The influence of yaw misalignment on wind measurement using nacelle-mounted LiDAR

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1. Introduction

The prevalence of using LiDAR for wind measurements has increased as LiDAR technology has matured. In future, LiDAR is expected to be adopted as a common technique for wind data collection.

Recent research has validated the use of LiDAR measurements. Antoniou et al. has investigated the influence of wind shear on vertically-mounted LiDAR power curves [1], while Rozenn et al. has determined the power curves and turbulence when a two-beam nacelle-mounted pulsed LiDAR is utilized [2]–[4].

Nacelle-mounted LiDAR has begun to be used for wind turbine control, as it is advantageous for measuring the wind in front of the turbine and for estimating the wind flow into the turbine. Some researchers have simulated feed-forward turbine control using nacelle-mounted LiDAR measurement.

NREL has developed feed-forward blade pitch control for simulated load mitigation [5] and Mirzaei has developed feed-forward individual blade pitch control for the reduction of power fluctuation [6]. Another suggested LiDAR application is its use for improved energy capture, through better yaw tracking and capture point tracking[7].

LiDAR wind measurements and turbine control have been field tested. Schlipf *et al.* has conducted field tests of scanning LiDAR-assisted feed-forward pitch control, which revealed that feed-forward control was disadvantageous when obstacles in front of turbine disturbed the LiDAR measurements [8]. Scholbrock *et al.* also conducted field tests, but used an optical control LiDAR system [9]; the LiDAR-assisted control rejected wind disturbances at low frequencies.

2. Approach

In nacelle-mounted LiDAR, the yaw angle of LiDAR works together with the turbine, which may result in yaw misalignment. If the yaw misalignment is large, the measured wind and the inflow wind to the turbine could be significantly different. It is expected that the larger the yaw misalignment of the nacelle, the larger the wind estimation error will be. However, the influence of yaw misalignment on LiDAR measurements has not been verified.

Therefore, this study investigates the applicability of wind estimation using a two-beam pulsed LiDAR system under yaw misalignment conditions. By using LiDAR-measured wind data, a nacelle anemometer, and a metrological anemometer, the LiDAR wind speed estimation error was determined and correlated with yaw misalignment.

3. Main body of abstract

3.1 Wind measurement

The LiDAR field test was conducted at Wakamatsu, Japan in November 2013, and Figure 1 shows the general view of the field test site. The wind turbine was located near the shoreline.

Sonic anemometers, wind vanes, and LiDAR were set up on the turbine nacelle. The metrological mast was located 190.1 m away from the turbine and supported sonic anemometers, wind vanes, and various metrological instruments.

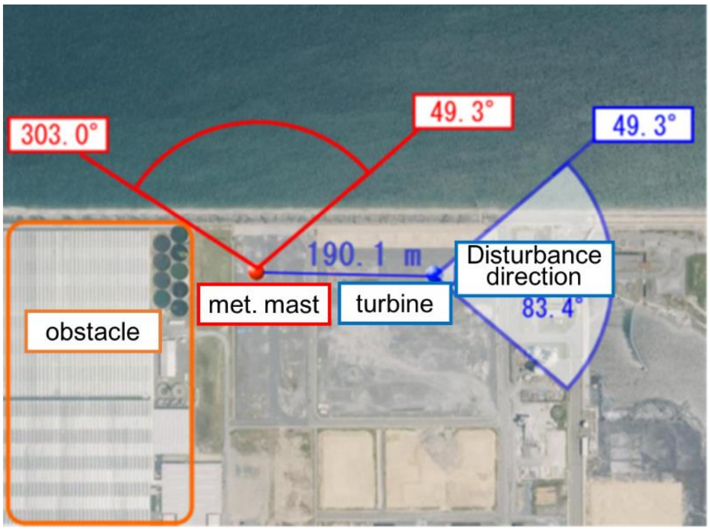

Figure 1 Field test site overview

The researched turbine was a J-100, manufactured by The JAPAN STEEL WORKS LTD., Japan. Table 1 shows the major specifications for the wind turbine.

Table 1 Wind turbine specifications.

Rated power	2,700 kW
Rotor diameter	103.4 m
Hub height	80 m
Rated Wind Speed	13 m/s
Cut-in wind speed	4.0 m/s
Type	Horizontal axis (upwind)

Wind Iris, provided by the Avent Lidar Technology, was used for the LiDAR measurements. The major specifications for the LiDAR system are shown in the Table 2.

Table 2 LiDAR system specifications.

Sampling rate	2 Hz
Laser source	Fiber pulsed laser 1.54 μm
Number of measurement distance	10 points (80, 130, 180, 230, 280, 320, 380, 430 m)
Speed accuracy	0.1 m/s
Direction accuracy	±0.5°
Opening angle	15° half angle

For this study, the measurement data was collected from 26/6/2014 through 18/12/2014. To compare wind data from different measurement distances, the data was interpolated and converted to 1 Hz data. Data was collected and averaged over 10-minute intervals for a total of 13,000 valid data points.

Firstly, we conduct the comparison between the 5 minutes averaged wind data measured by LiDAR (at 80 m in front of a turbine), a Nacelle anemometer, and a metrological mast in Figures 2 and 3. The wind speed between LiDAR and a mast were not much affected by yaw misalignment. This is because the measurement point of LiDAR and mast was pretty difference and the influence of the yaw misalignment was seemed to by little.

However, the wind speed between LiDAR and a nacelle anemometer was so influenced by the yaw misalignment Therefore the inflow wind speed would be measured by mistake when the yaw misalignment is large.

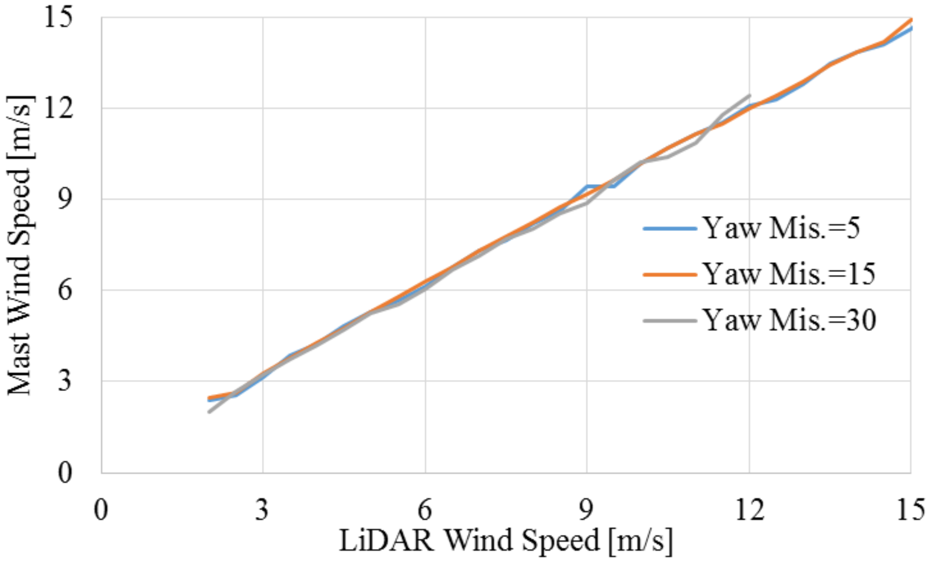

Figure 2 Comparison of mast wind speed and LiDAR wind speed

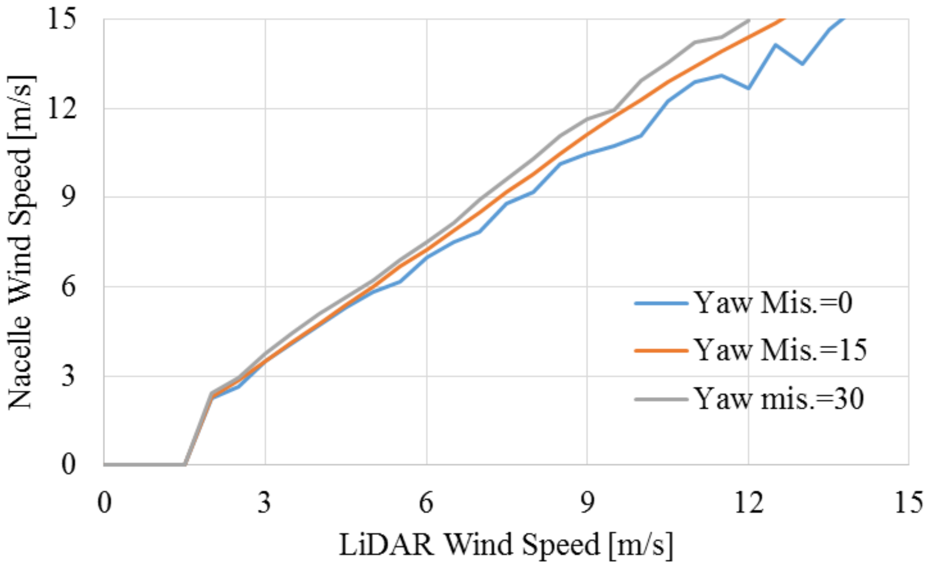

Figure 3 Comparison of nacelle wind speed and LiDAR wind speed

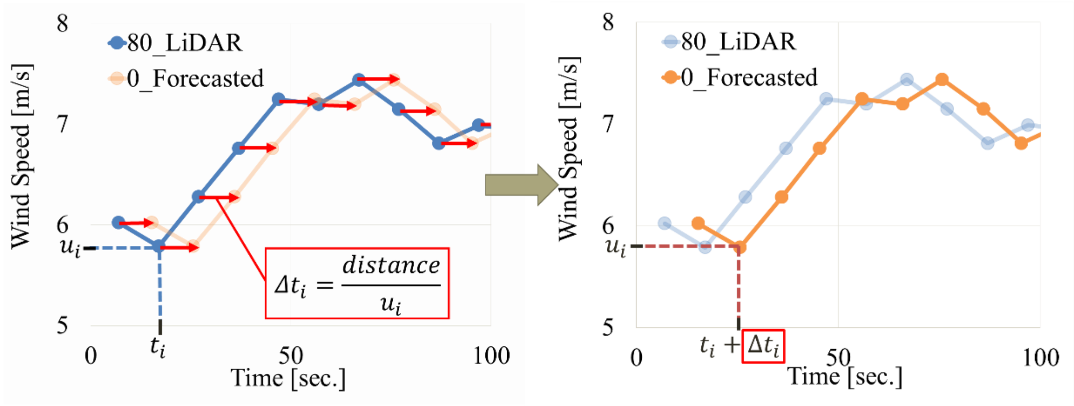

Figure 4 Outline of the wind estimation

3.2 Estimation method

We used a simple method for wind speed and direction estimation. The outline of the estimation technique is shown in Figure 4. For the estimation, Taylor's Hypothesis was applied, assuming wind movement and wind speed and direction were maintained. The transfer time, or lag-time, was calculated from Equation 1 for the every data point.

$$\Delta t = \frac{distance}{u_i}. \qquad \text{Equation 1}$$

All data points were delayed by Δt and interpolated in 1 s increments to facilitate measurement data comparison.

The wind estimation error (absolute error and simple error) was calculated using Equations 2 and 3.

$$absolute\ error = |u_{estimated} - u_{measured}| \qquad \text{Equation 2}$$

$$simple\ error = u_{estimated} - u_{measured} \qquad \text{Equation 3}$$

These errors were calculated for every 1 s of data and the bin mean values of the yaw misalignment were calculated and plotted. The distribution of the yaw misalignment for the 1 Hz-instantaneous data is displayed in Figure 5. Few data points registered a large yaw misalignment and were considered to be outliers. The total bin mean value remained below 600 s, so the discussion of the results focuses on the data collected between −35° and 50°.

We should note that the measurement of the yaw misalignment had 17° offset. So the median of the yaw misalignment was around 17°.

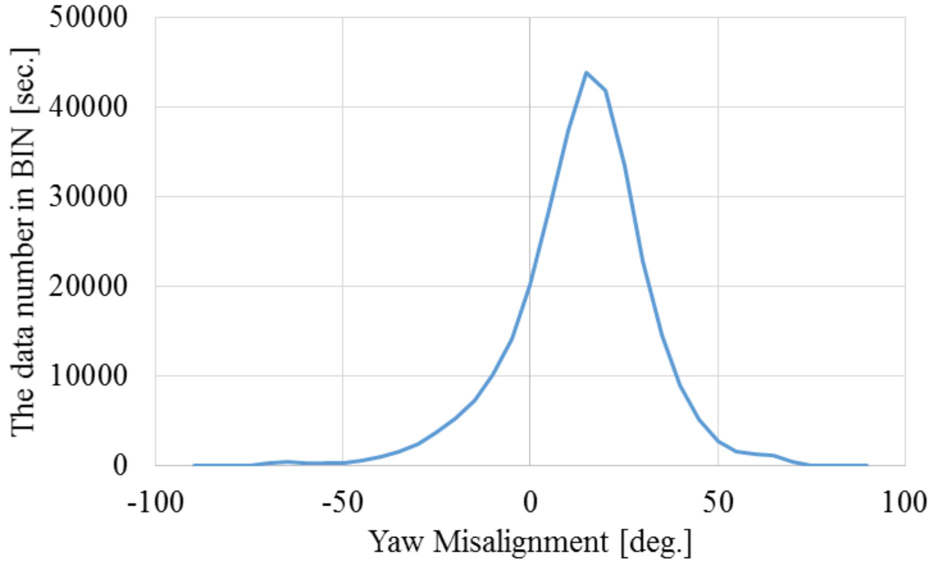

Figure 5 Distribution of the yaw misalignment

3.3 Influence of the yaw misalignment

In this study, we used wind data collected from 430 m in front of the wind turbine for wind prediction and the data collected from 380 m in front of the turbine for target prediction. The measurement location needed to be at least 3 D distant from the turbine, to prevent wind blockage by the turbine blades (D; the diameter of a turbine).

Before determining the LiDAR wind speed estimation error caused by the yaw misalignment, we confirmed that the estimation error was dependent on wind speed. Figures 6 and 7 depict the wind speed in relation to the bin mean LiDAR estimation error.

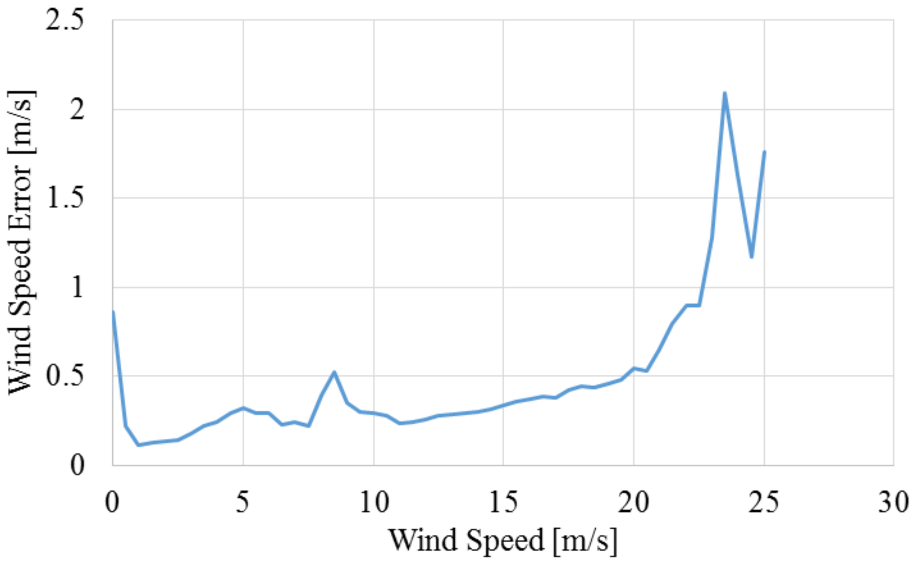

Figure 6 Influence of wind speed estimation error on wind speed (absolute error)

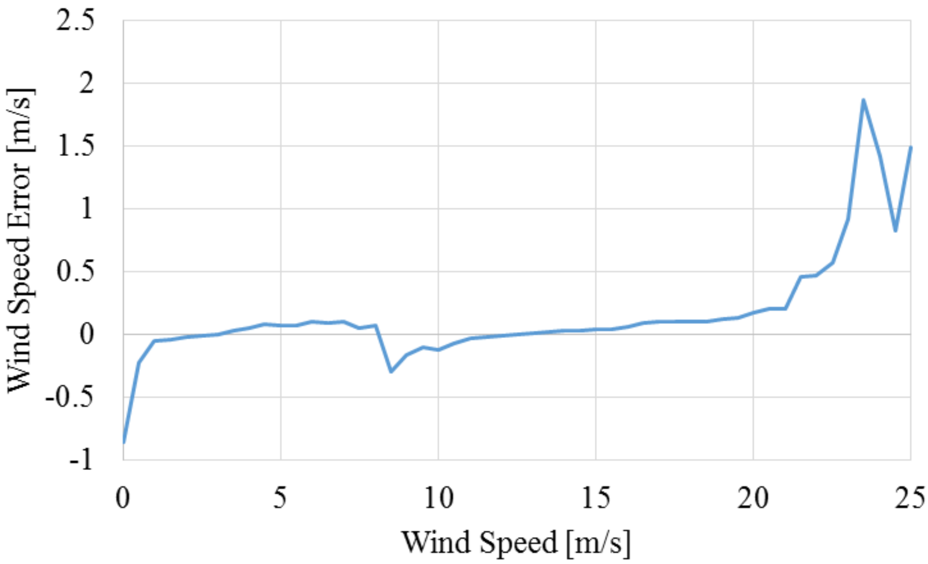

Figure 7 Influence of wind speed estimation error on wind speed (simple error)

Figure 6 indicates that wind speed had little effect on the absolute estimation error, although the error increased in proportion to wind speed. Figure 7 shows that the simple estimation error had little dependence on wind speed, except for data collected at wind speeds below 2.0 m/s and above 20.0 m/s. For wind speeds below 4.0 m/s, had such big error since they had long time while excursing to wind turbine. Although little data was collected for wind speeds above 20.0 m/s, the average bin values remained below 600 s.

Therefore, our study focused on data collected when the wind speed ranged from 4.0 to 20.0 m/s.

Figures 8 compare the bin mean values for the wind speed estimation against the yaw misalignment.

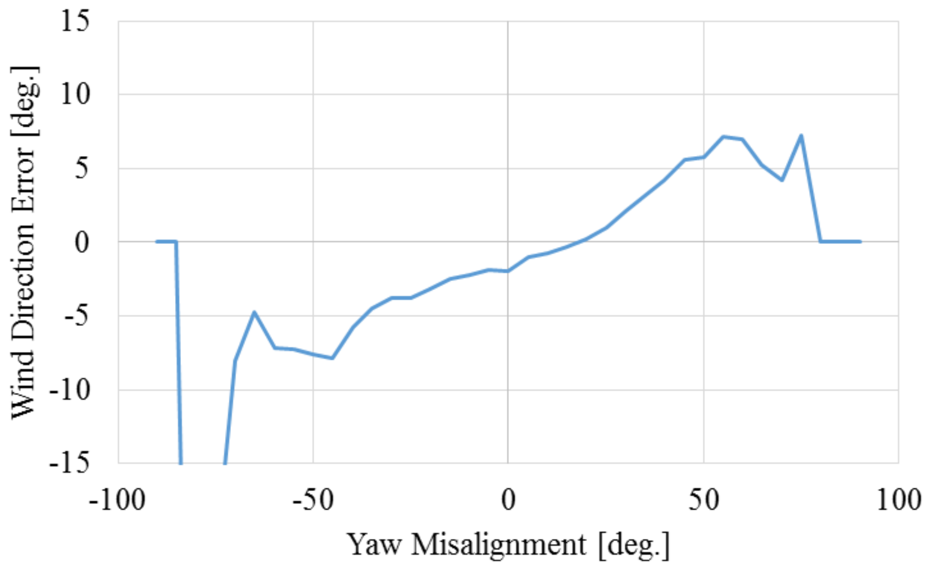

Figure 8 Influence of wind direction error on yaw misalignment (simple error)

Figure 8 indicates that the simple wind direction estimation error was affected by the yaw misalignment; the wind direction transited lower as the wind taken into the turbine decreased. Although, at this stage, we could not definitively determine the dependence of the direction estimation error, the results could still be used to correct the wind direction estimation error based on its relation to the yaw misalignment.

Figures 9 and 10 illustrate the relation between the wind speed estimation error and the yaw misalignment.

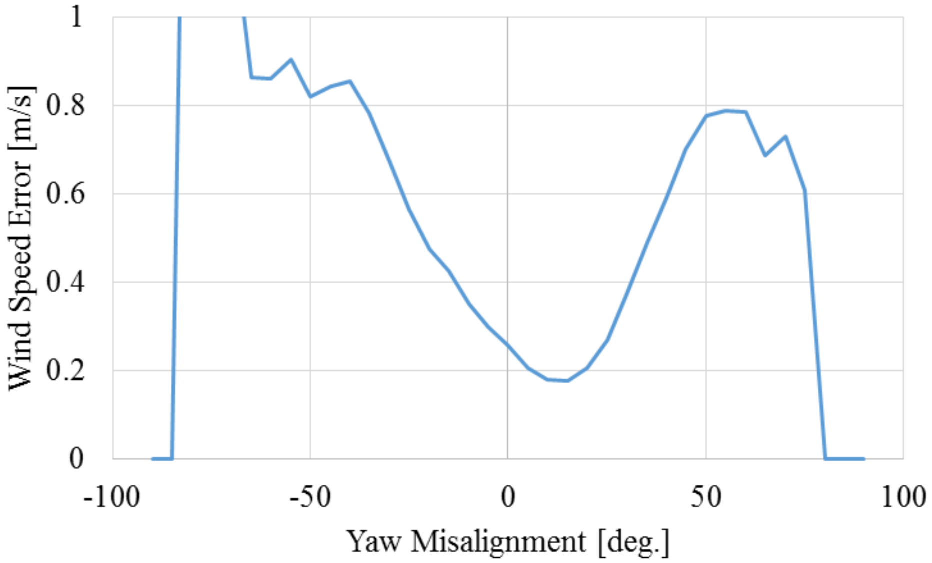

Figure 9 Influence of the wind speed estimation error on yaw misalignment (absolute error)

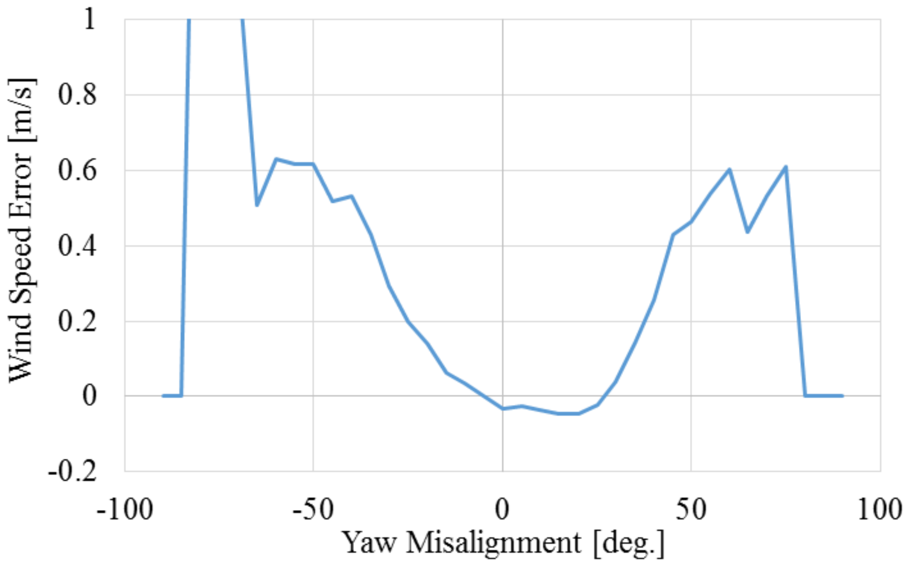

Figure 10 Influence of the wind speed estimation error on yaw misalignment (simple error)

Figures 9 and 10 reveal that the wind speed estimation error is significantly affected by the yaw misalignment. In particular, the estimation error when the yaw misalignment was below −20° or above 40° was large, above 0.5 m/s. Therefore, a large yaw misalignment prevents the accurate determination of wind speed bin means via

LiDAR.

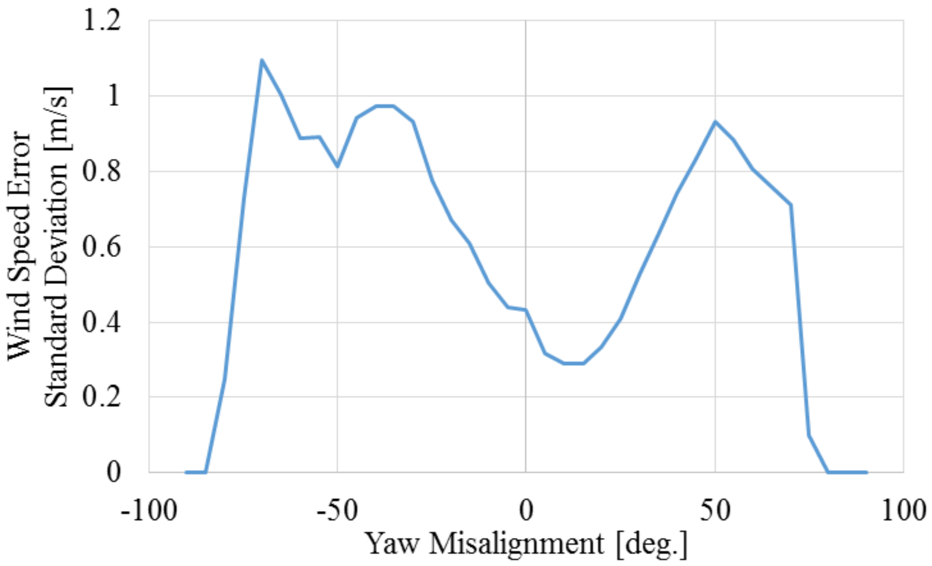

Figure 11 Influence of standard deviation of wind speed error on yaw misalignment (simple error)

However, Figure 11 also shows that the standard deviation of the wind speed error was also significantly affected by the yaw misalignment. Thus, large yaw misalignments invalidate wind speed data, as the standard deviations rise above acceptable levels.

4. Conclusions

For the practical application of LiDAR measurements for wind speed estimation, it was verified that yaw misalignment impacts the wind estimation error.

The comparison of the wind speed measured by LiDAR, a nacelle anemometer, and a metrological mast indicates that the inflow wind speed would be measured by mistake when the yaw misalignment is large.

A simple estimation method was implemented, which applied Taylor's hypothesis, and 1 Hz-wind estimation data was acquired. The absolute and simple estimation error for the wind direction and speed were collected.

The simple estimation error for wind direction and speed was influenced by the yaw misalignment; the larger the yaw misalignment, the larger the estimation error became. However, the standard deviation of the estimation error also increased with increasing yaw misalignment. Thus, the correction of LiDAR wind direction and speed estimation might be invalidated under large yaw misalignment conditions due to unacceptable standard deviation. This also suggests that a more robust turbine control should be designed if using LiDAR under high yaw misalignment conditions.

If yaw misalignment remains low, the data collecting term has little effect on the estimation error; thus, estimation error can be used for correction under low yaw misalignment conditions.

5. Learning Objectives

Long-term wind measurement and data collection requires the precise verification and correction of wind estimations. After correction, the conclusive error collection for the wind estimation methods should be calculated and the applicability of the estimation using LiDAR should be verified.

Finally, a robust control method for LiDAR should be utilized, considering the estimation error caused by yaw misalignment.

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