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AN INVESTIGATION OF BLADE SWISH FROM WIND TURBINES

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1.0 INTRODUCTION

This paper describes the analysis of some detailed wind turbine measurements with respect to blade "swish". "Swish" may be described as a modulation of the aerodynamic noise from the blade. Since the perception of noise depends both on its loudness and its character, an increase in blade noise modulation may make a wind turbine more noticeable than it would otherwise be. A description of the theory of noise modulation, its perception and masking, is given in reference [1].

The experimental set-up has already been described by J. Lowson reference [2]. The turbine selected for analysis was the Vestas Windane 34 (400 kW) pitch regulated turbine at Coal Clough wind farm, Lancashire. 12 microphones were mounted on hard boards placed in a circle of radius 30m around the turbine, each being separated from the next by a 30 degree interval. Recordings were made using three eight channel Tascam tape recorders, and synchronised measurements of wind speed (at five heights), wind direction (at 3 heights), yaw position, power, pitch and blade position were made.

The aim of this work was three fold: firstly, to investigate the modulation of noise from wind turbines in different frequency bands, and to identify those frequency bands most affected; secondly, to identify the conditions under which such modulation becomes prominent; and thirdly to determine the mechanism by which the modulation is produced. Several possible mechanisms have been suggested, including: the interaction of the blade with the potential flow around the tower; the directionality of radiation from the blades as they rotate; and a variation in noise levels due to the atmospheric wind profile, which would result in a slight variation in angle of attack as the blade rotates.

During the experiments, subjective assessments of the noise were made, and periods of strong "swish" were identified. It was noticeable that the character of the noise varied significantly with direction and wind conditions. Subjective descriptions of the noise ranged from "little modulation" to "rhythmical beat" to "very strong swishing noise".

The data have been divided into two sets of samples: the first set corresponds to conditions of constant wind speed (as averaged over 5 anemometers at different heights), constant power and constant yaw position; the second set corresponds to recordings which were identified subjectively as "swishy" or "beating". This paper describes the analysis carried out on these two sets of samples, and the results of this analysis. The results are preliminary only, and concentrate on the first aim of the project, namely to describe acoustically the nature of the modulation. Work is on-going to determine the cause or causes of the variation in modulation.

2.0 ANALYSIS PROCEDURE

Each sample starts at when blade 1 passes the tower, and lasts for 10 or 20 seconds. Separate files have been prepared for each microphone, and these may be synchronised with data from the blade position pulses. Using MATLAB, procedures were written to:

1. produce calibration factors from Fourier analysis of the calibration signals for each microphone.

2. identify the pulses from the 8/rev tachometer. Each pulse defines the start of a segment of data spanning 45 degrees of rotation.

3. split the 45 degree segments into nine 10 degree segments, with a five degree overlap. Each segment is 1024 points long.

4. perform Fourier analysis, using a Hanning window, to yield power spectral densities.

5. convert the spectra to octave band sound pressure levels. The frequency range covered is 63 Hz to 8 kHz. Lower frequencies can not be covered, owing to the short period of data examined.

6. plot the octave band signals against blade rotational angle.

7. average the 5 degree octave band signals over 10 or 20 rotational periods.

After steps 6 and 7, the user assesses the degree of modulation of the sound in each frequency band, for each microphone.

The effects of propagation delay are included in the analysis. The delay between sound emission and imission corresponds to between 16 and 35 degrees of blade rotation, depending on microphone location and initial position of the blade. Doppler effects have also been considered.

3.0 RESULTS

The two sets of samples will be described as "constant conditions" (CC) and "non-constant conditions" (NCC) respectively in the remainder of the paper. The main results for the CC samples are given below.

3.1 Assessment of Modulation for Constant Conditions

The "constant conditions" samples spanned a wide range of power from cut-in to approximately 240 kW. For each sample, the yaw position was constant to within 5 degrees. The mean wind profile exponent was positive for all samples. The results of this investigation were as follows:

- The highest A-weighted noise levels occur in the 500 Hz, 1 kHz and 2 kHz bands. The 4kHz band is sometimes affected by tones.
- Modulation is most apparent in the 1 and 2kHz octave bands, although noise in the 4kHz band frequently shows less pronounced modulation. Typical modulations have an amplitude of 2 - 3 dB, but amplitudes of 5 dB are occasionally recorded. Figure 1 shows a typical modulation of noise in the 2 kHz bandwidth versus time.
- Noise in the 500 Hz band may or may not show modulation. When it does, the modulation amplitude is generally 2 -3 dB, but may very occasionally reach 5 dB.

- Noise in the 63 and 125 Hz bands very rarely shows modulation, suggesting that this noise is primarily of mechanical origin. Figure 2 shows a comparison of noise in the 63 Hz band with noise in the 2 kHz band.
- The 8 kHz band usually shows a 1/rev modulation, indicating that one of the blades is noisier than the others in this frequency band. However, the SPL is usually low (5 - 20 dB(A)). The 4 kHz band may show similar behaviour, but the maxima are not necessarily from the same blade as the 8kHz maxima. Figure 3 shows typical modulation of noise in the 8 kHz band.
- Modulation of noise in the 1 and 2 kHz bands is almost always present in the upwind half or the rotor plane. It may also be present in the downwind direction.
- The maxima and minima of the modulations are not recorded at the same time at all microphones. This indicates that the modulation is not due to the blade passing the tower as might be supposed. Instead, it appears that it follows the pattern that might be expected from the predicted directionality of this sound and the rotation of the blade. Further work is needed to confirm this.
- The modulation does not appear to be strongly influenced by the wind speed for wind speeds below about 11 m/s. At higher wind speeds, the modulation seems to become less pronounced. This applies only in the case of steady conditions.
- Microphones between the crosswind (blade ascending) and downwind directions show sharp minima once per blade passage. These tend to occur at a blade rotation angle of 170 degrees (allowing for the time delay of the sound before it reaches the microphone). This suggests that the minima are due to shielding of the noise by the tower.
- Microphones between the downwind and crosswind (descending) directions do not usually show clear modulation.

3.2 Results from Analysis of Non-Constant Conditions Samples

Preliminary results indicate that the noise changes significantly at cut-in, but noise in different frequency bands is affected differently. The most obvious effects are:

- There is an abrupt increase in noise in the 63 and 125 Hz bandwidths (by 3 - 10 dB, depending on the microphone location).
- Noise in the 1, 2 and 8 kHz bands appears to be largely unaffected by cut-in, indicating that this noise is of aerodynamic origin.
- The behaviour of noise in the 500 Hz and 4 kHz bands is less clear-cut. It appears that both aerodynamic and mechanical processes are involved. More analysis is needed to clarify this point.

4.0 CONCLUSIONS

The main conclusions so far are:

- For samples taken under conditions of constant yaw, power, pitch and wind speed, the modulation appears not to be due to the blade passing the tower. Further work is required to determine whether the mechanism of the modulation.
- Noise in the frequency bands below 500 Hz appears to be mechanical in origin and shows no modulation as the blades rotate. Noise in the 500Hz band probably contains both aerodynamic and mechanical components. Modulation is most pronounced in the 1 and 2kHz octave bands.

5.0 FURTHER INVESTIGATION

The following investigations are planned or in hand:

- Comparison of the phase of modulation at each microphone with the predicted phase from RES's in-house wind turbine noise prediction program.
- Comparison of the phase of modulation for 1, 2 and 4 kHz frequency bands.
- Comparison of noise taken under constant conditions with that recorded under non-steady conditions.
- Investigation of noise before, during and after cut-in, when the blade pitch is changing.
- Assessment of possible mechanisms for the modulation, including the directionality of radiation from the blade and the possible effect of wind profile.
- Correlation of far-field noise with noise and accelerometer signals measured in the nacelle to establish the influence of tonal noise.

References

[1] "Noise from Wind Turbines and the Masking Effects of the Wind", J. Jakobsen and T. Pedersen, Lydteknisk Institut, Lyngby, Denmark, report 141, April 1989. (In Danish).

[2] "A New Approach to Wind Turbine Noise Measurement" , J. Lowsen, Internoise 1996.

Figure 1 - Noise Level in 2 kHz Octave Band versus Rotor Position (at Imission)

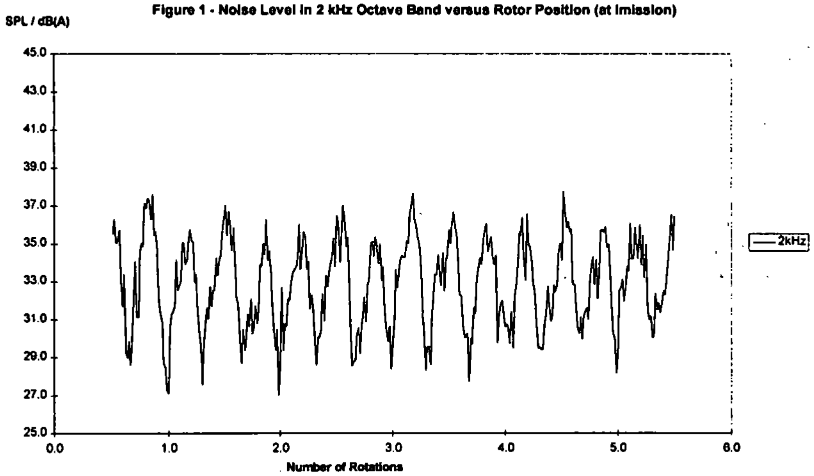

Figure 2 - Comparison of Noise at 2 kHz and at 63 Hz versus Rotor Position, 122 kW

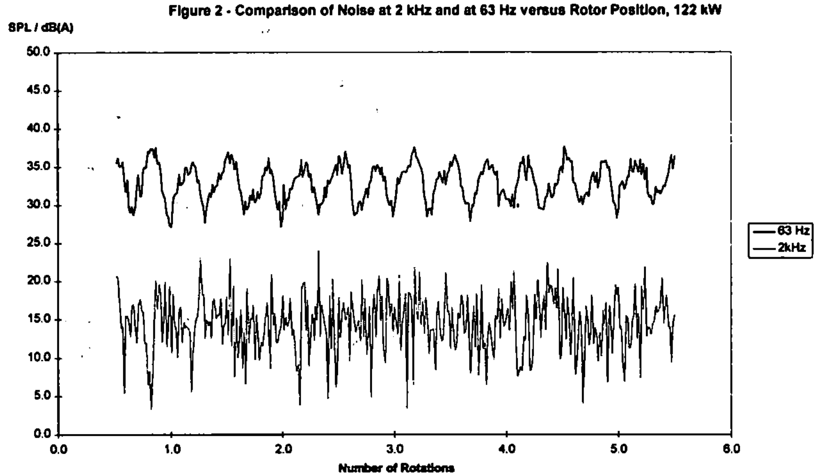

Figure 3 - SPL at 8 kHz versus Rotor Position

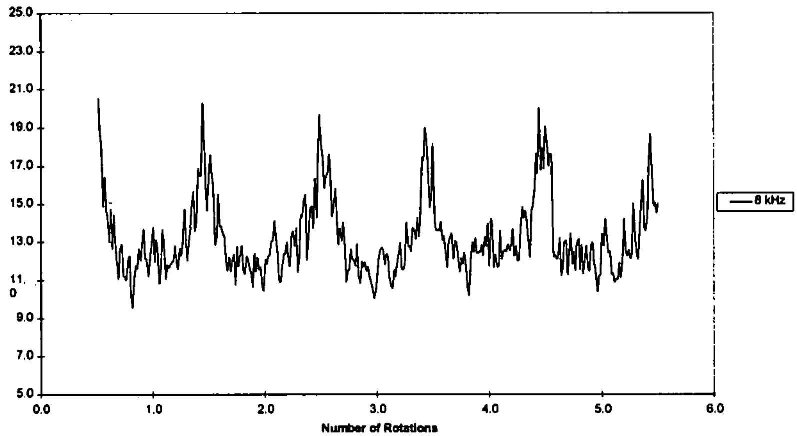

Figure 4 - 1 kHz Sound Pressure Level at 150 degree Microphone versus Rotor Position (Averaged over 5 Rotational Cycles)