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Assessing aerodynamic amplitude modulation from wind turbine noise

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This paper describes noise measurement results from a single wind turbine, which has revealed deficiencies when assessing amplitude modulation on wind turbine noise. The current assessment method for wind turbine noise guarantees according to the IEC 61400-11:2002 standard does not provide sufficient information nor measurement methods regarding the modulation. Since amplitude modulation may significantly increase the perception as well as annoyance of wind turbine noise, new near field measurement methods are required to ensure, that sufficient information from modulated noise and possible annoyance corrections from a single turbine installation are presented. When planning a new wind farm with new type of wind turbines, the guarantee test certificates are typically the only official noise measurement documentation available, which consultants and environmental impact assessment authors often refer.

1 Introduction

This paper discusses the results of a single wind turbine measurement case done in autumn 2011 in Finland. The measurements were performed because of continuous noise complaints caused by a single wind turbine located on a small hill 470 meters away from the dwelling. Measurements were performed simultaneously in two locations downwind from the turbine during four different time periods. Analysis of the wind turbine noise results focus on amplitude modulation and its directivity.

2 Amplitude modulation in wind turbine noise

2.1 General overview

Currently there are number of papers discussing the possible reasons of amplitude modulation or swish heard from the wind turbine noise. In wind turbine noise conference 2011 in Rome also many papers discussed about the different methods to identify modulation from recorded or logged sound pressure level results. In 2011 RenewableUK started a research project to identify exact causes of swish and thump and also identify the perception of different pulses by listening tests [1]. Amplitude modulation has a significant part of the wind turbine noise perception and annoyance [2],[3]. Modulation causes the sound level to rise and fall with time and thus creates fluctuating maximum sound pressure levels with approximately 1 s intervals. Many parallel wind turbines may create complex shape of pulses or heightened noise zones [4].

2.2 Current measurement practices

In Finland there are no specific rules for measuring modulated noise from industrial noise sources nor specific rules and recommendations for wind turbine noise measurements. The available rules and recommendations are for general purposes only which typically take account only the variable L_{Aeq} noise levels in typical industrial noise sources. However, a typical complaint or verification measurement procedure includes a measurement plan to be created prior to the measurements and handed over to the authorities for acceptance process. Authorities and local municipality environmental officers do not have a vast experience of wind turbine noise and its measurements practices which increase the importance of the measurement plan. This project and the first single turbine measurement case in 2007 [5] both had new type of rules specifically designed for wind turbine noise by using two measurement locations in two different distances directly downwind from the turbine. The measurement case presented in the next chapter included rules which specifically took account the possible amplitude modulation and its impulsivity [6]. WHO has repeatedly emphasized the importance of measuring maximum values of noise fluctuations, rather than averages. Thus, any measured or predicted noise levels should be accompanied by maximum levels, as sensitivity to the peaks of modulating noise waves are likely to better predict annoyance [7].

3 Measurement results from a single wind turbine case

The single turbine noise complaint case was measured in autumn 2011 in the Finnish south coast during four different measurement periods. The Enercon E66 2MW wind turbine with a hub height of 65m and blade span of 70m is located in a small hill about 30 meters above the sea level. The immission point was located close to the sea level 470 meters away from the turbine base in an open yard. The one-floor dwelling (a summer holiday cottage) situated about 15 meters behind the measurement point. The turbine was hardly visible to the immission point due to the high birch trees between the measurement location and the turbine. A simultaneous noise measurement was performed close to the turbine (later “near field measurement”) according to the IEC rules by using a hard ground board and protective wind screens. However, due to the fact that data from the turbine anemometers were only received during one measurement period only, the near field measurement location only provided mainly sound pressure level results thus leaving the results to be more informative than official regarding the turbine sound power level.

In both locations, class 1 microphones were used with simultaneous 44 kHz, 16bit sound recordings and data logging modes on with 5-10 second logging period including statistical loggings (e.g. L_{A95}). Measurement time was synchronized prior to each measurement period with the time error of not more than ±1 s to the National time. Sound level calibrators included one class 0 pistonphone calibrator with 250 Hz base frequency and a class1 sound level calibrator with a 1 kHz frequency. Both calibrators were calibrated in the National laboratory right after the final measurement period.

The weather was selected based on the assumptions of the worst case conditions meaning mainly downwind conditions with higher than 9 m/s wind speed at the hub height.

3.1 Measurement results related to amplitude modulation

Recorded sound pressure levels were analyzed by using a signal processing software together with the logged sound pressure levels from the sound level meters. Although almost all recorded results included modulated broad band wind turbine noise, one measurement period was exceptional and founds a basis for this analysis. A very high modulation period was recorded (and also partly witnessed during measurement equipment checkup times) during one day-time measurement period, which lasted several hours starting from the morning. As an example, one of the recorded and analyzed broad band A-weighted sound pressure level graphs is shown in figure 1. Events with exceptionally high modulation occurred several time during that one day period.

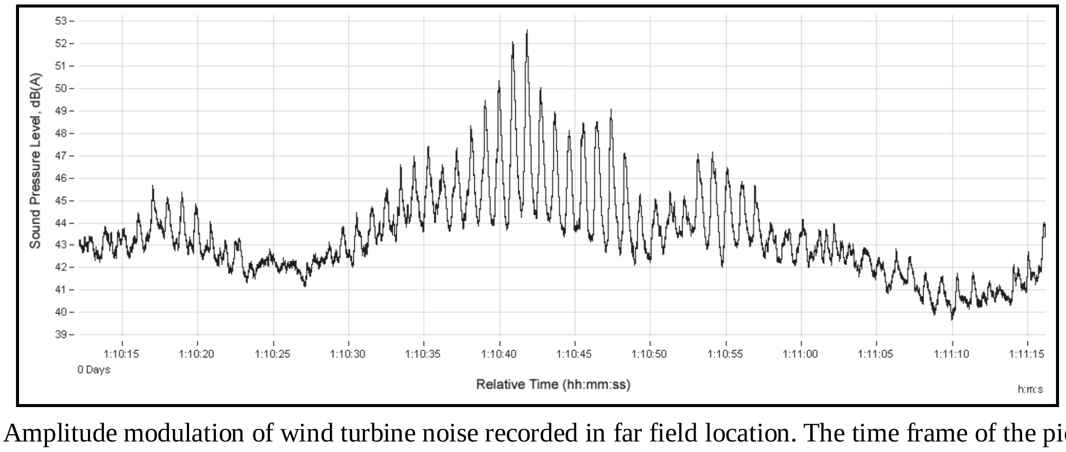

Figure 1. Amplitude modulation of wind turbine noise recorded in far field location. The time frame of the picture is 60 seconds.

Although simultaneous wind speed measurements from the nacelle were not received, the wind had strong gusts with pauses in between each gust. As the wind arrived first to the turbine about 100 meters above the sea level, the sound was the first indication of the wind gust. The same wind gust then arrived to the immission point location about 50 seconds later creating stronger background sounds. Average 10 minute wind speeds were about 10-11 m/s with higher gusts of about 14-17 m/s at the nearby national weather station and later it was verified to follow closely the wind speeds at the nacelle height. Such a cyclic variation of wind speed and thus background sounds was typical for many measurement periods under downwind conditions.

The strongest modulation peaks had sound pressure levels of above 50 dB(A), many between 51-54 dB(A). Indication of the turbine rotational speed was calculated from the near field and far field modulated sound pressure levels. Every time a strong modulation occurred, the rotor rotational speed and thus blade circumferential speed was found to be at it's maximum between 22-23 rpm. This equals about 85 m/s at the blade tip. At the same time, at the near field measurement location above the measurement board about 100 meters from the turbine, not more than 63 dB(A) sound pressure levels were measured, where $L_{Aeq, 5s}$ results typically were between 55-58 dB(A). Modulation depths of broad band sound at the immission point were 8-9 dB while at the same time in the near field location it was not more than 5-6 dB. If the turbine sound power level was calculated by using one minute L_{Aeq} results and basic sound propagation model used with a spherical sound source, the deviation to the measured maximum sound pressure levels at immission point would be about 10-12 dB and slightly less with L_{AFmax} near field results. The question of course is why there is such a high deviation from the maximum sound power level results and even greater deviation, if official guaranteed sound power levels are used?

3.1.1 Vertical directivity of the aeroacoustic blade noise

Again many papers discusses about the horizontal directivity of trailing edge noise [8], where newly made field measurements in Sweden indicate, that a variation in sound pressure levels at cross wind direction could be less than anticipated by using only the predicted trailing edge noise directivity function [9]. One of the open issues regarding the far field noise is the vertical component of the emitted sound directivity and it's variation in different wind conditions. A more detailed directivity analysis would mean, that the aerodynamic blade noise directivity should be analysed in 3D. And with modulated sound pressure levels in time domain it in fact becomes a 4D problem.

By using basic engineering sound propagation software with Nordic prediction method with a vertical directivity shape to a point source model, a 2D solution was found to explain the highest sound pressure level differences and variations in both locations (Figure 2). Because the immission point was located downwind from the turbine, one may conclude that it is the sound propagation in this condition explaining the results. This effect was clearly audible also in the upwind situation far field (a dipole noise source) and maximum modulation occurred throughout the day time with high wind speed occurring also at lower elevation levels close to the immission point (unstable atmosphere). None of the above reasons support a very high propagation influence to the measured results, although wind profile itself may attribute about 1-2 dB to the measured downwind results at the dwelling.

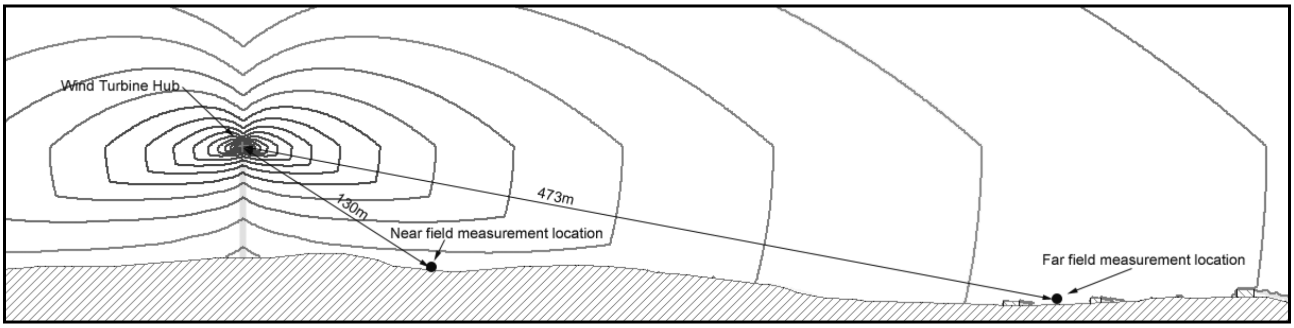

Figure 2. Sound level contours with a 3 dB level class from a vertical grid calculation. Upper level and upwind directivities are only assumed.

3.1.2 Assessing modulation impulsivity

The impulsivity of the broad band modulated noise was tested by using the Nordtest NT ACOU 112 method. Both the modulation level differences LD and onset rates OR were used to calculate the predicted prominence values P. Results of highest values found were plotted to Figure 3 below.

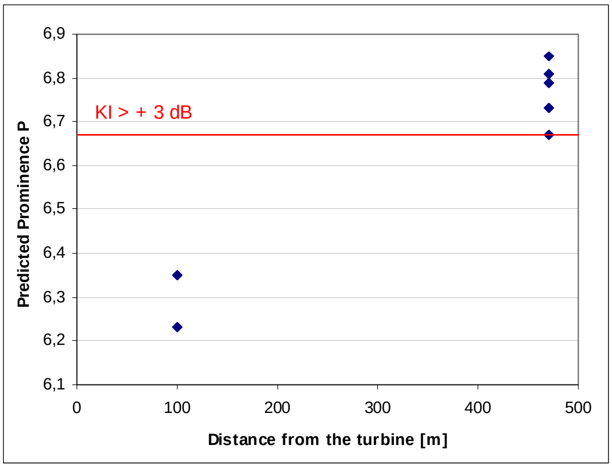

Figure 3. Modulation impulsivity in two measurement points according to the Nordtest method

From Figure 3 it can be clearly seen, that the modulation impulsivity increases as one goes further away from the turbine. This has been reported in some occasions with multiple turbines [10], but not from a single machine. The measured onset rates at the near field point were generally below 40 dB/s, where level differences were not more than 6 dB. At the same time at the immission point, onset rates above 60 dB/s were frequently measured with higher than 8 dB level differences. This resulted the noise to be impulsive at the immission point with the predicted prominence P value change rate of about 0.13 per 100 meters. The results of the impulsivity change with distance also support the idea that the swish noise emitted from the suction side of the blade (i.e. to the downwind side) has its maximum directivity values directly to the immision point with angles of 0-10 degrees below the horizontal z-line.

4 Discussion

This single wind turbine noise measurement case revealed some interesting results concerning the wind turbine noise amplitude modulation and its directivity. Though the measurement work was not intended to be any kind of a research project, the results clearly revealed, that a possible vertical directivity of the aeroacoustical noise may in fact influence heavily to the modulation experienced further away from the turbine. A link between a high rotor rotational speed and modulation depth was found indicating a higher that expected airfoil suction side noise emission levels somewhere during the blade revolution. Since the project did not consist any vertical wind profile measurements prior to the turbine at the upwind side, the final link between the expected wind profile, inflow turbulence levels or even sudden stalling events and modulation depth remained unclear. Yet it clearly showed, that placing several microphones in an array directly or partially to the downwind direction further apart from the turbine, may give more information regarding the amplitude modulation and its impulsivity. A logging period of 100 ms or faster should be used in order to plot the sound pressure level changes with time. Such a measurement practice is currently not used in the international wind turbine sound guarantee test code [11] nor has it any general measurement practices. The optimal placement of the second near field microphone location downwind from the turbine could be somewhere between 2 or 3 times the currently used reference location distance of hub height plus the blade radius. In any case more information regarding the vertical directivity factors of the aeroacoustical noise is clearly needed.

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