Lidar-assisted yaw control for wind turbines using a 9-beam nacelle lidar demonstrator

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Abstract. In this study, the relationship between lidar-assisted yaw control and the measurement parameters was clarified using an experimental approach. To investigate the influence of the nacelle lidar configuration on lidar-assisted yaw control, two scan patterns and pulse-integration number settings were varied. The field tests revealed that, in most cases, the relative wind direction was reduced by the lidar-assisted control. The condition with high lidar data availability avoids the influence of noise, and the lidar-assisted control reduces the relative wind direction. These results suggest that in lidar-assisted yaw control, the management of the appropriate lidar data availability is more important than the scan pattern.

1. Introduction

The lidar-assisted control of wind turbines using nacelle-mounted lidar is expected to improve various types of wind turbine control. To date, several lidar-assisted control concepts have been proposed. Scholbrock et al. [1] showed that lidar-assisted control can greatly decrease the energy cost of wind turbines and may reduce the wind turbine loads and increase energy production. Schlipf et al. [2] also proposed some wind turbine control concepts using nacelle-mounted lidar via a simulation approach. It is important to optimize the lidar measurement parameters and configuration because the control functions affect the lidar performance. Simley et al. [3] and Mirzaei et al. [4] tried to optimize the lidar scanning pattern required for lidar-assisted control using a theoretical approach. However, this approach has some limitations, difficult to reproduce the measurement error due to the passing of turbine blades, weather condition and turbulence.

The evaluation of lidar-assisted control based on experiment is complementary to theoretical approaches and beneficial for the development of lidar and lidar-based control systems. In this study, effective lidar configuration and measurement parameters were examined in field tests of wind turbine yaw control. Several reports have shown that a lidar-assisted control system is effective for yaw control. For example, Fleming et al. [5] showed that the power capture can be improved by correcting the wind vane measurements with lidar observations using a two-beam pulsed lidar. Scholbrock et al. [6] improved the power capture of wind turbines by incorporating a continuous wave lidar signal directly into the yaw controller without using a yaw bias correction function. However, these studies did not report the effective nacelle lidar measurement parameters for control. To develop a theoretical approach for lidar-assisted control, it is useful to discuss field tests with more lidar models and measurement parameters.

The purpose of this study is to clarify the influence of the scanning patterns and measurement parameters on lidar-assisted control by a nacelle lidar with nine telescopes in a field test. We used a demonstration nacelle lidar that can change its scanning pattern to investigate the influence of the number of lidar beams on the yaw control. The two-beam lidar is a simple and typical lidar configuration that has been also used for wind turbine power performance measurements [7] [8] and lidar-assisted
control field tests. The lidar configuration was compared to the highest spatial resolution, i.e., a 9-beam configuration.

2. Experimental Setup

2.1. Test field and wind turbine

This study was conducted at the test field of the Fukushima Renewable Energy Institute of the National Institute of Advanced Industrial Science and Technology (AIST). Figure 1(a) shows a bird’s eye view of the test field. One Komaialtech Inc. upwind turbine (KWT300) [9] was erected on the test field, and a Mitsubishi Electric Corporation prototype nacelle lidar unit was mounted on the nacelle. The wind turbine diameter \(D\) was 33 m, and the hub height was 41.5 m. The direction of the prevailing wind on the test field was northwest. A Mitsubishi Electric Corporation DIABREZZA_W ground-based doppler lidar [10] (ground lidar) was installed at a position 285° and 80 m \((2.4 D)\) away from a wind turbine. This lidar was capable of acquiring the vertical wind profile. Although it would have been desirable to install a meteorological mast on the test field to acquire a reference wind speed, there was insufficient installation space, so the ground lidar was used instead. Figure 1(b) shows wind speeds and turbulence intensities during the test period measured by the ground lidar. Since this test field is classified as complex terrain, high turbulence intensity was often observed.

(a) Test field and lidar arrangement  
(b) Turbulence intensity distribution  
(April to May, 2018)

![Figure 1. Test field and wind turbine (map imagery copyright Google 2019).](image)

2.2. Nacelle lidar

A doppler lidar is a device that irradiates an atmospheric volume with a laser and receives the light reflected from the aerosols contained within that volume. By measuring the resulting doppler shift by heterodyne detection, the line-of-sight (LOS) wind speed can be determined. The measurable wind speeds are limited to LOS wind speed \(v_i\), where \(i\) is the number of beams. Therefore, the determination of the wind speed components requires data of the LOS wind speed in multiple directions to solve the corresponding equation. Figure 2 shows an outline of a measurement system. The nacelle lidar has nine telescopes installed facing different directions, switching the telescope used by optical switch. This makes it possible to radiate beams in nine LOS directions (numbers 0 to 8).

In this study, the \(x\)-axis was defined as the central axis of the lidar (corresponding to LOS 0 in Figure 2). The wind turbine is under yaw control, so the \(x\) and \(y\)-axes rotate together with yaw direction. The opening angle, \(\phi_1\), between the center beam and the left and right beams was 15° (Figure 2(b)), and the
opening angle, $\varphi_2$, between the top and bottom beams and the center beam was 10° (Figure 2 (c)). Unlike nacelle-mounted cup anemometers, the lidar measures the average wind speed components within a wide probe volume. The length of the probed volume in the $x$-axis direction (probed length), as shown in Figure 2(a), was equal to 30 m. The lidar divides the LOS into 30 m intervals and, then, simultaneously measures the LOS wind speed in each range. The number of simultaneously measurable ranges was 20. Each range overlaps the other by 50% to increase the spatial resolution in the $x$-axis direction. The measurement range closest to the origin point (range 0) was $-80 < x < -50$ m. The wind speed components in the $x$ and $y$-direction ($V_x$, $V_y$), as shown in Figure 2(b), were calculated from the LOS wind speeds measured by beams opening to the left and right of the center. The LOS wind speeds $v_4$ and $v_5$ measured by LOS 4 and 5 are expressed by equations (1) and (2) using $V_{x,j}$ and $V_{y,j}$ ($j$ at each measurement positions), $V_x$ and $V_y$ are the inside probed volumes, and they are assumed to be temporally and spatially uniform (equations (3) and (4)), so $V_x$ and $V_y$ were calculated using equation (5). The nacelle lidar has three sets of left and right beam pairs ((LOS1, 3), (LOS4, 5), and (LOS6, 8)) , thus, can compute wind speed vector at three heights. The role of the center beam is to measure $V_x$ directly, which is helped to compensate for side beam signal loss.

$$v_4 = -V_{x,4} \sin \varphi_1 + V_{y,4} \cos \varphi_1 \quad (1)$$

$$v_5 = V_{x,5} \sin \varphi_1 + V_{y,5} \cos \varphi_1 \quad (2)$$

$$V_x = V_{x,4} = V_{x,5} \quad (3)$$

$$V_y = V_{y,4} = V_{y,5} \quad (4)$$

$$V_x = \frac{v_4 + v_5}{2 \cos \varphi_1} = v_0, \quad V_y = \frac{v_5 - v_4}{2 \sin \varphi_1} \quad (5)$$

![Figure 2. Nacelle lidar configuration.](https://example.com/figure2.png)
to noise (SN) ratio of the nacelle lidar signal is 7 db or less, it was treated as invalid data (this threshold is a device standard setting and cannot be changed). A small number of pulse integrations increased the sampling rate while reducing the SN ratio.

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**Table 1. Specification and measurement parameter of nacelle lidar.**

| Specification                                      | Parameter | Value     |
|----------------------------------------------------|-----------|-----------|
| Laser source                                       | Laser light wavelength | 1.5 µm    |
| Number of pulse integrations (Time required for LOS wind speed sampling) | 8000 (0.5s) | 4000 (0.25s) |
| Time required for beam switching                    | Approximately 0.15 s |
| Scanning pattern                                   | controllable |

Various types of nacelle lidars are being developed worldwide; thus, in research into remote sensing devices for wind turbines, it is crucial to identify the optimal nacelle lidar configuration and the measurement parameters for wind turbines. Borraccino et al. [11] arranged continuous wave and pulsed doppler lidar arrays on a nacelle and compared their performance. Unlike this approach, the nacelle lidar demonstrator was possible to reproduce various scanning patterns with one doppler lidar by controlling the number of telescopes used. In this field test, two scanning patterns were reproduced, and the effects of these patterns on the control were examined. Because this lidar demonstrator was not commercial, this scanning pattern control system, which is not a standard function of doppler lidar, was added only for the purposes of this study.

A typical example of a measurement with a pulsed nacelle lidar involves the emission of beams in two directions at the hub height. This measurement method is simple and allows for inexpensive system construction, although the measurement volume is limited to the hub height. The scanning pattern of the nacelle lidar used in the field test and the time required for one measurement cycle are shown in Figure 3. In two-beam mode, only two telescopes were used, and the measured LOS was limited to \( v_4 \) and \( v_5 \). The performance of the two-beam mode and nine-beam mode, in which all telescopes are used, was compared in the field test. The nine-beam mode sequentially measures the LOS wind speed (\( v_0 \) to \( v_9 \)) and calculates the wind speed vector at three heights. Although it is possible to observe the wind profile in front of the rotor, a relatively long measurement cycle time is required. The parameters for the number of pulse integrations were 8000 for the two-beam mode and 4000 for the nine-beam mode. More pulse integration increased the SN ratio, making it easier to detect the signal, even if the aerosol particles were present in insufficient concentration. In the nine-beam mode, the number of pulse integrations was set to 4000 because the many telescopes were used and this parameter setting increases the time required for one measurement cycle. The wind speed scanning time includes the LOS wind speed detection time and optical switching time (about 0.15 s). Consequently, the time required for one round of scanning was approximately 1.3 s for the two-beam mode and approximately 3.6 s for the nine-beam mode.

Because lidar data were often missing, it was necessary to eliminate statistically unreliable data. The data availability per unit time (\( \eta \)) is defined in equation (6). \( N_{\text{cycle}} \) is the number of measurement cycles per unit time, during which \( N \) is the number of times measurement signals were obtained.

\[
\eta = \frac{N}{N_{\text{cycle}}} \tag{6}
\]
2.3. Lidar-assisted yaw control system

In this study, the wind direction signals from the nacelle wind vane used for yaw control were replaced with those from lidar measurements upstream of the rotor and the verified lidar-assisted yaw control system. It is believed that there is an optimal value for the control threshold and data filtering method when performing lidar-assisted control. However, many measurement and control parameter changes result in complex analysis. Therefore, simple control system modifications where the nacelle wind vane and lidar measurements were replaced were applied.

The baseline wind-turbine-installed controller did not have functions for receiving signals obtained from the nacelle lidar and performing control calculations. Therefore, the controller was remodeled, and the ability to receive lidar measurements and perform control calculations was added. The nacelle lidar measurements were sent to an FTP server within the controller via ethernet. Furthermore, the nacelle wind vane measurements were input to the controller using an analog signal. A limitation of the lidar-based wind observation was that measurement signals are lost when there is a lack of atmospheric aerosols and when the beams collide with the blades. Consequently, the yaw controller used signals obtained from both lidar and a nacelle wind vane in the yaw control calculations. The control test was performed based on the following rules.

Figure 4 shows the yaw control diagram. At the beginning of control, the scanning patterns was selected. This was changed to two-beam or nine-beam mode every month. The signal input to the controller has been switched to the wind direction with respect to the x-axis (relative wind direction) measured by the nacelle wind vane $\theta_{\text{nacelle}}$ or lidar $\theta_{\text{lidar}}$ according to conditions. Because the signal strength of nacelle lidar measurements is mainly dependent on the weather, it was almost impossible to obtain data depending on the time of day. The lidar measurements were replaced by the nacelle wind vane if the controller could not reference the lidar signals. When the weather was stable and the signal strength was sufficient (SN ratio > 7 db and 30-s-averaged data availability $\geq 0.7$), the nacelle lidar signals were input to the controller. In the next step, the controller refers to the relative wind direction and controls the wind turbine yaw. The yaw direction was adjusted to the set point when the 30-s-average relative wind direction exceeded $\theta_{\text{threshold}}$ or when the relative wind direction was greater than the $\theta_{\text{threshold}}$ for $t_{\text{threshold}}$ seconds.

NOTE: The threshold for this control in the verification system references a baseline control system, and we have not reported these values because these are confidential information. Those thresholds were not changed during the entire test period. Therefore, the threshold for control is not a study subject.
2.4. Test conditions

Table 2 shows the test conditions. The experimental period was three months, from March to May 2018. Baseline conditions did not use lidar signals and only the measurements from the nacelle wind vane were input to the controller. These experiments were carried out in March 2018. However, lidar measurements were continued to observe the offset between the wind vane and lidar measurements in this period. In April to May 2018, the yaw controller referencing the nacelle lidar measurements and the lidar-assisted yaw control was tested. The nacelle lidar scanning pattern was switched between the two-beam and nine-beam modes every month. The nine-beam mode derives the average wind direction of the rotor swept area, but, in this study, the yaw controller only refers to the wind direction at the hub height to simplify the research task.

### Table 2. Test conditions.

| Test period | Lidar scanning pattern | Input to yaw controller | Yaw control   |
|-------------|------------------------|--------------------------|---------------|
| March 2018  | Two-beam               | Only nacelle wind vane   | Baseline      |
| April 2018  | Two-beam               | Nacelle lidar (hub height, range1) or nacelle wind vane | Lidar-assisted |
| May 2018    | Nine-beam              | Nacelle lidar (hub height, range1) or nacelle wind vane | Lidar-assisted |

3. Results

3.1. Basic characteristics of nacelle lidar

If the availability of the nacelle lidar data was low, the nacelle wind vane measurements were input into the controller. Therefore, high data availability was important to utilize the lidar-assisted controller fully. Figure 5 shows the relationship between the 5-min-averaged LOS4 wind speed data availability and rotor speed in April–May 2018. Because the two-beam mode has numerous pulse integrations, the signal intensity was high even when the measurement beam collided with the blades. The nine-beam mode has a lower signal intensity than the two-beam mode because of the low pulse integration number, and the data availability was also low. The low rotor speed increased the time for the passing of one blade to block the measurement beam. The data availability of the nine-beam mode significantly depended on the rotor speed.
To confirm the validity of the nacelle lidar measurements, the measurements acquired using the nacelle lidar and ground lidar were compared. Because the ground lidar beam did not collide with the blades, the signal strength and measurement reliability were higher than those of the nacelle lidar. Figure 6 (a) and (b) show the relationship between the 5-min-averaged hub-height horizontal wind directions measured by the nacelle and ground lidar per scanning pattern. Because the measurement coordinates for the nacelle lidar were rotated with the yaw direction, the absolute wind direction was calculated by adding the yaw direction and the relative wind direction. To match the positions of the probed volumes for both types of lidar, only data sets with 5-min-averaged yaw directions in the direction of $(285 ± 30)°$ were evaluated. These black plots show cases outside this range. Furthermore, these plots correspond only to the cases in which the data availability exceeded 0.7 for both the nacelle and ground lidar. A linear relationship was maintained even with the wind direction obtained from both scanning patterns; however, differences appear in the coefficient of determination depending on the scanning pattern. Because the data availability of the nine-beam mode was lower than that of two-beam mode, the number of data samples per 5 min period was reduced. The low wind speed and low data availability cases contributed to the reduction in the coefficient of determination.

(a) Two-beam mode  
(b) Nine-beam mode

Figure 5. Relationship between 5-min-averaged data availability (LOS4) and rotor speed.

(a) Two-beam mode  
(b) Nine-beam mode

Figure 6. Comparison of 5-min-averaged wind directions measured by nacelle and ground lidar.
The nine-beam mode measured the wind direction at three heights, as shown in Figure 2(c). The wind veer [12] was calculated from the 5-min wind direction standard deviation at heights of 27 m, 41.5 m, and 55 m at $x/D = -2.4$. Figure 7 shows the relationship between the wind speed and wind veer in the nine-beam mode. As the availability of each height was different, only measurements with $\eta > 0.7$ were used for wind veer calculation. The bin-averaged wind veer was around 4° in all wind speed zones. It is possible that the non-perfect availability of the nine-beam mode affected large variations in the measurements.

![Figure 7](image_url)  
*Figure 7. The relationship of wind veer and wind speed.*

### 3.2. Lidar-assisted yaw control test

Figure 8 (a) shows the relationship between the 5-min-averaged relative wind direction and wind speed obtained by the nacelle lidar under baseline conditions colored by availability. In the case of the baseline conditions, the bin-averaged relative wind direction was approximately $15° - 20°$. Figure 8 (b) shows the averaged relative wind direction and wind speed measured by the nacelle wind vane under the baseline conditions. Figure 8(a) and (b) show the measurements of the same time period. The nacelle wind vane measured the air flow decelerated and deflected by the rotor, and the controller minimized $\theta_{nacelle}$. During baseline control, the offset of the wind vane and lidar measurements was clearly detected.

Figure 9 (a) and (b) shows the relationship between the 5-min-averaged relative wind direction and wind speed obtained by the nacelle lidar under lidar-assisted conditions colored by availability. Under these conditions, the controller minimized $\theta_{lidar}$ if there was no loss in the lidar signal. This result also shows that the average relative wind direction differs according to the scanning pattern. The 8000-pulse integration setting prevented signal loss during the experimental period and allowed the lidar measurement to be input to the controller for longer periods than in the 4000 pulse case. The bin-averaged relative wind direction in two-beam mode was approximately zero, which is a significant improvement over that under the baseline conditions. However, the reduction in relative wind direction during the nine-beam mode condition was lower than that of the two-beam mode. As shown in Figure 9 (b), when the availability was low ($\eta < 0.9$), the averaged relative wind direction was between those in Figure 8 (a) and Figure 9 (a) because the lidar measurements were not input into the controller. Focusing only on the plots with high availability ($0.9 < \eta$), the average relative wind direction is around zero, which suggests that the availability was an important factor in this experiment.

The minimization of yaw misalignment was expected to increase the power obtained from the horizontal wind speed measured upstream from the rotor. Figure 10 shows the power curve of the wind turbine during the field test. The horizontal axis indicates the hub height wind speed measured by the
nacelle lidar. To exclude unreliable data, only data at hub height with $\eta > 0.7$ were evaluated. The power obtained when the control method was changed varied, and the averaged power obtained when the controller referenced only the nacelle wind vane was the smallest. The curve of the nine-beam mode has a position between those of the curve of the baseline and two-beam modes. The average power curve increment (wind speed range 5–12 m/s) was 13% in two-beam mode and 9% in nine-beam mode compared to the baseline condition. Note that the increment is dependent on the baseline conditions; therefore, these results are unique to this wind turbine. Figure 10 (b) shows the 5-min-average power and wind speed colored by wind veer in the nine-beam mode. As wind veer calculations require three height data sets with $\eta > 0.7$, these datasets led to the power curve. These plots with wind veer of about 3° occupy most of the data and were consistent with the curve trend shown in Figure 10 (a). On the other hand, several large plots of wind veer showed lower power.

(a) Two-beam mode

(b) Nine-beam mode

Figure 8. 5-min-averaged relative wind direction (baseline condition) and wind speed.

(a) Lidar-assisted yaw control (Two-beam)

(b) Lidar-assisted yaw control (Nine-beam)

Figure 9. 5-min-averaged relative wind direction (lidar-assisted condition) and wind speed.
4. Conclusion
The effects of the scanning patterns and measurement parameters of the nacelle lidar on the lidar-assisted yaw control were investigated experimentally. In the case of high data availability, control gains were obtained regardless of the scanning pattern. Because the pulse integration number contributed to the lidar data availability, the data input switch function to the controller was dominated by this parameter. Thus, maintaining high lidar data availability is essential in terms of lidar-assisted yaw control. For the stable operation of lidar-assisted control, data interpolation and filtering are needed to compensate for the lack of lidar measurements.

In our experiments, the relative wind direction measured at only the hub height was input to the control system. Nine-beam mode was useful for wind veer analysis, but the advantages of the nine-beam setup were not fully exploited. It is important to consider the wind shear and veer of the rotor area to achieve efficient control a large wind turbine. In the future, it will be necessary to optimize the data availability and scan patterns using the wind profile as an input into the controller.

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