Influence of upwind turbines on wind turbine sound power output

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ABSTRACT

One of the more common objections raised regarding acoustic assessments of proposed or existing wind farms is lack of accuracy of the noise modelling. In particular, objectors often allege that the modelling fails to consider a significant increase in sound power output of the turbines that may result when the turbine is in the wake of an adjacent wind turbine. This paper quantifies the increase in turbine sound power level that results when a turbine is in the wake of an adjacent turbine, through comparison of wake and non-wake affected sound power measurements at a site where a turbine was located at the end of a line of turbines. It was found that, while there may be a minor increase in noise levels at low wind speeds, this increase was inconsistent and did not occur at higher wind speeds where the turbine sound power is greatest. Furthermore, it is likely that this increase would be offset by the reduction in wind speed at the turbine resulting from the wake created by the upwind turbines.

INTRODUCTION

During the last ten years there has been significant growth in wind energy, in response to community demand for clean energy and government policies that encourage growth in the production of renewable energy. Wind energy has provided a large proportion of this growth in renewable energy, on the basis that is one of the most cost effective forms of renewable energy generation.

The growth in wind energy has not been welcomed by all members of the community, with objections raised against new and existing developments, primarily on the basis of perceived noise, visual amenity and health impacts.

One of the more common objections regarding acoustic assessments of proposed or existing wind farms is lack of accuracy of the noise modelling. In particular, objectors often allege that the modelling fails to consider a significant increase in sound power output of the turbines that may result when the turbine is in the wake of an adjacent wind turbine. The photograph of the Horns Rev wind farm (reproduced as Figure 1) showing condensation in the wake of the turbines has been used during community meetings to illustrate the alleged effect of turbulence on noise emissions from turbines.

To the authors' knowledge, no measurements have previously been provided to support the claim that the sound power level of a wind turbine is increased when in the wake of an upwind turbine. Both Thorne (2010) and Harrison (2011) have stated that turbulence induced when one turbine is in the wake of another can affect noise emissions but have not quantified this effect through measurements. Harrison cites research conducted by Barthelmie et al (2003) to suggest that this alleged effect may occur at distances of up to five blade diameters from the upwind turbine.

Figure 1. Horns Rev turbine wake.

Photographer Christian Steiness.

It is also often noted that the international standard used for the declaration of wind turbine sound power levels (IEC 61400-11, 2006) does require that the tested turbine not be in the wake of another turbine during the measurements. It has therefore been alleged by some wind farm opponents that the measured sound power level used for the assessments is an idealised sound power level, which is not often achieved under real operational conditions.

We note that our previous study of noise modelling accuracy (Evans & Cooper, 2012) indicated that some of the noise models used for wind farm assessments are sufficiently accurate when IEC 61400-11 measured sound power levels are used, based on the comparison of predicted and measured noise levels at a number of wind farm sites. Some of the turbines nearest to the measurement locations in that study were downwind of other turbines, so on that basis it appeared unlikely that wake effects are significant. However, this study aims to quantify the increase in sound power level that occurs when one turbine is operating in the wake of another.

MEASUREMENT SETUP

Tested wind turbine

The turbine used for this assessment was a modern commercial wind turbine with the blades located upwind of the tower. The turbine has a blade diameter of approximately 90 metres and hub height of 80 metres.

Measurement site

The tested turbine was at one end of a relatively straight line of approximately six wind turbines, such that for one wind direction the test turbine is located in the wake of all of the remaining turbines. Spacing between the turbines in this group of turbines averages approximately 3.7 turbine diameters, with the nearest turbine to the test turbine also being approximately 3.7 turbine diameters distant. This spacing is relatively close, but exceeds the manufacturer's minimum spacing requirements (typically 3 diameters) which are set to prevent excessive structural stress and fatigue due to unsteady wind loading. It is also within the spacing in which Harrison (2011) suggested noise level increases may occur due to turbulence induced in the wake of an upwind turbine.

Methodology

Measurements were undertaken at the test turbine based on the sound power measurement method provided by IEC 61400-11. This standard requires the microphone to be located on a ground board at a distance of approximately Height + ½ Diameter of the turbine. During a normal IEC 61400-11 test the ground board is placed on the ground +/-15º downwind from nacelle of the turbine, and the microphone of the sound level meter is laid flat in the centre of the ground board covered using a half wind shield. The positioning of the microphone on the ground board has the advantage of giving both low wind speeds over the microphone and a known (+6 dB coherent) reflection off the ground.

In a departure from the IEC 61400-11 method, our study used fixed measurement locations, rather than constantly relocating the ground board so that it was always downwind from the turbine. This resulted in a data set that contained measurements at a wide range of measurement directions relative to the heading of the nacelle.

A-weighted L_{eq} sound pressure levels were logged at the turbine in one minute intervals for approximately one week using Brüel and Kjær 2250 Class 1 sound level meters, calibrated both before and after the measurements using a Brüel and Kjær 4231 field calibrator. No drift in calibration was observed across the measurement periods.

The aim of the measurements was to determine the difference between wake affected and non-wake affected sound power measurements. This could have been achieved through two separate measurement locations; one downwind of the test turbine when the test turbine is in the wake of the others, and the second measurement location at 90º to the side (so the second location is downwind when the wind turns 90º to the line of turbines).

However, based on our previous sound power measurement experience, we note that the it is not uncommon for two sound power measurement locations downwind of the same turbine to measure a difference in sound power of up to 1 dB(A), even during simultaneous noise measurements separated by a short distance. The cause of this difference in measured level between downwind locations appears to be a combination of contact between the board and ground surface, distance from the turbine, and angle of incidence of sound onto the board relative to the board surface. For this reason, any differences measured during a test using two separate downwind measurement locations may have been the result of the different physical measurement location, rather than an actual difference in noise output due to the test turbine being in the wake of another.

Therefore, rather than using two separate downwind locations, our testing used a single primary measurement location to determine the influence of the upwind turbines on the test turbine, which was measured over a range of wind directions relative to the test turbines nacelle. A secondary measurement location at a different angle from the same turbine provided non-wake affected data over the considered range of angles at which the primary location was potentially wake affected. The data from the secondary measurement location was used to confirm the influence of measurement angle on measured noise level. This quantification of one of the variables in the sound power levels of the turbines allowed determination of the influence of upwind turbines at the primary location.

Measurement angles

Results are presented for three wake conditions in this report (at three measurement angles relative to the nacelle). Each of the three measurement bins consider data measured within +/- 15º from the bin centre.

Figure 2 illustrates the first test condition for the primary measurement location, where the test turbine is directly downwind of all of the other turbines (measurement angle -140º from upwind). The further turbines from the test turbine have been omitted from all figures for clarity, but were all located to the right of the page from the turbine labelled '2nd adjacent turbine'.

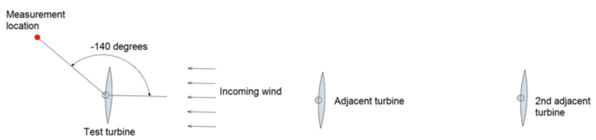

Figure 2. Test turbine in the wake of other turbines (measurement angle -140º from upwind).

Figure 3 illustrates the second test condition for the primary measurement location, which is the standard measurement location directly downwind of the turbine (180º). Under this wind direction there is a chance that part of the tested turbine rotor is in the wake of the upwind turbine, particularly at data points measured towards the -165º limit on this bin.

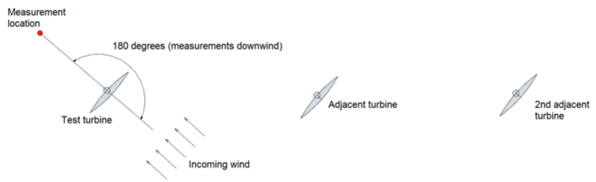

Figure 3. Test turbine may be partially in the wake of other turbines (measurement angle 180º from upwind).

Figure 4 illustrates the final test condition for the primary measurement location, where the measurement location is 140º from upwind (and the tested turbine is clearly not in the wake of the adjacent turbines).

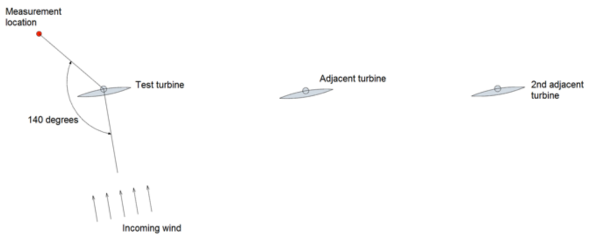

Figure 4. Test turbine clearly not in the wake of other turbines (measurement angle 140º from upwind).

RESULTS

The results in this paper are presented as sound pressure levels measured at the location used for sound power measurements under IEC 61400-11. It should be noted that any variation in the sound pressure levels at the measurement location will translate to an identical variation in the calculated sound power levels for the turbine under the IEC Standard, as long as background noise levels are low enough to not affect the measurement results.

Sound power measurements undertaken at the secondary measurement location included measurements over the same range of measurement directions relative to the nacelle as the primary location but, due to the different positioning of the secondary location, all measurements were undertaken when the test turbine was clearly not in the wake of another. This data was used to confirm the influence of measurement angle on the measured noise level.

Figure 5 provides the results of the measurements at the secondary measurement location. Background noise levels measured when the turbine was not operating are also presented and do not appear likely to have noticeably influenced the measurement results. The error bars presented on the figure are the uncertainty values calculated according to method defined in IEC 61400-11.

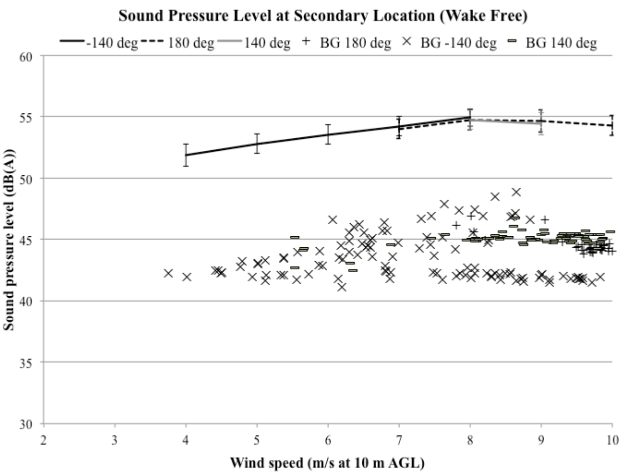

Figure 5. Measured noise levels at the secondary measurement location, which confirms measured levels are not influenced by measurement angle at primary location.

From Figure 5, the same sound pressure level is measured at angles of -140º, 180º, and 140º relative to the wind direction. Based on this result, the measurement angle (over the range of -140º, 180º and 140º) would not alter the measured noise level at the primary location. All differences in measured noise levels at the primary location are therefore likely to be the result of wakes from upwind turbines, rather than a result of measurement angle.

Figure 6 provides the results at the primary measurement location, where there is a varying degree of wind turbine wake incident on the test turbine. Background noise levels measured when the turbine was not operating are also presented and do not appear likely to have noticeably influenced the measurement results. As for Figure 5, the error bars are the uncertainty values calculated according to IEC 61400-11 with the background noise levels for wind speeds of 5 m/s to 6 m/s calculated based on adjacent wind speeds as no data points were available.

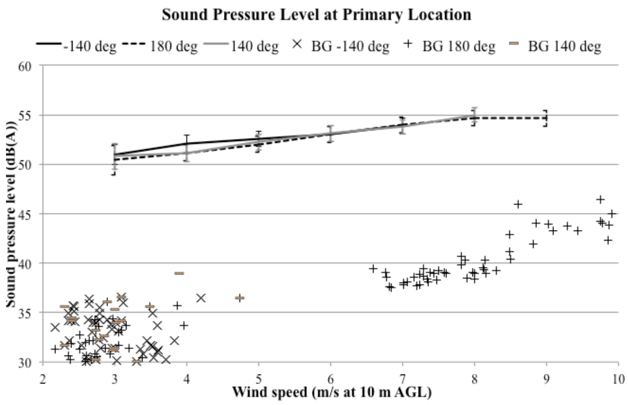

Figure 6. Measured noise levels at the primary measurement location, showing influence of wake on sound power level.

The results shown in Figure 6 indicate that there was no difference in the measured noise level with wind direction at high wind speeds. The ingested turbulence from the wake of an adjacent wind turbine therefore does not increase the sound power level radiated from a turbine at high wind speeds. We note that the maximum sound power level of a proposed wind turbine (which occurs at high wind speeds) normally controls the acoustic design of a wind farm site. These measurements confirm no wake induced increase in turbine sound power at those critical speeds.

At low wind speeds (3 to 5 m/s at 10 metres above ground level) an increase in measured sound pressure level was observed in some of the data points gathered when the test turbine was immediately downwind of the adjacent turbines (measurement angle of -140º). Data measured when the test turbine is in the wake of the adjacent turbine was sorted into bins of only 5º width with each individual data point replotted in Figure 7.

The results shown in Figure 7 indicate no increase in measured noise levels at angles of -155º to -145º. Several of the data points in the -140º to -145º bin have been increased by approximately 1 to 1.5 dB(A), with others in that bin closely matching measurements at -155º to -145º. An increase in all low wind speed measurements in the bins covering -140º to -120º is observed, with no increase in the -115º to -120º bin. Note that the reduction in level of higher wind speed measurements in the -115º to -120º bin is believed to be due to the onset of the noticeable reduction in sound power that can occur at angles at -90º and 90º degrees from the turbine.

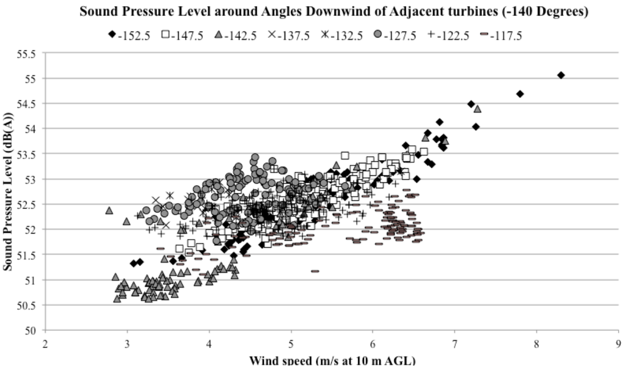

Figure 7. Measured wake affected noise levels, sorted into bins of 5 degrees width.

The increase in measured noise level at measurement angles greater than -140º with no corresponding increase at angles less than -140º was unexpected, given that -140º corresponds to the turbine being directly downwind of the other turbines, so both directions are assumed to be equally in the wake of the adjacent wind turbine.

Further review of the measured noise level data in the -140º to -145º bin indicated that the lowest measured levels were typically found at angles nearer -140º, with the highest levels occurring nearer to -145º (the reverse of what would be expected based on the results in adjacent bins). Additionally, measurements at the same angle and speed sometimes showed differences in measured noise levels of approximately 1.5 dB(A), indicating that the higher measured noise levels were not present for the full duration of the test.

A review of the times that data was measured in the wake affected wind directions indicated that all of the low wind speed measurements with increased noise level that occurred between -145º and -120º degrees were measured on only one night during the week of measurements. Measurements at the lower level in the -140º to -145º bins, and all of the measurements at angles of -145º to -155º occurred at other times in the measurement period.

It is unclear whether the inconsistent 1 to 1.5 dB(A) increase in sound power level at low wind speeds was the result of the wake of the upwind turbines or another factor. This relatively small increase is confined to only wind speeds below 5 m/s, with measurements at higher wind speeds on that same night showing no increase in measured level when compared to measurements at non-wake affected angles.

DISCUSSION

There is a possibility that the relatively small and intermittent increase in measured noise levels (when compared to the sound power that would be expected under a non-wake affected measurement the same wind speed) at low wind speeds was the result of the wake of the upwind turbines. The potential increase is relatively minor (a maximum of 1.5 dB(A)) and occurs at lower wind speeds which are not normally representative of the highest turbine noise levels at nearby residences.

A portion of this increase may be the result of uncertainty in the sound power measurement procedure under IEC 61400-11. This uncertainty was typically 0.9 dB for the dataset gathered as part of this study. However, it is noted that this uncertainty could also result in a minor underestimate of the difference in sound power levels. Regardless, the uncertainty in the sound power measurement is a relatively small amount.

It is also important to recognise that this study is based on wind speeds determined from the power output of the tested wind turbine. It is widely accepted that there is a wind speed deficit in the wake of a turbine, and that any turbine operating in that wake receives less wind than it would if it were operating in the absence of the upwind turbine. While there is a chance that the upwind turbines resulted in a small increase in noise radiated from the turbine, these same turbines will have reduced the wind speed at the test turbine relative to what would have occurred had the upwind turbines not been there.

Sound power levels of modern (pitch controlled) wind turbines typically increase with wind speed up until a speed just below rated power is achieved. Therefore, this reduction in wind speed results in a reduction in the anticipated sound power output of the turbine when compared to the sound power output that would occur in the absence of the upwind turbines.

For example, a 20% reduction of wind speed in the wake from a free stream speed of 5 m/s to 4 m/s results in a reduction in sound power of 1 dB(A), a reduction that approximately matches the intermittent increase in noise level that may be the result of wake turbulence. In this case, the net result of the upwind turbines on the wake-affected turbine would be no change in noise level for the higher wake-affected noise level measurements, with a reduction in noise level from others.

Further studies are required to determine the actual reduction in wind speed that occurred at the turbine due to the presence of the upwind turbines. However, given the relatively minor increase in sound power level at low wind speeds, it is considered likely that the decrease in wind speed would have largely offset any increase in sound power level.

CONCLUSION

This paper presents an analysis of measured noise levels from a wind turbine during periods when the turbine was affected by the wake of other turbines and periods when it is unaffected by the wake of those turbines. Noise levels were measured at the location where sound power level measurements of wind turbines are conducted, and in general accordance with the methodology outlined in IEC 61400-11.

The analysis found that there was potentially a relatively minor increase in sound power levels from the wind turbine of between 1 to 1.5 dB(A) due to the wake created by the upwind turbines. However, this increase did not occur consistently and only occurred at low wind speeds of approximately 3 to 5 m/s at 10 metres above ground level. At these wind speeds, the sound power levels of the turbines would be expected to be considerably lower than at rated power for the turbine.

Furthermore, the presence of the wake created by the upwind turbines would have reduced the wind speed at the turbine at which the measurements were taken, reducing the sound power level accordingly at these low wind speeds. This would have helped to offset any increase in sound power level that may have occurred due to the presence of the upwind turbines.

Therefore, the data gathered as part of this assessment does not support the proposition that the wakes of adjacent turbines will increase the level of noise emissions from wind farms.

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