Intentional Yaw Misalignment and the Effects on Wind Turbine Noise

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1 Introduction

HGC Engineering completed a sound study at a wind facility in order to investigate the potential for the intentional yaw misalignment of selected wind turbines to create elevated sound levels or potentially objectionable sound characteristics, specifically amplitude modulation. The yaw misalignment was part of a study conducted by Stanford University to investigate a potential increase in the annual energy production of the site through wake control [1].

The wind facility is located in southern Alberta, and includes a number of 2 to 3 MW pitch regulated wind turbine generators. The terrain surrounding the facility consists of flat agricultural land. The prevailing wind direction in the vicinity of the facility is from the west.

The trial involved the intentional yaw misalignment by 20° of five wind turbines (Group1-T1 through T5) from October 11 to October 25, 2018.

2 Method

Two Svantek 977 sound level meters were installed at the wind facility between October 5 and October 29, 2018. One sound level meter was installed approximately 115 m from the base of turbine Group 1-T1 in the prevailing downwind direction. As a reference, a second sound level meter was installed approximately 115 m from the base of turbine Group 2-T6, also in the prevailing downwind direction. The microphones were set at a height of 1.5 m and equipped with 175 mm diameter windscreens to minimize the effect of wind-induced microphone self-noise. Figures 1(a) and 1(b) show the approximate location of the sound level meters in relation to the project wind turbines.

The sound level meters were configured to measure and record spectral (frequency-dependent) one-minute, A-weighted L_{EQ} sound levels. For identification of dominant sources, the sound level meters also recorded audio files.

Correct calibration of the acoustic instrumentation was verified using an acoustic calibrator manufactured by Brüel & Kjær (B&K) at the start and end of the measurement period. All equipment was within its annual or bi-annual calibration period.

The following data from the project wind turbines was utilized in the analysis:

- Wind speed at hub height,
- Yaw position,
- Electrical power generation,
- Rotor speed,

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(a)

(b)

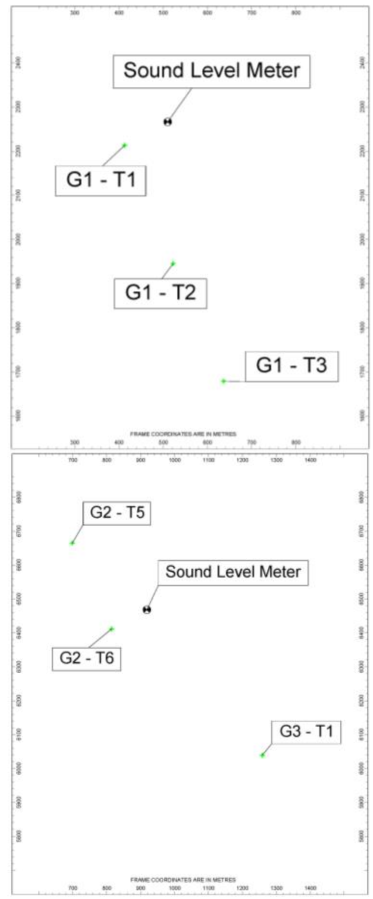

Figure 1: Sound Level Meter Location, Near Wind Turbine G1-T1 (a). Sound Level Meter Location, Near Wind Turbine G2-T6 (b).

- Blade pitch

The measured sound level data was filtered to exclude periods with inclement weather (rain and snow), gusty wind conditions and interference from birds, vehicles, and agricultural activity. Additionally, the data were filtered to only include downwind conditions (i.e. the turbine yaw position is within +/- 45 degrees from the line of sight between the measurement location and the closest turbine). The 20° yaw misalignment was taken into account for this filter.

Because of the correlation between the acoustic emission of a wind turbine and wind speed (and therefore electrical output), it is important to consider electrical output when completing a statistical analysis of wind turbine noise. Accordingly, the data were sorted into bins, 200 kW wide, based on the electrical power output of the closest turbine to the sound level meters.

The presence of amplitude modulation in the measured wind turbine noise was investigated using the methods described in the Institute of Acoustics: A Method for Rating Amplitude Modulation in Wind Turbine Noise [2]. The method uses sequential LA_{EQ} 100 ms data, calculated over three separate band-limited frequency ranges together spanning the range from 50 to 800 Hz. Each 10-second segment of data is de-trended using a third-order polynomial best fit curve. A Fourier transform is used to calculate a power spectrum, and the highest peak in a range of possible blade passing frequencies is found. The energy represented by this peak, and its possible harmonics, is used to calculate an inverse Fourier transform. Finally, the modulation depth is calculated by subtracting the L_{95} from the L_5 of the resulting time series. The method results in a series of 10-second data, as well as a series of 10-minute averaged results.

3 Results

Tables 1 through 3 present the A-weighted, energy-equivalent (L_{EQ}) sound level for each turbine power bin, as well as the number of valid data points and the standard deviation of the sound levels.

Table 1 presents the results from the sound level monitoring at wind turbine T1 in Group 1 during regular operation (i.e. not misaligned).

Table 1: Results - Turbine Group 1-T1, Regular Operation

Power [kW]	100 - 300	300 - 500	500 - 700	700 - 900	900 - 1100	1100 - 1300	1300 - 1500	1500 - 1700	1700 - 1900
Data Points	249	353	329	274	275	322	382	384	1147
L_{EQ} [dBA]	48.0	48.9	49.7	50.4	51.0	51.6	51.9	52.2	52.0
Std. Dev.	0.8	0.9	0.7	0.8	0.7	0.6	0.7	0.7	0.8

Table 2 presents the results from the sound level monitoring at wind turbine Group 1-T1 while the turbine was yaw-misaligned by 20°.

Table 2: Results - Turbine Group 1-T1, 20° Yaw Misalignment

Power [kW]	100 - 300	300 - 500	500 - 700	700 - 900	900 - 1100	1100 - 1300	1300 - 1500	1500 - 1700	1700 - 1900
Data Points	502	498	432	417	398	524	644	806	3355
L_{EQ} [dBA]	47.9	49.2	49.9	50.5	51.1	51.5	51.9	52.1	51.7
Std. Dev.	0.8	0.5	0.5	0.5	0.6	0.6	0.7	0.8	0.9

Table 3 presents the results from the sound level monitoring at wind turbine Group 2-T6 during regular operation (i.e. not misaligned).

Table 3: Results - Turbine Group 2-T6, Regular Operation

Power [kW]	100 - 300	300 - 500	500 - 700	700 - 900	900 - 1100	1100 - 1300	1300 - 1500	1500 - 1700	1700 - 1900
Data Points	1000	771	1103	936	641	682	722	679	1860
L_{EQ} [dBA]	48.2	49.3	50.2	50.8	51.4	51.8	52.2	52.7	52.6
Std. Dev.	1.3	1.2	1.3	0.9	1.0	0.8	0.8	0.7	0.7

Table 4 presents a comparison between sound level results from the regular operation of turbines Group 1-T1, and Group 2-T6, and the yaw-misaligned operation of turbine Group 1-T1.

Table 4: Sound Level Comparison

Power [kW]	100 - 300	300 - 500	500 - 700	700 - 900	900 - 1100	1100 - 1300	1300 - 1500	1500 - 1700	1700 - 1900
L_{EQ}, T6 Regular [dBA]	48.2	49.3	50.2	50.8	51.4	51.8	52.2	52.7	52.6
L_{EQ}, T1 Regular [dBA]	48.0	48.9	49.7	50.4	51.0	51.6	51.9	52.2	52.0
L_{EQ}, T1 20° yaw [dBA]	47.9	49.2	49.9	50.5	51.1	51.5	51.9	52.1	51.7

The change in sound pressure was analyzed in one-third octave bands. Where the turbine is expected to be operating near maximum sound level (1300 kW and above), the one-third octave sound level results indicate no change in any one-third octave band.

The results of the amplitude modulation investigation show no correlation between yaw misalignment and an increase in levels of amplitude modulation depth. Periods of elevated amplitude modulation depth were measured during yaw-misaligned operation and normal operation alike.

4 Discussion

The sound level results indicate that, on average, there is no statistically significant difference in the sound levels on an overall A-weighed or one-third octave basis between regular operation and yaw-misaligned operation.

A cursory review of the audio recordings collected during the yaw misalignment period did not indicate obvious changes in audible characteristics of the sound.

The results of the study indicate that the intentional yaw misalignment of wind turbines for the purpose of increased power production does not result in higher sound emission or an increase in amplitude modulation.

Acknowledgments

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References

[1] Howland, M.F., Lele, S.K., Dabiri, J.O., *Wind farm power optimization through wake steering*, 2019. https://doi.org/10.1073/pnas.1903680116

[2] Institute of Acoustics, *IOA Noise Working Group (Wind Turbine Noise) Amplitude Modulation Working Group Final Report A Method for Rating Amplitude Modulation in Wind Turbine Noise*, 2016. http://ioa.org.uk/sites/default/files/AMWG%20Final%20Report-09-08-2016_1.pdf