Wind turbine blade load characterization under yaw offset at the SWiFT facility

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Abstract. Wind turbine yaw offset reduces power and alters the loading on a stand-alone wind turbine. The manner in which loads are affected by yaw offset has been analyzed and characterized based on atmospheric conditions in this paper using experimental data from the SWiFT facility to better understand the correlation between yaw offset and turbine performance.

1. Introduction
Wind turbines operate in stochastic flow environments with constantly changing wind speed and direction. The varying atmosphere combined with slowly responding yaw systems means that wind turbines nominally operate with an unintentional yaw offset. Recently, there has been interest in intentionally yawing wind turbines out of the wind as a wind plant control strategy to provide system power benefits by steering wakes to avoid downstream rotors. The wind turbine’s power is reduced with yaw offset due to the reduction in the normal velocity component passing through the rotor plane, but in some conditions this reduction can be more than compensated for by power gains from non-waked downstream wind turbines.

For both intentional and unintentional yaw offsets, there is a need for better understanding of the effect on fatigue loads to improve the operation of future wind plants. To this end, research has been performed on intentionally yawing wind turbines out of the wind at the Scaled Wind Farm Technology (SWiFT) facility [1] during the wake steering experimental campaign that was executed during the summer of 2017. This experimental campaign was part of a collaboration between Sandia and the National Renewable Energy Laboratory, and was funded by the US Department of Energy’s Wind Energy Technologies Office through the Atmosphere to Electrons (A2e) program.

2. Methods
Data have been acquired at the DOE/SNL SWiFT facility during the A2e wake steering experimental campaign. This data set includes measurements from two of the three SWiFT turbines, a downstream-facing scanning lidar mounted in the nacelle of the nominally upstream turbine, and two meteorological towers with measurement stations at five heights. The upstream turbine was operated over several weeks with varying controlled levels of intentional yaw offset.

1 Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-NA-0003525.
The data for this analysis are from wind turbine WTGa1 and meteorological tower METa1 as identified in Figure 1(a). The relevant turbine loads measurements were acquired from two sets of fiber optic strain gages installed parallel and perpendicular to the rotor plane at zero blade pitch, to estimate edgewise and flapwise bending moments, respectively. The pairs are installed 180° apart from each other in the blade root, as depicted in Figure 1(b). These four gages were compensated to remove thermal strain and mechanical offset. The strain calibration to bending moment was then determined operationally for each gage as described by White [2].

![Blade Strain Gage Sensor Location](image)

**Figure 1.** DOE/SNL Scaled Wind Farm Technology (SWiFT) facility and blade gage location.

### 2.1. Rotational Spectral Analysis

The operational loads data are processed through a rotational Fourier analysis as defined by Equation 1, which contains amplitude and phase content for a given per-revolution (P) forcing. This analysis is performed by first resampling the data into evenly discretized angular positions through the rotor azimuth measurement. The data are then divided into bins with a constant number of rotations. For this analysis, the data are discretized to 15° and divided into 50-rotation bins. At the maximum rotational speed of 43 rpm this corresponds to a maximum sample rate of about 17 hz, and a minimum bin time of about 70 sec. The SWiFT turbine data rate is 50 hz which means that the rotational data discretization is not oversampling the actual time-series data. This spectral analysis is performed on turbine blade root strain measurements calibrated to flapwise (thrust-direction) and edgewise (torque-direction) bending moments.

\[
X_k(\omega_p) = \sum_{n=1}^{N} x(n) e^{-2\pi i (k-1)(n-1)/N}
\]

**Equation 1**

### 2.2. Fatigue Calculations

The data time-series is used to understand the implications of fatigue cycles on blade life due to yaw offset. Fatigue cycles are extracted through rainflow cycle counting of the first 60 sec of the time-series data within the rotational bins. A classic approach is used to convert the bending moment time histories into a damage-equivalent load, as described by Sutherland [3]. Fatigue damage is approximated using the power-law equation for fatigue, Equation 2, where a nominal fatigue slope of \( m=10 \) for fiberglass is used. The simple Goodman relationship is used to convert the moment’s rainflow-counted cycle mean (\( M_m \)) and amplitude (\( M_a \)) to an equivalent moment (\( M_e \)), Equation 3. Miner’s rule is used to estimate the damage caused by \( n \) fatigue cycles at equivalent amplitude moment values of \( M_e \), relative to the number of cycles to fatigue failure at this moment value, \( N \), Equation 4. Equations 2-4 are combined to calculate the damage equivalent load (DEL) which is defined as the bending moment that results in fatigue failure at one million cycles, as shown by Equation 5. The material ultimate bending moment constant (\( M_u \)) can be removed by comparing a ratio of DEL values as in Equation 6.

\[
DEL = \sum_{i=1}^{N} \frac{X_i(\omega_p)}{M_e(i)}
\]

**Equation 5**
In this paper normalized values of DEL will be shown. As the effect of loads on fatigue damage is exponential, a 10% increase in DEL corresponds to a 159% increase in the fiberglass blade damage accumulation. All fatigue calculations were performed using MCrunch [4].

\[
M = M_u \cdot N^{-1/m}
\]  

\[
M_e = \frac{M_u}{1 - \frac{M_m}{M_u}}
\]  

\[
D = \sum_{i=1}^{k} \frac{n_i}{N_1} |M_{e,i}|
\]  

\[
DEL = M_u \left( \frac{10^6}{D} \right)^{-1/m}
\]  

\[
\frac{D_2}{D_1} = \left( \frac{DEL_2}{DEL_1} \right)^m
\]

3. Experimental Results

The results shown in the following analysis are from SWiFT site data that were acquired between July 9-13th, 2017. The individual data points each represent a 50-rotation bin that was rotationally sampled in the case of the spectral analysis, while the damage equivalent load datasets contain the first 60 sec of the rotational bin time-series. Averages, such as for turbine power and definition of the bin’s atmospheric state are performed using the entire time-series data within each 50-rotation bin. In order to be consistent with well-understood values for turbulence intensity, this calculation was done using a 10 min moving average of the hub-height sonic anemometer centered at the midpoint of the rotational bin.

The experimental data are filtered based on a required minimum power threshold, operation in Region 2 where the turbine operates at a constant tip speed ratio, and by wind direction to ensure that the turbine and meteorological tower were not being waked. The remaining datasets that are analyzed contain atmospheric and operational conditions as described by the histograms in Figure 2. It is noted that these data were mostly acquired during overnight and morning hours where a stable atmospheric boundary layer is present, which was due to the objective of the wake steering experimental campaign being most demonstrable in stable atmospheric conditions. As a result, the data are dominantly characterized by low turbulence and high shear, and commonly with high veer levels. The data trends will therefore be biased towards high shear and low turbulence compared to the site averages of a shear exponent of 0.21 and turbulence intensity of 12% [5]. Wind shear and veer are calculated from 1 min averages of wind speed and direction. The shear exponent is determined from a power law fit of the five wind speed stations between 10 and 58 m. Veer is calculated across the rotor disk as the wind direction at 45 m minus the direction at 18 m. The yaw offset is calculated using the average hub-height wind direction minus the average nacelle yaw heading. Positive yaw offset means the wind is coming from the left of the rotor plane when looking downstream.

Results of the rotational spectral analysis are shown in Figures 3-4 for the flapwise and edgewise bending moments. Amplitude and phase are shown for the per-revolution forcing’s between 1-6 P versus the rotational bin’s average yaw offset. The phase angle is the location where the maximum of the sinusoidal cycle occurs in the rotor disk. A 0° phase corresponds to the blade pointing up, and is positive with clockwise rotation.

The per-revolution amplitude plots reveal a strong correlation between the 1P component and yaw offset for both the flapwise and edgewise bending moments. An interesting finding is
that the $1P$ amplitude correlation for the two bending moments are inversely related to each other. The flapwise bending moment is seen to increase with negative yaw offset and decrease with positive yaw offset, while the edgewise bending moment does the opposite. The phase for the $1P$ edgewise bending moment reveals a correlation with yaw offset where the location moves towards the downstream portion of the rotor disk with yaw offset. The $1P$ flapwise moment phase angle doesn’t appear to be affected by yaw offset, which is a surprising result. It is also noted that the $1P$ phase angle of the flapwise and edgewise moments do not occur at the same location on the rotor disk except for at around a $-10^\circ$ yaw.

The 2-6 $P$ amplitude components of the blade bending moments do not appear to be correlated with yaw offset. These components have significantly lower energy than the $1P$ component, but it is still considered to be an appreciable amount when taking into account that these cycles occur 2-6 times more frequently than the $1P$ cycles. Several of the 2-6 $P$ phase components of the blade bending moments reveal a correlation on the order of $30^\circ$-$50^\circ$ with yaw offset, although the trends are within the spread of the data making it difficult to determine the yaw offset from these signals for any single bin. The edgewise 3$P$ bending moment has the least spread of all of the phase components, meaning it would be a good signal to track. However, it is only weakly correlated to yaw offset, changing only around 20$^\circ$ for the 50$^\circ$ of yaw offset variation. The edgewise 3$P$ moment occurred in nearly the same location on the rotor disk for every rotational bin at around 290$^\circ$, which for a 3$P$ component means it also has maxima at 170$^\circ$ and 50$^\circ$. The regularity of the signal across all of the varying atmospheric conditions possibly means that this component is being forced by the three blades passing through the upstream potential field of the tower.

During the rotational spectral analysis a high 5$P$ amplitude component was observed for some of the rotational bins in the edgewise bending moment, on the same order as the $1P$ forcing amplitude, as seen in Figure 5. It was determined that the energy was reduced to a more expected roll-off seen in Figure 4(a) by removing the data outside of Region 2. In Region 2.5 and 3 operation the turbine is operating at a constant rotational speed of 43 rpm, which
Figure 3. Rotational spectral analysis flapwise bending moment per-revolution (P) content versus yaw offset (markers represent the result from one of the 50-rotation bins; the black line is the binned average of the set of bins).
Figure 4. Rotational spectral analysis edgewise bending moment per-revolution (P) content versus yaw offset (markers represent the result from one of the 50-rotation bins; the black line is the binned average of the set of bins).
corresponds to a 5P frequency of 3.6 hz. This frequency relates closely to the first and second edgewise asymmetric rotor modes [6]. An example spectrum for one of the bins is shown in Figure 5(b) which supports this resonance-sourced energy as the 5P forcing peak is broader in amplitude than it would be if it were an aerodynamically-induced excitation. In this analysis, only data from Region 2 operation are used to ensure that spurious trends are not concluded.

Figure 5. Rotational spectral analysis 5 per-revolution forcing amplitude content.

To understand the relationship between the cyclical forcing effects of yaw offset seen through the rotational spectral analysis and blade life, a fatigue analysis has been performed to characterize the damage equivalent load for each of the data bins. The wind speed affects the resulting loads to a greater degree than the single variable of yaw offset or atmospheric conditions, so the data are further grouped into wind speed bins in the comparison. Grouping the data by wind speed only is performed with the DEL values normalized to the edgewise 0° yaw average and shown in Figure 6. It is observed for the 27 m SWiFT rotor that the flapwise DEL values are 3-5 times greater than the edgewise DEL, on average. This is expected as the magnitude of the flapwise bending moment is typically an order of magnitude higher than the edgewise bending moment for wind turbines.

The effect of yaw offset on blade fatigue life is shown for edgewise and flapwise DEL average curves from 0.5 m/s wind speed divisions, plotted together in Figure 7 and normalized in both cases by the lowest wind speed division’s DEL value at a 0° yaw offset. One apparent trend from these plots is that the effect of wind speed on DEL can be more substantial than the effect of yaw offset. Another finding is that the DEL variation is directional with yaw offset, due to the presence of shear. The slopes of flapwise and edgewise DEL versus yaw offset match those observed in the rotational spectral analysis 1P amplitude plots, as expected, and are inversely related for flapwise and edgewise bending. The reduction of DEL for positive yaw offsets in the flapwise direction and for negative yaw offsets in the edgewise direction is a combined effect due to the presence of high levels of shear and the reduction in the normal component of velocity passing through the rotor disk. At 0° yaw an increasing wind speed from 5.5 to 6.5 m/s and 5.5 to 7.5 m/s corresponds to observed increases in flapwise DEL of 25% and 45%. The directionality of the trend is caused by wind shear either reducing or exaggerating the variation of wind speed across the rotor disk. Without the effects of shear, it would be expected with yaw offset that the mean would be reduced, but that the variation of loads would be increased due to a loading imbalance from fluctuations in angle of attack. The presence of velocity shear results in a balancing of rotor loads for flapwise moments with positive yaw offset.
Figure 6. Flapwise and edgewise damage equivalent loads separated by wind speed (markers represent the result from one data bin; the black line is the binned average of the set of bins).

The bulk trends of DEL versus yaw offset contains unrepresentative averages with high levels of shear and low levels of turbulence, as described earlier, so it is important to further separate out these effects by looking at atmospheric state divisions. This is performed using categorical levels of shear, turbulence intensity (TI), and veer as shown in Figure 8. Due to the limited amount of data available for some of the atmospheric conditions, the plots are shown for all wind speed cases from 6 to 8 m/s. The divided data histograms were checked and confirmed to ensure that the trends would not be skewed from having higher or lower wind speed distributions than the other cases.

Figure 8(a) shows the trend where as you move to lower values of velocity shear, the DEL values decrease at a lower rate with positive yaw offset than the high shear case. This is due to the relationship explained earlier where the normal component of wind speed is decreased, but now the rotor loading is not being balanced with yaw offset where there are low levels of shear. Turbulence intensity levels are seen to be most strongly correlated to DEL producing around
a 15-25% increase for the “high” levels. Were more data available, this trend would likely be more significant if looking at values less than or greater than the site average of 12%. Wind veer does not appear to have a strong correlation with DEL, although high negative veer seems to be related to higher DEL and high positive veer with lower DEL. These trends should be confirmed as more data become available.

![Chart](image1)

**Figure 7.** Normalized damage equivalent fatigue loads versus yaw offset.

![Chart](image2)

**Figure 8.** Flapwise damage equivalent load versus yaw offset separated by atmospheric state.

### 4. Discussion
The trends of damage equivalent fatigue loads have been analyzed for various atmospheric states and were seen to both increase and decrease with yaw offset, dependent on offset direction and velocity shear levels. While the dominant flapwise DEL values were observed to decrease with positive yaw offsets there is also a penalty in the turbine power production that should be understood. Figure 9 characterizes the turbine power versus yaw offset for the five wind speed divisions used previously. The average turbine power remains fairly constant from about -10° to 10°, and then drops off in both directions. A “cost” value can be defined as the ratio of change in DEL to change in turbine power when both are normalized at their 0° yaw offset values.
This cost is shown in Figure 9(b) and reveals that the optimal yaw offset to operate (when only considering these two impacts) is around positive $12^\circ$ for the statistically high-shear data being analyzed. The actual impact would depend on a value weighting of increase in blade life to reduction of produced power, but the minimum would remain in the same location.

![Figure 9](image)

**Figure 9.** Normalized power and cost of operation during yaw offset.

5. Conclusion
A Fourier analysis has been utilized to identify correlations between periodic rotational forcing and blade loads with wind turbine yaw offset. A strong correlation was observed between the 1P flapwise and edgewise bending moment amplitude, making this the strongest signal to track for understanding of yaw offset magnitude. Blade fatigue loads were analyzed and seen to increase and decrease directionally with yaw offset. Flapwise fatigue loads were inversely correlated with yaw offset, while edgewise fatigue loads had a direct correlation with yaw offset. An additional cost of yaw offset that must be considered is turbine power reduction. In the presence of shear, negative yaw offset values were seen to produce the highest level of flapwise blade damage while also reducing power. Negative yaw offset overall is seen to have the highest system “cost”, while a slightly positive yaw offset is an optimal location where wind turbines should be operated. The location of this optimal operation point is dependent on the level of shear, making shear a valuable measurement for an optimized turbine controller as would be used for wake steering.

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