Forecasting low frequency noise from wind farms

Rhys Brown (1), Andrew Mitchell (2) and Luis Najera Medina (1)

(1) AECOM, Brisbane, Australia
(2) AECOM, Melbourne, Australia

ABSTRACT

Wind farm noise is commonly forecast as an overall A-weighted noise level for comparison against legislative requirements. In Australia various regulatory bodies have begun considering low frequency noise criteria which can be applied to industrial facilities, including wind farms. One such example is the NSW Draft Wind Farm Noise Guidelines which presents criteria of 60 dB(C) for the night-time and 65 dB(C) for the daytime. Whilst the forecasting of overall A-weighted noise levels from wind farms is well documented and validated against measured wind farm noise levels, the forecasting of low frequency noise (noise above 20Hz but below 200Hz) has not been widely validated. This paper analyses wind farm compliance noise monitoring adjacent wind farms in Australia and compares the measured low frequency noise levels against forecast low frequency noise levels. The influence of various factors of the monitoring and modelling chain is discussed, including the effect of wind noise on the measurement microphone. It was found that modelling of C-weighted noise levels can be performed using the same model as used for forecasting A-weighted noise levels and the results obtained would likely be a conservative estimate of C-weighted wind farm noise levels in most cases.

INTRODUCTION

Wind farm noise is commonly forecast as an overall A-weighted noise level for comparison against legislative requirements. Various regulatory bodies in Australia have been requesting additional criteria be imposed on wind farm operations in addition to overall A-weighted noise levels. These commonly include tonality, infrasound and low frequency noise. Two states of Australia, New South Wales (NSW Government 2011) and Victoria (EPA Victoria 2013) currently have draft wind farm noise guidelines which prescribe low frequency noise criteria of 60 dB(C) for the night-time and 65 dB(C) for the daytime. Whilst a number of studies have been undertaken comparing the results of overall A-weighted computer modelling for wind farms against measured results, upon review the authors of this paper believe that there has been no significant published work to validate the forecasting of low frequency noise (LFN) from wind farms using conventional noise modelling when compared to measured wind farm noise. This paper seeks to investigate the ability of a conventional empirical acoustic model used to forecast overall A-weighted noise from wind farms to be adapted with minor adjustments to accurately forecast low frequency wind farm noise.

LIMITATIONS

The study reported in this paper has a number of limitations. The appropriateness of any proposed associated descriptors for low frequency noise has not been investigated. Furthermore the actual low frequency content of the modelled wind turbine noise has not been investigated to determine if it is actually a significant amount of low frequency noise. Indeed many guidelines for the assessment of wind farm noise specifically exclude the separate assessment of low frequency noise stating that an assessment of overall noise is sufficient. The authors note that the current low frequency criteria applied to wind farms are typically C-weighted, which does not exclude non low frequency energy (sound energy above 200Hz). The study was limited to the comparison of overall forecast levels against overall measured levels – the frequency content of measured and forecast results was not compared.

As an additional limitation, a comparison of the background low frequency noise levels was not able to be undertaken for all of the sites analysed, as only the overall A-weighted background noise monitoring data was available for most sites.

MEASUREMENTS

General

Eleven sets of wind farm noise compliance measurements from three large Australian wind farms were used to determine the measured wind farm noise for a range of descriptors commonly used to quantify low frequency noise. The eleven sites were chosen due to the varying proximity to the nearest turbines as well as the fact that the measurements were undertaken with noise loggers that recorded 1/3 octave L_{90}'s and L_{eq}'s to allow processing into various descriptors. For all of the sites, the original purpose of the measurements was to determine the overall A-weighted noise levels and as such the measurements were undertaken at four of the sites in accordance with the South Australian guidelines (South Australian Environmental Protection Authority 2009), and in accordance with New Zealand Standard NZS6808:2010 (Standards New Zealand 2010) at the remaining sites. The measurement methodologies in both cases are similar; both involve measuring the noise levels in 10-minute intervals, then determining the 'wind farm noise levels' from a curve fitted to a plot of the measured noise levels verses wind speed. For analysis of the low frequency wind farm noise levels, the same method of curve fitting was used as for the original A-weighted noise level analysis, except with the substitution of overall A-weighted noise levels with the relevant low frequency descriptor. Analysis of the results for low frequency noise has only considered data points in the worst case wind direction. Whilst this does not guarantee that only the wind farm is contributing to the measured level - it is one method commonly used for A-weighted post-compliance measurements to more accurately quantify wind farm levels (South Australian Environmental Protection Authority 2009).

Low Frequency Noise Descriptors

The first component of this study was aimed at identifying the best descriptor to quantify measured LFN and compare the forecast wind farm noise against. Four descriptors were analysed to determine their ability to reliably quantify measured low frequency noise from the wind farm:

- L_{Ceq}
- L_{C90}
- L_{C95}
- L_{pAlf} – this parameter is defined as the A-weighted 1/3rd octave L_{eq} measurements summed between 10Hz to 160Hz inclusive.

Processing Results

The four different LFN descriptors were analysed across the eleven sites to determine which descriptor appeared to provide the best representation of wind farm LFN. For three of the sites, insufficient data was captured to reliably determine the L_{pAlf} descriptor. A graph for each of the descriptors from two of the sites is presented in Figures 1 – 7 below. It is noted that for Location 5, insufficient data was collected to process the L_{pAlf} descriptor. The graphs show each 10-minute data point measured during the monitoring period as black dots. The polynomial fit-line to this data is shown on the graph as an orange line. For the purposes of comparing measured noise against modelled noise, the wind farm noise was taken from the polynomial fit at 10m/s hub height wind speed. This was approximately the wind speed at which the turbines under consideration generated their maximum A- and C-weighted sound power levels.

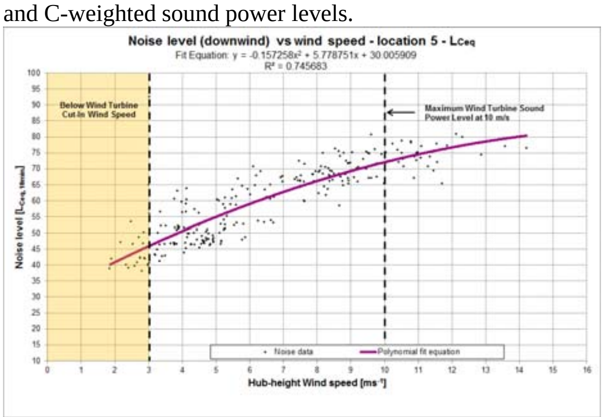

Figure 1. Location 5 – L_{Ceq}

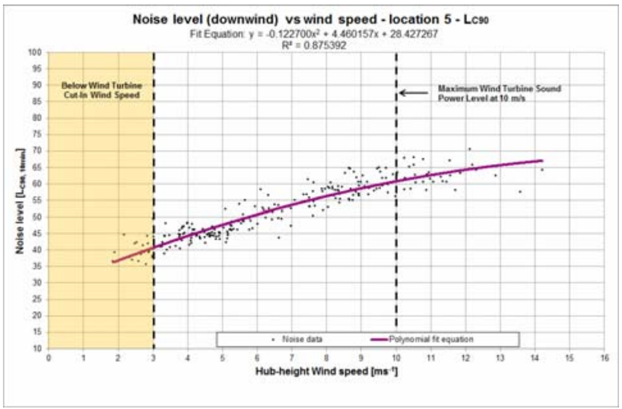

Figure 2. Location 5 – L_{C90}

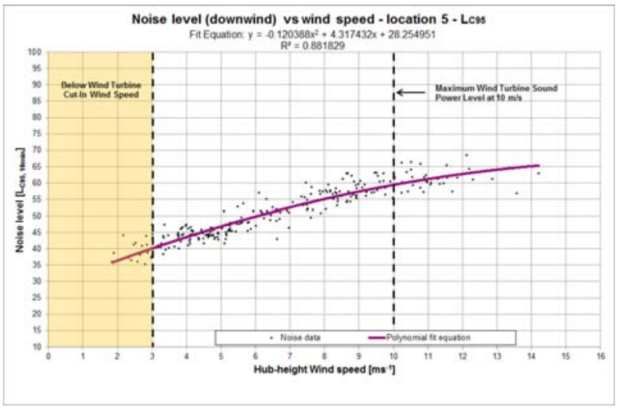

Figure 3. Location 5 – L_{C95}

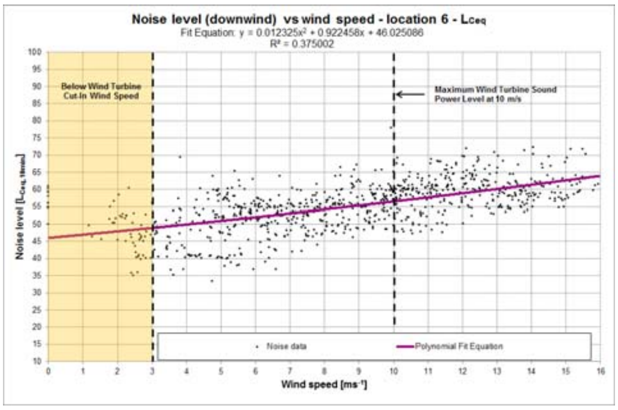

Figure 4. Location 6 – L_{Ceq}

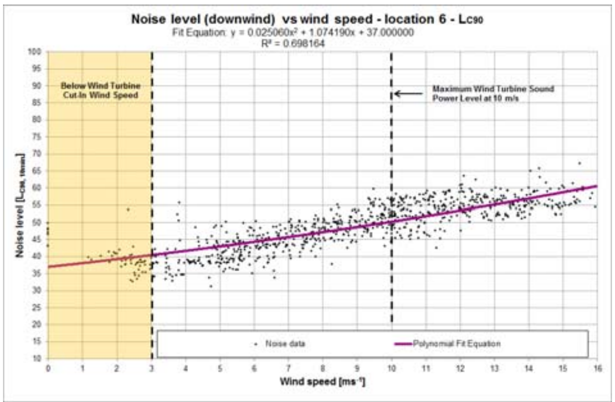

Figure 5. Location 6 – L_{C90}

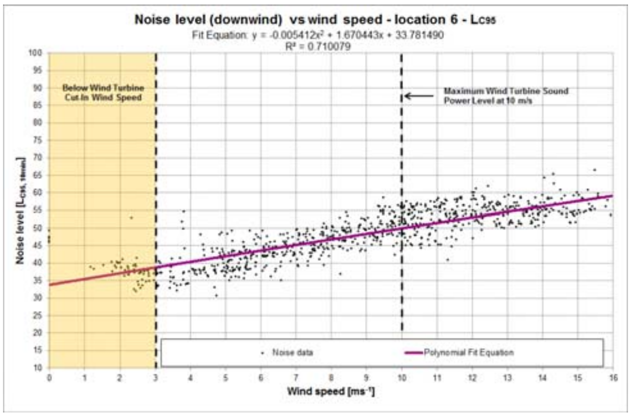

Figure 6. Location 6 – L_{C95}

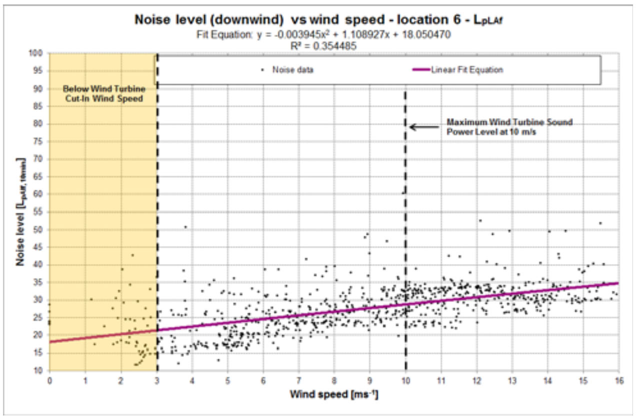

Figure 7. Location 6 – L_{pAlf}

Discussion of each descriptor

L_{Ceq}

Whilst the L_{Ceq} noise levels increased with increasing wind speeds as expected, the spread of noise data at any given wind speed was significant. The typical co-efficient of correlation (R^2) was low, around 0.5 when compared to the results of most of the sites for the L_{C90} and L_{C95} descriptors which were often between 0.7 and 0.8 or greater. This result is not surprising when using an L_{eq} based descriptor as the same issues are encountered when trying to quantify overall A-weighted wind farm noise levels using the L_{Aeq} descriptor. This is because wind farm noise rarely dominates the noise environment at typical receptor distances, as significant wind-induced ambient noise and wind induced microphone noise is often present. Additionally short term sounds of a high level e.g. birds, vehicle movements etc. can have a controlling effect when using an L_{eq} descriptor. Based on the analysis it was considered that the L_{Ceq} descriptor would not be the most reliable way to quantify the low frequency noise levels.

L_{C90}

The noise levels measured using the L_{C90} descriptor exhibited the expected trend in noise level with increasing wind speed, and showed with relatively little scatter in the data at any particular wind speed compared to other descriptors. This level of scatter is also typical of L_{A90} analysis for wind farms. It was hypothesised that this descriptor provided the best description of wind farm LFN and is the most logical as it is analogous to the L_{A90} descriptor most commonly used to quantify overall A-weighted wind farm noise.

L_{C95}

The L_{C95} descriptor provided similar results when compared to the L_{C90} descriptor. The measured L_{C95} levels were typically between 0.5 – 1 dB less than the measured L_{C90} noise levels, but had a very similar spread of data at any particular wind speed. Whilst the L_{C95} parameter appears to quantify noise similarly to L_{C90}, there doesn't appear to be any benefit in using this parameter instead of the L_{C90}.

L_{pAlf}

The noise levels measured using this descriptor showed the least increase with increasing wind speed. The rate of increase in the measured L_{pAlf} noise levels with wind speed was much less than expected based on the increase in wind turbine L_{pAlf} Sound Power Levels with increasing wind speed. This suggests either that the L_{pAlf} measurements were dominated by ambient or wind-induced noise across the measured wind speed range, or at the very least that background noise has influenced the measured L_{pAlf} noise levels more significantly at low wind speeds than for the other noise descriptors analysed. As a consequence the typical co-efficient of correlation (R^2) was low, typically around 0.3 – 0.4.

A review of the A-weighted spectrums showed that a significant component of the energy from the turbine at the wind farm was removed due to only considering noise between 10 – 160Hz. Additionally there were a large number of outlier data points which is to be expected when using an L_{eq} based descriptor. Due to these factors it is considered the least appropriate wind turbine LFN descriptor in this study.

Influence of wind noise

From the data available it was not possible to accurately determine the influence of noise from wind acting on the microphone or from ambient low frequency noise generated by wind acting on vegetation. No wind measurements were undertaken at the microphone height as part of this study. A good quality 90mm diameter wind screen was used on all microphones for the measurements in this study. For overall A-weighted noise these wind screens are generally considered sufficient (Cooper et al. 2008). It is noted however that some international guidelines recommend 180mm diameter or secondary wind screens. Additionally it is unknown at some sites as to the extent to which wind-induced vegetation noise may have influenced the measurements. Where pre commisioning (no operational wind farm) noise data was available an analysis was undertaken using L_{C90} background noise data. The analysis compared the downwind and upwind noise levels versus the upwind and downwind pre wind farm background noise levels to determine the likely contribution of wind farm noise (on the basis that a higher level of wind farm noise contribution would be observed during downwind conditions than upwind conditions, unless the measurements had been influenced by background noise or wind-induce microphone noise).

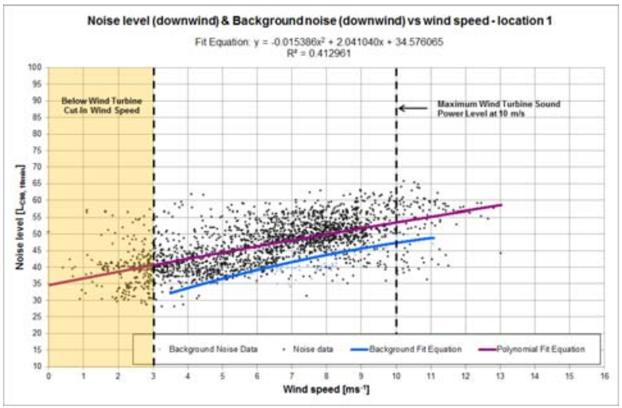

Figure 8. Location 1 – Downwind background vs downwind post construction

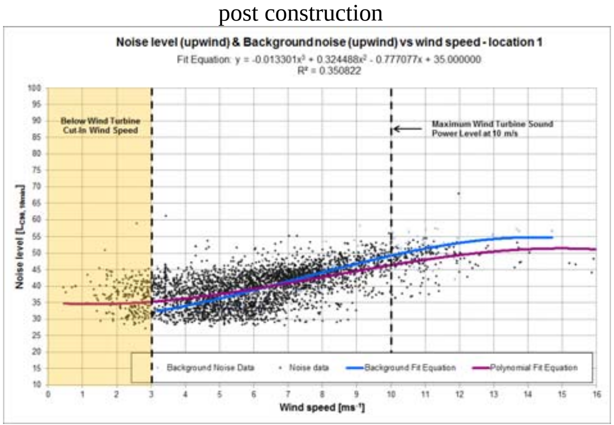

Figure 9. Location 1 – Upwind background vs upwind post construction

Figure 8 and Figure 9 suggest that under down wind conditions the wind farm noise increased the overall noise level by at least 5 dB for most wind speeds at location 1. The analysis suggests that whilst the measured L_{C90} noise levels are not completely controlled by wind farm noise (which is an expected result due to the presence of ambient noise generated by wind at all of the sites), that the measured noise levels are somewhat controlled by wind farm noise as demonstraited by the downwind/upwind analysis of the site above.

MODELLING LOW FREQUENCY WIND FARM NOISE

The second component of this study was to investigate if conventional wind farm noise modelling techniques used to predict A-weighted wind farm noise levels could be used, with no more than minor modifications, to forecast low frequency noise. The results of the modelling were compared to the measured L_{C90} noise levels discussed above. The modifications to the model were deliberately limited to standard adjustments to the model, i.e. not having to build an entirely new model, as it is hoped that when forecasting overall A-weighted noise levels minor modifications can be made to easily and relatively accurately forecast LFN levels and compare against relevant criteria.

Methodology

An existing computer based noise model for a large scale wind farm in Australia was modified to allow it to forecast dB(C) noise levels. Eight of the noise measurement sites used in this study were from this wind farm, and were represented in the computer model. The modelling was undertaken in SoundPLAN^{TM}, a modelling package commonly used for forecasting wind farm noise. The modelling was initially undertaken using the parameters outlined below.

- Concawe noise modelling algorithm (CONCAWE, 1981)
- Meteorological Category 6 (Bies and Hansen 2003)
- 100% soft ground
- Wind turbines operating at maximum A-weighted sound power level (10m/s at hub height) (Note that for this turbine model, the maximum C-weighted sound power level occurs at 8 m/s. At a wind speed of 10 m/s the C-weighted sound power level is within 0.5 dB of the maximum C-weighted sound power level).

These parameters were chosen based on previous studies which have found this to be a generally conservative method of modelling wind farm noise (Evans and Cooper 2012). Table 1 outlines the results of the comparison between the forecast and measured L_{C90} levels. For comparison, the differences between the measured and forecast overall 'A'-weighted L_{A90} noise levels are also presented.

Table 1. Comparison between measured and forecast levels

Location	*Approx. distance to nearest turbine (m)*	*Measured L_{C90}*	*Forecast L_{C90}*	*ΔMeasured L_{C90} to forecast L_{C90}*	*ΔMeasured L_{A90} to forecast L_{A90}*
1	1770	52.5	51.9	-0.6	-2.5
2	1820	56	56	0	2.9
3	1410	56	55	-1	1.1
4	2510	-	53.1	-	-*
5	720	61	62.9	1.9	3.5
6	2120	50.5	52.3	1.8	1
7	2650	49.5	51.1	1.6	5.8
8	840	56	62.6	6.6	4.7

**The measured noise levels at location 4 were not controlled by wind farm noise*

From the initial modelling it was found that as a general trend the model over-estimated noise levels for locations closer to the nearest turbine and under-estimated noise levels for locations further away from the nearest turbine. This result is not entirely unexpected as locations which are further away from the wind farm would not be as controlled by wind farm noise as the sites closer to turbines and therefore the measured levels represent a higher figure than what is actually generated by the wind farm due to the influence of background noise. The same general trends are evident between the measured and forecast L_{A90} noise levels; however the A-weighted forecasts appear to be slightly more conservative when compared to measured noise levels. As discussed earlier in the paper the measured C-weighted levels are likely to contain background noise not associated with the operation of the wind farm. This suggests that modelling of C-weighted noise levels can be performed using the same model as used for forecasting A-weighted noise levels and the results obtained would likely be a conservative estimate of C-weighted wind farm noise levels in most cases, based on the presence of ambient noise and possible wind induced microphone noise in the data. This provides a preliminary validation of the use of conventional noise models modified to predict C-weighted wind farm noise levels however the authors believe further study should be undertaken, including validating measured spectral levels of wind farm noise against the forecast spectral noise when using the methods outlined in this paper.

Further analysis

After the initial modelling comparison some additional investigation was undertaken. Modelling was undertaken using 1/1 octave sound power data instead of 1/3 octave data. It was found that the octave band consistently forecast approximately 1 dB(C) higher than when using 1/3 octave data. It is not known why this difference occurred however it was considered that where there is sufficient data available that modelling should be undertaken with 1/3 octaves.

Additionally comparison was made between the modelling results produced above and those using ISO9613 (International Organization for Standardization 1996) with fully hard ground, another methodology commonly used when forecasting wind farm noise levels in accordance with NZS6808:2010. It was found that this methodology forecast noise levels on average 0.8 dB(C) higher than the CONCAWE method, however for one site it did forecast 1.2 dB(C) lower than the CONCAWE method. The authors of this paper believe that there is insufficient data to draw the conclusion that either method (ISO9613 or CONCAWE) is more accurate at forecasting low frequency noise from wind farms than the other.

CONCLUSION

This study investigated forecasting low frequency noise from modern wind farms. The study compared various low frequency noise descriptors from measured wind farm noise data and found that the most appropriate descriptor for comparison of measured and modelled wind farm low frequency noise is L_{C90}. This is consistent with the generally accepted method of measuring overall A-weighted wind farm noise using L_{A90}. The possible effects of wind noise over the microphone was not able to be validated, but from an analysis of downwind and upwind noise levels and the modelled results it appears that this did not have a significant effect but warrants further investigation.

The measured noise levels were compared against forecast L_{C90} wind farm levels, based on an existing computer based noise model for one of the wind farm sites. It was found that as a general trend the model over-estimated noise levels for locations closer to the nearest turbine and under-estimated noise levels for locations further away from the nearest turbine. The same general trends are evident between the measured and forecast L_{A90} noise levels as was found for L_{C90} levels. This suggests that modelling of C-weighted noise levels can be performed using the same model as used for forecasting A-weighted noise levels and the results obtained would likely be a conservative estimate of C-weighted wind farm noise levels in most cases, based on the presence of ambient noise and possible wind induced microphone noise in the data.

REFERENCES

Bies, D & Hansen, C 2003, *Engineering Noise Control*¸3rd edn, Spon Press, New York.

CONCAWE 1981, *The propagation of noise from petroleum and petrochemical complexes to neighbouring communities*, Report No.4/81, CONCAWE, Den Haag.

Cooper, J, Leclercq, D & Stead, M. *Wind induced aerodynamic noise on microphones from atmospheric measurements*. International Congress on Acoustics 2010, Sydney, August 23-27 2010.

EPA Victoria 2013, *Application of New Zealand Standard 6808 for Wind Farm Noise – An EPA Victoria Guideline*, EPA Victoria.

Evans, T & Cooper, J 2012, *Comparison of predicted and measured wind farm noise levels and implications for assessments of new wind farms*, Acoustics Australia, vol.40, no. 1, pp. 28-36.

International Organization for Standardization 1996, *Acoustics – Attenuation of sound during propagation outdoors - Part 2: General method of calculation, ISO 9613-2:1996*, International Organization for Standardization, Geneva.

NSW Government 2011, *Draft NSW Planning Guidelines: Wind Farms*, Sydney.

South Australian Environmental Protection Authority 2009, *Wind farms: environmental noise guidelines*, Environmental Protection Authority, Adelaide.

Standards New Zealand 2010, *NZS6808:2010 Acoustics – Wind farm noise*, Standards New Zealand, Wellington.