PREDICTION OF WIND FARM NOISE PROPAGATION WITH RELATION TO THE SUBJECTIVE DOSE RESPONSE

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1 INTRODUCTION

In the face of the threat posed by climate change the UK Government's Renewable Energy Strategy[1] has the ambitious target of generating 15% of all the UK's energy from renewable sources by 2020. Given this short time scale and the ready availability of already tried and tested wind turbine technology, the greatest proportion of these renewable sources will have to be from wind turbines. As described in the report *'Building a Low Carbon Economy'*[2] which highlights that wind energy capture could deliver 30% of the UK's electricity supply by 2020 and be part of a radical decarbonisation of the economy by 2030.

As the UK tries to meet its climate change renewable energy targets local planning authorities are faced with increasing numbers of applications for wind farms and wind turbines. With this escalating demand there is increased potential for conflict with the amenity of occupiers of neighbouring land. Local planning authorities are tasked with a difficult balance between providing adequate protection of amenity; and facilitating renewable energy development vital to meeting future needs. At the heart of this balance is consideration of the noise impacts from wind farms and wind turbines. Any assessment of noise impact requires information on likely noise imission levels and the probable human response to these levels.

A quick scan of the internet shows that the prediction and assessment of noise from wind turbines is a complex and often contentious issue. This already challenging situation can be exacerbated by unfounded and exaggerated claims in relation to wind farm and wind turbine noise, of varying veracity, some times of dubious provenance and often of a partisan nature; made by both anti and pro - wind farm objectors and activists. However, it is clear that wind turbines are not "silent" or "quiet" and like any other noise source can cause adverse impacts. But equally they are not the source of harmful noise that we can't hear, and there is no robust evidence that noise from wind farms generates specific health effects or "syndromes" different to other sources of noise[3 & 4].

This paper considers how to predict the propagation of wind turbine noise in order to assess reasonable worst case likely significant impacts; and reviews the literature on wind turbine subjective noise response.

2 PREDICTION OF WIND TURBINE PROPAGATION

2.1 Engineering Vs Scientific Noise Propagation Prediction Methods

Reliable predictions of imission noise levels at sensitive receptors are required in order to undertake robust assessments of the likely significant impacts of wind turbine noise. Confidence in the prediction of wind turbine noise propagation is not only important in order to appropriately assess the potential likely impacts; but also to avoid unduly restricting important renewable energy generating capacity. For example, small differences in predicted imission values relative to a control limit can translate into large differences in the potential generating capacity of individual wind farm sites[5] e.g. a difference of ±3dB(A) may result in an effective limit on potential wind farm development areas to just 25% of what may potentially be available[8]; which has implications for reaching the national targets for renewable energy described in the introduction.

Leaving aside the matter of the quality and validity of any source sound power levels; the next most important factor in achieving accurate predictions of wind turbine noise propagation is the method used to predict the propagation of the noise from source and how it accounts for the factors that may affect propagation, such as:

a) Geometric divergence (distance),
b) Directivity,
c) Source and receiver geometry e.g. height above ground.
d) Ground effects,
e) Barriers and topography,
f) Reflections from surfaces other than the ground,
g) Air absorption,
h) Meteorological conditions e.g. temperature and humidity, wind direction and speed.
i) Miscellaneous factors e.g. vegetation

Methods for predicting environmental noise propagation generally fall into three broad categories, as follows[6].

a) Engineering methods – Relatively straightforward algorithms widely employed for practical noise assessments across a range of source types and includes ISO 9613, CONCAWE, BS 5228, Nord 2000, HARMONOISE etc. Engineering methods tend to be empirically based and use approximate average propagation conditions. They offer the benefit of rapid calculation times and reliable prediction of overall noise levels for relatively simple noise sources in environments of limited complexity. They generally only relate to total A-weighted noise levels over an average range of meteorological conditions; and potentially suffer inaccuracies for frequency analysis, short term meteorological conditions, and more complex topographies.

b) Approximate semi-analytical methods – These are similar to engineering methods, but are based on simplified analytical solutions of the wave equation rather than empirical results. Simple ray tracing models are the most popular methods within this category. While the practical engineering methods only take into account averaged meteorological effects, these methods allow a better tracking of the influence of specific meteorological conditions on noise levels, such as upwind or downwind situations.

c) Scientific methods – These are mostly employed for specialist research and are generally complex numerical methods based on direct solutions of the wave equation such as the Fast Field Program (FFP), the Parabolic Equation (PE) and the Boundary Element Method (BEM). Typically they are bespoke to a specific project and its circumstances. They can provide accurate representation of propagation for individual frequencies in specific conditions and can provide the basis for the 'reference models' used to validate engineering methods.

As with any data processing method the reliability of the output from all the above methods is only as good as the 'accuracy' of the input parameters e.g. source noise terms, directivity factors, temperature and humidity, time and distance, meteorological and ground conditions, topography etc. along the whole of transmission path. If faulty, incomplete, or imprecise input parameters are used, although the outputs may appear precise due to the complexity and sophistication of the chosen calculation method; they will not be more accurate than results calculated using a simpler method with better quality input data, and indeed can be less valid than data derived using less complicated methods but with more appropriate inputs.

In general terms, dependent on all the relevant input factors being available and correct, engineering methods of predicting environmental noise propagation are typically less accurate than semi-analytical methods which in turn are less accurate than scientific methods. The drawbacks of semi-analytical and scientific methods compared to engineering methods are that they require significantly greater resources due to the extended calculation time required and their requirements for large amounts of location specific input data, and the higher sensitivity of the accuracy of their outputs to the quality of input data.

Consequently, when deciding if engineering methods are adequate for predicting propagation of noise from wind turbines or if the commitment of additional resources to using scientific and semi-analytical methods is required. It is helpful understand whether in general engineering methods can provide suitably accurate estimates of turbine imission levels. Several investigations of the propagation of wind turbine noise have been carried since the late 1980's, many focusing on the comparison of measured noise levels with predictions of turbine noise propagation.

2.1.1 Comparison of measured and predicted turbine noise levels

In 1990 Hubbard and Sheppard[7] predicted the propagation of wind turbine noise using a relatively simple engineering method that only considered the geometric spreading of sound and the excess attenuation by air absorption and found a reasonable correlation with measured noise levels.

In a 1998 study Bass, Bullmore and Sloth[8] concluded that:

- Noise from wind turbines varies at all distances, but more so at larger distances, even if the source remains constant.
- At distances of 700m to 900m from the source, positive components of vector wind speed may increase noise immision levels by up to 5dB(A) compared with the level measured under neutral propagation conditions
- Scientific models are too sensitive to changes in meteorological parameters. Variations in noise levels of up to 30dB(A) were predicted by these models, whereas measured variations under the same range of meteorological conditions were limited to less than 10dB(A).
- The empirical engineering model ISO 9613-2 generally provides high levels of accuracy to within 2dB(A) in predicting received noise levels under downwind propagation '*conditions favourable to noise propagation*', for at least 85% of the time. Excepting the following two scenarios:
    - For acoustically screened locations under downwind propagation conditions the excess attenuation provided by the screening can be reduced to just 2dB(A). This is thought to be largely due to downwind refraction effects "bending" sound waves over the screening of topography or a barrier.

- Where the ground falls away significantly between the source and receiver, and particularly in the immediate vicinity of the receiver. In these cases the measured noise levels are approximately 3dB(A) higher than those predicted by the ISO method

In 2000 Bass and Bullmore[9] compared the reliability of wind turbine noise predictions made using a complex scientific method (ENM) with the empirical engineering methods of ISO 9613 and CONCAWE and the more simplified engineering method from the International Energy Authority. The study found much the same results as their earlier report described above.

More recently several studies have reported measured wind turbine noise levels compared with predicted levels and generally found adequate correlation with engineering methods. For example in 2009 Bullmore *et al*[10] reported in regard to 3 different wind farm sites, that based on the following assumptions:

- Source height equal to hub height;
- Receiver height equal to 4 m and free-field conditions;
- Temperature of 10 degrees Celsius and 70% relative humidity;
- Flat and level ground cover for two separate conditions: G = 0 and G = 0.5 (for source, middle, and receiver ground) to consider hard and mixed ground cover conditions, according to site-specific considerations;
- The turbine sound power data was corrected to take wind shear into account; and,
- the subtraction of 2 dB(A) to correct for the use of the L_{A90} rather than L_{Aeq} index,

That:

"The results of the study of noise emissions from large operating wind-farm sites have supported the view that engineering methods such as ISO 9613 offer a robust means of determining the upper turbine immission levels that may occur in practice under favourable, downwind propagation conditions."

Plovsing and Søndergaard[11] reported in 2010 that the NORD 2000 model showed promising results when used to predict noise from wind turbines. Whilst in the same year Forssen *et al*[12] investigated noise propagation from turbines at one site and found that the NORD 2000 and standard Swedish engineering models predict the average sound pressure levels satisfactorily under downwind conditions.

In 2011 Evans and Cooper[13] reviewed a range of prediction methods in regard to measurements at four different wind farms and reported that, excepting where the ground slopes sharply down from the turbines to the receiver; the ISO 9613 method with completely reflective ground or the CONCAWE method with completely absorptive ground and weather category 6 were the prediction methods that would minimise the risk of a potential exceedance of the limit criteria. A recent update on this study has found similar results for 13 different wind farms[14], and that at distances of 3 to 4 Km from the turbines the ISO 9613 standard performs better than the CONCAWE method.

The research reviewed above supports the recommendations of a working group formed by some of the members of the original Noise Working Group on wind farm noise, which drafted ETSU-R-97, and others who have often advised on opposing sides during public inquiries into wind farm schemes; gathered in order to build on experience and knowledge gained during the period since the adoption of ETSU-R-97. Their thoughts were published in an article in the Institute of Acoustics Bulletin, Vol 34 No 2, March/April 2009; which advises that ISO 9613 should be used to predict the propagation of wind farm noise and that in using this standard:

- The atmospheric conditions used in the calculation should be assumed as temperature of 10^0C and 70% Relative Humidity.
- The assumption of soft ground should not be made, and ground absorption G should be in the range 0 ("hard" ground) to 0.5 (mixed "hard/soft ground").
- Generally no account should be taken of barrier attenuation by land form unless there is no line of sight between the top of the rotor and the receiver, when normally a maximum attenuation of 2 dBA can be used. Any higher barrier attenuation must be fully justified.

The above is a summary of available information of wind turbine noise propagation and the reader searching for a more detailed analysis is referred to Dr Andrew Bullmore's chapter on sound propagation from wind turbines in Wind Turbine Noise (Editors Bowdler and Leventhall) Published by multi-science publishing, 2012.

3 WIND TURBINE NOISE DOSE RESPONSE

The subjective response to most types of noise is influenced by a range of factors, and wind farm noise is no exception to this; for example.

- The type and level of background noise against which the wind turbine noise is heard is important because it can help mask turbine noise and affects the connotation of the wind farm noise and can therefore influence its intrusion and the subjective response[15 & 16].
- Although wind turbine noise can be perceived at levels below the existing ambient noise level[15], the onset of significant levels of community annoyance appears to be at substantially higher levels[15] i.e. there appears to be a reasonable degree of community tolerance of wind turbine noise; although this varies significantly on an individual basis.
- A minority of persons report annoyance at relatively low levels of exposure to wind turbine noise[18]; and like other noises non-acoustic factors can strongly influence the annoyance response to noise for wind turbines e.g. the visual impact of the wind farms[19]; and real and perceived injustices regarding the development of such schemes[22].
- Evidence on the direct health effects of wind turbine noise is strongest for annoyance and sleep disturbance[23 & 24]. There is no robust evidence that wind farm and wind turbine noise has other health effects or gives rise to unique syndromes or sets of symptoms different from other noise sources.
- In common with other noise sources, the presence of acoustic features in wind turbine noise such as tonality and the amplitude modulation of aerodynamic noise (AM) and the influence of non-acoustic factors are important in dictating the degree of impact[25 & 26]. However, whilst there are various methods which can potentially be used to assess the tonality of noise emissions, there is little guidance regarding the objective rating of effects attributable to other acoustic features, such as AM. If methods of objectively rating the effects of these features can be developed, then it is likely that suitable corrections to take their impact into account are possible.

- Several studies suggest that wind farm noise can be more disturbing than transportation and general industrial noise sources[27, 28, 29 & 30].

- People who benefit economically from wind turbines have a significantly decreased risk of annoyance, despite exposure to similar sound levels[27, 28, 29 & 30].

In practice accounting for the effect of non-acoustic factors on the subjective response to wind turbine noise is probably impracticable as the prevalence and degree of effect on individual response varies substantially, and is location and scheme specific and volatile over time. Instead, as is common for many other noise sources, these factors are taken into account to some degree by the "averaging" inherent in the development of community dose responses and using them to derive control limits. However; this inevitably means that a minority of persons are still likely to be dissatisfied at noise levels equal to or less than such control limits.

In common with most investigations of the subjective responses to noise, virtually all studies so far on the impact of wind farm noise have been cross-sectional studies of the effects of the noise under steady state conditions i.e. studies of the reaction of a sample of individuals exposed to different wind turbine noise levels; not the reaction of individuals to changing turbine noise levels or the introduction of turbine noise into an existing soundscape without such noise. A cross-sectional approach only considers the impact of the absolute level of the noise and either does not take into account or takes much less account of how the characteristics of the noise; or how the change brought on by the introduction of the turbine noise into the soundscape may aggravate the noise impact; which is a well established effect, for example for transportation noise[20]. It has been suggested that when analysing possible statistical trends in noise annoyance reactions; even for steady-state noise conditions, and especially for changing soundscape situations, the effects of the change should also be taken into account[21].

The above is a summary of available information on wind turbine noise dose response and the reader searching for a more detailed analysis is referred to Fritz van den Berg's chapter on the effects of sound on people in Wind Turbine Noise (Editors Bowdler and Leventhall) Published by multi-science publishing, 2012.

4 CONCLUSSIONS

The prediction of the propagation of wind turbine noise is complex and challenging. At first sight the use of complex semi-empirical and bespoke scientific methods appears to offer advantages in terms of accuracy over established but simpler engineering algorithms.

However, an increasing body of work supports the view that reasonably robust predictions generally suitable for assessing the likely impacts of wind turbine noise can be made using existing relatively simple engineering methods. Although when predicting wind turbine noise these methods often have to be used outside their original limitations, they tend to show good correlation with measured noise levels over a wide range of significant operational parameters e.g. wind speed and direction; and offer significant advantages in terms of calculation time, input requirements and sensitivity.

However, care should be taken in applying relatively simple engineering methods to prediction of wind farm noise when considering locations upwind of the turbine, as they tend to overestimate the noise level compared to measurements. Similarly care should be taken when using engineering methods to predict wind farm noise under downwind conditions when the ground drops away substantially from the source to receiver or there is a potential barrier between the source and receiver, as they tend to overestimate the ground and barrier attenuation from these factors. These issues can normally be allowed for by setting the operating parameters of the engineering method so that no more than 50% acoustically soft ground is assumed and that the maximum barrier attenuation is less than 3 dBA.

The literature reviewed in this paper reveals there is relatively little research into wind farm noise dose response; and what has been carried out has mainly been in Scandinavia, the Netherlands and Germany. Transposing these studies to other Countries may not be reliable as methodological and analytical issues; and differences in topography, population density and distribution; and variation in societal, language, cultural, environmental and political factors between these countries and elsewhere, militate against the direct transfer of these dose responses.

This review has highlighted work which shows general trends in the response to wind turbine noise, but also indicates that there is sufficient uncertainty about human response to wind turbine noise to prevent a robust dose response being formulated at this stage. This is not unique for wind farm noise as similar uncertainty exists for other noise sources e.g. industrial noise in general; and it may be that due to the significant influence of non-acoustic factors such a dose response may never be achievable.

The dose responses established so far typically follow the already established pattern for many noises sources. That is the data on response versus level is widely spread and is different from one study to another; and the correlation between level and response not particularly strong due to the influence of non-acoustic factors. Consequently, there does not appear to be a step change in response at any specific noise level or over a narrow range of noise levels that can be reliably used as a suitable threshold of unacceptable impact. As a result, any guideline or noise limit values for wind turbines can only be informed by indicative trends in regard to response, weighed against the benefit of the turbines.

A major moderating influence in mitigating the impact of wind turbine noise is the reality and perception of public involvement in decision making in the planning of schemes; and the degree of direct benefit a person obtains from the scheme; in particular the financial gain they might receive. This suggests that wider involvement of communities in wind farm development and the greater distribution of the financial rewards can substantially alleviate potential noise problems.

However, it seems likely that unless national policy takes a unique and unduly prohibitive stance whereby the guideline or control noise level is such that wind turbine noise is never heard at any time by anybody; this will mean it is probable that some persons will inevitably be bothered by turbine noise wherever and whenever it is audible, no matter the noise level. Such a restrictive approach seems unlikely, at least in England, given that the Noise Policy Statement for England has an aim that it seeks to:

"*avoid **significant** adverse impacts on health and quality of life*".

And at paragraph 2.18 the policy states that:

"*There is a need to integrate consideration of the economic and social benefit of the activity or policy under examination with proper consideration of the adverse environmental effects, including the impact of noise on health and quality of life. This should avoid noise being treated in isolation in any particular situation, i.e. not focussing solely on the noise impact without taking into account other related factors.*"

Additionally the policy statement is very clear that judgements as to significance should be made *'in the context of Government policy on sustainable development'*. Consequently, some may be concerned that the NPSE may appear to lessen the rigour with which noise is controlled for proposals that may deliver high sustainable development gains, such as wind farm and wind turbine schemes. Whereby the negative impacts of noise could be outweighed by the wider benefits of such developments and noise impacts that might otherwise have counted against planning consent under a more restrictive regime may be allowed.

5 ACKOWLEDGMENTS

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