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ON-LINE WIND FARM NOISE CONTROL

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ABSTRACT

The results of wind turbines (WTs) noise calculations, calibrated with the outcomes of multi point continuous noise monitoring around the wind farm (WF) are presented in the paper. The Nord2000 noise calculation method was used to obtain contours of L_{Aeq}, taking into account instantaneous WTs parameters, its horizontal directivity and meteorological conditions . Noise contours of L_{Aeq} around a single WT are not symmetrical due to wind induced refraction and directivity of the source. This is why sound levels in the noise protected areas around WF are changing. Usually, L_{Aeq} may be reduced by a few decibels by switching WT into noise reduced mode. Using on-line calibrated noise calculation model this restriction can be applied only to a selected WT, dominating sound levels at the area where current sound levels might cause noise complaints (while all other WTs can operate in a normal mode). There are factors that both increase the probability of noise complaints, such as amplitude modulation, as well as decrease it, such as masking effect of wind induced noise or high ambient noise. It might also be taken into account while setting the current operation mode of individual WTs.

Keywords: *windfarm noise, noise monitoring, noise prediction, noise control*

1. INTRODUCTION

Environmental conditions for the operation of a wind farm are defined by law. In Polish regulations they are expressed by permissible values of A-weighted equivalent continues sound pressure levels, L_{Aeq}, for the worst 8 hours of the day and 1 hour of the night. The limit value depends on the land use and for the night period (between 10 p.m. and 6 a.m.) goes down to 40 dB, whereas permissible level for ground transportation noise equals to 56 dB for 8 hours of the night. Despite this, wind turbine noise is regarded as a more annoying than other sources. It may be the result of their locations which are in general characterized by low level ambient noise. Therefore, operational conditions can be defined in a different way - so that the WF does not cause noise complaints. As the WF noise impact is wind dependent these requirements:

- change over time (and may be predicted taking into account short-term weather forecast),
- are defined locally around WF.

Second premise arises from: different land use around WF, basic dependence on the distance to the nearest WT and is determined by wind speed and direction. The last factor causes sound refraction. In combination with directivity of the source we get noise contours around single WT which are not circles. Consequently, L_{Aeq} noise levels at a distance of ca 1 km from the WT vary by a few decibels [1] depending on the direction of noise propagation (chapter 3). It gives the possibility to shape acoustic conditions in real time by changing the operating mode (emission) of selected WTs (change of sound power level) or if necessary even switch it off. This selectivity is to ensure maximum energy production with minimal risk of noise complaints. The reason for switch off may be the presence of amplitude modulation (AM) of instantaneous sound pressure levels. It is an attribute of a rotating sound source, but not always is observed. Among other things, it depends on the background or ambient noise level. It may be detected by continuous WF noise monitoring system.

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2. WIND FARM NOISE MONITORING CONCEPT

The method of controlling noise emission of a WTs is based on computational model which has to be fed with the following real time data:

- operational parameters of WTs,
- meteorological conditions,
- background/ambient noise level,
- WTs immission noise level,

needed as input parameters to the model as well as to calibrate this model. A low-cost WF noise monitoring system has been planned which is sufficient to collect this data set.

2.1 Measuring equipment

The monitoring system developed in this project is based on a large number of noise monitoring stations (with weather modules in selected locations). These stations operate as autonomic unattended devices in the field so it was decided to design the system as a low-cost and as simple as possible design.
In principle, it was not intended to build another accurate class 1 measuring devices but low-cost alternative enabling the assessment of wind farm noise exposure. The prototype of such a station fulfils the requirements of class 2 sound level meter (according to IEC 61672-1:2013). The system is equipped with all-weather ½” microphone kit which is based on MEMS transducer with built -in digital output interface. Whole signal path starting from microphone capsule is in digital domain. The usable measurement range starts from 26 dBA. The weather conditions are measured by integrated device with ultrasonic wind speed and direction sensor as well as temperature, humidity and precipitation sensors. The core of the system is Raspberry Pi Zero platform (single board computer). It has implemented self-designed algorithm of AM detection (chapter 4) which is essential with regard to annoyance assessment, to confirm the dominant presence of WT noise compared to background noise at a given location. The data transmission is realized by LTE modem. The measured and precalculated data are sent to the server and stored in a dedicated database.

2.2 Location of monitoring points

The noise measurement points around a given WT have to be localized in a way assuring the minimized influence of other WTs and other potential noise sources. Regarding the above these points are located around the outermost WTs of the farm. Standard measurement height was set to 4 m. Some locations are equipped with the second microphone at 1.5 m height. The schematic location of noise monitoring stations is shown in the Fig 1. For a given WT noise monitoring points (at least 2 points, M1 and M2) are localized in at least two directions.

Figure 1. Location of measurement points scheme.

Regarding the data needs and distances from the WT four different types of measurement points can be identified:

- M1 - close to the WT (ca 250 m) - to adjust declared sound power level and directivity factor (chapter 3),
- M2 - in the mid-range (ca 500 m) – to adjust sound propagation model PARAMETERS (ex. flow resistivity of the ground) in order to minimize the difference between measured and calculated noise levels,
- M3 - at the residential area - to validate noise level predicted from M1 and M2 data points,
- M4 - away from WF noise impact – to get information on background / ambient noise, especially noise induced by wind itself and / or by rain, which is a potential masker of WT noise.

3. SOUND PRESSURE LEVELS CALCULATION

The goal of the analyzes is to modify acoustic environment (if it is necessary) in residential areas (point M3 on Fig. 1), i.e. over long distances from the noise source. To predict noise levels in this area three models have been tested, all with an easily accessible set of input parameters which may be collected in real-time conditions. What’s more model may not require high computing power. We tested ISO 9613-2, Cnossos-EU and Nord2000. The last method was chosen for further work.

3.1 Method of calculation

An important feature of Nord2000 method [2] is that it can handle short-term L_{Aeq} noise levels based on instantaneous input data for specific weather conditions, including upwind propagation. For this work, module Nord2000ABC provided by SINTEF Digital, was adopted. Here, letters ABC denotes free parameters of the logarithmic-linear effective sound speed profile. It may be expressed as a function of height, z,

$$c(z) = A \cdot ln\left(\frac{z}{z_0}+1\right) + B \cdot z + C \qquad (1)$$

where C is sound speed at height z = 0 m, coefficient B of the linear term is determined from temperature gradient (dt/dz) and logarithmic part of the profile can be determined from the wind speed component u(z) in the direction of propagation [2]

$$A = u(z) \cdot ln\left(\frac{z}{z_0}+1\right)^{-1}. \qquad (2)$$

Roughness length z_0 considered to be representative of the site is chosen from recommended values in [3], whereas coefficient A is determined as a best fit to instantaneous wind data available at three heights: 1.5 m, 10 m ad WT hub height (from SCADA data of the turbine). Wind data are averages over 10 minute intervals so the unit quantity in the model is $L_{Aeq,10min}$. Another sensitive parameter of the model, flow resistivity of the ground, σ, is also determined as a best fit by minimizing the difference between the calculated and measured $L_{Aeq,10min}$ at mid-range monitoring stations (point M2 at Fig. 1).
Each WT is modelled as a directional single point source located at hub. Tests showed no qualitative difference for the model with three sources as discussed in [4].
Horizontal directivity of WT is modelled by the function [5]

$$\Delta L(\theta) = 10\, log\left(\frac{1 + a\lfloor cos^b\theta\rfloor}{1+a}\right), \qquad (3)$$

where Θ is the angle between downwind direction and the direction of propagation. For A-weighted overall L_{Aeq} it was found in [5] that coefficients are equal to a = 1.9 and b = 0.9. It gives 4.6 dB decrease in crosswind direction. Initial value of coefficient "a" is then adjusted provided that instantaneous noise levels in the direction close to crosswind are available at the nearest measurement points (point M1 on Fig. 1).

3.2 Comparison with measurement results

Measurements were conducted at two windfarms located in Poland: farm G with 2.0 MW Vestas V90 (further denoted as WT-G) and farm B with 2.35 MW Enercon E92 (WT-B) wind turbines. Both turbines have a hub height of 105 m. Multiple measuring points were established around the turbine as shown in Fig. 2 and Fig. 3.

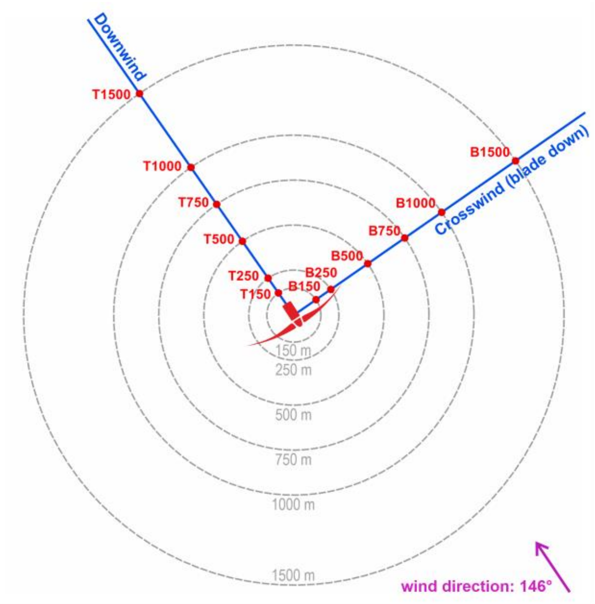

Figure 2. Measurement scenario of wind turbine no 11 at wind farm G.

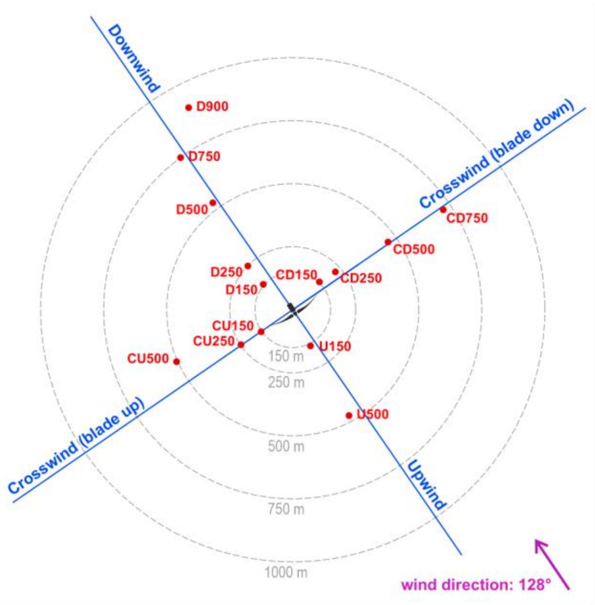

Figure 3. Measurement scenario of wind turbine no 1 at wind farm B.

Measurements were conducted simultaneously at all measuring points. Recordings were made simultaneously at three heights: on the board at ground level, at 1.5 m and 4 m above the ground. All nearby WTs were shut down during the measurements. The session started and ended with background noise recordings.

Meteorological conditions were monitored throughout the session: wind speed and direction at various heights (105 m, 10 m, 4 m, and 1.5 m), temperature and humidity (at heights: 10 m, 4 m, and 1.5 m). SCADA data of WT instantaneous operating parameters were provided.

The recorded noise was analyzed in 1/3 octave bands covering the Nord2000 range, from 25 Hz to 10 kHz. Turbine noise was background noise corrected and if signal-to-noise ratio was lower than 6 dB the result was discarded.

Sound power levels were calculated according to IEC 61400-11:2012 procedure, from $L_{Aeq,10min}$ on-board measurements at the distance of 150 m. Example of the results will be presented for one 10 min interval with highest wind speed at hub height (recorded during measurement session in spring time). Measured and rated sound power levels are presented in Tab. 1.

Table 1. Measured and declared sound power level.

WT	Period (p.m.)	V_{hub} [m/s]	L_{WA} [dB]	
			measured	rated
G	6:30 – 6:40	9.4	104.2	103.5
B	8:40 – 8:50	9.4	104.4	103.0

Average 10 min wind speeds at microphone heights did not exceed 5 m/s so wind induced noise was negligible. At both sites the terrain was relatively flat with soft ground surface (grass and farmland). Initial value of flow resistivity was set to 200 [kPa·s·m^{-2}] but best fit to the measurements at distances of 500 m and 750 m resulted in value ca. 500 [kPa·s·m^{-2}]. Roughness length was set to z_0 = 0.05 [m] as suggested in [3]. Coefficients of Eq. (1) are:

- WT-G: B=0.06; A ⊂ (-1.16 ÷ +1.54) - depending on the direction,
- WT-B: B=0.07; A ⊂ (-1.67 ÷ +1.83).

Comparison of the calculated A-weighted $L_{Aeq,10min}$ sound levels with field measurements is presented in Tab. 2 and Tab. 3. Only valid measurements (ie. S/N > 6 dB) are presented for two receiver heights 1.5 m and 4 m.

Table 2. Calculated vs measured $L_{Aeq,10min}$ sound levels around turbine WT-G (as of Fig. 2).

id	height [m]	Sound levels [dB]		
		calc.	meas.	diff.
T500	1.5	40.3	40.7	-0.4
	4	40.4	41.2	-0.8
T750	1.5	36.0	35.7	0.3
	4	36.1	36.3	-0.2
T1000	1.5	32.9	35.5	-2.6
	4	32.8	37.0	-4.2
T1500	4	28.1	29.8	-1.7
B250	1.5	46.3	43.6	2.7
	4	46.6	44.2	2.4
B500	1.5	39.5	38.7	0.8
	4	39.8	38.4	1.4
B1000	1.5	32.0	31.8	0.2

Table 3. Calculated vs measured $L_{Aeq,10min}$ sound levels around turbine WT-B (as of Fig. 3).

id	height [m]	Sound levels [dB]		
		calc.	meas.	diff.
U500	1.5	41.7	40.8	0.9
	4	42.0	41.7	0.3
CU250	1.5	46.4	45.9	0.5
	4	46.7	45.5	1.2
CU500	1.5	40.1	37.6	2.5
	4	40.2	38.1	2.1
CD250	1.5	46.5	47.0	-0.5
	4	46.7	46.9	-0.2
CD500	1.5	40.1	41.0	-0.9
	4	40.3	41.7	-1.4
CD750	1.5	35.4	36.4	-1.0
	4	35.4	37.4	-2.0
D250	1.5	48.4	48.0	0.4
	4	48.6	48.7	-0.1
D500	1.5	40.9	40.3	0.6
	4	41.0	40.8	0.2
D750	1.5	37.1	37.0	0.1
	4	37.1	37.3	-0.2
D900	1.5	34.9	36.7	-1.8
	4	34.8	35.5	-0.7

As can be seen from the tables above, the Nord2000 model generally gives good agreement with measurements. We are especially interested in this agreement for distant receivers, assigned to residential areas (point M3 at Fig. 1). Therefore, calibration factor is added to model predictions for these receivers.

3.3 Calibration factor

Calibration factor is determined from differences between calculated and measured (last column in Tab. 2 and Tab. 3) for receivers located at distances in the range of 500 ÷ 1000 m (M2 and M3 points on Fig. 1). In general, it may depend on distance and the angle between wind vector and the direction of propagation, Θ. For now we enforce elliptic form for the calibration function, r(Θ) [dB],

$$r(\theta) = \sqrt{(k_X cos\theta)^2 + (k_Y sin\theta)^2}, \tag{4}$$

where k_X and k_Y are constants expressed in decibels (semi-axes of the ellipse) representing calibration factor in crosswind and downwind direction, respectively (Fig. 4).

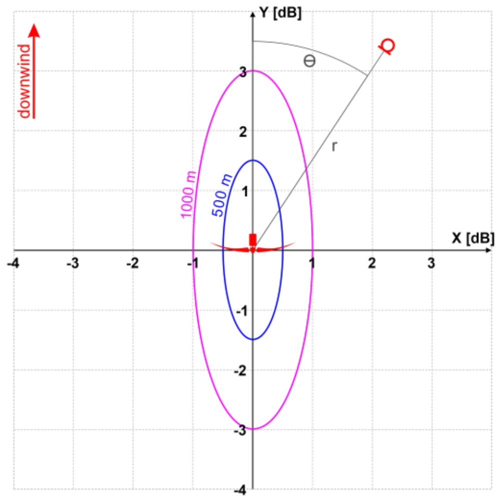

Figure 4. Example of spatial dependent calibration factor.

Calibration factor is updated every 10 min, taking into account longest possible time interval within wind speed change not exceeding 1 m/s referred to current sample.
Calibration data are stored in database. They are used to predict noise levels for the next few hours, what is carried out on the basis of a short-term weather forecast. This is relevant for noise indicators (averaged over longer time intervals) in case of major change in meteorological conditions.

3.4 Noise contours

For the set of input data from chapter 3.2 L_{Aeq} sound level isolines around turbine WT-B were determined. They are presented on Fig. 5 for two cases: with and without directivity function, defined by Eq. (e).
A similar distribution of sound levels as shown on Fig. 5, with a few decibels sound level difference at a distance of 1 km from the turbine, occurs around entire WF. These differences are due to: the current wind direction and speed (refraction strength), distance to the nearest turbine and on the number of turbines affecting overall sound level in a given location. All of these factors are parameters of the model thus it was possible to indicate which turbine have to reduce sound power level and to what extent.

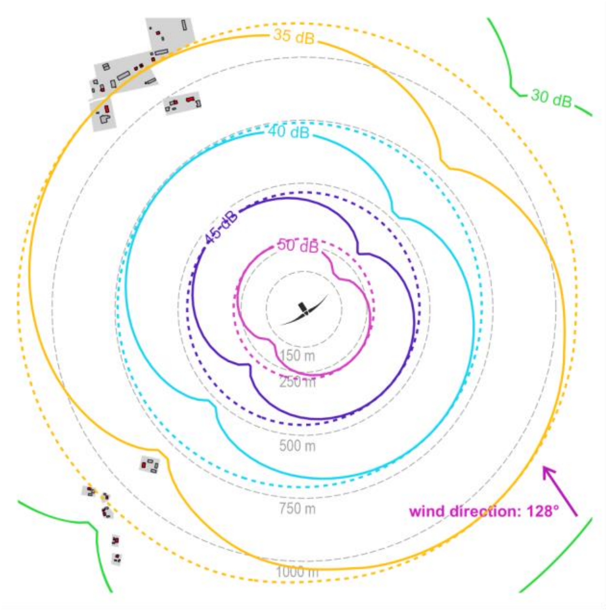

Figure 5. Example of noise contours around wind turbine calculated with and without (dashed color lines) directivity function.

4. FACTORS AFECTING NOISE COMPLAINS

In the assessment of WT noise annoyance two factors are taken into account:

- amplitude modulation,
- masking effect of ambient noise,

with the first effect increasing annoyance [6] while the second with potential to decrease it.

4.1 Amplitude modulation

The sample time history of WT noise with AM is presented on Fig. 5. It was recorded at D750 point (Fig. 3) at 10:00 p.m. (the upper) and at 09:45 p.m. (the lower) with wind speeds 9.0 m/s and 8.8 m/s, respectively.
To identify the presence of AM at first the direct component is removed from the L_{Aeq} time history (recorded at point M3, Fig. 1). This is done by applying the moving average lowpass filtering to the RMS time history of the signal and then the filtered data are subtracted from the input set. In the next step Welch power spectral density estimate (PSD) is performed which identify periodic components, if exist.
This PSD peaks corresponds to the periodic changes of the L_{Aeq} time history (or the L_{eq} time history in 1/3 oct. bands). If they are not present in the simultaneous recording at M4 station (Fig. 1) we assume that these peaks come from WT. In this case noise annoyance increases due to AM so it should induce sound power level reduction of a given WT.

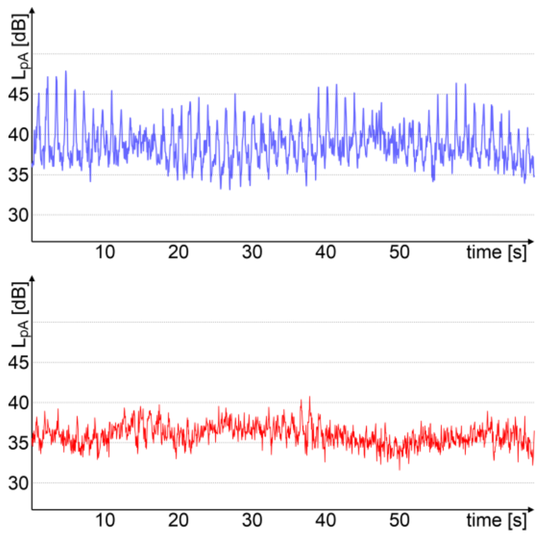

Figure 6. Example of 100 ms L_{Aeq} time history from single 2.35 MW wind turbine.

The detection criteria are still under investigation. Turbine rotation frequency may be observed on spectrogram presented in Fig. 6 (where frequency on ordinate axis is scaled to RPM). The horizontal line visible on this picture corresponds with ca. 15 RPM of wind turbine. Gaps on Fig. 6 corresponds with WT shutdowns.

The algorithm do not require much DSP computing power so AM is detected on the board of monitoring stations, without need of large data transfers (like wav files). Tests show that AM is detected for modulation depths above 3 dB which was considered as a satisfactory threshold (regarding AM perception as a function of its depth).

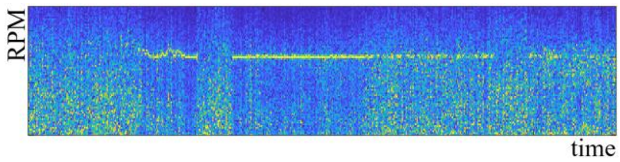

Figure 7. Spectrogram of WT noise.

4.2 Wind and rain induced noise

There are many situations when WT noise is masked by other sources such as road traffic, but also by natural sounds (ambient noise). A significant component of ambient noise comes from either the wind or rain. In some cases, even if WT noise is not completely masked (in psychoacoustic terms) it is not perceived as annoying. From a practical point of view, in such a case there is no need to reduce WT noise emission (and power production). The system under test is taking advantage from this phenomenon. Ambient noise is recorded at a distant locations (points M4 on Fig. 1), chosen so that the background noise was as similar as possible to the immediate vicinity of the farm. Based on these data noise reduction procedure may be activated provided that WT noise becomes significant with respect to other noise sources (as well as wind induced noise). It has to be confirmed by the absence of AM in time history of instantaneous sound levels which is detected (chapter 4.1) at monitoring stations located in noise sensitive (residential) areas (point M3 on Fig. 1).
At this stage of the project, wind induced noise is estimated from wind tunnel (laboratory) measurements. Wind induced noise spectra were measured as a function of wind speed. Set of various windshields was examined. Then, standard spherical model of 130 mm diameter was chosen for field applications.
Threshold values of masking effect are still being studied in another part of this project. There is also lack of data on the masking effect of rain noise. For now, it is simply assumed that WT do not cause noise annoyance if precipitation exceeds specific intensity, with threshold expressed in mm/hour.

5. SUMMARY AND DISCUSSION

The paper presented the concept of the system controlling acoustic environment around wind farm in on-line mode. It is based on live data collected from the low-cost multi point noise monitoring network, wind turbines operating parameters and meteorological data. Decision algorithm is based on outcomes from noise level calculation module that applies Nord2000 method.

In the simplest case, the method determines required reduction of sound power level of individual turbines so as not to exceed the limit value of noise level in a given location (residential area). It takes into account deformation of noise contours around point source due to wind induced refraction as well as directivity of the source.

It is still a matter of discussion what should be the assessment time for the equivalent noise level in view of day-to-day farm management keeping in mind the primary goal of the system, ie. no noise complaints which is not only affected by instantaneous noise levels.

In this context, effects influencing wind turbine noise perception are also taken into consideration. These are: amplitude modulation (increasing noise annoyance) and masking effect of background noise (including natural sounds: wind induced and rain noise) which are assumed to decrease annoyance.

For now, on-line detection of amplitude modulation is used only to confirm the predominant influence of turbine noise on the over-all sound level in a given area.

There are still open questions in the project:

- the amount of penalty added to the short-term A-weighted equivalent continues sound pressure levels (or another noise index) depending on the modulation depth,
- time intervals for the assessment of short-time noise indicators necessary to quantify the risk of noise complaints,
- whether and how to take into account short-term weather forecast which may affect daily dose of noise.

6. ACKNOWLEDGMENTS

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