the velocity deficit and its rate of recovery as the wake progresses downstream. Using the same aggregated scans shown in Figure 5, the average velocity within the disk area predicted by FLORIS can be computed. This average can then be compared with the same average velocity that would have been computed in the same way within FLORIS. This comparison is shown in Figure 6.

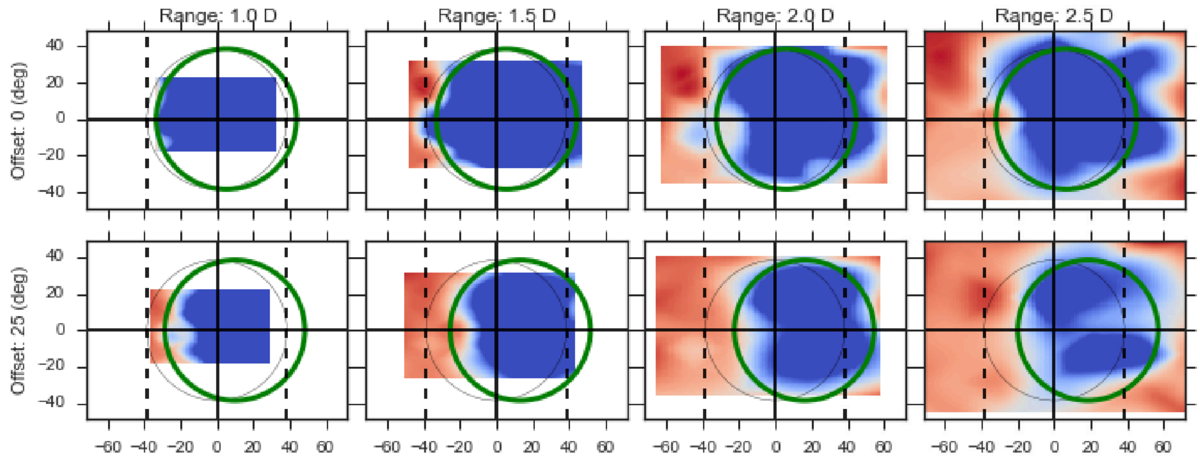

Figure 5: Median scans of the wake at 8 m/s for aligned and yawed conditions. The green circles indicate the position of the wake predicted by SOWFA/FLORIS.

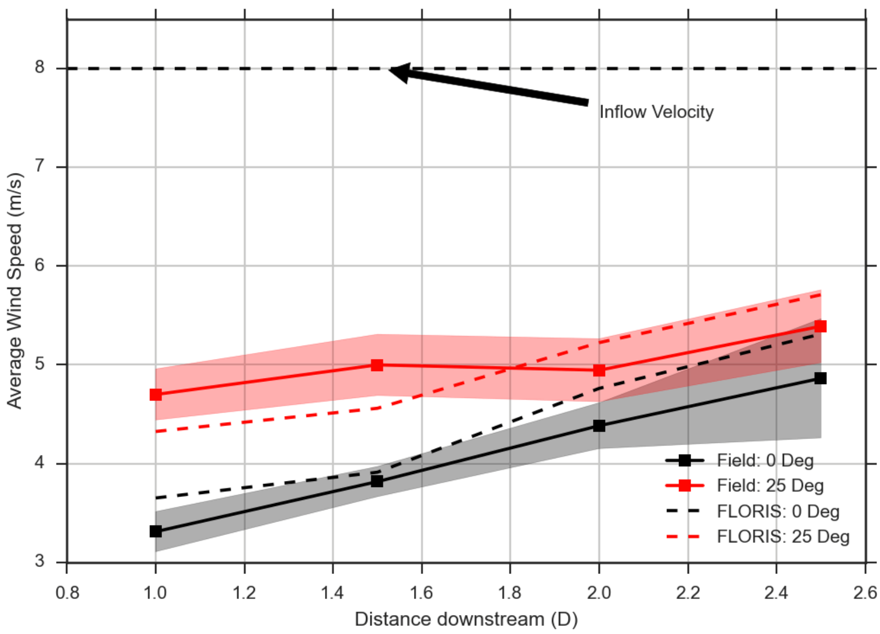

Figure 6: Comparison of the deficits predicted by FLORIS with those of observations. The deficits from field tests are computed by averaging over the circles shown in Figure 5. Additionally, to indicate some range of possibilities, for each range, 10 separate median scans are made from a random subset of all scans, and the standard deviation of the 10 aggregates provides the band radius. Finally, the values predicted from FLORIS, using the same approach of averaging over the rotor disk, are shown.

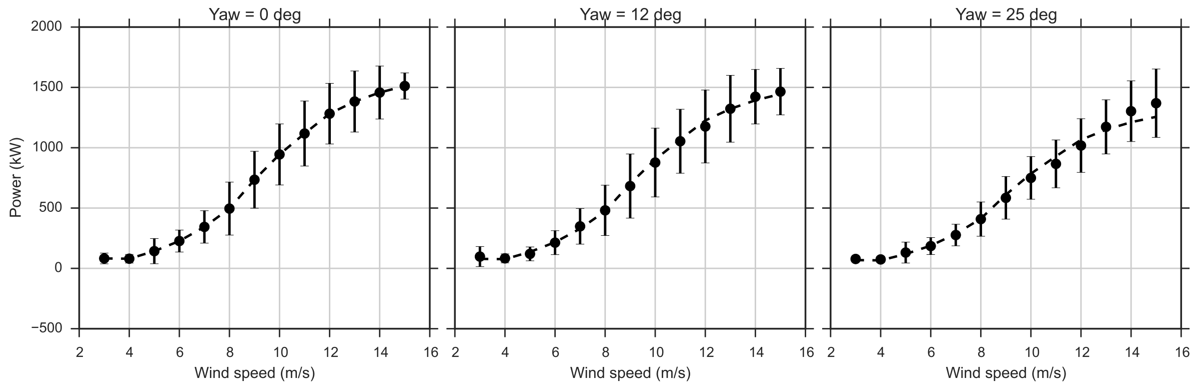

Figure 7: Comparison of the observed power curves for three yaw operating points to those assumed by FLORIS. The dashed lines are power curves drawn assuming the power loss of cosine of yaw with exponent 1.88. The points show the mean and standard deviation of observed powers.

Although the results shown in Figure 6 are not an exact match, the overall initial deficit level at 1D, the rate of recovery, and the difference in velocity between aligned and yawed conditions, are reasonably similar between model predictions and field-test data.

5.3. Power

Another important value predicted by FLORIS is the rate by which a turbine loses power because of yaw misalignment. FLORIS uses the standard rule that power is lost according to the cosine of the yaw misalignment raised to a certain exponent. Through comparisons with SOWFA, this exponent (called pP) has been fit to 1.88 [6]. In Figure 7, this function of power loss is compared with the data. The results show reasonable agreement.

5.4. Influence of the atmospheric stability and shape

A final comparison with FLORIS can be made with respect to the shape of the wake. In [13], the FLORIS model is extended to predict that the shape of the wake will go from circular to a skewed ellipsoid in the presence of veer.

In Figure 8, the scans of the wake at 7 m/s are divided by a simple function of veer, which compares the difference between the wind direction measured at 87 m and 38 m and divided the data into groups depending on the size of this difference.

Additionally, a contour algorithm is used to describe the shape of the wake in greater detail. Determining contours of wake data can be achieved through different methods and present an important method for quantifying wake behavior. Determining the “center” of a wake can be challenging when wake cut-throughs take shapes such as the bottom right of Figure 5 or in Figure 8, and contours provide a way to describe a wake shape within a given slice. Observing the contours in Figure 8, the skewing impact of veer can be observed.

In this analysis, contour detection algorithms for wake tracking are used mainly for identifying a wake shape visually, however, contours present a good opportunity for implementing systematic comparisons between wake models and test data and are the subject of ongoing research and development [20].

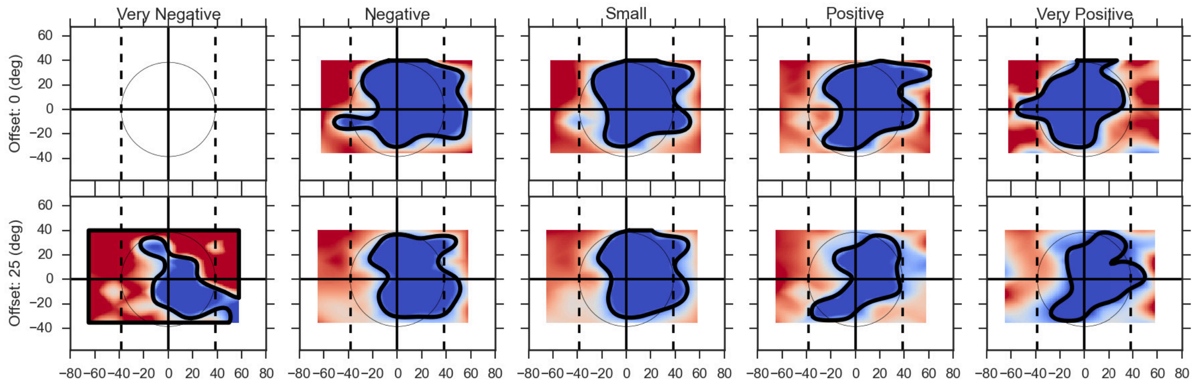

Figure 8: Using contour detection to demonstrate the change in wake shape under different veer conditions. The data is divided by the amount of difference in velocity between wind direction measurements at two heights.

6. Conclusions

In this work, the preliminary results of a field test of wake steering at full scale are reported. The wake of a full-scale turbine is measured by a lidar and compared to the predictions of FLORIS, a control-oriented wake model used in the design of wake steering controllers. Comparisons in terms of the key predictions of FLORIS, wake deflection, wake deficit and recovery, power loss, and wake skew, indicate good agreement between the model and observations. FLORIS simulations indicate wake steering can make a positive impact on wind farm annual energy production (AEP), and this work helps to validate the conclusions of AEP studies such as [8].

The results reported in this paper are based on the data that were available at the time of writing. However, the field test is ongoing and future results can be better converged when based on the larger data set. Additionally, this full data set will be made publicly available on the Atmosphere to Electrons Data Archive and Portal (https://a2e.energy.gov/about/dap).

An important aspect of future work will be to characterize the wake shape from field data. The relationship between veer and wake skew was demonstrated in this study, however, the tendency of the wake of a yawed turbine to form a kidney-bean shape (as discussed in [12]) was observed clearly in the full data, but is not currently modeled in FLORIS and was considered outside of the current scope of work.

Additionally, future work will employ a more rigorous approach to quantify the performance of wake models with respect to field measurements. Following the completion of data collection and quality control, a thorough quantitative analysis can be undertaken.

Finally, although this work has focused on validating reduced-order wake models to predict the wake behavior under wake steering control, it is possible that a wake control strategy will need direct wake measurement to operate fully. Therefore, this work can also be seen as aligning with other activities that focus on a closed-loop wake redirection concept based on direct lidar feedback of wake position. A first controller concept was introduced in [14]. Further, a $\mathcal{H}_\infty$ controller design approach for closed-loop wake redirection was described in [21]. To provide real-time wake tracking with lidar data, we refer to [22], wherein a model-based approach was presented and successfully tested to track the wake center. An application of this work demonstrates the ability of a scanning lidar to measure and estimate wake properties.

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