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WIND TURBINE NOISE IN THE DTI WIND ENERGY PROGRAMME

M L Legerton

ETSU, Harwell, Oxon, OX11 0RA, UK

1. INTRODUCTION

Noise generated by wind turbines is an environmental constraint on the exploitation of wind energy. It is a consideration when seeking planning consent for the siting of machines due to the high population density in the UK and low levels of background noise in rural areas. There is, therefore, a need to identify the magnitude and characteristics of noise emitted by wind turbine generators, assess the influences on the propagation of noise through the atmosphere, and provide information to both wind farm developers and planning regulators on likely noise levels. Additionally, wind turbine manufacturers need to understand noise producing mechanisms on wind turbines to develop widely acceptable products.

This paper reviews recently completed work and current projects in the DTI's Wind Energy R,D&D Programme in the above areas. It then discusses more widely ranging activities which relate to wind turbine noise together with plans for work which should increase our understanding of the problems and allow more definitive guidance on noise levels to be given.

2. SOURCES OF NOISE

It is important to reduce the noise emissions from wind turbines to the minimum practicable levels and to be able to predict the level of noise output. A number of projects with these objectives have been initiated in the DTI's programme.

2.1 The Influence of Noise on the Design of Horizontal Axis Wind Turbines (James Howden & ISVR)

This work was undertaken jointly by James Howden and the Institute of Sound and Vibration Research. The objectives of the work were to identify the principal sources of noise and to make practical recommendations for the reduction of noise from wind turbines The final report (1) is a useful summary of measures available to the wind turbine designer to control noise emissions from wind turbines. It is in four parts: a summary report including a costing of various noise control measures, an experimental investigation of noise emissions from the 1MW Richborough machine and separate studies on the generation and control of aerodynamic and mechanical noise. The report provides a comprehensive review of the aerodynamic and mechanical noise sources of a wind turbine with practical suggestions for their attenuation.

2.2 Sources of Noise on a Wind Turbine (Windpower & Co)

A comprehensive range of experiments were undertaken to find sources of noise on a 140 kW wind turbine (WP1). In addition to monitoring the usual parameters such as wind speed, power and rpm, the turbine was fitted with strain measurement and a flow visualisation rig which used a rotating video camera focused on flow indicating tufts. Flow visualisation made possible the association of a three per rev noise with dynamic stall, helped identify an acceptable rotor/tower clearance for the avoidance of upwind thumping and identified the noise associated with fully stalled blades. The flow visualisation technique was used in the development of a new sound measuring method where microphones were suspended close behind the rotor plane to enable blade aerodynamic states to be related to noise generation.

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Some of the results reported by the authors are:

- At 25m from the turbine, maximum tone level varied by 5 dB, as a function of direction from the machine. The amplitude of one per rev machinery noise modulation was 4 dB on WP1.
- Slowing tip speed from 60 m/s to 40 m/s reduced rotor noise by about 7 dB.
- Sound power levels varied with wind speed by 0.59 dB per m/s at 59 rpm and 0.46 dB per m/s at 39 rpm. Least scatter occurred in the data when sound power level was related to power, rather than wind speed.
- No evidence was found for noise arising from rotor/tower interaction due to tower acoustic blockage, tower acoustic reflection, or due to the tower's interference with the air flow.
- In winds of over 12 m/s and greater than 10° of yawed inflow, the flow visualisation showed conditions of dynamic stall. This was matched by a 3P, staccato, "chomping" sound which raised spectral levels between 1250 Hz and 3500 Hz by 10 dB, attracted attention and doubled the downwind distance at which the turbine could be heard.
- A continuous "shooshing" sound was heard immediately the flow visualisation showed the blades to have chaotic flow and to have become fully stalled. Spectral frequencies between 450 and 2000 Hz were raised by 1.5 dB but the noise did not attract attention and was not considered a nuisance.
- Mean background levels and to a lesser degree wind turbine sound pressure levels varied over time. This meant that when the long term, mean sound pressure level from the machine and mean background level were nominally equal, they could be intermittently up to 7 dB different when measured concurrently. At times, background noise swamped turbine noise and vice versa. This continuing, apparent modulation made noise from the turbine more noticeable.
- This effect, combined with the "chomping" and modulation of tones from the gearbox due to changes in power combined to draw people's attention to the wind turbine during higher winds. This contradicts the view, often expressed in the literature, that higher winds mask turbine noise.

2.3 Assessment and Prediction of Wind Turbine Noise (Flow Solutions)

The need to be able to make accurate predictions of noise source levels to assist in the design of wind turbines with low noise levels had been identified. As a result a project was placed with Flow Solutions to develop a prediction method for aerodynamic noise from wind turbines.

A literature review was carried out early on in the programme of work covering aerofoil noise and rotor acoustics, including fans, propellers and helicopter rotors as well as wind turbines. The mechanisms of noise radiation by a wind turbine identified in the study can be separated into the following distinct areas.

- Discrete frequency noise at the blade passing frequency and harmonics.
- Self induced noise sources.
  - Trailing edge noise
  - Separation-stall noise
  - Tip vortex formation noise
  - Laminar boundary layer vortex shedding noise
  - Trailing edge bluntness vortex shedding noise
- Noise due to turbulent inflow.

It was found that self noise sources will dominate at low wind speeds, while inflow turbulence sources will be most significant at higher wind speeds at rated power and beyond. Analysis has suggested that the two most important sources are the trailing edge noise due to the passage of the turbulent boundary layer over the trailing edge and inflow turbulence. New prediction models have been developed for both of these sources based upon a combination of theoretical and experimental analysis.

The result of this work was the development of a basic method for predicting aerodynamic noise from wind turbines. The final recommended method was based on a generalised description of the wind turbine and predicted the aerodynamic noise resulting from the passage of atmospheric turbulence over the blades and the convection of boundary layer turbulence past the trailing edge.

A large body of wind turbine noise data from the UK, Europe and the USA was collected. Data from the MOD 2, prototype MS3 and Vestas 39 were compared with predictions from the model. Reasonable agreement has been obtained for these cases. The theoretical methods developed for the model were also used to investigate parametric trends and formed the basis for some design guidelines. Methods for avoiding the appearance of the two vortex shedding noise sources have been discussed. The results of the work have been published (2)

2.4 Systematic Comparison of Prediction and Experiment for WT Aerodynamic Noise (Flow Solutions)

Detailed comparisons of experiment and predictions were undertaken to test the strengths and weaknesses of the prediction method developed in the previous work and to identify any areas requiring improvement. The model was found to under predict the noise by an average of 2.25 dB(A), believed to be due to the presence of mechanical noise and/or excess aerodynamic instability noise in the experimental data. The full report is now available (3).

2.5 Design Prediction Model for Wind Turbine Noise (Flow Solutions)

This is the third of three linked projects undertaken by Flow Solutions. The model previously developed was based upon a rather generalised description of the wind turbine as it was not possible at that time to use a full detailed description. Whilst the model is useful in demonstrating the parametric trends associated with the key noise generating mechanisms it cannot be used to study the effects of detail design changes on wind turbine noise. Recent advances in aerodynamic prediction methods and greater understanding of the key mechanisms now make it feasible to develop more detailed models which could provide the basis for design of minimum noise turbines. Work is now in progress to extend the model so that the effects of detail design changes on wind turbine noise can be predicted. The objectives of the work are:-

- To develop a prediction model for wind turbine aerodynamic self noise which reflects full details of the wind turbine design.
- To develop new models for stall and tip noise radiation related to existing theory and experimental data.
- To integrate these models in a comprehensive prediction model for wind turbine noise.
- To compare the results with wind turbine noise data.
- To provide suggestions for reduction of wind turbine noise by design.

The work is currently in progress.

2.6 Noise Control Development of the WEG 40 (Wind Energy Group)

This project is primarily concerned with the validation of noise reduction measures already taken and the attainment of further reduction in noise levels. The objectives of the work are to:-

- Verify the accuracy of the noise emission predictions made for the WEG 400, including tonal levels. Noise emission values predicted for the WEG 400 will be verified by taking measurements on the pre-production machine at Cold Northcott. Measurement data from MS-3 production machines will be used to calculate how much allowance must be made for the variation in noise levels between identical examples of the same machine type when establishing sound power level and tonal content that can be guaranteed to clients.
- Assess development of noise control/reduction methods for the purpose of further reducing noise levels of production machines. Areas to be assessed will include as examples:-

  The effectiveness of absorption and insulation materials by investigation and machine trials.

  The construction and shape optimisation of the cladding.

  Anti-vibration mountings.

  Air flow and duct design.

  Aerodynamic noise (including the effects of tip speed, wind speed, pitch, boundary layer trip and trailing edge fitting)

- Assess the variability of noise emissions that can be expected from a production batch of WEG 400 wind turbines. The correlation between measured vibration levels on gearbox cases and noise level in service will be investigated. This will involve the construction of a load test rig at the gearbox manufacturers together with noise and vibration measurements both on the test rig and repeated on site.
- In conjunction with manufacturers and suppliers, develop more suitable noise emission specifications, with particular emphasis on the practicality of testing for conformance.
- Review currently available techniques of predicting noise radiation and transmission from complex components and structures associated with wind turbines, e.g. gearbox, blades, tower cladding. Determine if such techniques can be used at the concept design stage for optimisation with respect to low noise emissions.

The work is currently in progress.

3. PROPAGATION OF NOISE

By applying a model for the propagation of sound through the air the noise levels at the nearest properties or other noise sensitive areas can be estimated. The simplest and most commonly used method is that outlined in the IEA Recommended Practices (4). This assumes hemispherical spreading of the sound with some additional attenuation due to absorption by the air. Secondary effects such as topography, ground type and wind direction and shear are not included. A number of projects have been commissioned which have assessed and developed noise propagation models.

3.1 The Prediction of Propagation of Noise from Wind Turbines with regard to Community Disturbance (ISVR)

This study reviewed aspects of outdoor sound propagation relevant to wind turbines, considers the adaptation of semi-empirical propagation models to wind turbine noise, develops an analytical ray-tracing model and compares predictions from this model and others with measured wind turbine noise data. The ray tracing model was applied to a parametric study on the influences on the propagation of sound. The report concluded that there is an initial zone stretching several hundred meters downwind of the turbine in which the influence of individual parameters is small and gradual, whilst beyond this zone more complex effects could be expected. A report of the work is available (5).

3.2 Noise Propagation Studies at Carland Cross and Coal Clough (Renewable Energy Systems Ltd)

A study on the propagation of sound over two wind farm sites has been carried out by RES. The sound source was an omni-directional calibrated loud speaker mounted on a 25m mast. Noise levels were recorded over a range of distances from the mast and compared to those predicted by various models. Although the final report has not yet been completed, early indications are that a simple spherical spreading model with air absorption is at least as accurate as some of the more complicated models tested. A report on the work will be available by the end of 1993.

3:3 Noise from Wind Turbines - Joule II project PL920313 (NEL and European partners)

There are two areas of uncertainty associated with the use of propagation models. Firstly, the sound power of the wind turbine used in the calculation is often the result of measurements on one example of its type and may not be representative of all turbines. Secondly, propagation models that are commonly used do not model the effects of changes in the speed of sound with height, ground type and turbulence. This project attempts to quantify the variation in sound power between nominally identical machines and to reduce and evaluate the errors in propagation models by developing and testing a propagation model suitable for wind farm applications.

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NEL in conjunction with the Netherlands Energy Research Foundation (ECN), dk-Technik, Danish Acoustical Institute and Deutches Windenergie-Institut, have obtained 50% funding from the CEC Joule II programme for the work which is being topped up by National Governments. The overall objectives of the Joule II project, managed by ECN are:-

- To provide statistical information on the noise production of 6 different wind turbine types, the noise of each type measured from 5 different machines. Sound pressure levels will be measured on a reflecting board in the downwind position in accordance with the draft IEC standard in preparation. The measurements will be analysed to give the apparent sound power level at a wind speed of 8m/s at 10m height, sound power level as a function of wind speed and narrow band frequency spectra.
- To provide statistical information on the variation in the acoustic noise production of wind turbines with time (ageing effects). Similar measurements will also be made on turbines which have already been monitored giving the variation is noise characteristics over a period of 3-7 years.
- To develop and validate a simplified propagation model suitable for use in wind turbine planning procedures. A sound propagation model suitable for use in wind farm planning procedures is to be developed. This to be based upon the work of Rasmussen of the Technical University of Denmark (6). Rasmussen has developed a model which takes the effect of ground impedance as well as wind and temperature shear into account. Extension of the model to cater for raised source height and a wider range of wind speeds are required. The resulting model will be validated using measurements from an elevated sound source and wind turbines.

The project is of two years duration and started in January 1993.

4. MEASUREMENT OF NOISE FROM WIND FARMS

4.1 Noise Monitoring at Delabole Wind Farm (Windelectric Ltd)

A comprehensive survey of the characteristics of wind turbine noise is being undertaken at the Delabole wind farm. Topics under investigation include:-

- A comparison of noise levels with and without the turbines operating. Noise levels, wind speed at microphone position, wind speed and direction from the wind farm mast and turbine operational status are being continuously monitored. Noise levels are measured at four locations. Two locations are at a distance of at least 1km from the nearest turbine, one in a sheltered position and one in a more exposed position and so provide measurements of typical background noise levels in a rural area. Spot checks are made to ensure that operation of the wind farm does not affect the noise levels at these locations. Measurements at each site are to be made in two periods, one in Winter and one in Summer. The two other locations are at a distance of approximately 350m from the nearest turbine, one in a sheltered position and one in a more exposed position. Spot checks are made with the turbines switched off to verify that background noise levels at these two locations are similar to those at the 1km locations.
- Measurement of the sound power and spectral analysis of the noise from each turbine.
- Propagation. The propagation of sound from a single turbine is to be assessed by measuring sound levels downwind, crosswind and upwind at distances of 50m, 100m, 200m and 350m from a turbine together with background noise levels. The measurements will be taken at wind speeds as close to 8m/s as possible.
- Variation in turbine noise with wind speed. The noise from a single wind turbine shall be measured over a range of wind speeds at a distance of 50m.

The one year experimental programme commenced in April 1993, the final report is expected in June 1994.

4.2 Noise Monitoring at Cold Northcott and Llangwyryfon (National Wind Power)

An extensive noise monitoring programme, centred around the Cold Northcott and Llangwryryfon Wind Farms is being undertaken by National Wind Power with 50% funding from the DTI. Areas of investigation include:-

- Measurement of the sound power and spectral analysis of the noise from individual turbines.
- Long term monitoring of noise levels at 50 m from an individual turbine to determine the change in noise levels with time and operating conditions.

- An examination of the suitability of currently available tonal assessment methods to establish which most accurately ranks wind turbine tones.
- Long term monitoring of wind farm noise at nearest residences. Comparisons will be made of background levels prior to installation of the turbines to noise levels now experienced at several nearby locations.
- Noise propagation monitoring. An examination will be made of the factors affecting the propagation of noise over different terrain types and over distances ranging from 50m to 800m. The measured noise levels will be compared to predictions from generally available propagation models.

The project has an expected completion date of June 1994.

5. WIDER RANGING ACTIVITIES

5.1 IEC TC 88 and BSI Sub Panel PEL 123/-/1, Acoustic Noise Measurement Techniques

The starting point for an assessment of the effect of any noise source on the environment is a knowledge of the characteristics of the source. The characteristics of a source can be described by the sound power, expressed in dB(A) (ref 1pW), narrow band and octave frequency spectra. Due to its size the sound power of a wind turbine is difficult to measure but an 'apparent' sound power is commonly derived from sound power measurements from a microphone mounted on a hard board at ground level at a known distance from the turbine. By assuming that the sound propagates spherically from a point at hub height in the nacelle, the apparent sound power can be calculated from the sound pressure. Planners and developers frequently require information on how the turbine noise level varies with hub height wind speed and also on the tonal content of the noise.

The most frequently used methods at the moment are those described in the IEA Recommended Practice "Acoustics - Measurement of Noise Emission from Wind Turbines" (4), The Danish Standard written by Andersen and Jakobsen (7), and the AWEA Standard 2.1 "Procedure for Measurement of Acoustic Emissions from Wind Turbine Generator Systems" (8).

The current situation is unsatisfactory for a number of reasons:-

1) The measurement methods are all different in detail, which can result in misleading comparisons being made.
2) None of the methods produce information in a form ideally suited for use by planners and developers.
3) The requirements for frequency spectra are poorly specified, if at all.

An international IEC standard is currently under preparation that will provide a standard method for the measurement of acoustic emissions from wind turbines. The UK is represented on the working group responsible for its drafting by Mr R Henderson of the National Engineering Laboratory and Dr J Bass of Renewable Energy Systems Ltd.

In parallel to the IEC standard a revised version of the IEA Recommended Practice on Acoustic Measurement of Noise Emission from Wind Turbines is being prepared by another working group made up largely of members of the IEC panel. The procedures for preparation of the IEA document are simpler than the IEC standard and hence the revised Recommended Practice should be available earlier.

It is unlikely that either document will be able to fully address issues such as the variation in sound power between identical turbines of the same model or site specific factors like the effect of inflow turbulence.

5.2 Planning Policy Guidance Note on Renewable Energy (PPG 22)

The Planning Policy Guidance Note on Renewable Energy, PPG 22 (9), was published by the Department of the Environment and the Welsh Office on 3 February 1993. PPG 22 contains an Annex on Wind Energy which includes some discussion on noise from wind turbines. This annex includes a description of the sources of noise from wind turbines, a discussion on the limitations on the use of BS4142 (10) and advice on noise related information that could usefully accompany a planning application. At the time of writing there was insufficient relevant experience of noise from wind farms and public reaction to the noise, to be able to provide quantitative guidance on suitable noise limits to be set at nearest residences.

5.3 British Standard BS4142

The PPG explains that the use of BS4142 1990, 'Method for rating industrial noise affecting mixed residential and industrial areas', may be inappropriate for the assessment of noise from wind farms for several reasons. These are listed as:-

a) Wind farms are likely to be developed in areas outside of the scope of BS4142 as indicated by the title.
b) The scope precludes situations where background noise levels are below 30dB(A). This level is typical of the background noise level which might be found at wind farm sites.
c) BS4142 states that noise measurements should not generally be made in winds greater than 5m/s average. This restriction guards against the effects of wind noise on the microphone (and influences on sound propagation). Wind farms are likely to be sited in windy areas where the BS4142 conditions may not be satisfied.

A more fundamental problem that may occur using BS4142 for the assessment of wind farm noise lies in the choice of units used to describe the specific noise source and the background noise. BS4142 specifies that the noise source is to be measured as L_{Aeq} and the background noise as L_{A90}. A characteristic of background noise in rural areas is that measurements of background noise measured in these two units can differ by 10dB(A), especially when background noise is wind related or contains relatively loud, intermittent sources. The rating method proposed in BS4142 would therefore indicate the likelihood of complaints even in the complete absence of other noise sources.

5.4 Working Group on Noise from Wind Turbines

With no generally agreed procedure for determining noise levels that are acceptable to nearby residents, planners and developers have been required to use their own experiences to bring forward workable solutions by reference to the particular character and sensitivity of the area. Planners have the benefit of local experience on what the existing noise environment is in their area combined with the public's reaction to new noise making developments, whilst developers have a knowledge of the noise characteristics of wind turbines. Many wind farms, though not all, have had conditions relating to noise levels from the wind farm specified in the planning consents. These have varied in noise level and measurement units (eg L_{90} or L_{50}) from site to site but generally fall in to two classes. Either a flat rate noise level which shall not be exceeded at the nearest residence or a margin above the existing background noise which shall not be exceeded.

It is however recognised within the DTI that there is still a degree of uncertainty among planners and developers. Planners do not have much experience of noise from wind turbines in rural areas. Developers have no noise targets for guidance when selecting sites for wind farms or deciding upon turbine layout. Therefore the DTI has set up a Working Group largely consisting of outside experts on wind turbine noise. The objectives of the Working Group are:

1) To review recent experience in the field of wind turbine noise. This will include an attempt to relate measured data to complaints and provide an expert assessment of the issues relating to wind turbine noise.
2) Define a framework which can be used to measure and rate the noise from wind turbines. This will include parameters to be measured, measurement methods, units and measurement periods and will fulfil all the necessary criteria required for planning conditions.
3) Provide indicative noise levels thought to offer a reasonable degree of protection to wind farm neighbours and encourage best practice in turbine design and wind farm siting and layout.
4) Encourage the widespread adoption of the Working Group's recommendations.

The Working Group has been asked to address the issues of broadband noise, tonal content and blade swish (the modulation of broadband noise at blade passing frequency). It is intended to produce a report in Spring 1994 which will serve as a working guide to assessing the environmental impact of the noise from wind turbines and establish a framework for associated planning conditions.

5.5 Workshop on Noise from Wind Turbines

A workshop on noise from wind turbines was organised by ETSU and held at Harwell on 30 June 1992 (9). This workshop attracted a wide audience including representatives from local government, industry and environmental bodies and most of the issues were discussed. The views expressed were taken into account in formulating future plans. Several of the papers presented have also appeared in the journal of the BWEA, Wind Engineering.

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