ANALYSIS TECHNIQUES FOR WIND FARM SOUND LEVEL MEASUREMENTS

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NZS 6808 and other similar wind farm assessment standards require sound level measurements at neighbouring houses with and without the wind farm operating. While outlining a procedure for assessment using regression curves, the standards allow significant discretion in how the data are analysed. Issues with this analysis are reviewed and suggestions are made as to how specific parts of the process could be standardised. These issues are illustrated with background sound datasets from actual wind farm proposals. In particular, this paper examines: the process for separation of data by time-of-day and wind direction; the effects of altering the wind speed range for analysis; use of bin analysis; and removal of outliers.

INTRODUCTION

Assessment of wind farm sound usually requires pre- and post-construction sound surveys, to establish a baseline and to demonstrate compliance with noise limits. In a survey, between 2,000 and 4,000 10 minute measurements are typically made and a relationship between sound levels and wind speeds is determined. Statistical techniques are used to address the significant and unavoidable scatter in the sound data caused by relationships with other factors in addition to variances associated with wind speed. Achieving a robust analysis is dependent on careful inspection and separation of data.

General noise assessment standards such as NZS 6802 [1] and AS 1055 [2] do not provide an assessment framework for this analysis of wind farm sound. Wind farm specific standards discussed below do provide guidance, but still allow significant discretion in the analysis. This can leave the assumptions and choices in the analysis open to debate during statutory approval processes for wind farm proposals.

This paper reviews the analysis of background sound level data under the wind farm noise standard NZS 6808 [3], and explores methods for reducing variability. This paper does not critique the noise limits recommended by the standard. The issues discussed are common to other standards such as the 'ETSU' method [4], on which NZS 6808 was originally based, and AS 4959 [5], which in turn is partly based on the old 1998 version of NZS 6808 [6]. Similar topics have been raised as part of a broader review of wind farm acoustics [7], and a working group is currently formulating guidance [8].

In contrast to NZS 6808, the standard for measuring wind turbine sound power levels IEC 61400-11 [9] has a precise methodology, but in that application measurements are adjacent to a wind turbine rather than hundreds of metres away at the nearest houses as required by NZS 6808. However, some aspects of that method can still be applied to analysis under NZS 6808 and these are discussed in this paper.

Regression analysis

The mainstay of analysis under NZS 6808 and similar standards is determination of the regression between sound levels at receivers and wind speeds at the wind farm site. This analysis is performed using a large number of background sound level measurements (L_{A90}) under varying wind conditions. In NZS 6808, wind farm noise limits are then set at the higher of 40 dB or 5 dB above the regression curve.

Figure 1 is an example graph of background sound levels plotted against wind speeds, as would typically be produced when analysing background sound measured outside a neighbouring house.

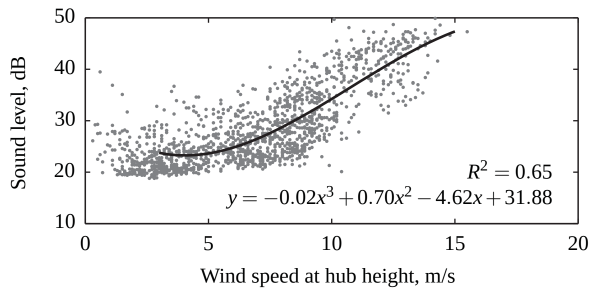

Figure 1. Example of regression analysis

In this example a third order polynomial curve is shown fitted to the data, although the different standards provide varying guidance to the choice of regression function. In NZS 6808 the parameters are not fixed, whereas AS 4959 limits curves to no more than third order polynomials, and the ETSU method recommends the use of logarithmic curves, although it also shows examples with polynomial curves.

The accuracy of a fitted curve between sound level and wind speed is sometimes expressed as a correlation coefficient (R^2), as defined in Equation 1. While this is referenced in this paper, it is not considered a key parameter for analysis.

$$R^2 = \frac{\left(\sum(x_i - \bar{x})(y_i - \bar{y})\right)^2}{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2} \quad (1)$$

The focus of this paper is on how fitting a regression curve or an alternative could be standardised. As the curve defines the noise limits and compliance for a wind farm, the effect of any variation in the analysis could be significant. This paper looks at examples for the analysis of background sound data as the first step in wind farm noise assessment, but the issues apply equally to analysis of measurements including wind farm sound. Different example datasets have been used to illustrate the various issues discussed in this paper.

TIME-OF-DAY

In situations where the background sound is dominated by sources such as vegetation moving in the wind, there is usually a clear relationship between background sound and wind speed. However, in many situations there is a poor correlation, for example due to other sound sources in the area such as insects, birds, and road-traffic, or due to houses being more sheltered by terrain in certain wind directions. As a first step, separating the sound level data into day and night periods will generally improve the correlation with wind speed.

NZS 6808 requires viewing of the sound level versus wind speed graph, and separation of data if there are 'markedly different groups'. Procedures for defining different groups are not provided, although time-of-day is given as a possible factor. In New Zealand, time periods for day and night are usually defined in local council planning documents, together with an evening period in some instances, with different noise limits for each time period. For wind farm sound there is a single fixed noise limit, and separation of time periods is only used to identify wind farm sound over the background. Therefore while potentially an attractive option for background sound analysis, the council time periods are usually inappropriate as they do not define the actual daily variation in sound levels. The following example illustrates an alternative whereby a visual inspection is made of sound levels plotted against time-of-day, to establish time periods based on the actual environment.

For this example, Figure 2 shows the variation in sound levels throughout the day, measured over two weeks at a house near a proposed wind farm. Patterns can be seen on the graph and based on visual inspection of the sound levels in this example a daytime period has been identified as 0630 h to 1800 h, with night-time from 1800 h to 0630 h. Care is required in this visual inspection as there are lots of overlapping data points and outliers can appear to have undue prominence. Sunrise and sunset times will vary during the sound survey, potentially by 30 minutes over a month, leading to a blurred transition between time periods. Plots of sound level versus wind speed are shown in Figure 3 for these day and night periods, in addition to the complete dataset.

There is no minimum duration specified for day, night or other time periods in NZS 6808. It could be interpreted as allowing a noise limit to be based on the quietest one hour period in the middle of the night. To standardise this matter and to provide an assessment of a representative scenario, it is suggested that a minimum of eight hours should be used for any time period. If background and compliance sound surveys for the same site are performed at different times of the year, the day and night periods may have different definitions.

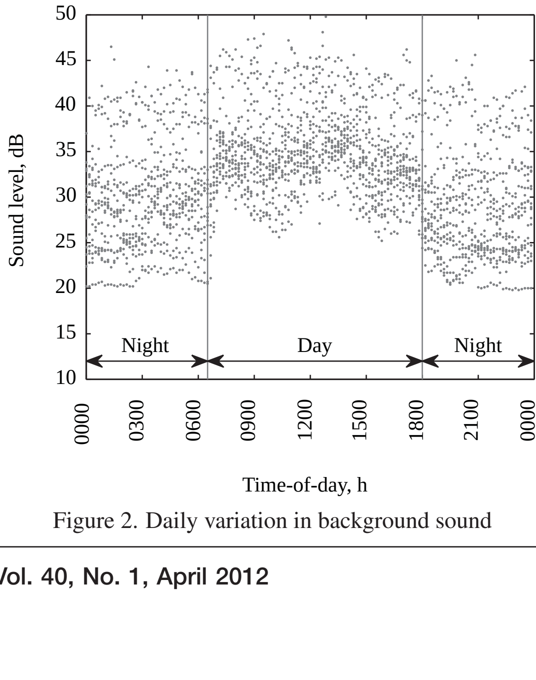

Figure 2. Daily variation in background sound

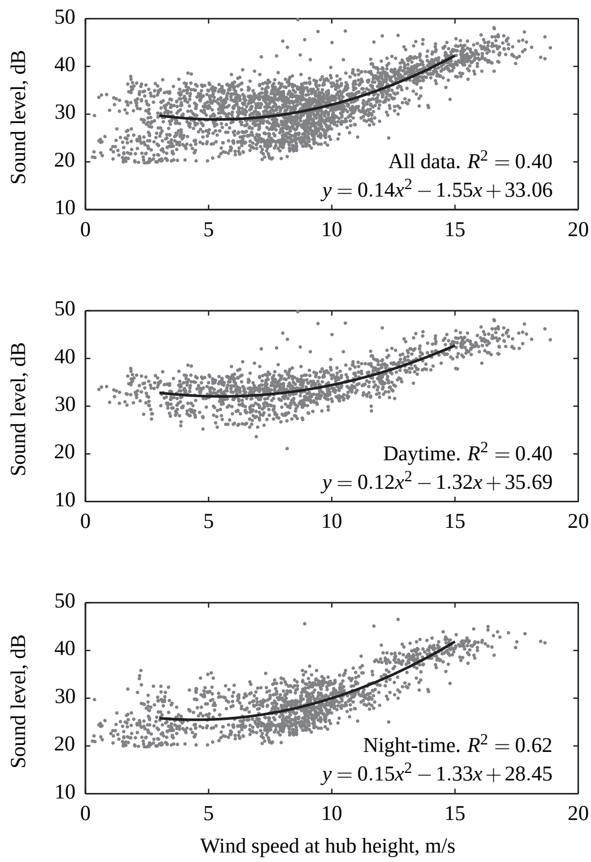

Figure 3. Regression curves for day and night periods

The example in Figure 3 is similar to most locations in New Zealand in that there is better correlation between wind speed and background sound levels at night. This is due to a lesser contribution from man-made sound sources and birds at night, so the background sound is controlled to a greater extent by sources such as rustling leaves and vegetation, which depend on the wind speed. Similarly, the correlation generally improves at higher wind speeds during both day and night, when wind-induced sources become more prominent.

NZS 6808 requires further investigation if correlations are 'poor' but does not specify a correlation coefficient. In this example there are relatively low correlation coefficients due to the unavoidable scatter of environmental sound levels, although the regression curves do still provide a reasonable representation of the data. Also, the greatest spread of sound levels giving rise to the low correlation coefficients is at lower wind speeds where the 40 dB fixed part of the NZS 6808 noise limit would apply rather than the 'background +5 dB' part of the noise limit. At these low wind speeds the position of the regression curve is not critical.

WIND DIRECTION

Wind direction effects can be another cause of markedly different groups in sound level versus wind speed plots. In New Zealand, neighbouring houses are often in valleys below a wind farm, and there can be variation in wind at a house relative to wind at the wind farm depending on whether the wind is blowing across or along the valley. In such cases separation of data by wind direction can improve the correlation of sound levels and wind speeds. Again, no method is provided by NZS 6808, and no guidance is given as to how many wind directions should be used when separating the data.

It is common to see measurement data separated into 4 or even 8 wind directions, based on the cardinal points. However as for time-of-day, better results can be obtained by basing the separation on the actual environmental conditions. Unnecessary separation of data should be avoided as it complicates compliance assessment and can result in sparse datasets.

To determine appropriate wind direction sectors, the wind distrubution during the sound survey should be reviewed, along with the annual distribution. This is typically presented as a wind rose, such as Figure 4. In this example it can be seen that there would be little value in separately analysing the south quadrant independently. From visual inspection of this graph and after experimenting with different splits, in this instance the data was separated into two sectors: the west quadrant and the other three quadrants combined.

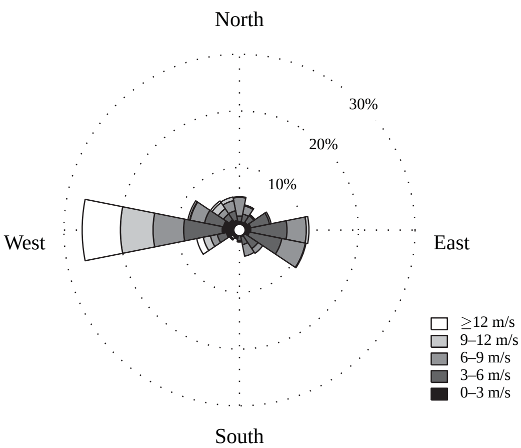

Figure 4. Wind speed distribution

The wind distribution during the sound survey should be representative of the annual wind distribution, however this is difficult where there are large seasonal variations. It is desirable for the background and compliance surveys to be performed at the same time of year, however it is common for consent conditions to require compliance surveys within 3 months of completion. If surveys are performed at different times of the year, the chosen direction splits in the background survey may result in sparse data sets in the compliance survey. It may be necessary to re-analyse the background sound data to best establish the wind farm sound levels.

Figure 5 shows the sound level versus wind speed for the west quadrant, also including graphs for time-of-day separation of that reduced dataset. Starting with 1703 data points, only 330 of these are in the west quadrant at night, and if a south quadrant had been used there would only have been 40 points for that regression analysis at night. For the night period, the correlation coefficients in Table 1 show the benefit of separating the west quadrant, and also show that for the other wind directions there is not a significant range of wind speeds controlling the sound levels.

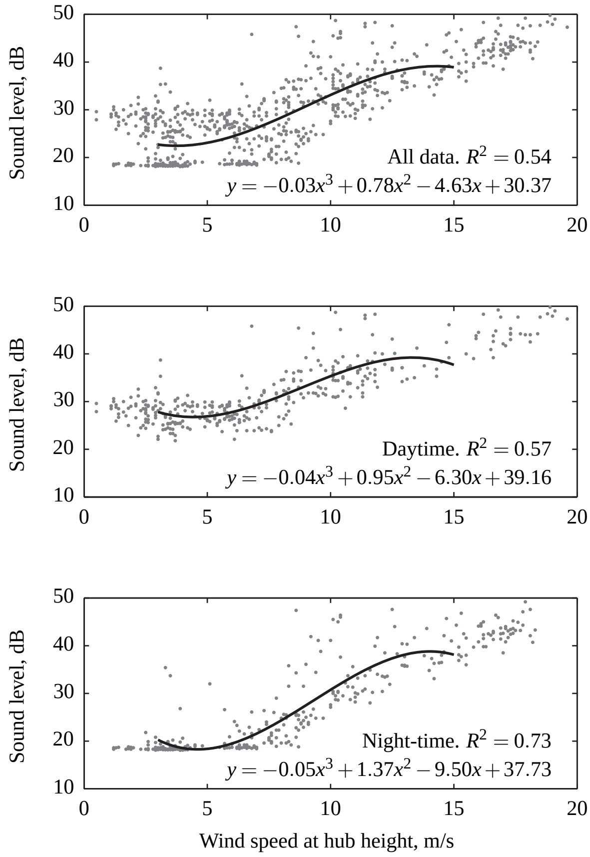

Figure 5. Regression curves for west quadrant

Table 1. Separation by wind direction

Item	All	West	North–East–South
Total data points	1703	693	1010
Night-time data points	840	330	510
Night-time R^2	0.42	0.73	0.12

WIND SPEED RANGE

A related issue to the separation of data discussed above is the selection of the wind speed range over which data are included in the analysis. NZS 6808 does not provide guidance on the wind speed range for fitting a curve. The ETSU method bases analysis on a 0–12 m/s wind speed range (10 m height), assuming an average wind resource of 8 m/s.

The suitability of fitting a curve to a wide wind speed range is dependant on the data set. In many instances three distinct regions can be observed: at low wind speeds, the background sound level is independent of wind speed; at medium wind speeds (often the critical range) there will be increasing sound level with wind speeds; and at higher wind speeds there can often be a flattening off. The inclusion of data outside of the critical range may disturb the fit of a polynomial curve. In other instances, the wider wind speed range may result in a better fit, as demonstrated in Figure 6. In general, a wider wind speed range is more likely to include different trends in sound level versus wind speed, requiring a higher order polynomial.

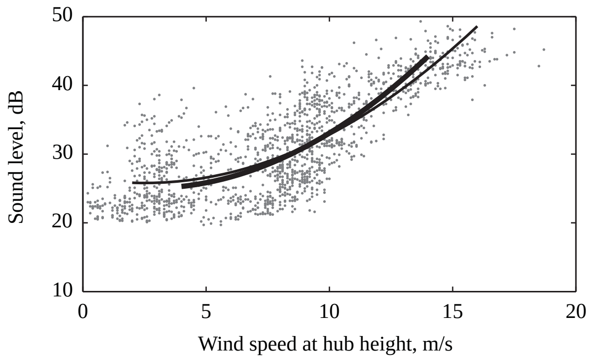

Figure 6. Effect of wind speed range on regressions analysis

As demonstrated in Table 2, the correlation coefficient is highly sensitive to the wind speed range. While it is a useful parameter for comparing curves for a given dataset, it does not provide a direct and consistent measure of the scatter in the data in the critical range. NZS 6808 does not require correlation coefficients to be reported.

Table 2. Correlation coefficients (R^2) for different wind speed ranges

Wind speed range	Polynomial order 2	3	4
4–12 m/s	0.23	0.23	0.24
4–13 m/s	0.37	0.37	0.37
4–14 m/s	0.52	0.52	0.53
4–15 m/s	0.62	0.62	0.63
4–16 m/s	0.66	0.67	0.67
4–17 m/s	0.67	0.69	0.69
4–18 m/s	0.67	0.69	0.69

NZS 6808 specifies that the wind farm noise limit should be met at any wind speed, although the controlling wind speed range is between cut-in and 95% of rated power. For example this might be from 4 m/s to 12 m/s at hub-height. At higher wind speeds background sound levels increase, but the wind turbines will have already reached their maximum sound output. Therefore analysis of background sound levels at higher wind speeds should not be required. Likewise for low wind speeds below cut-in. As an aside, sound power levels measured in accordance with IEC 61400-11 are only provided for wind speeds corresponding to approximately 7 m/s to 14 m/s at hub-height. Wind farm sound level predictions are based on that data, and therefore do not extend to higher wind speeds.

To standardise the wind speeds used for analysis it is suggested that curves should only be fitted to data in the range between cut-in and 95% of rated power. Compliance with noise limits at all other wind speeds can be inferred from compliance in this range.

Another issue encountered at low wind speeds is the noise floor of measurement equipment. Type 1 equipment typically has a noise floor of 18 dB to 25 dB, which can be readily observed by the 'flat lining' in sound level graphs for most rural areas. While there is sometimes concern this will affect a regression curve, in practice, given the fixed part of the noise limit is 40 dB, any errors in measurements below 25 dB should be inconsequential.

DATA BINNING

NZS 6808 includes a comment that in some cases 'bin analysis' may be more appropriate than a regression curve. In bin analysis sound level data is separated into wind speed 'bins' centred on integer or half-integer wind speeds. A representative sound level is then determined for each bin in isolation. Potentially, this could resolve some of the issues discussed above with regression analysis, and in a future version of NZS 6808 it seems likely that bin analysis will replace regression analysis, as is occurring with IEC 61400-11 version 3[10].

For measurements adjacent to wind turbines IEC 61400-11 version 2 details both regression analysis and data binning techniques. Regression analysis is used where a correlation coefficient of 0.8 is achieved when fitting a fourth order polynomial to the data. A high degree of correlation is common when measuring in close proximity to wind turbines. The standard requires turbine sound level to be 6 dB above the background sound level, and far less scatter is observed. In contrast, correlation coefficients above 0.8 are uncommon when measuring at neighbouring houses as required by NZS 6808, where contributions from other sources are significant.

Under IEC 61400-11 version 2 the data binning option is relatively complex and still involves a linear regression analysis within each bin and curve fitting to the results. A regression curve is then fitted through the bin values over a fixed range of 6 to 10 m/s wind speeds at 10 m height. An example of the linear regression used within each bin, under the current version of IEC 61400-11 to determine the bin centre value, and the regression curve through those values, is shown in Figure 7.

The proposed IEC 61400-11 version 3 will require the sole use of data binning but will refine the process by changing the time interval, bin width, and averaging method. Table 3 summarises the key parameters from each version of the standard.

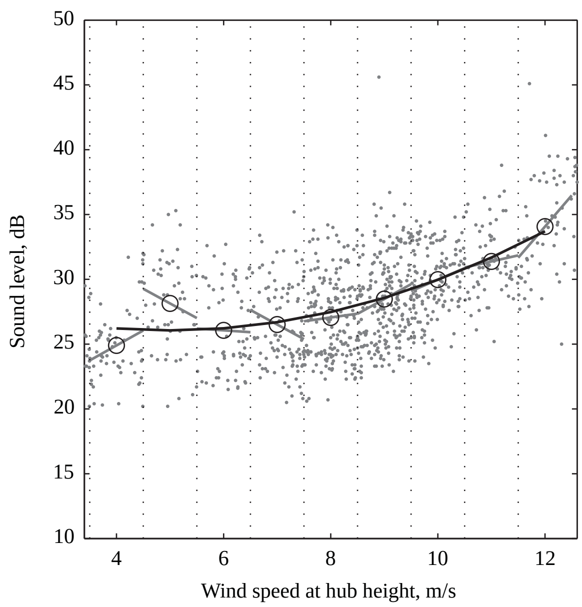

Figure 7. Linear regression in 1 m/s bins used to determine bin centre values

Table 3. IEC 61400-11 bin analysis parameters

Version	Parameter	Bin width	Average type
v2 (current)	$L_{\text{Aeq(1 min)}}$	1 m/s	Linear regression
v3 (proposed)	$L_{\text{Aeq(10 s)}}$	0.5 m/s	Energy average

In addition to using an energy average for sound levels, IEC 61400-11 version 3 uses an arthimetic average of the wind speeds in each bin to determine the bin average. To determine the sound level at the bin centre, linear interpolation between adjacent bin averages is used. The benefit of this procedure for narrow, 0.5 m/s, bins is unclear.

Some of these parameters are not appropriate for use under NZS 6808. IEC 61400-11 also uses the time average level, L_{Aeq}, rather than the centile level L_{A90} used under NZS 6808. Energy averaging a centile level does not make mathematical sense. For bin analysis under NZS 6808 it is suggested here that to obtain the bin sound level a simple arithmetic average of all sound levels in the bin should be made, rather than regression or energy averaging.

A possible weakness of data binning is that certain bins may have sparse data, whereas when fitting regression curves that issue is avoided by reliance on neighbouring data. However, IEC 61400-11 can provide ample data in each bin with a measurement time interval of only 10 seconds or 1 minute, compared to 10 minutes measurements used for NZS 6808.

In practice, most surveys under NZS 6808 are for two or more weeks and sufficient data would be generated for 1 m/s bin widths across the critical range from cut-in to 95% rated power. Figure 8 shows the bin values using a simple arithmetic average with one standard deviation for an example dataset. The standard deviation is a useful parameter for describing the amount of scatter in the data, and where wind farm sound is clearly measured over the background can be used to describe the measurement uncertainty. The solid line is a conventional regression curve fitted to the complete dataset. It can be seen that the average bin values show good agreement with the regression. It is suggested that for bin analysis under NZS 6808, 1 m/s wind speed bins should be used, and the bin arithmetic average sound level values should be taken as the final results without further regression analysis.

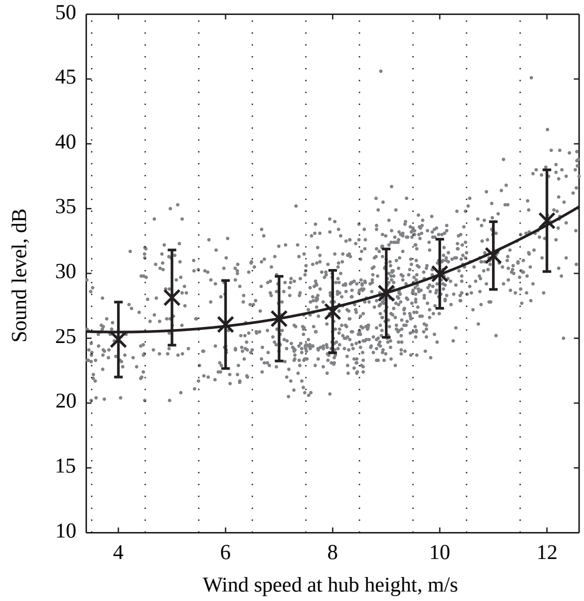

Figure 8. Bin analysis using 1 m/s bins and averaging, showing 1 standard deviation and a conventional regression curve.

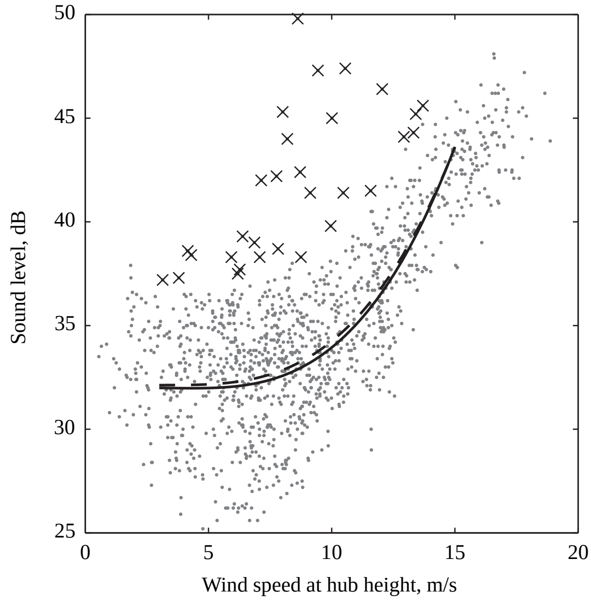

Figure 9. Removal of outliers

OUTLIERS

Extraneous events should not unduly influence the regression curve or bin analysis. A typical source of extraneous sound is extended periods of precipitation, but these should be simply excluded from the dataset on the basis of rainfall monitoring at the site. Another common issue is seasonal insect noise or watercourses, which is best avoided by monitoring at an appropriate time of year. For other sources of momentary sound such as a dog bark or car door slam, as noted in NZS 6808, the L_{A90} metric is effective at removing most short-term events from the measurement.

Despite the controls described above, there will always be significant scatter in environmental sound measurements, and some events such as mowing grass near the measurement location could cause spikes in the dataset. NZS 6808 states that obvious outliers should not be allowed to unreasonably influence the regression curve. However, the following example demonstrates how 'obvious' outliers generally have a minimal effect on results.

Figure 9 shows an example sound level versus wind speed graph. The dashed line represents the regression with the entire data set included, and the solid line is the regression with the × data points manually identified and removed. The fitted values at integer wind speeds vary by less than 0.5 dB.

CONCLUSIONS

Sound level measurements are required by NZS 6808 and similar standards at neighbouring houses, with and without the wind farm operating. The analysis has to take into account the presence of wind, which is not a factor when measuring general environmental noise as wind generally can be avoided. Due to the high variability of sources and locations encountered, assessment standards such as NZS 6808 are not prescriptive as to how measured sound levels are analysed. However, this can affect noise limits and compliance assessment. There are some aspects of the analysis process which could be standardised to provide better consistency.

When separating data it is suggested that:

- daily patterns should be visually examined on a plot of sound level data against time-of-day, and ‘day’ and ‘night’ periods identified,
- day and night periods should not be less than 8 hours each,
- clusters/trends should be visually examined on a plot of sound level data against wind direction to identify wind sectors for analysis, and
- sectors for wind direction should be limited and not based simply on cardinal points.

Analysis should only be conducted for the wind speed range from cut-in to 95% rated power.

Bin analysis is already used in IEC 61400-11, and is allowed for in certain circumstances in NZS 6808. Data binning offers some advantages over regression curves and removes some variability from the analysis options. IEC 61400-11 differs substantially from NZS 6808 in that it uses L_{Aeq} rather than L_{A90}, the measurements are adjacent to a turbine, and the measurements are 1 minute rather than 10 minutes. For bin analysis in the context of NZS 6808 it is suggested that a simple arithmetic average should be used to determine the bin value for 1 m/s bins, with no further interpolation or curve fitting.

Providing steps are taken to control known effects from sources such as precipitation, seasonal insects and watercourses, other data outliers generally have a minimal effect on sound level results.

The issues raised in this paper are only significant in environments with high background sound levels or where wind farm sound levels are predicted to exceed 40 dB L_{A90}. In other instances background sound level measurements might not be required.

ACKNOWLEDGEMENTS

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