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Statistical and curve fitting post- process of wind farm noise monitoring data

Valeri V. Lenchine

SA EPA, GPO Box 2607 Adelaide SA 5001, Australia

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ABSTRACT

Control of noise exposure from proposed and existing wind farms becomes a priority in assessing environmental impact from the wind turbines in many cases. In accordance with regulatory procedures the noise limits are to be met statistically. It involves noise monitoring at the relevant receivers to collect sufficient amount of data at wind speeds of interest and consequent post- process comprising the data curve fitting or computing data in the bin at the particular wind speed. When the total noise in the vicinity of the wind farm exceeds the regulatory limits the measured level is corrected for background noise to calculate the wind farm noise. Generally the background data acquisition is performed before the wind farm construction and the result of the logarithmic subtraction can be doubtful. For example, at some wind speeds the background levels can be higher than the total noise. Change in the background noise or just peculiarities of the data post process may create difficulties in implementing the correction for background method. The paper suggests performing statistical analysis of the total noise and background data gathered at the particular wind speed on the basis of arbitrary combination of the measured levels and their probability analysis. Process of the data rectification is considered to eliminate the improbable combination of the measured parameters. The method enables calculating more realistic wind farm noise magnitude and it is supposed to be statistically viable.

INTRODUCTION

Control of noise exposure from proposed and existing wind farms becomes a priority in assessing environmental impact from the wind turbines in many cases. Due to changes in environmental conditions and contribution from extraneous sources, noise measured at the receiver of interest may have significant variations. Therefore, in accordance with many regulatory procedures the noise limits are to be met statistically [1,7,8]. Noise from a wind farm may exceed statutory limits at particular time periods.

Compliance checking procedures normally involve noise monitoring at the relevant receivers to collect a sufficient amount of data at wind speeds of interest, and consequent post- process comprising the data curve fitting [1,7,8] or analysing the data in the bin at the particular wind speed [4,5].

If the combined wind farm and background noise in the vicinity of the wind farm exceeds the regulatory limits, the measured level is corrected for background noise to calculate the wind farm noise [1,7,8,10]. Generally the background data acquisition is performed before the wind farm construction and the result of the logarithmic subtraction can be doubtful. For example, at some wind speeds the background levels can be greater than the total noise. It can be caused by significant change in the background noise in comparison with time when the measurements have been taken. However, just peculiarities of the data post- process may create difficulties in implementing the correction for background method.

Alternative data- postprocess routine can be utilised in this case. One can suggest performing statistical analysis of the total noise and background data gathered at the particular wind speed on the basis of arbitrary combination of the measured total and background noise and their probability analysis. Process of the data rectification is considered to eliminate the improbable combination of the measured parameters. The method enables calculating more realistic wind farm noise magnitude and is statistically viable.

ACOUSTIC DESCRIPTORS AND DATA POST- PROCESS

Prediction of wind farm noise is normally made for wind speeds of interest using equivalent A-weighted sound pressure level. However, noise measured at the relevant locations can be affected by domestic and other activities and hence L_{Aeq} may reach high values due to events which are not associated with the wind farm operation. Therefore statistical descriptors (normally L_{A90}) often are utilised for wind farm noise monitoring [1,3,7,8,10]. The statistical descriptor indicates L_{Aeq} which is exceeded for certain fraction of the time (90% of the time if L_{A90} used). This approach serves as a statistical filter to decrease influence of extraneous noises on the measurement results. Assuming that extraneous noise events are relatively short, increase of the integration time also reduces the influence of non- wind farm noise sources on the measurements. Noise is correlated with the wind speed so there should be a reasonable balance between reporting wind speed and noise descriptors. Compliance or complaints checking procedures recommend 5- or 10-min intervals for data acquisition.

It should be mentioned again that variations in the measured levels can be high, and monitoring of a wind farm noise involves gathering a sufficient amount of original data (Figure 1). At a particular time the descriptor may exceed the specified limit. It is expected that the regulatory limits will be met statistically, i.e. the calculated wind farm noise should be below a certain criteria.

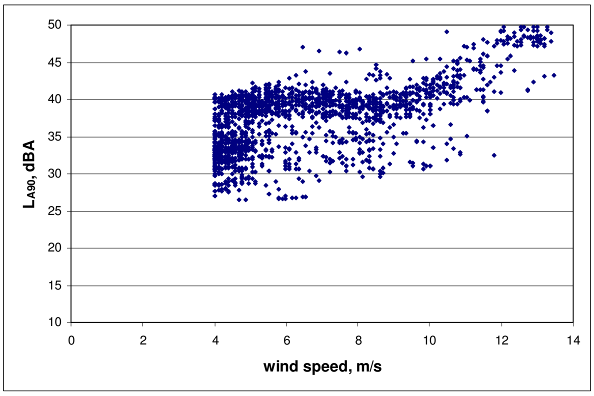


Figure 1. Total wind farm and background noise at the receiver versus wind speed at the hub height, 10-min intervals

In cases where the data post- process based on the total noise measurements show compliance with the noise criteria, no further noise monitoring is required [1,8]. However, if the total noise is above the statutory limits the correction for background procedure is employed. Peculiarities of the data post- process in the latter case are discussed below.

CORRECTION FOR BACKGROUND PROCEDURE

Meeting criteria as a result of data post- process requires a long term collection of noise monitoring data. It is desirable to have sufficient amount of data evenly distributed over range of the wind speeds. There are two practices which are normally used for the data analysis; curve fitting or data analysis in the bin at the particular wind speed of interest.

If data analysis is performed on the basis of curve fitting, the total noise values are obtained by the linear or polynomial curve fitting of the entire dataset. A similar procedure is performed for the background noise measurements which might be gathered before the wind farm is constructed. The logarithmic subtraction of values obtained as a result of the curve fitting may be doubtful. To improve validity of such approach some routines recommend different procedures for the data rectification [1,8,10]:

- truncation of data in accordance with downwind conditions only;
- excluding data below the cut-in speed of the turbines and above the speed of the rated power;
- disregarding data with known extraneous noise events and rainfalls.

An alternative approach requires calculating combined wind farm and background noise data corresponding to the wind speed bin where the noise levels are calculated. The same procedure is performed for the background noise only and, then the values are used for the logarithmic subtraction of the levels to calculate the wind farm noise.

Both of the post- processing techniques can not be applied in case when the background noise exceeds the total (wind turbine and background) levels. Figure 2 demonstrates one of such cases where the data have been post- processed using the curve fitting procedure. A similar situation can occur with the bin data analysis at the particular wind speed of interest.

If the calculated background levels are above the total noise magnitudes it can be due to changes in the pre- existing conditions at the places of measurement, seasonal variations in the background etc. However such situations can happen because of the particular data analysis routine.

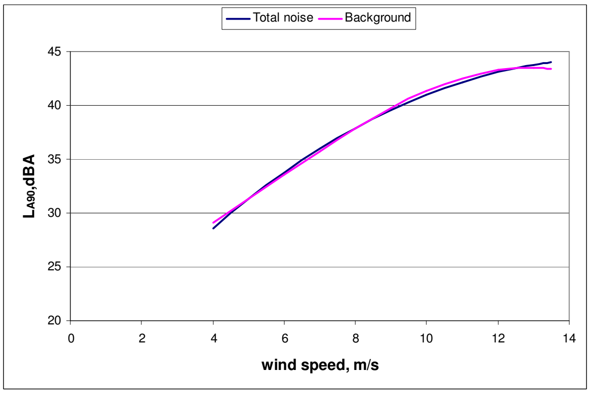


Figure 2. Calculated background and total noise versus wind speed at the hub height, data measured approximately 500m from the nearest turbine

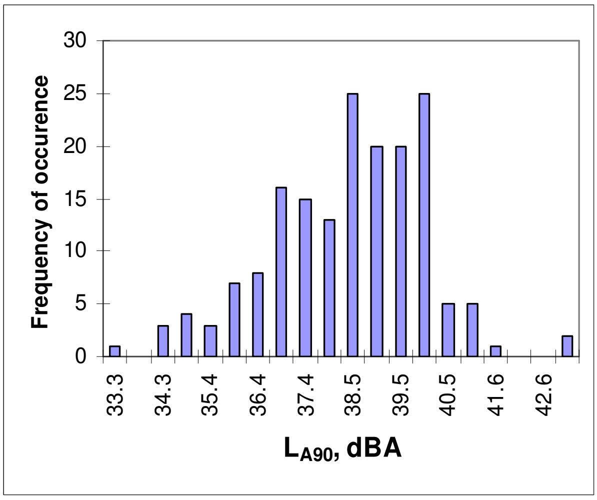
NOISE RESULTING FROM TIME VARYING SOURCES

The conventional data post- process for wind farms assumes that there is a correlation between wind farm noise, background levels and wind speed measured at the wind farm site. Modern procedures recommend reporting the wind speed at the hub height to avoid influence of the atmospheric stability effect on the data analysis [1,7,8].

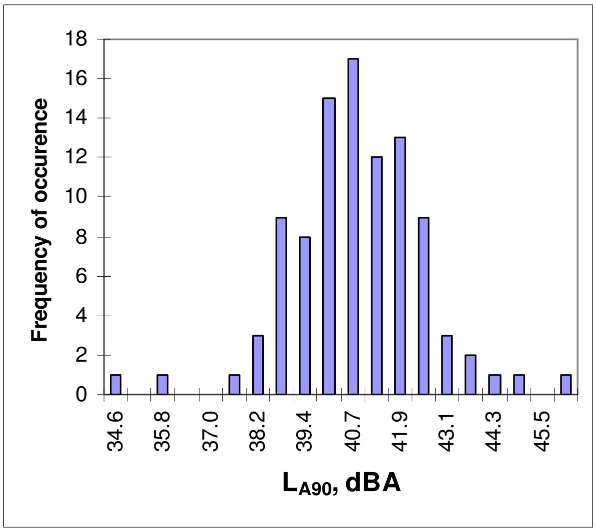
Another assumption is that the wind farm noise levels and background around the wind speed of interest (designated for the wind speed bin) can be combined in an independent manner to give a better ground for combining levels from wind farm and not associated sources. Similar assumptions generally are accepted in the calculation of total noise levels from traffic and background. Significant simplification for the calculation of total levels from time varying sources can be achieved if distribution of the noise descriptors is close to Gaussian. Statistical analysis of the combined wind farm and background noise and just background noise shows that the noise level distribution in the wind speed bin is generally not normal (Figure 3a). Even if the distribution appears to be Gaussian, the consequent test indicates that the hypothesis about normality of the distribution is wrong. For example, Figure 3b represents the combined noise levels distribution which might be Gaussian, but chi- square test [2,9] at probability level 0.05 (95% confidence limits) indicates that the distribution is not normal.

The frequency of occurrence distributions in Figure 3 are gathered for the wind speed bin with tolerance ±0.5m/s which corresponds to the accuracy of the wind speed measurements. One can think that tightening the limits for the wind speed bin improves "normality" of the magnitudes distribution in the bin. Generally this is not the case and a decrease of the tolerance for the wind speed bin just reduces number of data points available for the post- process.

Analysis of many case studies shows that the assumption about Gaussian character of distribution for noise data within the wind speed bin generally is not valid. It does not depend on whether you measure total noise or background; the data do not pass the normality test for reasonable confidence limits.



a)



b)

Figure 3. Frequency distribution for total noise (descriptor L_{A90}) measured approximately 500m from the nearest turbine at wind speed a)- 7m/s, b)- 10m/s (hub height, 10-min intervals)

COMBINATION OF WIND FARM AND BACKGROUND NOISE

Procedures based on arbitrary combination of levels gathered during the total and background noise monitoring can be developed for the general case. Methods (1) and (2) in work [6] are intended for use where the character of the statistical distribution is not important. Method (2) is based on relatively simple mathematic expressions that could be easily utilised for the computational routines. However there is no clear explanation about fraction of events when the combined values are within certain intervals (Appendixes I and II in work [6]). Also the expressions might not be applicable for many practical situations in the wind farm noise monitoring (refer to Appendix A).

Both of the methods incorporate logarithmic summation of the noise levels. They do not account for situation when values from the background data exceed the total levels for particular combinations of noise levels in the wind speed bin since we have operation of the logarithmic subtraction in place.

Measurements of the total and background noise give us two arrays of independent values for each wind speed bin: L_{Ti} – measured total noise levels, L_{Bj} – measured background noise levels. Conventional compliance checking procedures [1,7,8] recommend collection of 1000~2000 pairs of data (*i* and *j* are the data indexes in total and background noise data arrays), thus every wind speed bin of interest should contain a few hundred values. The collected data are not evenly distributed over the wind speed bins. At some particular wind speeds, for example at high velocities, the number of available pairs can be noticeably less. But normally it does not go below 50.

Combination of the levels can be calculated by formula:

$$L_{ij} = 10\log(10^{L_{Ti}/10} - 10^{L_{Bj}/10}), \qquad (1)$$

with probabilities:

$$p_{ij} = p_i p_j, \qquad (2)$$

where p_i and p_j are probabilities of the total and background noise levels within the wind speed bin.

New array of combined levels can be very big. To reduce the number of analysed data, the measured levels can be divided into class intervals similar to that in Figure 3. In accordance with conventional statistical analysis procedures [2,9], total or background levels are assigned to one of the class intervals if:

$$\begin{aligned} L_m - 0.5\Delta L_T &\le L_i < L_m + 0.5\Delta L_T \\ L_n - 0.5\Delta L_B &\le L_j < L_n + 0.5\Delta L_B \end{aligned},$$

where m=1,2…M and n=1,2…N are class interval numbers, ΔL_T, ΔL_B are the intervals' width for total and background noise respectively that define the number of the intervals *M* and *N*. Grouping of the data into 12~20 classes is recommended [2,9] with a smaller number of classes if only 50 magnitudes are available in the wind speed bin and closer to 20 if few hundred data points are analysed.

It is convenient to represent results of the operation (1) in matrix form where matrix $[L_{i,j}]$ has size $M\times N$. The corresponding probability matrix $[p_{i,j}]_{M\times N}$ can be computed by multiplication of the string matrix $[p_i]$ by row matrix $[p_j]$:

$$[p_{i,j}]_{M\times N} = [p_i]_{i,1} \times [p_j]_{1,j}. \qquad (4)$$

Sum of the elements of the probability matrix must meet condition:

$$\sum_{i,j=1}^{N,M} p_{i,j} = 1 \quad . \tag{5}$$

It is obvious that elements of the matrix $[L_{i,j}]$ can not be calculated in case $L_i < L_j$. One can suggest considering this combination of levels as improbable and replacing the values by zeros. Let us call this matrix "rectified level matrix" $[L_{i,j}]^*$. Respectively, the rectified probability matrix $[p_{i,j}]^*$ should have zeroes in place of the probability values where we consider the combination of parameters improbable. The rectified probability matrix will not satisfy condition (5) since some of the matrix elements are substituted by zero. Assuming that the rectified array represents all possible combinations of the values we have to scale the rectified probability matrix with parameter α:

$$\alpha = 1 / \sum_{i,j=1}^{N,M} p_{i,j}^* \ . \tag{6}$$

The scaled probability matrix $\alpha[p_{i,j}]^*$ meets condition (5). The wind farm noise can be computed as the mathematical expectation for new array of data [2]:

$$L_{WF} = \alpha \sum_{i,j=1}^{M,N} L_{i,j}^* p_{i,j}^* \ . \tag{7}$$

The expression (7) denotes scaled sum of the matrix elements where the elements are computed via element by element multiplication of the rectified matrixes $[L_{i,j}]^*$ and $[p_{i,j}]^*$.

The standard deviation for the rectified data can be computed by formula [2,9]:

$$s = \sqrt{\alpha \sum_{i,j=1}^{N,M} (L_{WF} - L_{i,j}^*)^2 \, p_{i,j}^*} \ . \tag{8}$$

It should be noted that in general the calculated values of the wind farm noise cannot be approximated by the Gaussian probability distribution. Therefore it is difficult to derive a universal relation for 95% confidence limits. The standard deviation (or variance) still can be used as a measure of the data scattering.

CASE STUDY

Let us consider a sample computation of the wind farm noise for a receiver which is situated approximately 500m away from the nearest turbine. The curve fitting process was performed for the post- construction noise monitoring data (total noise measurements) and pre- construction background noise acquisition. The conventional correction for background techniques can not be applied to all of the wind speeds of interest since the background curve fitting results sometimes are greater than the total noise values at particular wind speeds (Figure 2). Implementation of the wind speed bins approach does not improve the situation.

Analysis of noise sources in the neighbourhood area and environmental conditions during pre- construction and post- construction noise measurements show that significant change of the background levels is practically impossible. Therefore the alternative data post- process can bring statistically viable results.

The original noise levels (L_{A90} descriptor) were grouped in 20 class intervals for each of the integer wind speed bins (tolerance is ±0.5m/s). The post- processed data has been filtered in accordance with the down- wind conditions as described in References [1,8]. Estimates of the values gathered by three post- processing routines are represented in Table 1. It is possible to obtain valid values for each of the wind speeds utilising the statistical probability approach for the combination of total and background levels. The statistical method values do not demonstrate a trend similar to the measured sound power characteristic of the WTG. The control system might influence the measured data as it changes the operating mode depending on the environmental condition and electricity demand.

Table 1. Calculation of the wind farm noise by different methods

Wind speed, m/s	*5*	*6*	*7*	*8*	*9*
Curve fitting, dBA	-	20.6	22.6	18.9	-
Bin aanalysis, dBA	31.6	34.0	33.4	30.1	-
Statistical probability, dBA	32.5	34.5	35.9	36.4	36.0
Standard deviation, dBA	4.7	4.1	5.0	3.0	4.7

Wind speed, m/s	*10*	*11*	*12*	*13*
Curve fitting, dBA	-	-	-	31.2
Bin analysis, dBA	-	-	36.2	40.2
Statistical probability, dBA	35.3	36.9	39.8	41.2
Standard deviation, dBA	6.7	4.9	4.9	4.5

SUMMARY

Due to influence of many factors environmental noise monitoring frequently gives significant variations in the measured levels. A similar situation is observed during noise monitoring programs of wind farms. Therefore many regulatory procedures target statistical compliance with the noise limits. The outcome of compliance checking might depend on the method employed for the data post- process. Conventional computation routines are based on curve- fitting of the available data or analysis of the noise levels in the wind speed bins. Implementation of these methods in conjunction with the correction for background procedure sometimes can not result in a valid noise level estimate for the wind farm contribution. Such a situation may be encountered even if significant background noise variations were not detected since the pre- construction background noise data acquisition has been performed. Analysis of possible combinations of noise levels from independent noise sources can be employed as an alternative method. The wind farm noise contribution is calculated from total noise and background noise measurements at every wind speed of interest. The procedure is more statistically viable and enables wind farm noise calculations where traditional procedures are not applicable.

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APPENDIX A

Some works consider summation of levels from random sources with arbitrary statistic distribution of levels. Method 2 in paper [6] suggests a simplified formula for calculation of probability for the combined levels:

$$C(L) = 0.7[A(L) + B(L) - A(L)B(L-3) - B(L)A(L-3)] + 0.4A(L-3)B(L-3) + 0.3[A(L-3) + B(L-3)] \quad ,$$

where C(L) is the probability that the combined level exceeds *L* and *A(L), A(L-3), B(L), B(L-3)* are probabilities for the sources A and B that the associated levels exceed *L* or *(L-3dB)*.

Let us designate *A* as the probability for the wind farm levels and *B* as the probability for the background levels. At the combined level $L=L_{Tmax}$ we have $C(L_{max})=0$. From the equation above we obtain:

$$A(L_{\max} - 3) = \frac{0.7A(L_{\max})}{0.4B(L_{\max} - 3) - 0.7B(L_{\max})} .$$

To get a valid number for probability $A(L_{max}-3)$ (between 0 and 1), the wind farm noise must have at least one value above L_{max} and the probability distribution for the background noise must meet conditions:

$$B(L_{\max} - 3) > \frac{7}{4}B(L_{\max}).$$

Additional relations can be obtained considering $L=L_{Tmin}$ or other intermediate numbers. It gives an auxiliary set of conditions that depends on assumptions about distribution *A(L)* and characteristics of distribution *B(L)*. In general, the probability of the background levels for the class interval can be arbitrary, the condition above and other derived conditions might not be met in many practical cases. Therefore the proposed method lacks universality and is not considered to compute the wind farm noise in this paper.