Statistical study of the effect of wind characteristics on the main shaft loadings of an active-stall controlled wind turbine

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Abstract. The dynamic loadings of the wind turbine main shafts are important for drivetrain components as external excitation force, and the evaluation of their dependence on wind characteristics is necessary for both the understanding of the drivetrain behavior and the extrapolation of the loadings at different sites. In this study, the load measurements of the wind turbine main shafts were performed along with the wind field measurement. Next the multivariate regression analysis was utilized to identify the influential wind parameters that affect the statistics of the dynamic loadings of the shaft. Finally, the dependence of the load statistics on the identified wind parameters was evaluated qualitatively using the observed data. Obtained regression results showed that there were more effects of wind field parameters on shaft loadings at low and middle wind speed regions than at the high wind speed region. Among the identified parameters, the incline angle and the vertical turbulence were found to be dominant for most of the shaft loadings, though the turbulence intensity is the parameter that is generally used for characterization of a wind field. For the mean tilt bending moment and the standard deviation of the torque, which are recognized as the influential factors for the loadings of drivetrain component, the differences the identified parameters caused were about 15% and 100% respectively.

1. Introduction

Failures in wind turbine drivetrain components, such as bearings and gears, cause high cost for repair and replacement operation and the study of failure mechanisms is an urgent task. The dynamic loadings of the main shaft are important factors for drivetrain components as external excitation forces. As studies have shown that not only torque but also non-torque loadings of the main shaft have a large effect on the component failures\(^1\), the evaluation of the characteristics of the dynamic loadings, such as bending moment and torque acting on the main shaft is necessary for the understanding of the drivetrain behavior.

Meanwhile, the peculiarity of wind turbine loadings is their large variation driven by the fluctuating wind. Therefore a qualitative evaluation of the impacts of wind field parameters on the shaft loadings would help not only to get insights of the mechanism of wind oriented drivetrain behavior, but also to estimate the difference in drivetrain loadings for different sites. Considering that the aerodynamic analysis of wind turbines includes the uncertainties of aerodynamic coefficients and control algorithms, previous studies have performed statistical analysis of field measurement data. The impacts of wind field parameters are analyzed using multivariate regression for fatigue loads by Mouzakis et al.\(^2\), Fragoulis\(^3\), and Sutherland\(^4\), and for extreme blade bending loads by Nelson et al.\(^5\). However, there are limited studies that have focused on the main shaft dynamic loadings.
Therefore, the aim of this study is to provide qualitative information on the dependence of main shaft loadings on wind characteristics that can be used for future studies on drivetrain behavior. In this study, the field measurement was first carried out on the main shaft and the tower of a 1MW wind turbine along with the wind measurement. Next, the multivariate regression analysis was applied to the obtained data to identify the dominant wind parameter for various statistics of the tilt bending moment, yaw bending moment, and the torque of the main shaft. Finally, the dependence of the load statistics on the identified wind parameters was evaluated from the observed data.

2. Outline of field measurement and data analysis

2.1. Field Measurement

The target wind turbine was a 3-bladed horizontal axis, two speed active-stall controlled BONUS 1MW wind turbine with the rotor speed of 15rpm and 22rpm. The hub height was 45m and the rotor radius was 27m. The main shaft was supported at three points by the main bearing and the torque arms. The gearbox was a 3-stage planetary-helical type and the generator was of asynchronous type. The measurement campaign was carried out from November 2015 to January 2016 during which the bending moment, torque, and displacement of the main shaft were observed along with the wind field. The bending moment and torque were measured with the full-bridge strain gauges at 50Hz sampling frequency. The azimuth angle was obtained from the pulse sensor attached to the shaft, and was used to calculate the tilt bending moment and the yaw bending moment of the shaft from the rotating strain data.

The wind measurement was carried out with the Doppler Lidar “WindCube v2” located about 120 m west to the target turbine. The device transmitted the laser beam in four directions at 15° half-opening angle, and the obtained signals were converted into the horizontal and vertical wind speeds by coordinate transformation. The wind data was obtained at 20 m pitch from 40 m height to 220 m height, where the 10 minutes mean, standard deviation and maximum wind speeds calculated from 1 Hz sampling frequency were recorded. The mean horizontal wind speed from the Lidar was compared to the SCADA data, and the correlation coefficient was found to be 0.93.

The outline of the measurement site is shown in Figure 1. The wind farm was located near the shore at Tomamae, Japan. The ground surface of the western section was open sea while it was a flat land for the eastern section. As shown in Figure 1, both the wind turbine and the Doppler Lidar are affected by the wake from the nearby wind turbines, and the data within these wind directions were removed in the analysis.

![Figure 1. Outline of the test site and the location of target wind turbine and Doppler Lidar](image)

2.2. Outline of the multivariate regression analysis

Multivariate regression analysis was used to evaluate the effect of wind characteristics on the main shaft loadings. The regression assumes that the dependent variable \(y\) is expressed with the independent variables \(x_k\) with the regression coefficient \(b_k\) as follows:

\[
y(x_i) = a_0 + \sum_{k=1}^{M} b_k X_k(x_i) + E(x_i)
\]  
(1)
where $X_k(x_i)$ is the $k$ th independent variable at point $x_i$, $a_0$ is the intercept term and $E(x_i)$ is the associated error which is assumed to be independent and normally distributed with constant standard deviation. Using the least square method, the regression coefficients are obtained as follows:

$$b_k = \sum_{k=1}^{M} \left[ \sum_{i=1}^{N} X_k(x_i)X_k(x_i) \right]^{-1} \left[ \sum_{i=1}^{N} y_iX_k(x_i) \right]$$  \hspace{1cm} (2)

The assessment of the multivariate regression analysis was performed statistically using the F-test and t-test. First, in order to reject the hypothesis that there is no significant overall regression using the M-independent variables, the F test was performed. The F-statistics is the ratio of the explained variance to the unexplained variance and is defined as follows;

$$F = \frac{\sum_{i=1}^{N}(y_i - \bar{y})^2}{\sum_{i=1}^{N}E(x_i)^2/(N-M)}$$  \hspace{1cm} (3)

When the hypothesis is true, the F statistic is known to follow Fisher’s F sampling distribution with $M - 1$ and $N - M$ degree of freedom. If the obtained F-statistics was within the 95% confidence interval, the hypothesis is rejected and the significance of the overall regression is indicated. In this study, the F statistic for each regression was confirmed to satisfy this criterion. Next, the t-test was conducted to reject the hypothesis that the regression coefficient $b_k$ is zero. The t-statistics is the normalized regression coefficient and is defined as follows:

$$t = \frac{b_k/\sigma(b_k)}{a_0/\sigma(a_0)} = \frac{1}{\sqrt{\sum_{i=1}^{N}(X_i(x_i) - \bar{X}_k)^2}}$$  \hspace{1cm} (4)

When the hypothesis is true, the t statistic is known to follow student’s t sampling distribution with $N - M$ degree of freedom. If the obtained t-statistics was within the 95% confidence interval, the hypothesis is rejected and the significance of the effect of the independent parameter on the dependent parameter is indicated. For the dependent parameters of which the p-value were lower than 0.05, the parameter was removed and the regression was performed again using the remaining parameters. The iteration was repeated until the t-statistics for all independent variables satisfied the criteria. This backward elimination method for linear multivariate regression was used in previous studies$^{2}$ for wind turbine fatigue parameter identification and gave reliable results. Finally, the magnitudes of t-statistics were utilized to compare the effect of each wind parameters on the main shaft loadings.

2.3. Parameters selection for the multivariate regression analysis

For the independent variables, the mean wind speed, incline angle, gust factor, turbulence intensity, vertical turbulence, wind direction variance, and the vertical wind shear exponent are chosen. The incline angle is the ratio of the vertical mean wind speed to the horizontal wind speed, the gust factor is the ratio of the maximum horizontal wind speed to mean horizontal wind speed, the turbulence intensity is the ratio of the standard deviation of horizontal wind speed to mean horizontal wind speed, the vertical turbulence is the standard deviation of vertical wind speed, and the wind direction variance is the standard deviation of wind direction. All wind statistics were calculated from the 10 minutes data at 60 m height except the shear exponent which was estimated from the 10 minutes data from 40 m height to 200 m height. In order to eliminate the effect of the difference of the units of the dependent variable dataset, each variables was standardized to have zero mean and unit standard deviation. Also the dataset was checked for its multicollinearity, and all correlation coefficients between each parameter were confirmed to be under 0.3.

For the dependent variables, the mean, the standard deviation, the maximum and the dominant modal component of the tilt bending moment, yaw bending moment, and the torque were chosen, and the regression was performed for each statistics. The dominant modal component for tilt and yaw bending moment was 3P, and for torque it was 1P. All the statistics were calculated from the 10 minutes data. The power spectrum density was estimated using the Fast Fourier Transform method, where the data was divided into eight sections and windowed with a Hamming window.

Since Eq.(1) assumed the linear relationship between the dependent and independent variables, the observed data was divided into three bins by mean wind speed according to the basic control strategy:
3 m/s to 10.5 m/s for the range of optimum control, 10.5 m/s to 14.5 m/s for the transient range of optimum and rated control, and 14.5 m/s to 25 m/s for the range of rated control. In the following discussion, the bins are referred to as the low wind speed range, the middle wind speed range, and the high wind speed range, respectively. The regression analysis was performed for each bin separately assuming that the linearity of Eq. (1) holds within the same bin. The data was selected by rotational speed and the mean torque for normal operation condition. Removing data affected by turbine wake, the total number of 10 minutes data used for the regression analysis was 5213.

3. Influential wind parameters on the shaft loadings

3.1. Shaft tilt bending moment

The t-statistics for the shaft tilt bending moment are shown in Figure 2, where $U$ (m/s) is the mean wind speed, $\theta$ (deg) is the incline angle, $G$ is the horizontal gust factor, $I_u$ (%) is the turbulence intensity, $\sigma_w$ (m/s) is the vertical wind turbulence, $\sigma_d$ (deg) is the wind direction variation and $\alpha$ is the vertical shear exponent. Figure 2(a) shows that for the mean bending moment the incline angle and the vertical shear exponent are influential at the low and middle wind speed regions. This result is reasonable considering that the identified parameters create an over-turning moment on the rotor in the opposite direction to the rotor dead load. Figure 2(b) shows that for the standard deviation of the bending moment, the incline angle and vertical turbulence are the dominant parameters at the low wind speed region, and the vertical shear exponent is influential at the middle wind speed region. This result agrees with the regression results in previous studies conducted for the fatigue loadings of the main shaft (2) and the blade root (4). Figure 2(c) shows that for the maximum moment, the vertical turbulence and gust factor are influential at the low wind speed region. Figure 2(d) shows that the influential parameters for 3P modal component are the incline angle, the vertical turbulence and the vertical shear exponent at the low wind speed region, which corresponds to the results for the standard deviation of the bending moment.

![Figure 2. t-statistics for the shaft tilt bending moment](image)

3.2. Shaft yaw bending moment

The t-statistics for shaft yaw bending moment are shown in Figure 3. Figure 3(a) shows that the mean bending moment is affected by the mean wind speed positively, and by the incline angle and vertical turbulence negatively. Figure 3(b) shows that the mean wind speed, incline angle, vertical turbulence
and vertical shear exponent are influential for standard deviation of the yaw bending moment at the low wind speed region, while for high wind speed only mean wind speed and vertical turbulence are identified to have small effects. Figure 3(c) shows that the effect of the mean wind speed, incline angle and vertical turbulence is large for maximum bending moment at the low wind speed region. The vertical shear exponent is also influential but the effect is limited to the middle wind speed region. Figure 3(d) shows that the mean wind speed, incline angle and vertical shear exponent are influential for 3P modal bending moment. The identified parameters agree with those identified for the standard deviation.

Figure 3. t-statistics for the shaft yaw bending moment

Figure 4. t-statistics for the shaft torque
3.3. Torque
The regression results for the torque are shown in Figure 4. Figure 4(a) shows that the mean wind speed is dominant for the mean torque at the low wind speed region while the effect becomes smaller at the middle and high wind speed region. This corresponds to the basic control strategy of wind turbines. The incline angle has negative effect on the mean torque for all wind speed regions. Figure 4(b) shows that the effect of mean wind speed for the standard deviation of the torque is positive at the low wind speed region but negative at the middle wind speed region. The incline angle, turbulence intensity and vertical turbulence are also contributing to the variation of the torque. Figure 4(c) shows that the maximum torque is mostly affected by the mean wind speed at the low wind speed region and by both the mean wind speed and vertical shear exponent at the middle wind speed region. Figure 4(d) shows that for 1P modal torque the dominant wind parameters are both the mean wind speed and the vertical turbulence at the low wind speed region and are both the mean wind speed and the vertical shear component at the middle wind speed region. The effect of wind parameters is limited for all torque statistics at the high wind speed region where the pitch-control is active for all wind speeds.

4. Dependence of main shaft loadings on wind characteristics
In order to study the effects of the identified wind parameters on the distribution of the shaft loadings, the observed data were divided into bins by the identified parameters and the bin averaged results were plotted against the mean wind speed. Due to the limitation of space, the results for the two most influential parameters apart from the mean wind speed were chosen for discussion. When the dominant parameters differed between the wind speed regions, a priority was given to the low wind speed region. The range of the bins used for each wind parameter and the number of data in the bins are shown in Table 1.

| Incline angle | Gust factor | Turbulence Intensity | Vertical turbulence | Shear exponent |
|---------------|-------------|----------------------|---------------------|----------------|
| −10<θ<-5     | 3350        | 1.0<G<1.25           | 1129                |                |
| −5<θ<0       | 1047        | 1.25<G<1.5           | 3068                |                |
| 0<θ<5        | 490         | 1.5<G<2.0            | 958                 |                |
| 5<θ<20       | 336         | 2.0<G<2.5            | 61                  |                |

4.1. Shaft tilt bending moment
The bin averaged results for the main shaft tilt bending moment are shown in Figure 5. Figure 5(a) shows that a large bending moment which is largely caused by the rotor dead load is acting on the shaft for all wind speeds. The decreases caused to the mean bending moment by the incline angle and the vertical shear are both about 15% at the low wind speed region. Figure 5(b) shows that the standard deviation of the bending moment is about two times larger for positive incline angles than the negative incline angles. The difference caused by the incline angle becomes larger with the increase in the mean wind speed. This is contrast to the difference caused by the vertical turbulence which is large at the low wind speed region and is about 100% around 9m/s. Figure 5(c) shows that effect of the vertical turbulence to the maximum bending moment is uniform for all wind speeds and is about 20%. Figure 5(d) shows that the distribution of 3P modal bending moment with the incline angle and the vertical turbulence shows the same trend with that of standard deviation.

4.2. Shaft yaw bending moment
The bin averaged results for the shaft yaw bending moment are shown in Figure 6. As shown in Figure 6(a), the mean yaw bending moment takes positive value for negative incline angles at higher wind speeds, while it remains negative for positive incline angles at all wind speeds. Figure 6(b) shows that the incline angle and the vertical turbulence also cause large difference in the standard deviation of the yaw bending moment. The distributions are similar to those of the standard deviations of the tilt
bending moment. Figure 6(c) shows that the differences caused by the incline angle and the vertical turbulence to the maximum yaw bending moment are both about 20%. As can be seen in Figure 6(d), the distributions of 3P modal bending moment with the incline angle and the vertical turbulence showed similar trend with those of the standard deviation.

![Graphs showing the effect of identified wind parameters on the main shaft tilt bending moment](image)

**Figure 5.** Dependence of the main shaft tilt bending moment on the identified wind parameters

4.3. Torque

The effect of the identified wind parameters on the shaft torque is shown in Figure 7. Figure 7(a) shows that the large positive incline angle and turbulence intensity cause decrease in the mean torque at the middle wind speed range. Figure 7(b) shows that the standard deviation increase with the mean wind speed at low wind speed region and reaches highest around 9 m/s. Bin averaged with the vertical
turbulence, the standard deviation decrease with mean wind speed at higher wind speed region while the value remains high in higher wind speed region when bin averaged with turbulence intensity. Figure 7(c) shows that the incline angle causes about 10% increase in maximum torque at the middle wind region, and the turbulence intensity causes about 20% difference for all wind speeds. Figure 7(d) shows that the vertical shear exponent causes two times larger value for 1P modal torque. Unlike the tilt and yaw bending moment, the similarity in the standard deviation and the modal are not seen for the torque.

Figure 6. Dependence of the main shaft yaw bending moment on the identified wind
5. Conclusions

In this study, field measurements were carried out for a 1MW active-stall regulated wind turbine and the obtained main shaft loadings were used to study their dependence on wind characteristics. By applying the backward elimination method, the multivariate regression assuming a linear relationship gave reasonable results for the identification of the influential wind parameters. Obtained regression results showed that there were more effects of wind field characteristics on the shaft loadings at the low and middle wind speed region than at the high wind speed region. Among the wind parameters, the incline angle and the vertical turbulence were found to be dominant for most of the shaft loadings,

Figure 7. Dependence of the main shaft torque on the identified wind parameters
though the turbulence intensity is the parameter that is generally used for characterization of a wind field. For the mean tilt bending moment and the standard deviation of the torque, which are recognized as the influential factors for the loadings of drivetrain component, the incline angle, vertical turbulence and turbulence intensity were identified to be the dominant parameters. These loads at the low wind speed region were equal to or greater than those at the high wind speed region, and the difference the identified parameters caused on the loadings was 15% and 100% respectively. Although the active stall controlled wind turbine is targeted at this study, the results also give quantitative information for pitch-regulated and stall-regulated wind turbines at low wind speed region where the basic control algorithm is shared with active-stall regulated turbines.

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