

DEVELOPMENT OF A WIND FARM NOISE PROPAGATION PREDICTION MODEL

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1. INTRODUCTION & OBJECTIVES

Although wind is considered a 'clean' source of energy, wind farms can give rise to a form of pollution that is often overlooked: noise pollution. The problem with wind farm noise is that it is difficult to control retrospectively once the wind farm is operational. It is therefore essential to avoid noise problems at the planning stage.

Uncertainties in the prediction of far field noise levels using current analytical or empirical models can be significant, and valuable wind resources can be totally lost or under-exploited through fear of noise nuisance. Were it possible to more accurately calculate wind farm far field noise levels, then the environmental acceptability of proposed developments could be assessed at the planning stage.

Unfortunately, the noise propagation problem with respect to wind farms is not straightforward. Measurements of far field noise levels around operational wind farms often reveal significant fluctuations in noise level. Much of this variation can be attributed to the sound power output of the wind turbines being a function of wind speed, but it is also known that some of the fluctuations result from changes in the propagation paths from turbines to the receiver.

The primary objective of this project is to further the understanding of outdoor noise propagation from elevated noise sources, particularly with respect to the effects of meteorological conditions. The ultimate objective is to specify an 'optimised' calculation procedure applicable to environmental noise radiation from wind farms. The 'optimisation' of the calculation procedure refers here to the balance achieved between accuracy and ease of implementation. The major objectives of this project are thus:

- to establish by measurement the important parameters controlling the propagation of wind farm noise to the far field;
- to develop a planning tool for predicting the wind farm noise imission levels under practically encountered conditions;
- to place confidence limits on these noise predictions by defining an envelope in which sound pressure levels are likely to lie, thus enabling

developers to quantify the risk of whether noise imission from wind farms will cause nuisance to those living in the vicinity.

2. TECHNICAL DESCRIPTION

2.1 Outline of project requirements

Calculating environmental noise levels at large distances from wind farms requires two major steps. First, the sound power output of the wind turbines must be known across the entire range of operational wind speeds. Second, the manner in which sound attenuates as it propagates from the wind turbines to the receiver locations must be known. It is the second of these two steps which forms the major part of the present study.

The influence of the majority of parameters affecting sound propagation outdoors is generally well understood from a theoretical standpoint. However, the problem of predicting noise propagation over large distances in an outdoor environment is that the properties of the medium through which the sound travels are constantly fluctuating. This leads to non-steady propagation conditions and the possibility that noise levels at distant locations can vary significantly with time, even when the sound power output of the source remains constant. These effects can only be analytically modelled to any degree of accuracy if the state of the atmosphere through which the sound waves propagate is known. In practise this requires knowing the state of the atmosphere at all points in space through which each sound wave propagates. Even if the precise meteorological state is known on the site at a given location and time, the chances are slight that an identical state will exist 1000m away and almost 3 seconds later, which is the time it takes for sound to travel this distance.

The current project is unique in that it doesn't attempt to model the effects of changing atmospheric conditions on propagating sound waves. Instead it makes use of extensive measurements to obtain the highest quality noise and meteorological data. This data is then used to quantify variations in noise level observed in practise due to changing propagation conditions, and to identify the controlling meteorological parameters and quantify their effect.

When undertaking a programme of work designed to identify the influence of specific parameters on noise propagation, it is important to isolate as fully as possible the effects of those parameters. It was therefore decided to undertake the major part of the noise measurements using a specialist noise source rather than around an operational wind farm.

The use of an operational wind farm as the test noise source was considered unlikely to allow the effects of individual parameters to be isolated, with only a low degree of confidence thus being attributable to the results. This conclusion arose for a number of reasons:

- Wind farms comprise multiple distributed noise sources spread over large areas. Therefore at any receiver location the resultant sound pressure level comprises the sum total of contributions from many different sources. Each

of these contributions will have arrived at the receiver via a number of possible propagation paths, some screened and some direct. To undertake a parametric study on the basis of this data would almost certainly lead to inconclusive results due to the number of variables involved.

- Due to the nature of wind turbine sound power levels, which are themselves functions of wind conditions, an exact knowledge of the source sound power output will not be available for wind farms. It will not be known, therefore, whether measured variations in the far field noise levels are due to changes in source sound power or due to propagation effects.
- Distances from wind farms at which environmentally radiated noise are often perceived as a problem are typically 350m to 750m. At these distances wind farm noise levels are typically between 35dB(A) and 45dB(A). However, these noise levels are also typical of the background noise climate expected around wind farms. Therefore, the use of wind turbines as the noise source in any evaluative tests would not enable confidence to be placed on the results obtained due to the contamination of the results by background noise.

2.2 Experimental methodology

The major part of the data collection exercise was undertaken using a constant sound power output, broad band noise source having a spectral content similar to that of a modern wind turbine. The actual source selected was a weatherproofed dodecahedral loudspeaker having a nominal sound power output level of 113dB(A). The loudspeaker was mounted on a telescopic mast at heights of between 15m and 30m above local ground level. The experiments were repeated on three different sites with topographies varying from flat to highly complex.

On each site a combination of $L_{Aeq,1min}$, $L_{A90,1min}$ and $L_{A10,1min}$ noise indices, together with third octave band noise levels levels, were simultaneously logged at 15 locations at distances ranging from less than 50 metres up to 900 metres from the sound source. Data acquisition lasted for up to six weeks per site.

On the rolling and complex topography sites specific monitoring locations were selected to study effects such as distinctive ground profiles and ground screening between the source and receiver.

Meteorological conditions were logged simultaneous with the noise data using monitoring equipment mounted on the same mast used to support the sound source. Parameters recorded included wind speed, wind direction and temperature at two heights, plus rainfall, relative humidity and atmospheric pressure. Time synchronisation between noise and meteorological measurements was central to the success of the project.

The use of a high-powered, constant sound power noise source enabled sound pressure levels higher than those produced by wind turbines to be generated

at large distances from the source. This resulted in a higher signal-to-noise ratio being achieved at large distances from the source, thereby overcoming the problem of higher than source background noise levels as outlined above. It also removed any uncertainties associated with the variable sound power output of wind turbines.

In order to perform a meaningful analysis of this data it had to be ensured the noise data used for the study related solely to the source noise, and not to any other extraneous noise such as wind induced background noise. Based on simple geometrical spreading it was calculated that the source sound power level of 113dB(A) would result in a sound pressure level of around 45dB(A) at 750m from the source. The original hope was that this would be sufficiently loud to provide a reasonable signal to noise ratio at all but the highest wind speeds, especially given that all sites were specially selected to offer a low background noise environment. However, following preliminary analysis of the first data downloads it became apparent that much of the data was corrupted by background noise.

To overcome the problem of extraneous noise, a switching circuit was introduced into the signal line input of the amplifier. This circuit automatically switched the input to zero and then back up to its maximum level every 20 minutes. The signal was ramped on and off over an approximate 20 second period to prevent transients damaging the loudspeakers at the on/off transition points. The measured data for all the microphone locations was then filtered according to the following rules:

- all periods during which the loudspeaker was off, or in a transitional on/off state, were rejected;
- all periods during which there was site activity involving vehicle movements were rejected (site visits had to be made at least twice a day to refuel the petrol generator used to supply power to the noise generation system);
- all periods during which rainfall was recorded were rejected;
- all periods where the sound level meter overloaded were rejected;
- all periods where the sound level meter underloaded were rejected;
- all periods where the $L_{Aeq} - L_{A90}$ difference exceeded 3dB(A) were rejected (meters 1 to 8 only : meters 9 to 15 only recorded L_{Aeq});
- all other periods during which problems (of whatever type) were reported in the meter download log were rejected;
- All periods during which the background noise was within 10dB(A) of the noise level with the source on were rejected*;
- For the remaining periods, the measured noise levels with the source on were corrected for the effects of background noise*;

* The correction for background noise was performed by taking the 20 minute $L_{Aeq,1min}$ 'source off' data samples each side of the 20 minute 'source on' period of interest, and imposing a best fit straight line on the

approximately 40No. measured background noise levels as a function of wind speed. The background noise level was then calculated for the measured wind speed corresponding to each of the 1 minute 'source on' samples, thus allowing the correction for background noise to be made.

As a result of the filtering process just described it was ensured that the resulting data sets on which all subsequent data analysis was undertaken contained only the highest quality data.

The problems of distinguishing variations in far field source noise levels resulting from propagation effects as opposed to changes in the background noise level or source level have introduced significant uncertainty into the results of other projects. The approach adopted here dramatically reduced this potential for error. In similar experiments reported elsewhere corruption by background noise has proved a stumbling block to an accurate evaluation of the results. The confidence that has been gained from the current set of results is therefore seen as a major step forward in solving the noise propagation problem.

2.3 Data analysis

The 'raw' data sets for each of the three sites comprised up to 22,000 one minute averages of noise and meteorological measurements per monitoring location. The first task involved the separation of this data into source 'on' and background noise components using the procedure outlined in section 2.2. Due to the rigorous application of this filtering technique the number of source 'on' points typically reduced to around 2,000 per monitoring location. This may appear a waste of valuable data, but the view of the project team was that it was preferable to work with a smaller data set of the highest quality than to place any reliance on a much larger data set containing potentially misleading noise results.

Once filtered, both the background data and the source 'on' data were sorted into 1ms^{-1} wide wind speed bins for subsequent analysis. This analysis concentrated on the $L_{Aeq,1min}$ data set. Check comparisons were made with the $L_{A90,1min}$ data set which revealed all trends to be the same, although the $L_{A90,1min}$ noise levels were consistently 1dB(A) to 2dB(A) lower than the $L_{Aeq,1min}$ results.

Background noise data was analysed purely to establish the effect of wind speed on measured levels at each site.

Source 'on' data was analysed to identify the mean noise level at each monitoring location, along with the distribution of the measured data about this mean. This statistical distribution gave a measure of the practical variations in noise levels expected in practice due to changes in meteorological conditions.

The question to be answered was whether the scatter in the measured noise levels could be systematically attributed to a physical mechanism. If this was

the case, and the physical mechanism could be positively identified, then it would be possible to develop a theoretical model capable of accurately calculating noise propagation effects.

A detailed statistical analysis of the measured data was therefore undertaken to investigate this question. Two different techniques were used to test the dependence of the measured noise levels at each microphone location on the full range of meteorological parameters monitored during the tests.

The first analysis technique employed standard statistical methods, treating each of the meteorological parameters as an independent variable and assessing the dependence of the sound pressure level measured at each microphone location on each of the meteorological parameters in turn. The assumed model for the noise level at each microphone location comprised a constant term (accounting for a fixed noise level attributable to geometric spreading and atmospheric absorption) plus a variable term accounting for the drift of the measured noise level below and above the fixed noise level term.

The second analysis technique employed a neuro-fuzzy model. This type of model is capable of identifying and modelling underlying relationships in cross-coupled systems with interdependent variables based on observations of the inputs and outputs of that system. A fundamental objective of the present study was that noise data should be collected simultaneously at all microphone locations, and that this noise data should also be synchronised with measurements of the meteorological parameters. The neuro-fuzzy technique was thus able to model the effects of interdependent meteorological parameters on the measured noise levels at a single microphone location. However, in addition to this it was also able to refine the model by including the effects of the various meteorological parameters on the noise levels measured simultaneously at all the microphone locations.

2.4 Comparison of measurements with predictions

Noise levels at all of the monitoring locations around all of the sites were calculated using various selected calculation procedures. These procedures comprised IEA [1], ISO-9613 part II [2], ENM [3] and CONCAWE [4]. Where appropriate, calculations were undertaken accounting for the full range of topographical and meteorological conditions encountered during the noise monitoring exercise.

The results of the calculation procedures were compared with the measured noise levels and the degree of accuracy of the noise predictions established. Each model was critically assessed and compared with a view to determining:

- prediction errors;
- which model performed best, and in what circumstances;
- in which areas the models were deficient;
- the effect of the various variable parameters;

- if improvements to the models were possible;
- whether a composite model could be developed to improve prediction accuracy whilst simplifying the calculation procedure.

The information from this comparison exercise fed directly into the 'ground-up' development of an optimal noise prediction code.

2.5 Specification of an optimal calculation procedure

From the combined results of the experimental measurements and the comparison of these measurements with predicted levels, an optimum noise calculation procedure has been developed. This calculation procedure included those parameters demonstrated to have an important controlling factor on the far field noise levels. Error bounds were then placed on the far field noise levels predicted using this model.

2.6 Validation of results on an operational wind farm

The final part of the project involved a repeat of the measurements undertaken around the loudspeaker noise source, but this time in the vicinity of operational wind farms. The aim of this series of measurements was to validate the proposed noise calculation procedure under practical conditions, and further to assess the impact of multiple, variable sound power output sources (wind turbines) on the scatter of the measured results. The supposition here was that when calculations of wind farm noise are undertaken, it is usually assumed that all turbines see a common wind speed. In practice this is known to be an incorrect assumption, as many turbines lie in the wakes of other turbines and therefore experience lower wind speeds. Of particular interest was the increased uncertainty this effect would place on the predictions.

3. RESULTS & CONCLUSIONS

3.1 Measured background noise data

The measured background noise data at all locations demonstrated the characteristic increase with increasing wind speed. However, an unexpected feature of the background noise data at all sites was the large variation of the results between monitoring locations. A spread of almost 20dB(A) was apparent between the mean levels at each of the monitoring locations on each site over the wind speed range from 5ms⁻¹ to 8ms⁻¹. This was even the case for the flat topography site where all monitoring locations were exposed to what should have been identical conditions.

This finding has implications with regard to background noise measurements undertaken to assess the acceptable levels of specific noise radiation from wind farms. Users of any technique that sets wind farm noise levels relative to measured background noise levels should be aware of the differences between measurements. Further work is suggested to establish whether the large measured differences are real changes in background noise level or whether they are due to the differing susceptibility of individual items of measuring equipment to wind induced noise.

3.2 Measured source 'on' noise data

The results of the loudspeaker noise source tests revealed several consistent features in the measured data. The observations could be divided into three main categories, as follows:

Unscreened propagation over all terrain types -

- In accordance with the theory for geometric spreading, sound pressure levels decrease with increasing distance from the source.
- The plus or minus one standard deviation variation of sound pressure levels about the mean level at any given location increases at a rate of approximately 0.004dB(A) per meter increase in the source to receiver separation distance.

This spread includes the effects of all parameters, including the full range of wind conditions experienced on each site. These wind conditions typically included wind speeds from 0ms^{-1} to 10ms^{-1} over a good spread of wind directions.

The primary cause for the observed variation in noise levels is the systematic dependence of the sound pressure level on the component of vector wind speed from the source to the receiver. Variations in vector wind speed account for approximately 0.003dB(A)/m of the observed 0.004dB(A)/m variation in sound pressure levels.

- Sound pressure levels at unscreened locations generally increase with increasing positive vector wind speed component blowing from the source to the receiver.

The dependence of the sound pressure level on positive vector wind speed increases with increasing distance from the source.

The maximum observed increase in the sound pressure level due to a change in vector wind speed from 0ms^{-1} to $+6\text{ms}^{-1}$ is approximately +5dB(A). This was measured 600m from the source over rolling terrain.

The scatter of measured sound pressure levels under the condition of a $+6\text{ms}^{-1}$ or higher positive wind vector blowing from the source to the receiver has been observed to increase at a rate of approximately

0.001dB(A) per meter increase in the source to receiver separation distance.

- Sound pressure levels at unscreened locations generally decrease with increasing negative vector wind speed component blowing from the source to the receiver.

The dependence of the sound pressure level on negative vector wind speed increases with increasing distance from the source.

The maximum observed decrease in the sound pressure level due to a change in vector wind speed from 0ms^{-1} to -6ms^{-1} is approximately -3dB(A). This was measured 700m from the source over flat terrain.

- At receiver locations within 200m of the source, the effects of vector wind speed described in the previous two bullet points can be reversed and increasing positive vector wind speeds can result in a reduction in the measured noise level.

This reverse effect is, however, marginal with observed reductions of no more than 2dB(A) for an increase in the vector wind speed from 0ms^{-1} to $+8\text{ms}^{-1}$.

Unscreened propagation over heavy rolling or complex terrain profiles –

- Where the land falls away significantly between the source and receiver (such that the mean propagation height is around 1.5x or more what it would have been over flat ground, and particularly where the land falls away steeply from the receiver location) the observed sound pressure levels are higher than those expected for propagation over flat or light rolling terrain.

Noise levels at these locations have been measured 2dB(A) to 3dB(A) higher than the noise levels expected for propagation over flat and gently rolling terrain. The same observations have been made at all distances ranging from 200m to 900m from the source.

Acoustically screened propagation -

- Sound pressure levels at locations that are fully or partially screened from the noise source are lower than the equivalent levels with no screening present. However, this conclusion only holds under conditions of neutral or negative vector wind speed blowing from the source to the receiver.

Acoustically screened locations are highly susceptible to changes in the vector wind speed, even at distances less than 100m from the source, with increases in sound pressure level of 16dB(A) being measured for increases in vector wind speed from -8ms^{-1} to $+8\text{ms}^{-1}$.

Under neutral propagation conditions the excess attenuation offered by the screen is between approximately 5dB(A) and 10dB(A). The actual attenuation depends on the extent to which the direct line of sight between the source and receiver is interrupted, and on the proximity of the barrier to the receiver.

Under conditions of negative vector wind speed, the attenuating effect of the screen can be enhanced and reductions in excess of 10dB(A) have been observed.

Under conditions of a positive vector wind speed blowing from the source to the receiver, the excess attenuation offered by a barrier reduces. It has been observed that for higher positive vector wind speeds of around 8ms^{-1} the excess attenuation offered by the barrier can reduce to just 2dB(A) to 3dB(A).

- The scatter of measured sound pressure levels about the mean in partially or marginally screened locations is much greater than that experienced for unscreened locations at an equivalent distance from the source. This increased variation is due to the heavy systematic dependence on vector wind speed just described.
- The large dependence of screened sound pressure levels on vector wind speeds referred to in the previous five paragraphs does not occur if the barrier is located close to the receiver, and if this barrier provides a sharp cut-off to the direct line of sight between the source and receiver. The observed excess attenuation offered by this type of screen has been measured at around 10dB(A) regardless of vector wind conditions.

3.3 Comparison of measurements with predictions

The results of this part of the project demonstrated three of the four calculation procedures tested (IEA, ISO 9613-2 and ENM) to be capable of providing a high degree of accuracy when calculating far field noise levels radiated from elevated noise sources. The ENM implementation of the CONCAWE procedure was found to over-predict noise levels within a few hundred metres of the noise source. The decision as to a recommended calculation procedure therefore rested on the simplicity of the models and the confidence limits that could be placed on their output.

ENM

Considering the ENM calculation procedure first, this is a relatively complex model that requires the specification of multiple input parameters. The use of the model to calculate average noise levels based on a typical range of meteorological parameters was found to give results accurate to within 2dB(A) of the mean measured levels even on the rolling and complex sites. However, the procedure was found to be acutely sensitive to small changes in meteorological parameters. Variations in noise levels of up to 30dB(A) were predicted by the models, whereas measured variations under the same range of meteorological conditions were limited to less than 10dB(A). For this reason confidence levels in this calculation method were reduced.

ISO 9613

The ISO 9613 model is well defined and relatively easy to program. It is empirically based and so does not exhibit the same over sensitivity to input

parameters as ENM. It also has a reduced requirement for specifying input parameters compared with ENM. It is designed to calculate far field noise levels under conditions favourable to the propagation of noise. Favourable conditions are suggested to be a 1ms^{-1} to 5ms^{-1} component of wind speed blowing from the source to the receiver. The ISO model also includes the effects of terrain, including excess attenuation due to ground effects and acoustic screening.

The accuracy of output from the ISO model is impressive. Agreement with sound pressure levels measured under conditions of an 8ms^{-1} positive vector wind speed has been measured to within 1.5dB(A) on flat, rolling and complex terrain sites. The only observed exceptions to the excellent accuracy achieved by the model occur in the presence of marginal or partial acoustic screening, and also where the ground falls away significantly between the source and receiver. However, these two situations are easily accounted for by means of simple correction factors.

In the case of marginal or partial acoustic screening, it is proposed that the excess attenuation attributable to the barrier effect should be limited to no more than 3dB(A). This is because it has been observed experimentally that the presence of a positive component of wind from the source to the screened receiver can significantly reduce the effective barrier performance.

Where the ground falls away significantly between the source and receiver, such that the mean propagation height is at least 1.5x that over flat ground and particularly where the ground falls away steeply from the receiver, it is recommended that 3dB(A) be added to the calculated sound pressure level. This correction factor is based on experimentally measured levels. It accounts for the reduction in excess ground attenuation due to the increased height of propagation.

Provided the suggested correction factors are applied to the output of the ISO 9613 model, the calculated sound pressure levels have been validated to agree to within 2dB(A) of noise levels measured under practical 'worst case' conditions at distances of up to 1000m from a noise source. Also, based on the observed scatter of measured sound pressure levels under these same conditions, it is concluded that the one standard deviation spread of data above the calculated levels will be limited to below 1dB(A), even at the furthest distances from the source. It is therefore finally concluded that an 85% level of confidence can be placed on the noise levels measured in practice not exceeding the calculated level by more than 1dB(A).

IEA

The IEA model can be considered as a 'sub-model' of the full ISO 9613 model. All that is included in its derivation is the attenuation associated with geometric spreading plus a single excess attenuation factor resulting from atmospheric absorption. Attenuation factors associated with terrain or ground types are excluded. Consequently the IEA model is very simple to program and run. The only input parameters required are the sound power output of the source, the

distance between the source and receiver, and the air temperature and relative humidity. These last two parameters are required to enable the attenuation factors of the air to be established from look-up tables. The method therefore has ease of use in its favour.

Comparison of calculated levels from the IEA model with measured levels has revealed a surprisingly high level of agreement. Over flat terrain the IEA model tends to overpredict far field noise levels, although the observed discrepancy at 700m from the source was only 2dB(A) higher than the noise level measured under an 8ms^{-1} wind speed component blowing from the source to the receiver. Over rolling and complex terrain the general agreement between calculated and measured results was again within 1.5dB(A).

The only observed exceptions to the above finding are the cases already discussed under the ISO model. These situations must again be treated as special cases. Where partial or marginal screening is present between the source and receiver an excess barrier attenuation of 2dB(A) should be allowed for. Where the screening effect is complete, with the barrier being located close to the receiver and providing a sharp cut-off to the direct line of sight, then the excess barrier attenuation may be increased to 10dB(A). Finally, for situations where the land falls away significantly between the source and receiver, 3dB(A) should be added to the calculated sound pressure level.

It is therefore concluded that the preferred calculation procedure should comprise a modified version of the IEA method. The model is simple to program and run. It is also capable of calculating far field sound pressure levels that have been observed to agree to within 2dB(A) of measured far field noise levels under 'worst case' conditions of a strong component of vector wind speed blowing from the source to the receiver.

3.4 Recommended noise propagation calculation procedure

On the basis of the findings outlined in sections 3.2 and 3.3, it has been concluded that the adoption of the IEA model as the basis for a simple noise propagation prediction scheme is the preferred choice. However, in order to account for the specific cases where the model has been shown to be deficient, an additional excess attenuation factor must be included. Provided this additional attenuation factor is included, the output of the proposed model has been validated to the stated limits of accuracy. This validation has been undertaken for the case of broad band noise radiation from an elevated source over arable or pasture land of all topographical complexities, from flat to complex. The results have further been validated at distances up to 900m from the source.

The proposed model uses as its starting point the A-weighted sound power level, L_w , of the noise source under consideration. This sound power level is then modified by three attenuation factors to arrive at the received sound

pressure level, L_p , at a given line of sight distance 'd' meters from the source due to the operation of that source in isolation:

$$L_p = L_w + 10 \cdot \log \left(\frac{Q}{4 \times \pi \times d^2} \right) - A_{atm} (-A_{ter}) \quad (1)$$

The total received sound pressure level at any given location is then calculated by energetically summing the calculated sound pressure levels at that location due to all the individual noise sources.

The first attenuation factor in equation (1) accounts for the directivity, Q , of the source in its installed location and the effect of geometrical spreading over the propagation distance, d .

The second attenuation term, A_{atm} , accounts for excess attenuation due to atmospheric absorption. Values for A_{atm} can be found in ISO 9613-1 [5].

The first two attenuation terms of equation (1) should be applied separately for each octave frequency band from 63Hz to 4000Hz inclusive, and the octave band results then summed to arrive at the overall A-weighted sound pressure level at the receiver.

The third attenuating term, A_{ter} , is applied to the resulting overall A-weighted level. It accounts for additional effects arising from the presence of certain ground effects between the source and the receiver. This term is zero except for the following two special cases.

Case 1:

$$A_{ter} = -3dB(A) \quad \text{if} \quad h_m \geq 1.5 \times \left[\frac{abs(h_s - h_m)}{2} \right] \quad (2)$$

where h_m is the mean height above the ground of the direct line of sight from the receiver to the source, and h_s and h_m are the heights above local ground level of the source and receiver respectively. Note that where this condition exists it serves to increase the received sound pressure level, hence A_{ter} in this instance is negative.

Case 2:

$$A_{ter} = +2dB(A) \quad (3)$$

where the direct line of sight between the receiver and the source is just interrupted, or the interruption occurs due to a natural terrain feature that does not provide a distinct and pronounced interruption to the direct path and does not lie within 5m of the receiver.

Case 3:

$$A_{ter} = +10dB(A) \quad (4)$$

where the direct line of sight between the receiver and the source is interrupted by a barrier that lies within around 5m of the receiver and provides a significant interruption to the direct line of sight path (a minimum interruption of 0.5m is suggested). Where any doubt exists it is suggested that the excess attenuation due to barrier effects should be limited to the 2dB(A) given in equation (3).

Based on the results of extensive measurements, the use of equations (1) to (4) have been shown to result in calculated sound pressure levels that lie within 2dB(A) of the level not expected to be exceeded for at least 85% of the time. The calculated levels correspond to conditions favourable to noise propagation over flat, rolling or complex terrain comprising typical arable or pasture land. Conditions 'favourable to noise propagation' relate to an 8ms^{-1} component of wind speed in the direction from the source to the receiver measured at 10m height on the wind farm site. The increase in noise levels for stronger components of positive vector wind speed have been measured to be marginal.

3.5 Validation of the recommended model using wind farm data

The proposed calculation procedure has also been validated against measurements undertaken at a 42 turbine wind farm, with predicted levels agreeing with measured levels under favourable propagation conditions to within 2dB(A). However, the results of the wind farm measurements have indicated a greater degree of scatter of the results than for the controlled loudspeaker test measurements. This increased scatter arises from variations in the source sound power level as the wind conditions vary. Sound power output levels of turbines within a wind farm are usually calculated assuming a single wind speed applies across the whole site, whereas in practice each turbine sees a different wind speed depending on the sheltering afforded by the other turbines.

It is therefore recommended that when the proposed calculation procedure is used to predict far field noise environmental levels from wind farms, an uncertainty factor should be included for the variation of wind speeds seen by the different turbines. The actual correction factor included will be dependent on the layout of the site. However, the effect of this feature in practice is likely to reduce worst case noise levels at receiver locations compared with those calculated using the assumption of a singly applicable site wind speed. This is because under downwind conditions the turbines lying closest to nearby properties should see a reduced wind speed due to the shielding effects of the upwind turbines. It is these closest located turbines whose noise output will dominate the overall noise level received at these properties.

3.6 Concluding remarks

As the result of an extensive measurement and analysis exercise, an empirical model has been proposed for calculating noise levels at large distances from elevated noise sources. The work is innovative in that it encompassed a complete experimental study of outdoor noise propagation in relation to wind farms, the results of which have fed into the development of an optimum code for the prediction of wind farm noise radiation.

Most importantly, the work provides a unique, highly empirical approach to solving the propagation problem, being led by observations and measured data rather than starting from a theoretical standpoint. This approach is at odds with models currently available for predicting environmental noise radiation from wind farms which tend to be of a theoretical origin with little or no formal validation against noise levels actually measured around wind farms. Experience has shown that these existing models are inadequate in that only low levels of confidence can be placed on the results obtained from them. This is most often due to their high sensitivity to changes in meteorological parameters.

The output of the model resulting from the present work has been shown from the controlled measurements to be accurate to within 2dB(A) for conditions of

strong downwind propagation, with the results being validated for an 8ms^{-1} component of wind speed blowing from the source to the receiver.

The results of the measurement and analysis exercise have allowed confidence limits to be placed on the calculated long term averaged noise level under varying wind conditions. These confidence limits are based on the typical variation of the measured noise level around the calculated level. This variation is shown to be dependent primarily on the wind speed component blowing from the source to the receiver, with the confidence level increasing for increasing component of vector wind speed blowing from the source to the receiver.

The derived noise calculation procedure provides a compromise between simplicity and accuracy in predicting the noise levels not expected to be exceeded for at least 85% of the time. Thus the use of the calculation procedure allows the acoustic risks associated with the development of a wind farm to be quantified, to the benefit of all concerned.

4. EXPLOITATION OF RESULTS & PROJECT BENEFITS

The following major potential benefits are expected to result from the work reported here:

- Sites that previously had not been exploited owing to potential noise disturbance at nearby dwellings may become accessible.
- Propagation of sound in complex terrain will be more fully understood, thus allowing sites where the dwellings are sheltered from the wind to be exploited.
- Greater realisation of site resource resulting from an increased understanding of noise propagation.
- Lower perceived risk from investors.
- Less likelihood of a justifiable nuisance complaint resulting in curtailment of the operation of one or more wind turbines.

General benefits

- The results will be of significant use to the general acoustics fraternity in the context of a better understanding of noise propagation.

With regard to the exploitation of project results, the output of the project is already in use by the three project partners in their continued involvement with wind farm developments. Also, the calculation procedure for environmental noise radiation from wind farms derived from this project is very simple. It is therefore easily adopted by others in the field of wind farm acoustics.

It is intended that the results of the project should feed into the deliberations of the current EU working groups on noise. The results of the project will be communicated formally to relevant members of the current EU working groups

on noise. Conference papers reporting the project's findings will be presented at British and European Wind Energy Conferences over the forthcoming year.

5. REFERENCES

- [1] Acoustics – Attenuation of sound during propagation outdoors – Part 2: General method of calculation, ISO 9613-2, International Standards Organisation
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- [3] Description of ENM Module Algorithms, RTA Software Pty Ltd, Program ENM.
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