Amplitude modulation in wind turbine noise

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ABSTRACT

Wind farms are gaining more and more popularity as a source of renewable energy. At the same time the public is expressing concerns about the environmental impact from the existing and proposed developments. One of the most challenging tasks in the assessment of possible impacts is the prediction and post- construction measurement of wind farm noise. Amplitude modulation frequently evokes higher annoyance in the perception of wind farm noise. Many environmental noise regulations and policies consider a penalty which is added to the measured noise descriptor if the amplitude modulation is present. Some researches state that in many cases fluctuation in the wind turbine noise level is readily perceivable even at large separation distances from the turbine. This paper details results of investigations of noise immission from modern wind turbine generators and possible influence of amplitude modulation on the noise perception. It also discusses the possible role of the noise character in human perception at a distant receiver.

INTRODUCTION

Wind turbine noise emission can be annoying. People living in areas adjacent to wind farms frequently describe noise from wind turbines as "swishing", "lapping" etc (*Research into aerodynamic modulation of wind turbine noise: Final Report,* 2007). This effect can be explained by the amplitude modulation of the wind turbine noise level. The modulation is generally distinct at short distances from the wind turbine generator (WTG) and may not be audible at a greater distance. Objective evaluation of the amplitude modulation in the WTG controlled noise can help in assessing presence of the amplitude modulation at the distant receivers.

ANNOYANCE CAUSED BY AMPLITUDE MODULATE SOUND

Psychoacoustic effect of the amplitude modulated sound has been thoroughly explored by Fastl and Zwicker (Fastl and Zwicker, 2007). The fluctuation strength model is applicable for noise with the frequency of modulation of up to 20~30Hz. Perception of noise with higher modulation frequency is better explained by the model of roughness.

It is suggested by Van den Berg (Van den Berg, 2006) to use the following formula for assessing the fluctuation strength F of a wind turbine noise:

$$F = \frac{5.8(1.25m - 0.25)(0.05L_A - 1)}{(f_m/5)^2 + (4/f_m) + 1.5} \quad , \qquad (1)$$

where the fluctuation strength F is estimated in vacil, f_m is the modulation frequency in Hz and L_A is the broad band A-weighted noise level, m is the modulation factor (or "degree of modulation"):

$$\Delta L = 20\log(\frac{1+m}{1-m}), \qquad (2)$$

where the modulation depth ΔL for sinusoidal variations in the noise level is calculated as the difference between maximum and minimum values.

The fluctuation strength is a non-linear function which equals zero until a modulation depth (variation of noise level) is about 3dB and then reaches maximum (approx. 1.75 vacil at the modulation depth of 40dB) with increase of the modulation factor (or modulation depth).

MODULATION FREQUENCY OF NOISE FROM WIND TURBINES

It is considered that noise level in the area where the noise immission is controlled by the wind turbines varies with the blade passing frequency. Further simplification of formula (1) is based on assumption that the modulation frequency for modern industrial wind turbine generators is about 1Hz (Van den Berg, 2006). In fact many high power wind turbines have optimised pitch and angular speed (rpm) control programs. Typical variation in the blade passing frequency for modern 3 blade turbines is between 0.5 and 1.5Hz.

Figure 1 shows dependence of the fluctuation strength for the amplitude modulated sound from the modulation frequency and modulation factor that can be expected during wind farm noise monitoring. The annoyance has incremental trend as the modulation frequency or modulation factor increases. The trend is in compliance with the fact that a human ear is more sensitive to the amplitude modulation at frequencies around 4Hz. Sensitivity of the fluctuation depth to change of the modulation frequency can be analysed using partial derivative of the fluctuation strength (formula (1)) by the modulation frequency f_m:

$$\frac{\partial F}{\partial f_m} = \frac{0.464(1.25m - 0.25)(0.05L_A - 1)(50 - f_m{}^3)}{(0.04 f_m^3 + 1.5 f_m + 4)^2}.$$

The formula above indicates that an increase in modulation frequency (within the frequency span of interest) causes higher fluctuation strength in a sensation. If the broad band noise is characterised by the higher average sound pressure level it causes a similar effect. Therefore, designing turbines for lower operating speeds and lower overall noise levels reduces the importance of the amplitude modulation in a human perception of the WTG noise.

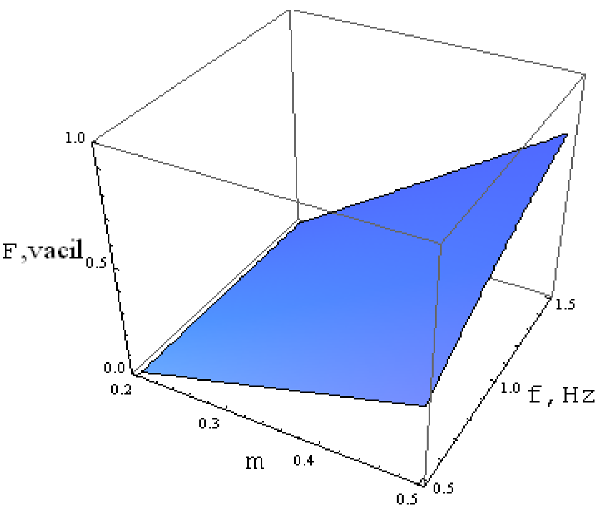


Figure 1. Fluctuation strength of the broad band amplitude modulated noise at 50dBA average noise level as function of the modulation factor and modulation frequency

IDENTIFICATION OF THE AMPLITUDE MODULATION IN WIND TURBINE NOISE

Some wind turbine noise assessment routines recommend a penalty to be added to the measured sound pressure level (SPL) values if amplitude modulation is detected. The decision about presence of the modulation can be made by subjective assessment. The fluctuation strength model was introduced for quantitative assessment of the amplitude modulation. Originally it was proposed by Fastl (Fastl, 1983) and the formula for calculation of the fluctuation strength contained average linear broad band level L (not A-weighted as in expression (1)):

$$F = \frac{5.8(1.25m - 0.25)(0.05L - 1)}{(f_m/5)^2 + (4/f_m) + 1.5}. \qquad (3)$$

It should be noted that there is no clarification on how a modulation factor can be determined if fluctuation of the noise level is significantly different from the sine dependence. Both of the formulas (1) and (3) have slight discrepancy with the conventional principles of the amplitude modulation perception. The formulas show that the fluctuation strength becomes discernible at the modulation factor above 0.2. It corresponds to the modulation depth of about 3.5dB. As it is noted in the second section of the text, the amplitude modulation is generally perceivable if the modulation depth ΔL reaches 3dB. Also in accordance with psycho- acoustic research (Fastl and Zwicker, 2007) just noticeable amplitude modulation at the modulation frequencies around 1Hz can be perceived at a modulation factor as low as 0.02.

Alternative formulas to determine the fluctuation strength are based on dependences involving ΔL where the descriptor is the temporal masking depth. The temporal masking depth is not measured directly and generally not available for practical investigations.

The fluctuation strength as a measure of annoyance due to the noise amplitude modulation can not be easily calculated from data collected using standard wind farm monitoring procedures, which are based on analysis of L_{Aeq} or statistical descriptors (L_{A90}, L_{A95}) correlated with 5-min or 10-min wind speed data. Conventional noise loggers or sound level meters usually don't have capacity to save data more often than once in a second which might be not sufficient to detect the amplitude modulation in accordance with the Nyquist-Shannon theorem. The sampling frequency (in relation to saving the acoustic descriptors) should be high enough to make an appropriate data post- process.

The further research on objective evaluation of amplitude modulation in the noise imission should be undertaken. However a procedure based on available approaches and instrumental technique can be utilised in the interim. Similar to the compliance checking procedures, the data can be collected and analysed for particular wind speeds of interest.

It could be expected if the data are acquired by an instrument with advanced functionality, the modulation frequency and modulation depth can be extracted from the analytic signal (Bendat and Piersol, 1986) corresponding to the original time-domain signal (acoustic pressure measured by the microphone), the modulation depth can be calculated as a variation of the envelope signal. The parameters of interest could be extracted by other signal processing techniques (Sklar, 1988). The time signal should be chosen from available records with least variation of the wind speed around the wind speed of interest. The original acoustic pressure time traces are not affected by the time weighting filters and would be preferable to analyse. However, variations of the acoustic pressure can have too complex character (Figure 2) and results of the signal post- process do not correlate well with results of the amplitude modulation assessment which is carried out by conventional SPL time history analysis or subjective assessment.

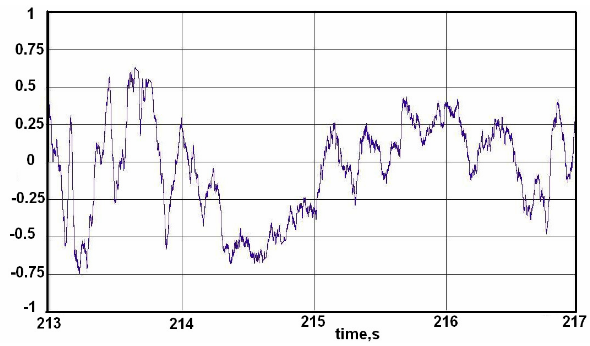


Figure 2. Acoustic pressure time history, measured 125m from the WTG tower

CALCULATION OF THE FLUCTUATION STRENGTH BY SPL TIME HISTORY

The fluctuation strength F may be calculated by using expression (3). It is suggested in (Fastl and Zwicker, 2007) that perception of the amplitude modulation becomes significant if it reaches about 10% of the relative fluctuation strength (100% can be produced by amplitude- modulated broadband noise of 60dB SPL at 4Hz modulation frequency and modulation depth 40dB or greater). For amplitude- modulated broad band noise it is achieved at about 0.2vacil. This number is suggested as criterion to decide if the amplitude modulation is a characteristic of the WTG noise.

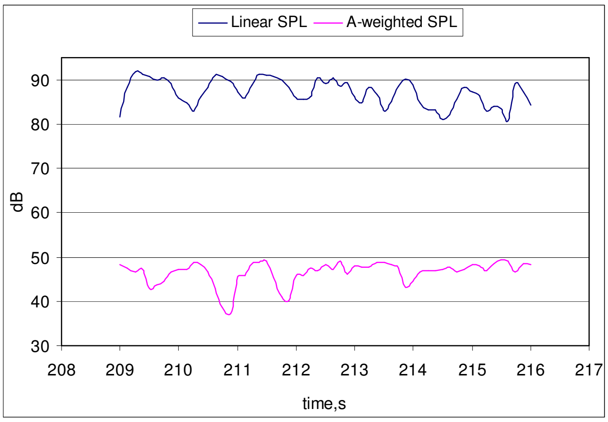
If WTG noise data is gathered by conventional noise loggers and only time histories of the standard acoustic descriptors are available, one can employ a simplified routine to discriminate the presence of the amplitude modulation. If linear SPL variations are significantly different from the sine dependence, L and ΔL can be extracted from statistical analysis of SPL where the ΔL is approximated by the double standard deviation, and the modulation frequency is estimated from average period between SPL minimums or maximums. Otherwise it can be assumed that f_m=1Hz. It should be noted that in many cases (for purpose of WTG noise monitoring) L_{Aeq} variations are less than in L (see Figure 2a, “Fast” time weighting) and it is difficult to judge about presence of the modulation by the shape of the A-weighted time trace. Generally amplitude modulation of WTG noise is clearly perceivable at any atmospheric conditions (not only in stable atmosphere) if the receiver is relatively close to the wind turbine. The amplitude modulation assessment based on the analysis of non- weighted SPL is more practical and correlates better with subjective assessment of the amplitude modulation.

If it is not possible to save acoustic descriptors at higher sampling rate, SPL histories collected with the larger sampling intervals may not be sufficient to make an objective assessment of the noise amplitude modulation (Figure 2b, “Fast” time weighting).

For example, analysis of the WTG noise (SPL time histories) with 1/8sec sampling gives ΔL of 6dB (modulation factor 0.43, L=87.1dB) and f_m=0.96Hz, the resulting fluctuation strength is 0.97vacil. Considering modulation frequency about 1Hz for A-weighted time history, it brings estimation of the fluctuation strength around 0.29vacil (ΔL=5.1dB, m=0.37, L_A=46.5dBA). Both of the estimates are above the proposed criterion of 0.2vacil, however the fluctuation strength gathered from the linear SPL correlates better with the subjective evaluation of the WTG noise.

Similar post-process for SPLs saved in one second intervals, that is conventional maximum data saving rate for many commercially available instruments, does not allow detecting amplitude modulation (Figure 3b) and it contradicts the result of the subjective assessment. Theoretically it is still possible to derive the parameters to calculate the fluctuation strength if the modulation frequency is low.

To be applicable for situations where the noise is not controlled by the WTG noise emission, the procedure should be modified. This would be the case in many practical situations where the noise measurements are being performed at a distant receiver. Nonetheless, it is generally possible to find a measurement place where WTGs are still the main noise contributors (for instance 300~400m away from the nearest WTG). Absent or faint perception of the amplitude modulation in the noise immission at this location can be used as sufficient proof that the amplitude modulation is not important factor in noise assessment at the distant receiver of interest (generally more than 500m away from the nearest WTG).



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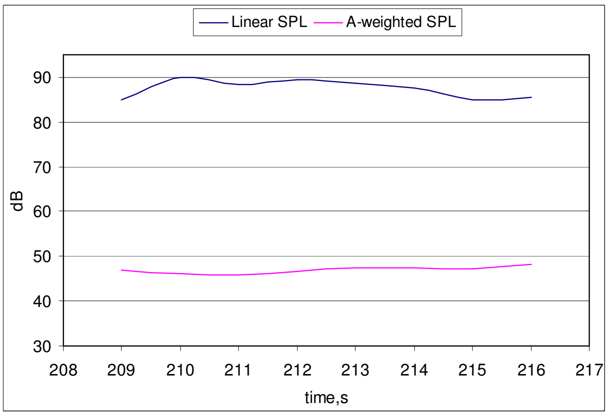

b)

Figure 3. SPL time histories measured at 125m from WTG, a)- saved every 1/8s, b)- saved with 1s interval.

SUMMARY

Amplitude modulation in WTG noise is clearly perceivable in the near field. Audibility of the amplitude modulation frequently evokes additional penalty added to the measured data in accordance with noise monitoring procedures. At present it is difficult to recommend any specific routine to assess amplitude modulation in the wind turbine emission. The classical fluctuation depth model for broadband noise can be employed for approximate evaluation of the modulation audibility. More precise results can be obtained by post-process of the SPL time history acquired with the advanced storage capability. However, a rough estimation of the amplitude modulation can be made utilising conventional noise logging instruments if the time histories of non-weighted noise levels can be gathered at the sufficient sampling rate. The information acquired at locations where the noise is controlled by the WTG noise can be used to predict perception of the amplitude modulation at the distant receivers.

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