Task 39 Fact Sheet

AMPLITUDE MODULATION IN WIND TURBINE NOISE

Task 39: Quiet Wind Turbine Technology

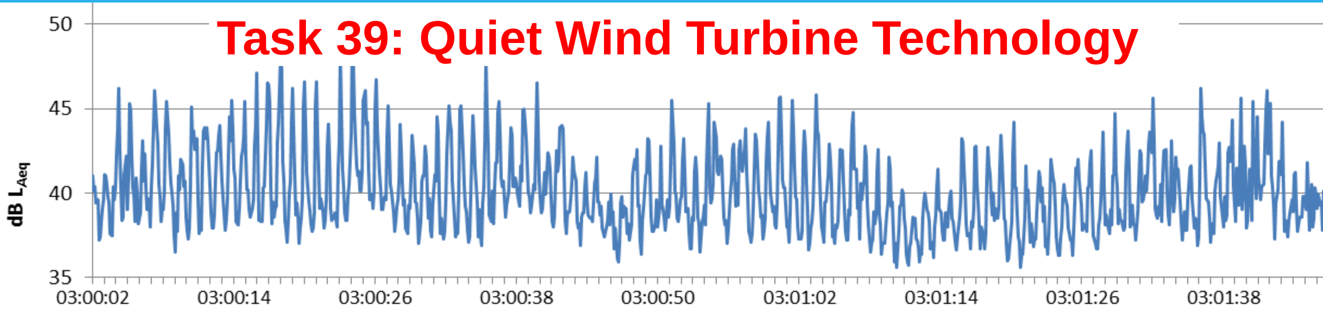

Figure 1. Measured Amplitude Modulation

Wind turbines produce sound which can be modulated. In other words, the sound level is not constant. The modulation is often periodic and related to the blade passing frequency (Figure 1). The characteristic might be described by a listener as a regular 'swish', 'whoomph' or 'thump'. This modulation will stand out from the underlying background sound, and is therefore potentially more annoying than a sound of similar, but relatively constant level. This fact sheet presents the current state of knowledge and discusses control measures and mitigation.

General considerations

According to International Standard IEC 61400-11 [1], wind turbine sound is evaluated in 10-second averages from a microphone located on the ground near the turbine. Multiple recordings are made, and averaged together within wind speed bins, so as to cover the whole operational wind speed range of the turbine. This yields a sound output characteristic, an example of which is displayed in Figure 2. The values are stated in terms of A-weighted, sound pressure values. That is, a frequency weighting filter is applied so that the measured values are representative of the sensitivity of human ear.

However, various unsteady effects may occur with time scales shorter or longer than 10 seconds. These translate as temporal variations of the sound levels. Such unsteady features may not be present at the IEC measurement position and are, in any case, averaged out when evaluating wind turbine sound levels. However at residential distances there is strong evidence that amplitude modulation is more annoying than sounds with a constant level [2, 3, 4].

Although phenomena with different time scales may occur, Amplitude Modulation (AM) is usually defined as a fluctuation in sound level with a period corresponding to the blade passing frequency. For a large three-bladed turbine this is usually just less than once per second.

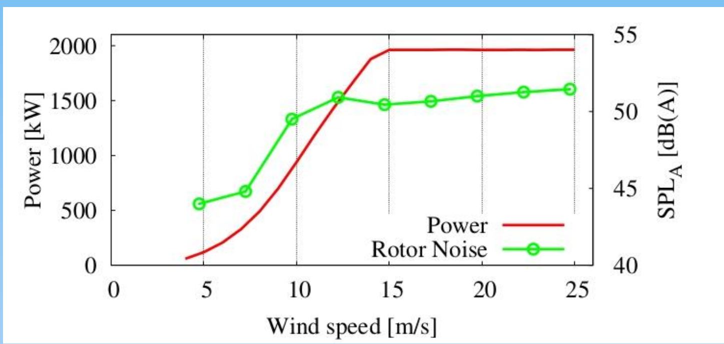

Figure 2. A-weighted Sound Pressure Level and power output of a typical 2 MW wind turbine as a function of wind speed

Wind turbine noise "Swish" - AM

Anyone standing close to a wind turbine will experience the obvious periodic variation in the sound as each blade turns. Several mechanisms may be contributing to this AM. Two of these are discussed below.

1. AM due to trailing edge noise directivity

The most important feature of wind turbine noise is trailing edge noise. It has a cardioid directivity pattern characterized by a highest noise emission direction pointing toward the leading edge of the aerofoil/blade [5]. Therefore a person located nearby in the extended rotor plane (i.e. crosswind) will hear prominently each blade approaching toward them in sequence while the receding blades will be quieter. This will also be experienced as amplitude modulation, often described as 'swish'.

Nonetheless, a person located directly downwind or upwind of a turbine may also experience this swish although to a lesser extent, as illustrated in Figure 3.

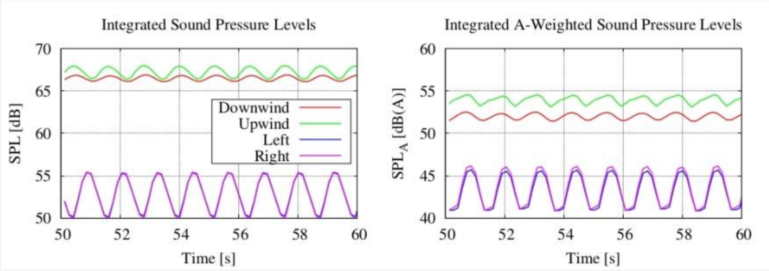

Figure 3. Time-series of integrated SPL showing amplitude modulation due to rotation of the blades and directivity effects illustrated by four listeners' locations relative to the wind turbine (Left: sound pressure levels, Right: A-weighted sound pressure levels)

The expected lower AM stems from the facts that the noise directivity pattern is roughly symmetric relatively to the aerofoil chord and that the listener is always facing the same side of the blades as these rotate. Therefore, the changes of noise level in terms of directivity are expected to remain fairly low. Nonetheless, directivity patterns are complicated and the blade sections along the span are not exactly aligned with the rotor plane such that AM can be observed depending on the listener position relative to the rotor disk.

2. AM due to wind shear

As the blades rotate, they are moving up and down across the atmospheric boundary layer which is characterized by a wind speed gradient from low velocity near the ground to high velocity at blade tip (i.e. for a blade pointing upward, see Figure 4). From knowledge of the velocity triangle for a wind turbine aerofoil section, the periodic variation in wind speed experienced by each blade results in a periodic variation of the angle of attack for the same blade pitch.

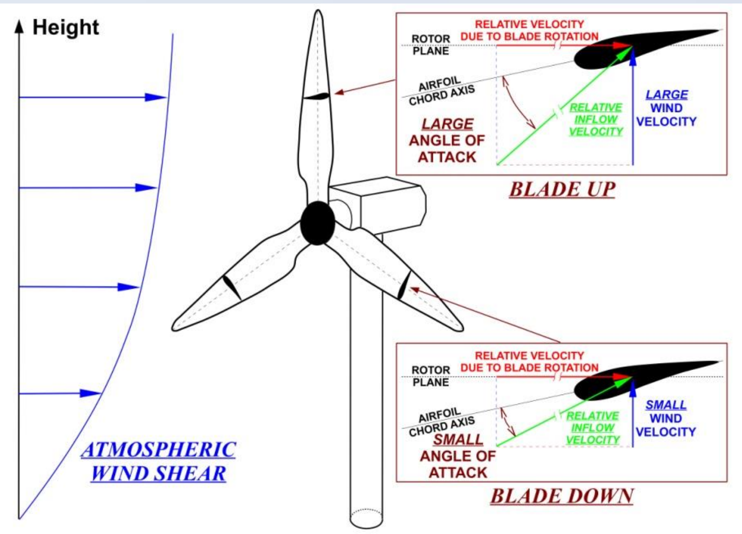

Figure 4. Sketch illustrating the varying angle of attack of the relative velocity impinging on a blade section as it rotates within the atmospheric wind shear

This temporal variation of the angle of attack will periodically alter the frequency content of the emitted noise and its perception. These varying frequency characteristics can be interpreted as AM by human ear, even though it does not necessarily imply that the actual overall noise energy content is modified when integrating the sound pressure levels over the whole spectral range. See Figure 5.

Other Amplitude Modulation mechanisms

The two mechanisms described in the previous sections are considered to be known and accepted explanations for AM. However other mechanisms may produce AM.

Stall noise, or partial stall from flow separation has been often mentioned as a source of AM. High wind shear values can occur in stable atmospheric conditions and this may yield large angles of attack when the blade is pointing upward, possibly sufficient to trigger temporary stall and increased noise. Such noise is characterized by an increased low frequency content. Stable atmospheric conditions often occur during the hours of darkness when there is less turbulence and wind shear gradients tend to be higher. Flat landscapes also tend to have higher wind shear gradients and the highest values of AM as measured from peak to trough have been found to occur in flat landscapes at night.

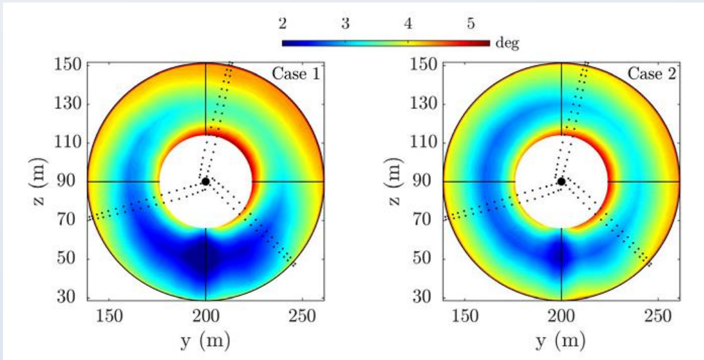

Figure 5. Time-averaged angle of attack across the rotor plane with the same hub height wind speed for two wind shear examples: high shear left and low shear right. See Reference 6.

However AM has also been found to occur on sites where the turbines were located on the downwind side of a hill such that the lowest point of the rotor was sheltered from the wind when it was blowing in a particular direction, but the upper sections remained exposed. Again this resulted in high wind shear conditions.

Similar occurrences of near stall conditions may be caused by non-optimal operation of the rotor such as when the turbine operates with a yaw error or because of an atmospheric wind veer.

A somewhat similar scenario was found to occur during a measurement campaign [7] when the average wind speed was relatively low. In such conditions, a turbine typically operates at constant pitch but with a variable rotational speed below rated power. When a wind gust or a rapid increase of the average wind speed occurs, the wind turbine controller will allow the rotational speed of the rotor to increase in order to maximize the power output. However, due to the inertia of the rotor itself, it cannot reach this optimal rotational speed immediately and there exists a time delay between its original rotational speed and the optimal one. For this period of time, the turbine will operate in conditions for which it is not designed, and which in fact may produce transient stall of the flow on parts of the blades, and thereby again produce stall noise.

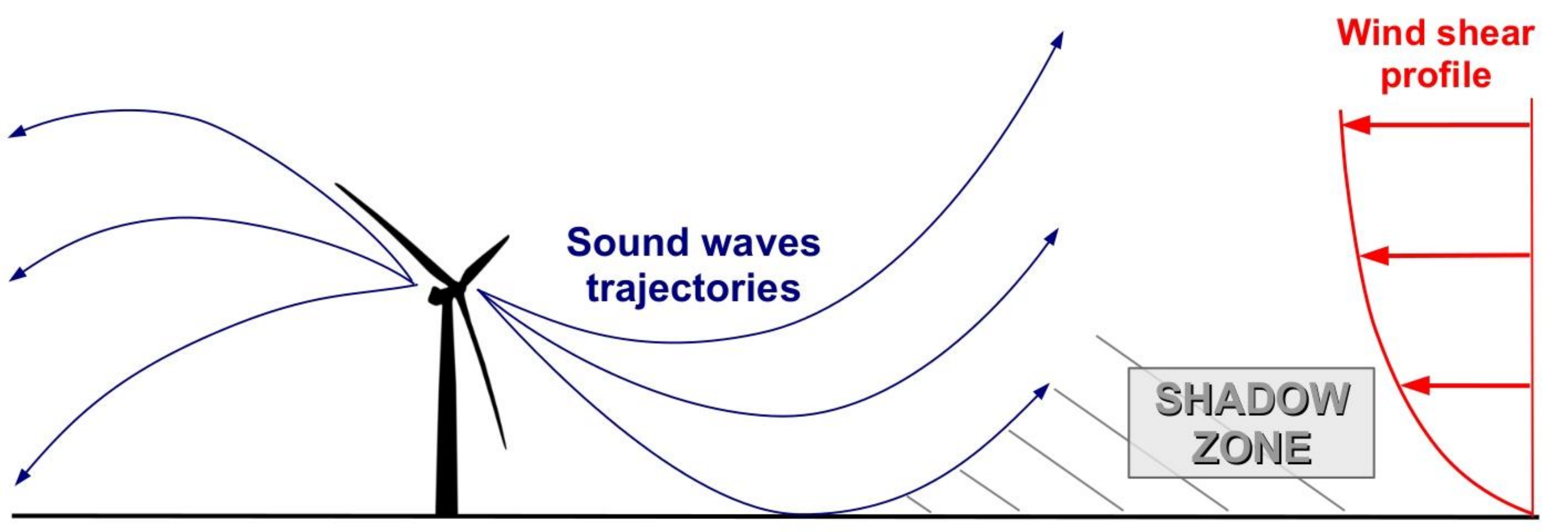

Figure 6. Shadow zone for the noise produced by a wind turbine

Finally, atmospheric conditions have been suspected to also play a role in creating AM. Indeed, the propagation of noise in the atmosphere is largely affected by velocity and temperature vertical gradients bending the trajectory of acoustic sound waves [8]. Sound wave trajectories are typically bent upward when travelling upwind (and downward when travelling downwind), see Figure 6. Variations in the trajectories will cause variable noise levels. Inflow turbulence and wake effects can also cause variations in sound level and AM. These issues were modelled in Reference 6.

Methods for Rating AM

Over the last decade, a large variety of methods have been proposed in order to provide a reliable metric to assess AM. They all attempt to quantify, the peak to trough amplitude of the sound level time-series, or in other words, the modulation depth. However the modulation depth can also vary from each successive peak and trough and a simple visual assessment is not sufficiently robust for use in regulatory control.

In the first instance, the sound pressure values in the time-series must be evaluated with a sufficient sampling rate in order to accurately capture the peak to trough of the AM. It appears that a sampling rate of the order of 100 ms seems to be the consensus among the wind turbine noise community. From here, AM can then be evaluated by defining a measure of the peak to trough values, or further by carrying out a Fourier transformation of the time-series to determine the resulting peaks which correspond to the blade passage frequency and its harmonics. The advantage of the Fourier transform technique is that periodic AM can be evaluated and other transient or non-periodic noise can be excluded.

In recent years, two methods have emerged in the scientific community as the most popular candidates for practical application of wind turbine AM assessment: the so-called Fukushima method [9] and IOA method [10] which was an enhancement of a method proposed by Renewable UK [11]. The IOA Method can be used to process large data sets as it is efficient at identifying periods of AM and excluding spurious data such that relatively little manual inspection of the data is required. See Figure 7.

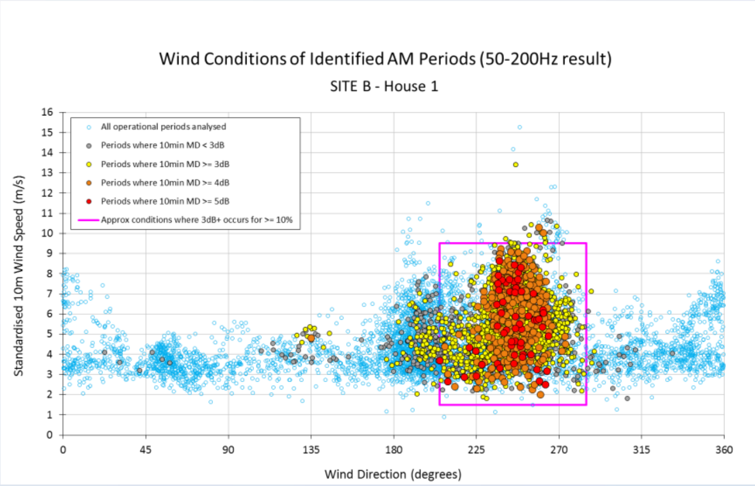

Figure 7. Analysis of site data from Reference 12

Subjective Response

A first important attribute for any rating system is that it should reflect the potential annoyance for the wind farm neighbours. Therefore, it is important that it is connected to psycho-acoustic analysis of human response to AM and the associated subjective annoyance ratings. Various studies have been carried out as discussed in Reference [13].

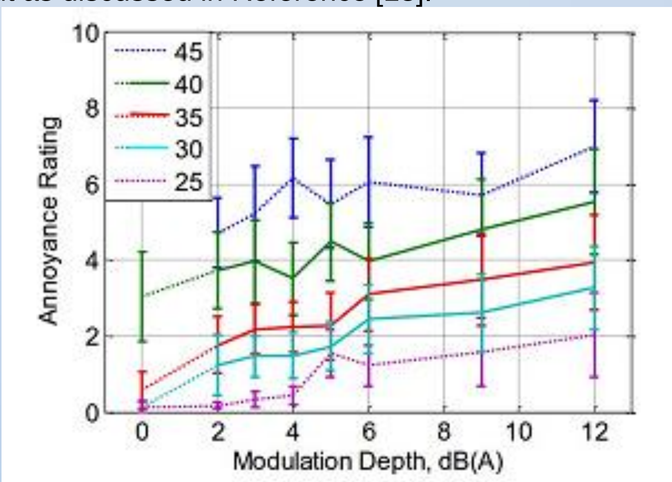

Figure 8. Relationship between modulation depth and annoyance rating with overall average level (L_{Aeq}) as a parameter. From von Hünerbein et. al. Reference 11 WP 2(B)

Such relationships could be used to construct a numerical penalty to be added to the measured sound levels where amplitude modulation is present. The proposed penalty from Ref. 13 is shown in Figure 9.

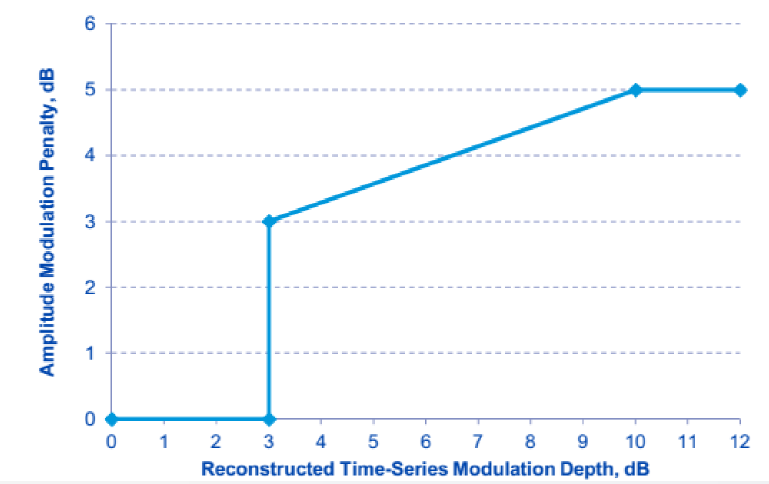

Figure 9. Example Penalty Scheme from Reference 13. This uses the IOA rating method as the modulation depth.

The penalty curve above is only one example and there is some debate regarding the actual values since it is possible to derive other curves. Furthermore, it must also be agreed how any control measures would work. There could be several ways that a planning limit could be applied:

- Use the AM metric value and add it as a penalty to the overall noise limit – this is what is done for tonal values for example in ISO 1996-2.
- Identify a trigger value for the AM metric above which action must be taken, irrespective of the overall level.

Mitigation

At present, the development of AM rating systems and penalties can allow AM to be controlled at the planning stage. However there is no known method for predicting whether and when AM will occur at the development stage, although it is possible to state that AM under downwind conditions in flat landscapes at night is often experienced and therefore might require special consideration.

Where AM has occurred previously, mitigation measures have successfully been employed. Such measure have usually involved either:

- Modifications to pitch control mechanisms or;
- Modifications to the blades.

Results of such modifications are presented in [14].

Another possible development which is being investigated is to use cyclic pitch control to adjust the pitch of the blades during each revolution of the rotor. This is likely to reduce transient stall but will increase wear on the pitch control motors.

More information

This Fact Sheet draws from the work of IEA Wind Task 39, a research collaboration among various countries. Its goal is to promote contacts between international experts in order to exchange learning, identify and report best practices in the measurement and assessment of noise, and develop an IEA Wind Recommended Practice contributing to the ongoing development of IEC standards for wind turbine noise.

References

[1] International Standard, Wind Turbines - Part 11: Acoustic Noise Measurement Techniques. IEC 61400-11, International Electrotechnical Commission, Geneva (CH), 2012.

[2] T. Gjestland. Annoyance Reactions Caused by Intermittent Noise. J. Acoust. Soc. Am., 76(S1):19–29, 1984.

[3] U. Landström, A. Kjellberg, and M. Byström. Acceptable Levels of Tonal and Broad-band Repetitive and Continuous Sound During the Performance of Nonauditory Tasks. Perceptual and Motor Skills, 81:803–816, 1995.

[4] C. Ioannidou, S. Santurette, and C.-H. Jeong. Effect of Modulation Depth, Frequency, and Intermittence on Wind Turbine Noise Annoyance. J. Acoust. Soc. Am., 129(3):1241–1251, 2016.

[5] S. Glegg and W. Devenport. Aeroacoustics of Low Mach Number Flows - Fundamentals, Analysis, and Measurement. Academic Press, 2017. (ISBN: 978-0-12-809651-2).

[6] E. Barlas, W.J. Zhu, W.Z. Shen, K.O. Dag & P. Moriarty, Consistent modelling of wind turbine noise propagation from source to receiver J. Acoust. Soc. Am. 142(5) 3297.

[7] H. Aa. Madsen, F. Bertagnolio, A. Andreas, and C. Bak. Correlation of Amplitude Modulation to Inflow Characteristics. In Inter-noise 2014, Conference Proceedings, Melbourne, Australia, November 16-19 2014.

[8] A. D. Pierce. Acoustics - An Introduction to its Physical Principles and Applications. McGraw-Hill Series in Mechanical Engineering. McGraw-Hill, New York, 1989.

[9] A. Fukushima, K. Yamamoto, H. Uchida, S. Sueoka, T. Kobayashi, and H. Tachibana. Study on the Amplitude Modulation of Wind Turbine Noise: Part 1 - Physical Investigation. In Internoise 2013, Conf. Proceedings, Innsbruck, Austria, September 2013.

[10] J. Bass, M. Cand, D. Coles, R. Davis, G. Irvine, G. Leventhall, T. Levet, S. Miller, D. Sexton, and J. Shelton. A Method for Rating Amplitude Modulation in Wind Turbine Noise. URL: https://www.ioa.org.uk/sites/default/files/AMWG Final Report-09-08-2016_1.pdf, IOA Noise Working Group (Wind Turbine Noise), UK, August 2016. Accessed: 2017-07-27.

[11] Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause and Effect. URL: https://www.renewableuk.com/resource/collection/4E7CC744-FEF2-473B-AF2B-135FF2AA3A43/ruk_wind_turbine_amplitude_modulation_dec_2013_v2_(1).pdf, RenewableUK, UK, December 2013. Accessed: 2018-07-30.

[12] M. Cand, M. Hayes, G. Irvine and T. Levet, Site Experience with Wind Turbine Noise AM Analysis Proceedings for the Institute of Acoustics 40 (1) 2018

[13] Review of the Evidence on the Response to Amplitude Modulation from Wind Turbines. URL: https://www.gov.uk/government/publications/review-of-the-evidence-on-the-response-to-amplitude-modulation-from-wind-turbines, Department for Business, Energy & Industrial Strategy, UK, October 2016. Accessed: 2018-07-30.

[14] Measurements demonstrating mitigation of far-field AM from wind turbines M. Cand, A. Bullmore 6th Wind Turbine Noise Conference Glasgow 2015

See our website at
www.ieawind.org/task_39.html#