Mathematical modelling of noise mapping at wind turbine farms

J. M. Mihăilă, C. Bigan, V. Panduru

Abstract. Considering the mathematical properties of the sound propagation function, a range of models for turbulence characteristic and inflow noise prediction for a turbine and wind turbines farm is discussed. The resulted mapping function is plotted versus the distance between source and receiver, resulting in an inverse square dependence, since the acoustical field is a Newtonian field. The study of the dependence from the horizontal distance between the turbine base and the receiver will show useful results for positioning individual wind turbines and wind turbine farms and further modelling features such as the disappearing of singularity and the presence of an inflection point. The modelling results can be compared with other similar simulations.

M.S.C. 2010: 74H45, 68N30, 97M10, 97M50, 68U10, 68U20.
Key words: noise control; wind turbine; source modelling; noise propagation.

1 Introduction

Acoustical noise produced by wind turbine is an interesting field of investigation because of the growing interest in renewable energies and of the impact that these structures have on the environment. Noise levels at nearby residences may be managed through the siting of turbines, the approvals process for wind farms, and operational management of the wind farm.

2 Noise emissions from wind turbines

Noise from wind turbines is another problem facing the developers of new wind farms. The rotating rotor blades produce noticeable noise, which must be addressed in the design process of new wind farms.

Applied Sciences, Vol. 16, 2014, pp. 48-55.

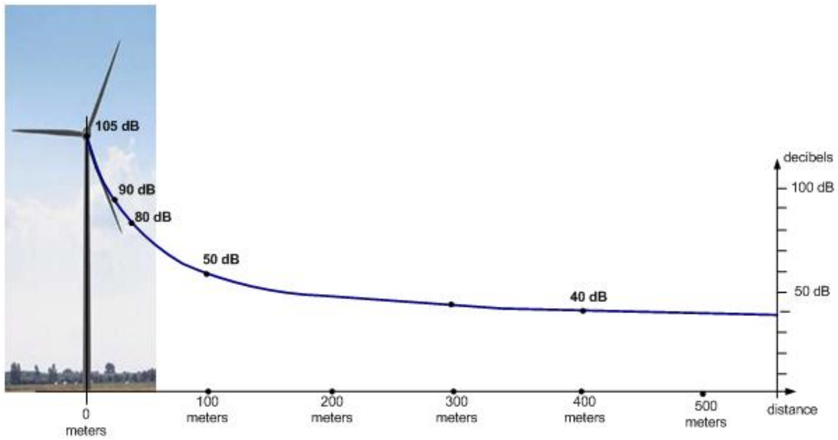

Fig. 1. General noise comparison between wind turbine and other noise sources (© GE Healthcare - All rights reserved).

The noise emission from wind turbines comes from mechanical noise and aerodynamic noise. The mechanical noise is mainly caused by the gearbox, and in lesser degree the generator (EPA, 2010). Also the cooling fans and oil pumps can contribute to the mechanical noise. Accordingly, the nacelle must incorporate insulation to prevent airborne transmission of mechanical noise. However, the wind turbine development during the latest decades has put strong effort to reduce mechanical noise, which is a minor concern today.

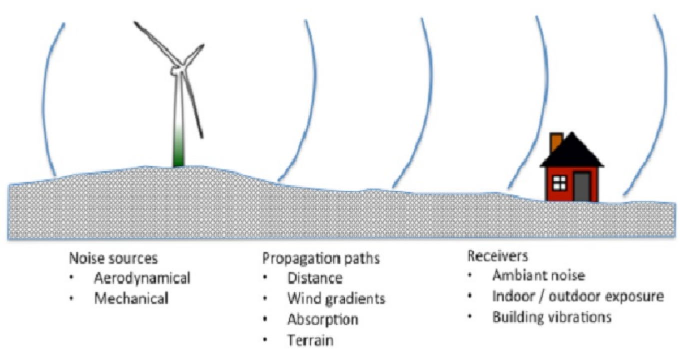

Fig. 2. Sources, receivers and propagation paths (after Rogers et al, 2006).

The aerodynamic noise component originates from the rotating blades, which speed at the blade tip approaches the speed of sound with 340 km/hr. for a 90 - meters blade diameter. Therefore the aerodynamic noise from a large wind turbine can be rather significant. Nevertheless, the noise generated by wind turbines is a major obstacle for wind energy development, and besides the general rules from, for example, the World Health Organization and the European Union, all countries has defined their own requirements, which must be satisfied before the approval of new wind farms.

3 Prediction model for inflow turbulence noise

3.1 Turbulence characteristic

Prediction of the turbulence characteristic is very important question for estimations the noise level. The turbulence intensity and the length scale are dependent at the given height of the wind turbine above the ground and also the meteorological conditions at the given site. The turbulence can be considered isotropic because the height of the wind turbine above the ground is fixed. This indicates that the fluctuations are approximately the same in all direction. We further consider the following variables:

- the turbulence velocity w;
- the longitudinal frequency ω_z;
- the down-stream direction z;
- the mean free stream wind velocity V_0.

With these notations the mathematical model becomes:

$$w = \overline{w} e^{i\omega_z (t - z/V_0)}. \tag{3.1}$$

The must important component is the longitudinal turbulence. It is assumed to be a horizontal sinusoidal gust of the form as the equation (3.1). Furthermore, the neutral atmospheric stability conditions are assumed to have a negative temperature gradient as a function of the height. It is known the following

Proposition 3.1. [16] *a) The mean square turbulence fluctuation at the height H is given by:*

$$\overline{w}^2 = \int \Phi_z d\omega. \tag{3.2}$$

b) The average longitudinal turbulence spectrum Φ_z is a function of reference turbulence velocity w_r, namely:

$$\Phi_z(\eta, V_0) = \frac{w_r^2}{\omega} [\frac{0.164\eta/\eta_0}{1 + 0.164(\eta/\eta_0)^{5/3}}], \tag{3.3}$$

where η_0 is the frequency at ground level and $\eta = \omega h / V_0$ is the reduced frequency.

The *referenced turbulence velocity* is defined as:

$$\omega_r^2 = 0.2[2.18 V_0 h^{-0.353}]^{(1.185 - 0.193 lgh)^{-1}}. \tag{3.4}$$

By integrating the relation (3.2), we obtain:

$$\overline{w}^2 = w_r^2 \{h w_r [V_0 R (w_r - 0.014 w_r^2)]\}^{-2/3}. \tag{3.5}$$

By far we can calculate the turbulence intensity from the given speed and the height above the ground level. The intensity can be calculated by another method introduced in the present model. So, the mean wind speed varies with height and is described with a power law relationship:

$$V_z = V_{ref} (Z/Z_{ref})^{\gamma}, \tag{3.6}$$

where γ is the power law factor which gives the amount of the shear.

In 1975, Counihan has estimated the power law factor by the relation:

$$\gamma = 0.24 + 0.096lgz_0 + 0.016(lgz_0)^2. \tag{3.7}$$

The turbulence intensity can be found using the relationship given by Snyder in 1985:

$$\overline{w}/\overline{V} = \gamma \frac{\ln(30/z_0)}{\ln(z/z_0)}. \tag{3.8}$$

The turbulence length scales is crucial to characterize the turbulence of wind. It is given by ESDU - Report [16]:

$$L_{ESDU} = 25z^{0.35}z_0^{-0.063}. \tag{3.9}$$

The turbulence length scale gives measurement of average size of a gust in a certain directions which is used to determine how rapidly the gust properties vary in space.

A second model is given by Counihan as follows:

$$L_C = 300(z/300)^{0.46+0.074\ln z_0}. \tag{3.10}$$

3.2 Inflow noise prediction

The adopted prediction model for turbulence inflow-noise in this report is based on the model on Amiet [1]. A semi-empirical model was given by Amiet which was valid against wind tunnel measurement with an single airfoil section under turbulent inflow. The model from Amiet can be used for each blade segments along the blade span. For the case of rotating wind turbines, a correct model was given by Lowson [7]. For both high and low frequency regions, Lowson shows a model with smooth transition between the two regions:

$$L_{p,INF} = L^H_{p,INF} + 10lg\frac{K_c}{1+K_c}. \tag{3.11}$$

We consider the following variables:

- the turbulence length scale l,
- the turbulence intensity I,
- blade segment semi-span ΔL.

With these notations, the sound pressure level for high frequency region $L^H_{p,INF}$ is given by:

$$L^H_{p,INF} = 10\langle[\varrho_0^2 c_0^2 l\frac{\triangle L}{r^2}M^3 I^2 \hat{k}^3(1+\hat{k}^2)^{-7/3}] + 58.4. \tag{3.12}$$

The law frequency correction K_c in relation (3.11) is given as follows:

$$K_c = 10S^2M\frac{\hat{k}^2}{\beta^2}, \tag{3.13}$$

where S is the sear function denoting the compressibility of the flow. The formula is suggested by Amiet:

$$S^2 = (\frac{2\pi\hat{k}}{\beta^2} + \frac{1}{1+2.4\hat{k}/\beta^2})^{-1}, \tag{3.14}$$

where

$$\beta^2 = 1 - M^2. \tag{3.15}$$

The wave number is given by Lowson which is corrected from Amiet:

$$\hat{k} = \pi f c / V_{ref}. \tag{3.16}$$

4 Software simulation results

4.1 Model implementations

The noise model included in the noise calculation module is based on the Danish Noise Model.

4.1.1 Assessment of a single turbine

The noise level at a receiver (house) at 1.5 m above ground level is obtained using the following equation:

$$Lp = Lwa - 10lg2\pi r^2 - ar, \tag{4.1}$$

where:

- the source (a wind turbine) is broadcasting noise at $Lwa\ dB(A)re\ 1\ pW$;
- Lp is the sound pressure level at R in $dB(A)re\ 20\ \mu$Pascal;
- r is the line of sight distance between source and receiver in meters;
- a is the attenuation coefficient in dB/m.

If Lwa exists as a single, broadband sound power level, then $a = 0.005\ dB\ m/s$. Therefore, the noise load, Lr, is defined as follows:

$$Lr = \begin{cases} Lp, & \text{if there are no clearly audible tones} \\ Lp + 5, & \text{if clearly audible tones are present.} \end{cases}$$

Following the presented procedure we have studied the results of software implementations of this model over turbine simulation on windFarmer software simulation on the same inputs.

The corresponding wind noise simulation over the same turbine system by using the wind farm software is shown in the next figures:

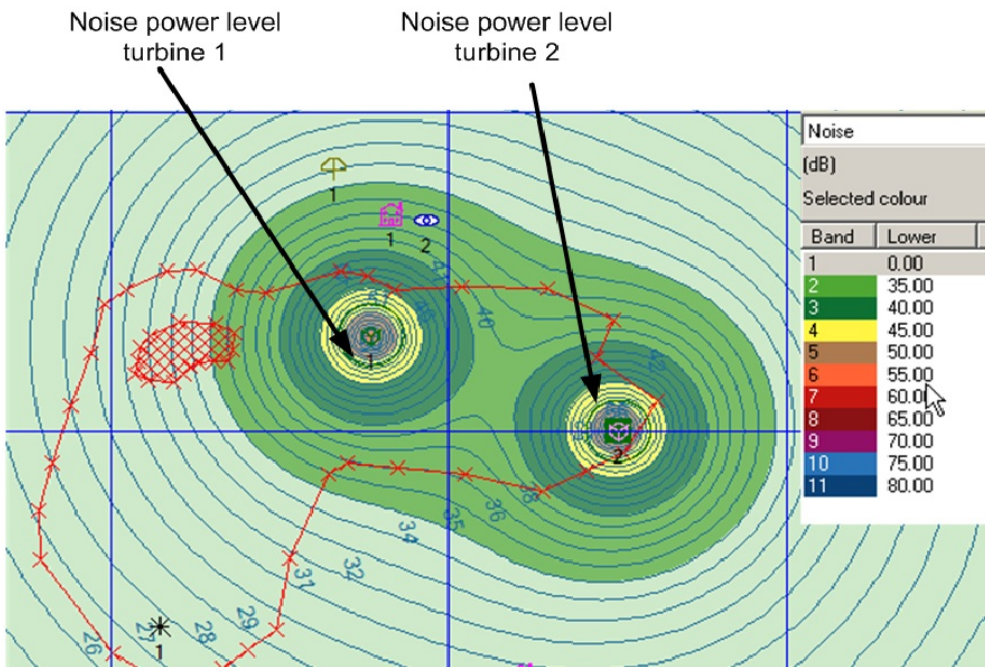

Fig. 3. WindFarm software simulation results of Noise power level for each turbine when the distance is over 500 m between turbines 2D view.

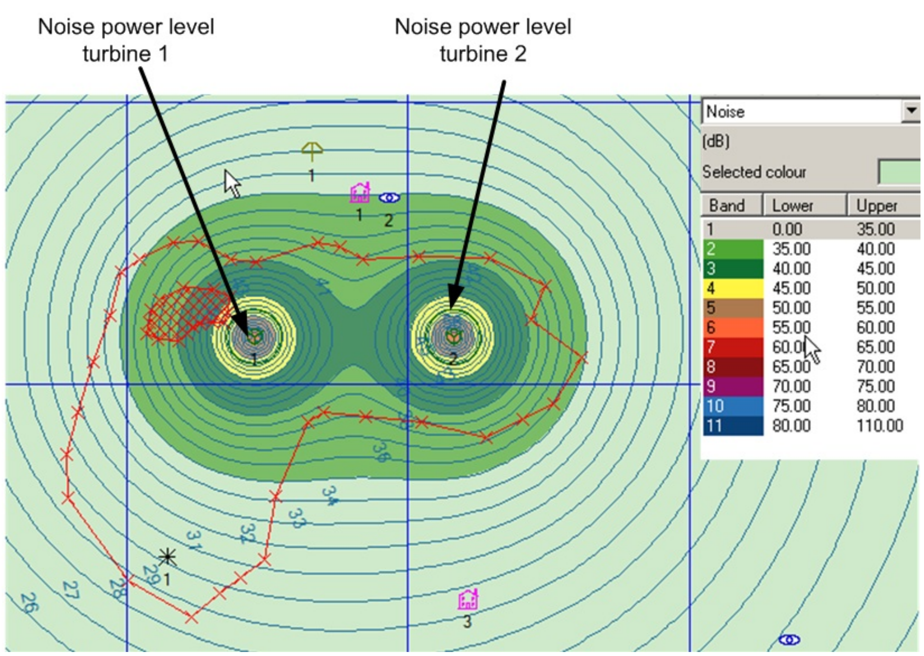

Fig. 4. Noise power level for each turbine when the distance is less than 100 m between turbines 2D view.

5 Conclusions

In order to specify the wind speed at some other height than 10 m, then the wind profile exponent or roughness height is used to calculate the corresponding wind speed at the reference height. This value is substituted into the equation above to determine the correct value of Lwa to use. We note that the sound power level for a turbine, Lwa, varies if the turbine hub height is changed. The sound power level depends as well on the wind profile at the noise measurement site. By the same reasoning, the noise emitted by a turbine is also dependent on the wind profile at the turbine location on the wind farm. The presented results show similar performance due to the power, height and distance from the source analyzed model. However, differences occur at separated noise turbines, where the WindFarm still shows computational presence of supplementary noise due to the occurrence of the two turbines and those are explainable due to the remote ground noise level choice. We conclude that the proposed method shows a realistic estimation of the wind turbines noise over the discussed area and slight sophistications can occur to slightly disturb the shown model. Further improvements can include the precise wind direction and speed impact on such described noise propagation.

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