

The Relationship between L_{A90} & L_{Aeq} Wind Turbine Sound Level Descriptors in NZ



Lindsay Hannah¹, Wyatt Page² and Stuart McLaren²

(1) Acoustic Consultant, Malcolm Hunt Associates, Noise and Environmental Engineers. Wellington, New Zealand

(2) Acoustics and Human Health Division, Institute of Food, Nutrition and Human Health Massey University. Wellington, New Zealand

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Abstract

The New Zealand Wind Turbine Standard NZS6808 provides guidance on the methods for the prediction, measurement and assessment of sound emissions from wind turbine generators. This study attempted to quantify the potential variability between measured wind turbine generator sound emissions using the descriptors L_{Aeq} and L_{A90} [specified in the standard], both on the wind farm site [near-field] and at a remote receiver dwelling location [far-field] where people reside. Results of the field study showed that the mean sound level difference between the descriptors, measured at a residential location remote from the wind farm was 2.4 dB compared to 1.4 dB on the wind farm site. Of the 11,150, 10 minute sound pressure level sample pairs recorded over a 12 month period at the remote location, only 39 remained for the analysis after post-filtering to remove samples contaminated by extraneous noise. The study illustrates the difficulty in making robust measurements of wind turbine sound in the far-field.

INTRODUCTION

The current New Zealand wind turbine acoustic standard, 'NZS6808:2010 Acoustics - Wind Farm Noise', took effect in 2010. It places priority on received sound pressure levels measured at dwellings remote from the wind turbine rather than sound emission received on the wind farm site. As part of the NZS6808:2010 assessment process, L_{A90} background sound levels are required to be measured at the relevant off-site receiving locations [] before a wind farm site is developed. Allowable wind farm design noise limits are then derived from a comparison of the predicted wind turbine sound pressure levels and the measured background sound at the nominated off-site receiving location.

Two sound level descriptors are specified in NZS6808:2010. The first is the A-frequency weighted time-average equivalent level, L_{Aeq} , and the second is background sound level referred as the L_{A90} centile level, the A-frequency weighted level that is exceeded for 90% of the measurement period. A possible disparity arises with the use of these two different descriptors and in order to account for the potential variation between the descriptors, the standard recommends that predicted L_{Aeq} sound pressure levels at any receiver location are to be treated as equivalent to the L_{A90} value when setting wind turbine design noise limits. This means that once the wind farm is operational, compliance measurements [if required] are made using the L_{A90} descriptor and directly compared to a wind farm noise limit criterion also defined in terms of a L_{A90} .

The 2010 New Zealand Standard for wind turbine generators states that "the predicted wind farm L_{Aeq} at any receiver location is deemed to be equivalent to the L_{A90} value", that is, we are told to assume that $L_{Aeq} = L_{A90}$. It is understood that such a statement was included in the standard to deal with the

potential uncertainty or possible perceived discrepancy of the actual imprecise and variable differences between these two descriptors. At the time of commencing this study, the then-current standard [NZS6808:1998] did not specifically account for the difference in the two descriptors then used, L_{A95} [the 95% centile level] and L_{Aeq} , other than to state an expected range difference between the two sound level descriptors which was described within the 1998 Standard as being that L_{A95} is 1.5 dB - 2.5 dB lower than the L_{Aeq} level. This was based on the work done in the United Kingdom by the Working Group on Noise from Wind Turbines, documented in ETSU-R-97[].

Clauses 4.2.1 and 4.4.2 of NZS6808:1998 for assessing sound from wind turbine generators depicts the following relationship between the L_{Aeq} and L_{A95} descriptors:

$$L_{Aeq} = L_{A95} + 2.5 \text{ dB or } L_{A95} = L_{Aeq} - 2.5 \text{ dB}$$

It was not entirely clear in NZS6808:1998 whether the difference in sound descriptors was on the wind turbine site itself or off-site however the implication of this 2.5 dB difference is quite clear - the equivalent L_{Aeq} wind farm design limit could be up to 2.5 dB above the background L_{A95} for the same measured level of wind farm noise. Thus, under the 1998 Standard there may be a perceived discrepancy as a wind farm designed to achieve a predicted level of L_{Aeq} of 40 dB at a given receiver location could only measure L_{A95} of 37.5 dB at this location, thus implying a 2.5 dB 'safety margin' when assessing compliance. A key implication of this is that wind turbine sound could potentially exceed the allowable 40 dB design noise limit [or average background sound level +5 dB] by up to a further 2.5 dB and still remain in compliance with the limits recommended under NZS6808:1998.

STUDY SITES

Two studies were conducted into the relationship between L_{A90} and L_{Aeq} sound level descriptors for commercial three-bladed horizontal contemporary wind turbine generators in a New Zealand environment. The principal study made measurements in the 'far-field', adjacent to a dwelling in the 'Project West Wind' wind farm area [Wellington, New Zealand [also referred to as Makara Wind Farm or just Project West Wind]]. The secondary study made measurements in the 'near-field' at the nominated IEC 61400-11 R_o measurement location [3] on the second site, the 'Te Apiti Wind Farm', located in the Manawatu area, New Zealand.

In addition to these two data sets, significant additional measurements were made using handheld instruments to assess the frequency spectrum characteristics and time varying nature of the sound environments. These data sets were supported with lengthy on-site observations covering both day and night time periods.

Principal Study Site - Project West Wind

Sound pressure level measurements were made approximately 15 to 20 metres south of the selected dwelling [4] with direct line-of-sight of wind turbine generator 'D12'. This turbine is a 'Siemens 2.3 MW' [SWT-2.3-82VS] generator, with a hub height of approximately 67 metres and has three blades each of 40 metres in length. The Project West Wind, turbines are pitch-controlled variable-speed turbines. This allows the blade pitch angle to be set dependant on the electrical power output, wind speed and rotational speed. As the wind turbines are variable speed, this allows the rotor to change rotational speed between 6 revolutions per minute [rpm] and 18 rpm, depending upon the wind speed. The wind turbine generators at Project West Wind have individual programming allowing them to be 'de-rated' if required. The variable speed programming also maps to an alternative power curve relationship, such that the turbines can run at lower rotational speed to reduce the aerodynamic sound output. Sound produced by the wind turbine generators, as received at locations in the far-field, subjectively ranged from low levels of audible sound to levels of sound that were at the majority of times inseparable in the context of unwanted background sound via the use of a sound level meter as the measurement tool.

Secondary Study Site - Te Apiti Wind Farm

Sound level measurements were made at the IEC 61400-11 R_o location, with direct line-of-sight with wind turbine generator, 'Tap 44', which is a 'Vestas V72' model. This generator has a hub height of approximately 60 metres and three blades, each 35 metres in length. It is noted that the NM72 [Neg Micon NM72] was renamed the Vestas V72 with the V72 being the first commercial 'mega-watt' class wind turbine generator used in New Zealand. The maximum power output of the Te Apiti wind turbine generators is controlled through active stall and as they are fixed rotational machines the ability to control their acoustic emission output is limited.

Wind Conditions and Terrain Factors at the Study Sites

The two study sites are located at the bottom of the North Island of New Zealand, at latitudes between 40 and 50 degrees

south of the equator. The Project West Wind, wind farm has two predominant wind directions [relative to true north] described as 'North North West [NNW]' and 'South South East [SSE]'. The Te Apiti wind farm has two predominant wind directions described as 'North West [NW]' and 'North North West [NNW]'.

The terrain at the measurements locations on both study sites was fairly level with the wider surrounding area being undulating terrain. At the primary study site, consideration had to be given to access, proximity of local dwellings, line-of-sight to the source, wind exposure and ground vegetation when siting the measurement instrumentation. Also, the terrain between the wind turbine source and measurement location at Project West Wind, was a 'complex heterogeneous terrain', meaning that there was varying altitude between source and receiver, varying ground conditions and surface gradients. This is in contrast with secondary study site at Te Apiti, with a relatively flat undulating, grass covered terrain.

MEASUREMENT APPROACH

The underlying philosophy of this study was to assess the relationship between the L_{Aeq} and L_{A90} sound level descriptors at the two wind turbine sites and capture measured sound pressure levels from the wind turbine generators, as free as possible from any additional extraneous noise.

Conceptually this approach is in line with the total-sound approach described in the base New Zealand environmental acoustics standards [NZS6801:2008 and NZS6802:2008] for finding the residual sound, the sound that remains when the target sound source[s] are removed. In principle for wind farms, this could be achieved during commissioning by taking sound measurements with the turbine rotors locked [parked] and then repeating the measurements with the turbines operational [also known as on/off testing]. However, this is much more problematic to undertake if the wind farm is to remain fully operational and generating power.

A number of measurement approaches were initially trialled, including short- and long-term sample periods, in conjunction with concurrent audio recording of the sound. Lengthy periods were also spent studying the measurement locations when the turbines were operational and when parked. The final measurement method employed was to use the sound level meters directly and then to post-filter the data to remove measurements contaminated with extraneous sources. Figure 1 graphically illustrates this measurement approach and shows at the bottom, the five post-filtering steps used to remove contaminated data. The key to the potential robustness of this approach is the ability to capture a large sample set of data over a relatively limited study period of one year. The sound level meters were set up so they were synchronised with the 10 minute wind speed sampling periods [at hub height, $V_{Hub\ Height}$] of the target wind turbine generator[s] and the local 10 metre high test site meteorological mast [V_{10m}]. Wind speed measurements at the microphone were also captured.

Principal Study - Project West Wind

In total, 11,150 raw [10 minute] sound level pressure sample pairs were made, representing a continuous duration of just under 75 days. Data was collected over a period of approximately 12 months, covering all four seasons; however the majority of

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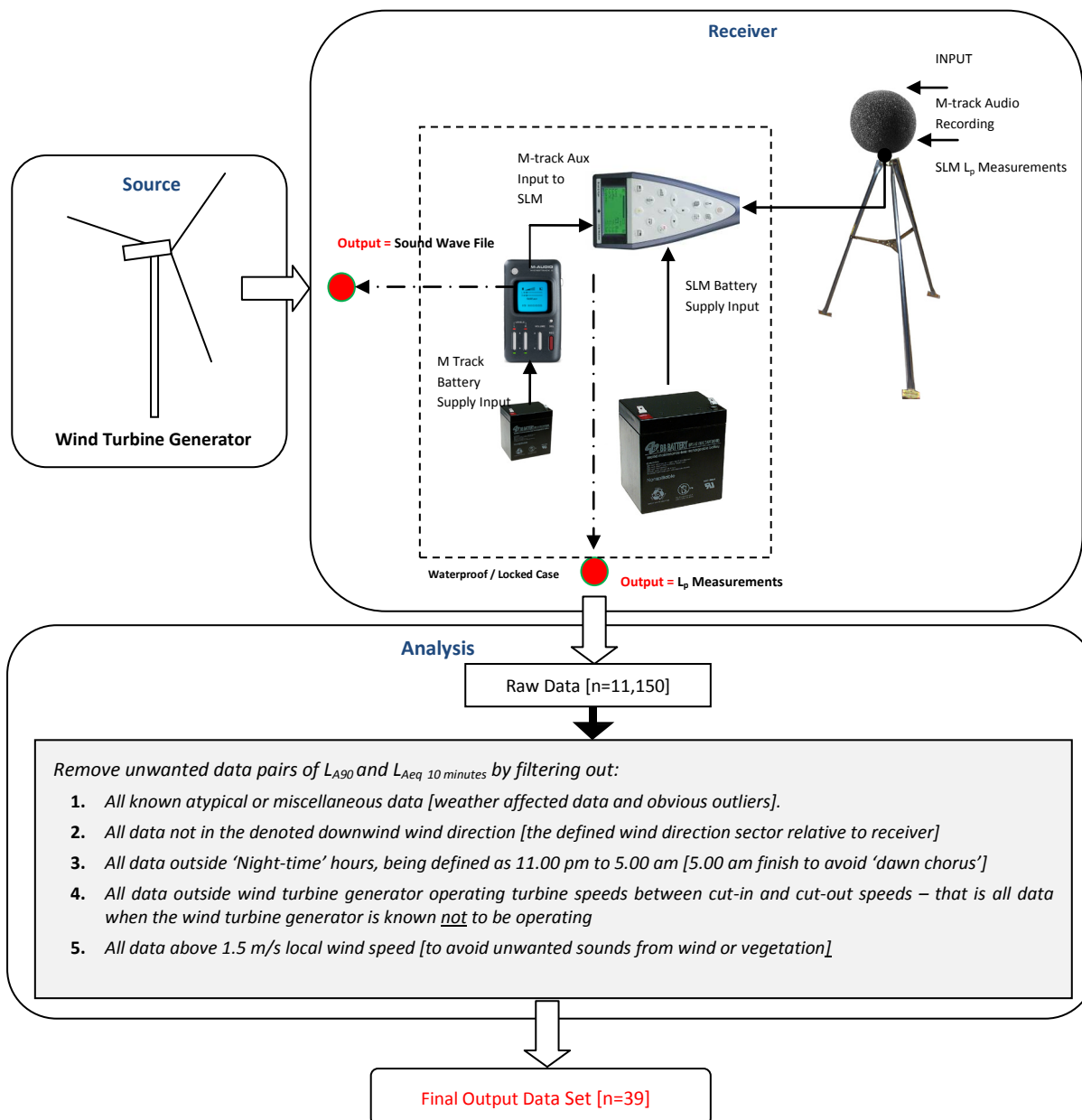


Figure 1. Graphic of field measurement approach and showing the filtering steps of the data.

survey sampling time was during the cooler winter months to avoid the more profuse effects from such influences as foliage, increasing local wind speeds and unwanted background sound from cicadas in the surrounding bush.

Equipment was synchronised so that the 10 minute averaging periods correspond meaningfully in terms of sound pressure levels, wind data and any audio recordings. It should be noted that for modern GPS equipment and sound level meters, any 'clock drift' would be expected to be significantly less than 1 minute over a period of several weeks.

Table 1 shows a summary of the data collected, starting from the entire 11,150 raw samples, than then sequentially applying each subsequent post filter step, to finally arrive a set of only 39 samples, free from extraneous noise contamination. Table 1 also shows how the levels for the two sound descriptors change as the contaminated date is removed and the mean difference between these two descriptors estimated.

Secondary Study - Te Apiti Wind Farm

The measurement approach at the Te Apiti site involved making

measurements at the IEC 61400-11 Ro measurement position. Data collection was to align with 10 minute measurement periods of wind speed and wind direction measured at the hub height, over a 10 day period. The post-filtering stages adopted in the secondary study included removal of known atypical data and data affected by weather. There were no filtering restrictions on 'local wind speeds' at the microphone however filtering was applied to ensure all data pairs were directly downwind of the measurement location and included the known periods when the wind turbine was operating.

RESULTS

The results of the principal study [see Table 1] at Project West Wind, show that based on the 39 uncontaminated samples, the overall mean sound level difference between the two sound level descriptors L_{Aeq} and L_{A90} , was 2.4 dB at a remote residential location some 1200 metres from the wind farm site. The mean sound pressure level for the L_{Aeq} descriptor was 25.4 dB and 23.0 dB for the L_{A90} descriptor.

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Product News: Noise Control Services Ltd. Name Change



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Table 1. Summary results showing each post-filtering stage and the resulting number of data samples, measured sound pressure levels [with the standard deviation - SD] for the two descriptors and the mean difference [with the standard deviation - SD]

Filter	Description of Filter	Number of samples [N]	% Of raw data	L_{Aeq} [SD] dB	L_{A90} [SD] dB	Mean diff [SD] dB
0 All raw data	No filtering.	11,500	100%	-	-	-
1 Atypical data	Removal of all erroneous data, weather affected data and so forth.	8,682	75%	39.2 dB [8.2]	34.5 dB [7.5]	4.7 dB [4.5]
1+2 Downwind	Downwind data: [0 to 90 degrees and 270 to 360 degrees quadrants] and [315 degrees with 90 degree quadrant \pm 45 degrees] - Observations indicate highest levels occur downwind from turbines.	3,321	29%	39.7 dB [8.0]	35.2 dB [7.2]	4.5 dB [4.3]
1+2+3 Night-time	Night-time: Winter 10.00 pm to 7.00 am - Observations indicate unwanted background sound is lowest at night; Summer 11.00 pm to 5.00 am - Observations indicate dawn chorus present and unwanted sound present up to 10.00pm.	1,981	17%	35.6 dB [7.6]	32.5 dB [7.1]	3.1 dB [2.6]
1+2+3+4 Operating speeds	Wind turbine operations between cut-in and cut-out wind speeds at Hub Height - Must be operational to produce measurable aerodynamic noise emission.	1,174	10%	38.0 dB [6.8]	34.9 [6.3]	3.1 dB [2.0]
1+2+3+4+5 Local wind speeds	Wind turbine operations with local wind speeds between 0 to 1.5 m/s - Observations indicate local wind speeds must be less than 1.5 m/s to exclude background sound masking occurring.	39	0.34%	25.4 dB [2.3]	23.0 dB [2.0]	2.4 dB [1.4]

The standard deviation of the two descriptors reduces as the filtering stages are applied and background sound contamination removed. If the normal two-standard-deviations rule for a 95% confidence interval is applied to the mean difference between the two descriptors, this mean value could be as high as 5.2 dB or as low as 0 dB. This range simply reflects the natural variability of the data.

The overall mean sound level difference between the two descriptors at the secondary study site [on the wind farm and at the nominated R_0 location] was 1.4 dB. The mean difference between the two descriptors in a far-field and near-field situation, are shown graphically in Figure 2.

Relationship between L_{Aeq} and L_{A90}

Statistical techniques were applied to the final data set from the

principal study site to assess if there was a direct relationship between the two noise descriptors. Two rank [order-based] correlation tests, the Kendall tau Rank Correlation Coefficient and Spearman Rank Correlation Coefficient were chosen for this purpose because they provide robust results when measuring the relationship between two variables that are non-linear.

The Kendall's tau test provides an output range of $-1 \leq \tau \leq +1$, where a value of $\tau = +1$ means a perfect positive correlation between the data sets, that is, the two sets are exactly the same. A value of $\tau = 0$ means the data is completely independent and unrelated, and a value of $\tau = -1$ means one variable has a perfect 'inverse' relationship with the other variable.

A value of $\tau = 0.64$ was calculated for the relationship between L_{Aeq} and L_{A90} , showing that there is a strong positive correlation between these two sound descriptors.

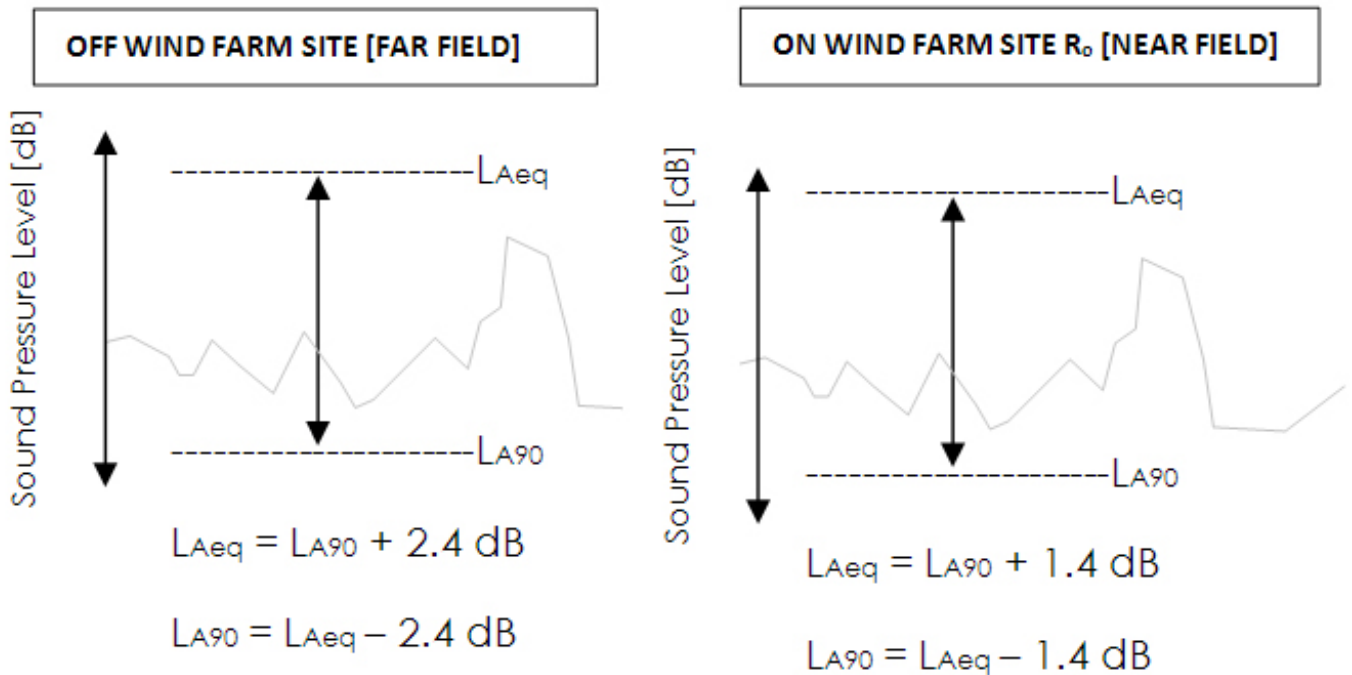


Figure 2. Mean sound level differences for Project West Wind and Te Apiti Wind Farm.

A value of 1 for the Spearman Rank Correlation Coefficient implies that two variables are monotonically related, that is if, one goes up the other goes up, and if the one goes down, the other goes down. A value of 0.8 was calculated for the final data set [n=39], illustrating a very strong correlation between the two sound level descriptors.

DISCUSSION

The key objective of the principal study was to attempt to quantify the difference between the sound level descriptors, L_{Aeq} and L_{A90} , in a typical far-field location, where people are located, from an existing commercial wind farm in the New Zealand environment. A raw data set of 11,150 [10 minute L_{Aeq} and L_{A90}] samples was collected over a 12 month period at Project West Wind, Makara. It is worth noting that the minimum sample set recommended by NZS6808:2010 is 10 days' continuous monitoring, resulting in about 1,440 [10 minute] samples [See NZS6808:2010 Section 7.2]. The standard also gives guidance on when extended periods of monitoring are required to ensure that the measurements are representative of the range of wind conditions and account for significant variation due to seasonal factors. As monitoring at the principal study site was the equivalent of 75 days distributed across the entire year, it might be concluded that this data set should adequately represent the situation. However, after post-filtering the raw data set for noise contamination, only 39 samples remained for analysis, which is equal to 0.34 % of the 11,150 samples collected.

The analysis of these samples showed that L_{A90} averaged 2.4 dB lower than L_{Aeq} , equivalent in power terms to a difference of 42%. But when the natural variability of the data was accounted for, the mean difference could be as high as 5.2 dB which is slightly more than the background +5 dB rule, used in both the 1998 and the current 2010 standard. The statistical tests for a direct relationship between these two noise descriptors showed that they were strongly correlated. While the final sample size for the analysis appears small [n=39], compared to the raw

number of samples collected, it is nevertheless still statistically significant when tested.

Looking at the results from the raw data set after the first post-filtering stage [the removal of all atypical or miscellaneous samples [See Table A] the difference between the two descriptors is significantly higher at 4.7 dB and also the mean levels of both these noise descriptors of this larger [contaminated] data set were typically 11 to 15 dB higher than for the final analysis set. This is what would be expected given that the data set contains many extraneous sources of noise.

Ideally data should be collected covering a sufficient range of wind speeds, and across the operating modes of the wind turbine under investigation. The raw data set covers a wide range of wind speeds but the final analysis set [free from extraneous noise] covers a wind speed [at hub height, $V_{Hub\ Height}$] range between 4 m/s and 15 m/s [34 samples were in the 4 to 7 m/s range and 5 samples for wind speeds > 7m/s]. It should be noted that possible issues occur in the derivation of the wind turbine sound levels if wind speeds are only collected up to, say, around 8 m/s and such issues become important for variable speed machines such as those at the principal site, where noise levels would likely to continue to rise for wind speeds above 8 m/s.

Background Sound Levels and Noise Contamination

It is common in environmental acoustics to use L_{A90} as a proxy for the background sound level or residual sound level, especially where it is not practical to make measurements with and without, the target sound present. For wind farm noise monitoring, this sound level descriptor is said to provide a 'fair' representation and reduce contamination by other non wind turbine sound sources.

As wind farm sound level measurements must normally be conducted in the presence of wind, the use of L_{A90} over L_{Aeq} for sound level measurements is preferred so as to avoid influence from high level transitory events and minimise the influence

of unwanted background sounds. This is because transitory high energy events such as wind gusts across the microphone or aircraft overfly may artificially increase the measured L_{Aeq} hence possibly allowing for a higher design limit, thus allowing wind turbine sound to be greater at receiver locations. Statistically such extraneous influences are less likely to affect sound levels measured using the L_{A90} . Results from the principal study show that the mean difference between L_{A90} and L_{Aeq} can be as much as 3 dB higher than the 2.4 dB difference derived for the final [uncontaminated] data set.

The acoustic output from a modern wind turbine generator is complex and depends on various factors such as the turbine design itself and surrounding environment. The difference between the L_{Aeq} and L_{A90} descriptor levels is a product of the variability in received sound levels as a function of variations in wind turbine operating mode, wind turbine design, wind turbine operating environment and the variability induced by sound propagation effects between source and receiver location. To what degree such differences actually occur in practice also depends on other complex factors including the relative temporal variations of the wind turbine, propagation conditions and the background sound environment at the receiving position.

As the sound output from a wind turbine generator will increase as a function of wind speed, so to generally will background sound level increase in a windy environment. In regards to the two study sites, increasing wind speeds generally caused increased background sound levels and hence the wind generated significantly higher local background sound levels, in part because of the movement of low lying vegetation, such as long grass. This background sound tended to mask the sound from the wind turbine generator at the receiver location and hence data samples under these conditions were removed from the data set before analysis.

A study into the difference between the operational wind farm noise and the background sound levels [5] at the Project West Wind site, revealed that the greatest level difference between historic measured background sound levels [pre-construction of the wind farm] and actual measured wind farm sound levels [with all background sound removed] occurs between 4 m/s and 15 m/s, with the background sound levels being higher than wind turbine sound at wind speeds below 3 m/s or above 15 m/s. This again illustrates how difficult it is to capture robust wind turbine sound pressure levels in isolation even when a great deal of care is taken including applying correct filtering.

Data collection and analysis of uncontaminated wind turbine sound was not an issue on secondary study site at the Te Apiti Wind Farm, because measurements were made in the near-field in close proximity to the turbines, where the turbine noise is significantly higher than the local background sound level. For commercial reasons wind speeds at Te Apiti Wind are not able to be discussed.

Comparing the difference in measured L_{Aeq} and L_{A90} wind turbine sound pressure levels between the near-field, close proximity results and the off-wind farm [far field] results, the findings indicate that L_{Aeq} sound pressure levels are on average 1.4 dB greater than L_{A90} levels at the near field location, with the L_{Aeq} sound pressure levels being on average 2.4 dB greater than L_{A90} levels at the far field location. This finding indicates

the process of propagation of wind turbine sound over distance has the effect of increasing the difference between L_{Aeq} and L_{A90} in received wind turbine sound levels. This is not unsurprising when considering the effects of wind causing fluctuations in received sound levels, with these fluctuations increasing with increasing sound propagation distance.

Accuracy and Uncertainty

Every experiment has a level of uncertainty and limits which need to, at the very least, be understood and noted in terms of the scientific results. New Zealand Standard NZS6808:2010 makes reference to the University of Salford Guidelines on uncertainty of environmental noise [6] and promotes this as good practice for practitioners. No corrections or adjustments have been made to the data gathered in this study other than post-filtering to remove samples contaminated by extraneous noise. There were numerous factors which should be noted if the study were to be repeated or results used by external parties. Because the final data is likely to be specific to the study sites, caution should be taken when applying any results from the study to all wind farms or sites without first understanding the full background and possible restrictions.

CONCLUSIONS

- A limited one year semi-empirical field study was completed to review the variability between wind turbine generator sound descriptors in the typical far-field locations where people are located and on the wind farm site itself in a typical New Zealand environment.
- There is a quantifiable difference between the L_{Aeq} and L_{A90} sound level descriptors for wind turbine sounds in the far-field. At a distant receiver location some 1200 m away, the L_{Aeq} averaged 2.4 dB higher than the L_{A90} , with an upper limit of 5.2 dB difference.
- On the wind farm at the nominated Ro location in near-field, the L_{Aeq} averaged 1.4 dB higher than L_{A90} .
- The findings indicate the propagation of wind turbine sound over distance increases the difference between L_{Aeq} and L_{A90} of wind turbine sound.
- Due to the high number of intervening variables, based on the study methods adopted, it is difficult to collect a large robust sample set in a wind turbine sound investigation that does not include any superfluous background sound. For the principal study, only 0.34 % of the 11,150 [10 minute L_{Aeq} and L_{A90}] samples were free from contamination.
- If time and resources had allowed, further work such as investigating and analysing sound pressure levels as a function of frequency would have been beneficial, as would have a review of the intervening variables, conditions and full details of all uncertainties around the measurement chain.
- Further review work and measurements of possible special audible characteristics, ultra or infrasound is also recommended in distant receiver environments where people reside.

Although the study results indicate a quantifiable difference

between the two sound level descriptors, the current wind turbine noise standard [NZS6808:2010] adopts a conservative approach by assuming the predicted L_{Aeq} is the same as the likely operational measured L_{A90} - noting that any differences in predicted sound pressure levels found to exist during any required compliance measurement phase would have to be rectified to achieve full compliance with any stated relevant noise conditions.

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2. See ETSU-R-97 "The Assessment and Rating of Noise from Wind Farms Report published in 1996. The ETSU working group was made up of independent experts being established by the Department of Trade and Industry of the United Kingdom Government [now the Department of Business Industry and Skills, UK Government].
3. The R_0 location is defined in detail in Wind Turbine Generator Systems Part 11: Acoustic noise measurement techniques, International Standard IEC 61400-11. Ed 2.1. 2006. The location is a standardized measurement location where acoustic measurements are made close to the turbine in order to minimise the influence of terrain effects, atmospheric conditions or wind-induced noise.
4. The receiver location was an address in Makara Road, Wellington.
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International IEC Standard

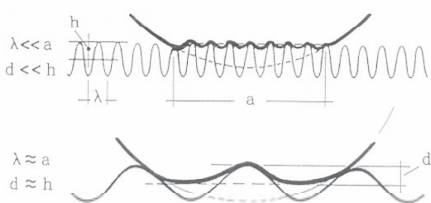
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sound weighted standardized impact sound pressure levels structure born sound low frequency noise octave band time weighting sabin speech intelligibility noise reduction engineering sound level environment spectrum resource management SIL ambient sound insulation vibration rumble sound level meter noise map silencer emission speaker amenity value reverberation time noise reduction coefficient Dntw speech transmission index dBA frequency band noise Hertz or Hz far field octave airborne sound impact sound pressure level immission plane wave SEL line source random incidence sound reduction index, R best practical option frequency spectrum noise exchange rate logarithm live room limiter calibration room criterion curves habitat structure sound power sound pressure level hiss free field Ctr articulation class ambience Bel acoustics environment assessment structural analysis apparent sound reduction index resonance natural frequency flow kinetic measurement prediction signal processing threshold shift shadow zone transducer wavelength narrow band overtone reflection percentile level impedance directivity fresnel number harmonic echo ambient active noise control attenuation coverage angle coincidence hearing point abatement temperature diffusion indoors reflections concave node anti-node wind

Malcolm Hunt Associates

Noise and Environmental Consultants

www.noise.co.nz - email mha@noise.co.nz

