# Modeling the uncertainties of wind farm noise predictions

Bill Kayser[1], David Ecotière
UMRAE, Cerema, Université Gustave Eiffel
11 rue Jean Mentelin, 67035, BP9, Strasbourg, France

Benoit Gauvreau
UMRAE, Université Gustave Eiffel, Cerema
Allée des Ponts et Chaussée Route de la Bouaye, 44340, Bouguenais, France

**ABSTRACT**

*Representative predictions of wind turbine noise require to accurately model the main mechanisms and characteristics of acoustic emission (i.e. extended sound source with aeroacoustic noise generation) and acoustic propagation in outdoor environment (i.e. ground effects and atmospheric properties). As these phenomena fluctuate over time and space, it leads to great uncertainty on Sound Pressure Level (SPL) estimated at local resident buildings/facades. Such uncertainty is not yet properly quantified by engineering noise prediction models. Thus, this paper presents a modeling tool developed in the framework of the French project PIBE, which aims at quantifying the SPL uncertainty involved in wind farm noise predictions. Ultimately, this modeling tool will be freely available online and will help to better understand the risk of noise pollution at each stage of a wind farm's life, in order to guarantee compliance with the regulatory requirements concerning the exposure of local populations.*

## 1. INTRODUCTION

The objective of this paper is to present a method of uncertainty quantification of SPL spread in presence of a wind turbine farm. To do so, the estimation of SPL at a receiver takes into account the aeroacoustic sources at the blades of the wind turbines, [1–3], as well as propagation phenomena between thoses sources and the receivers, *i.e.* meteorological and ground effects. Such environmental phenomena fluctuate over both time and space, which lead to variable SPL at long range [4–7] and thus to significant SPL uncertainty [8–10].

Previous works already focused on sensitivities of environmental parameters in SPL estimation (*i.e.* determine the parameters that drive uncertainty) [11–13], as well as quantifying SPL uncertainties induced by a single wind turbine for downwind conditions only [14]. This work intends to go further by considering a complete wind turbine farm, even for upwind conditions, which is a key step toward obtaining representative assessments of wind turbine noise.

The methodology consists in modeling different scenarios thanks to a stochastic technique based on quasi-Monte Carlo sampling. This allows one to determine the distribution of the SPL induced

[1] bill.kayser@cerema.fr

by the probability distribution of uncertain environmental parameters (*e.g.* wind properties, ground properties, etc). In practice, thousands of simulations may be required to conduct such uncertainty analysis, which leads to prohibitive calculation costs. As done in [14], one solution is to replace the initial wind turbine noise model by a metamodel that reproduces the expected SPL with highly reduced computational costs and small errors in the SPL estimation. Thus, the metamodel is built to determine the SPL spread at receivers locations in presence of a single wind turbine. Then, the methodology is to conduct uncertainty calculations for each wind turbine of the farm, in order to assess the overall SPL spread at receivers locations near the wind turbine farm.

## 2. THE WIND TURBINE NOISE MODEL

### 2.1. The source model

The moving monopoles approach [15] is used to model the noise emitted by the wind turbine. It consists in a strip theory that splits each blade into segments of variable chord and span in order to be able to consider a non-uniform incidence flow along the blades. The angle-dependent sound power level of each segment is obtained using Amiet's theory as detailed in [16]. An attenuation term is used to account for the propagative effects that occurs between the wind turbine and far field receivers. The attenuation term is calculated using a propagation model based on the wide-angle parabolic equation (WAPE), derived without the effective sound speed approximation [17]. The summation of the contributions from all blade segments is then performed at the receivers by assuming that all the contributions are uncorrelated [18].

The wind turbine has a nominal electrical power of 2.3 MW, a rotor diameter of 93 m, a hub height of 80 m and three blades of 45 m length. The speed of rotation increases linearly from 6 rpm at the cut-in wind speed of 4 m/s measured at the hub height, to 16 rpm at the wind speed of 12 m/s. The reader may refer to [12–14] for details about the wind turbine noise modeling.

### 2.2. Atmospheric flux profiles

The refraction of the acoustic waves is taken into account through the wind vertical profile $U(z)$ and temperature vertical profile $T(z)$:

$$U(z) = U_{\text{ref}} \left( \frac{z}{z_{\text{ref}}} \right)^{\alpha}, \tag{1}$$

$$T(z) = T_0 + a_T \ln \left( \frac{z}{z_0} \right), \tag{2}$$

where $U_{\text{ref}}$ (m/s) is the wind speed at height $z_{\text{ref}}$ (m) above ground level (typical hub height), $z$ (m) is the height above the ground, $\alpha$ is the wind shear factor, $T_0$ (K) is the air temperature at the ground surface, $a_T$ (K/m) is a refraction coefficient that determine the influence of temperature profile, and $z_0 = 0.13 h_v$ (m) is the roughness height that depends on vegetation height $h_v$ (m).

### 2.3. Atmospheric absorption

The atmospheric absorption is taken into account in accordance with the standard [19] that depends on air temperature $T_0$ (K), atmospheric pressure $p_{\text{atm}}$ (Pa) and the relative humidity of air $h_r$ (%) chosen here as 80 %.

### 2.4. Atmospheric turbulence scattering

Althought the WAPE model allows for explicitly modeling turbulence scattering by perturbing the acoustic refractive index [20], a large number of realisations (typically 50-100) are needed to end up with SPL estimation. The computational cost of this technique is too high for uncertainty analysis purpose. It was chosen to correct the SPL attenuation in refracting atmosphere that neglect turbulent scattering ($\mathrm{SPL_{noscatter}}$), by adding a scattering contribution ($\mathrm{SPL_{scatter}}$), as proposed in *Harmonoise* project [21, 22]. The attenuation term $\Delta_L$ is thus given by:

$$\Delta_L = 10\log_{10}\left(10^{\frac{\mathrm{SPL_{noscatter}}}{10}} + 10^{\frac{\mathrm{SPL_{scatter}}}{10}}\right), \tag{3}$$

with:

$$\mathrm{SPL_{scatter}} = 25 + 10\log_{10}\gamma_T + 3\log_{10}\frac{\omega}{1000} + 10\log_{10}\frac{r}{100}, \tag{4}$$

where $\omega = 2\pi f$ with $f$ (Hz) the frequency, $r$ (m) the source-receiver distance, and $\gamma_T$ a measure of turbulence strength [22].

### 2.5. Ground properties

The ground influence on sound propagation (sound absorption and scattering by surface roughness) is taken into account using an effective admittance model [12, 23]. The sound absorption is modeled through the Miki's impedance model [24] that depends on the airflow resistivity parameter $\sigma$:

$$\frac{Z}{Z_0} = 1 + 6.17\left(\frac{\rho_0 f}{\sigma}\right)^{-0.632} + i9.44\left(\frac{\rho_0 f}{\sigma}\right)^{-0.632}, \tag{5}$$

$$\frac{k}{k_0} = 1 + 8.73\left(\frac{\rho_0 f}{\sigma}\right)^{-0.618} + i12.76\left(\frac{\rho_0 f}{\sigma}\right)^{-0.618}, \tag{6}$$

Note that Miki's model should be used in the frequency validity domain: $f > 0.01\ \sigma/\rho_0$ [25] where $\rho_0 = 1.24$ kg·m$^{-3}$ is the density of air.

The scattering by ground roughness is taken into account through an effective admittance term (see [14]) that depends on 2 parameters: $\sigma_h$ (m) which is the standard deviation of the ground roughness heights and $l_c$ (m) which is the correlation length of the horizontal variations of the ground.

## 3. METAMODELING

The objective of the metamodel is to reproduce the behavior of the original physic-based model with a reduced computation time (a fraction of a second for each calculation) and reasonable accuracy (less than 1 dB of error). The output of the physic-based model is a 2D $(x, z)$ SPL map with $x \in [500; 3000]$ m and $z \in [0; 10]$ m, with a resolution of 0.5 m. A direct application of metamodeling is to reproduce the behavior of each acoustic receiver using a statistical emulator, which in itself would not drastically reduce computation time because of the excessive number of receivers considered (5001 in $x \times 20$ in $z = 100020$ receivers). Thus, the SPL maps need to be represented by a limited number of scalars (*i.e.* on the order of ten), which will become the emulated quantities. The method consists of three steps, as detailed in [14] and recalled below.

### 3.1. Training sample

The first step of building the metamodel is to generate a training sample $\mathbf{Y}$ composed of $N$ SPL maps calculated with the physic-based model. The $N$ SPL maps explore the input set space of the physic-based model thanks to a Latin-Hypercube Sampling [26]. The centered training sample $\overline{\mathbf{Y}}$ is created by removing the mean of the training sample $\overline{\mathbf{y}}$ from each SPL map $\mathbf{y}$ in the full training sample $\mathbf{Y}$.

### 3.2. Output dimension reduction

Reduction of dimension of the physic-based model outputs through a principal component analysis [27] of the centered training sample $\overline{\mathbf{Y}}$. Then, each SPL map $\mathbf{y}$ can be defined as a linear combination of principal components $\mathbf{\Psi}$ on a reduced subspace such that $\mathbf{y} = \sum \boldsymbol{a} \times \mathbf{\Psi}$. Each principal component $\mathbf{\Psi}$ can be represented in the same form as an SPL map ($5001 \times 20$ elements, they can be seen as "elementary maps"), and the scalar members of $\boldsymbol{a}$ are coefficients that represent the weight of each component $\mathbf{\Psi}$ in the SPL map $\mathbf{y}$.

### 3.3. Kriging interpolation

For each new SPL map calculation, it is only necessary to determine the coefficients $\boldsymbol{a}$ because the principal components $\mathbf{\Psi}$ are already known. A fast statistical emulator based on kriging interpolation [28] is then used to emulate the relation between the projection coefficients $\boldsymbol{a}$ and the inputs $\mathbf{X}$. Krigin interpolation is a linear interpolation method (meaning that predictions at a target point are linear combinations of the training data), that is unbiased so that the predictions at training points match with the data.

## 4. UNCERTAINTY ANALYSIS

The objective of uncertainty analysis is to determine the probability distribution $\mathbb{P}(\mathbf{y})$ of the output $\mathbf{y}$ of the model (*i.e. SPL*), induced by the probability distributions $\mathbb{P}(\mathbf{X})$ of the uncertain parameters $\mathbf{X}$ (*i.e.* environmental parameters). The distribution $\mathbb{P}(\mathbf{y})$ is estimated numerically by sampling the distributions of the inputs $\mathbb{P}(\mathbf{X})$ to propagate the uncertainty of the inputs $\mathbf{X}$.

### 4.1. Input parameters interval values

The input parameters interval values are chosen to be representative of wind turbine context, for temperate climate. The table 1 presents these intervals.
Quasi-Monte Carlo Sobol sequences [29] are then used to generate samples distributed according to the probability distributions of these input parameters $\mathbb{P}(\mathbf{X})$. The Sobol sequences are deterministic versions of the Monte Carlo method that provide a faster convergence, up to a factor of 10 compared to the classical Monte Carlo method, with a lower discrepancy [30]. When the distribution laws of the input parameter are not known, we recommend using a uniform distribution so as not to favor any particular condition. It should be noted that this choice of uniformity may lead to overestimation of the uncertainties.

### 4.2. Uncertainty analysis for a whole wind farm

The metamodel is built to model the SPL emitted by a single wind turbine, in a 2D $(x, z)$ domain where $x \in [500; 3000]$ m and $z \in [0; 10]$ m. In order to assess the SPL uncertainty for a whole wind

Table 1: Set of inputs **X**, whose interval values are chosen to be representative of wind turbine context and temperate climate conditions.

| Parameter | Description | Value |
|---|---|---|
| $\sigma$ (kN·s·m$^{-4}$) | airflow resistivity of the ground | $\in [50; 5000]$ |
| $l_c$ (m) | spatial correlation length of rough ground | 0.5 |
| $\sigma_h$ (m) | standard deviation of the roughness height | 0.025 |
| $h_r$ (%) | relative humidity of air | 80 |
| $T_0$ (°C) | ground surface air temperature | $\in [-10; 30]$ |
| $a_T$ (K·m$^{-1}$) | temperature profile coefficient | $\in [-0.5; 0.25]$ |
| $\alpha$ | wind shear coefficient | $\in [0; 0.8]$ |
| $\theta$ (°) | wind // source-receiver angle | $\in [0; 180]$ |
| $\gamma_T$ | turbulence strength | $\in [0; 10^{-4}]$ |

farm, the methodology is to conduct uncertainty analysis for each wind turbine of the farm. Then, the contributions of each wind turbine $i$ is considered at the receivers of interest, taking into account the different propagation angles $\theta_i$ between the wind turbines and the receivers. The Figure 1 illustrates this approach.

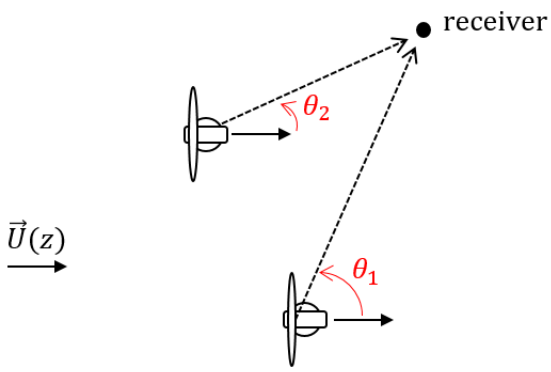


Figure 1: Schematics of the methodology for a wind farm composed of 2 wind turbines.

## 5. CONCLUSIONS

This work takes place in the context of uncertainty estimation of wind turbine noise. This paper presented a methodology in order to build a fast metamodel for wind turbine noise estimation. The metamodel will consider bot downwind and upwind conditions, and its low computational cost will allow to perform uncertainty analysis for a whole wind turbine farm. Ultimately, the metamodel will be freely available as an online tool, which will help to better understand the risk of noise pollution of wind farms.


## ACKNOWLEDGEMENTS

This research is funded by the French National Agency for Research in the framework of the PIBE project (contract ANR-18-CE04-0011).


## REFERENCES


[1] S. Oerlemans and J. G. Schepers. Prediction of Wind Turbine Noise and Validation against Experiment. *International Journal of Aeroacoustics*, 8(6):555–584, August 2009.

[2] Steven Buck, Stefan Oerlemans, and Scott Palo. Experimental characterization of turbulent inflow noise on a full-scale wind turbine. *Journal of Sound and Vibration*, 385:219–238, December 2016.

[3] F. Bertagnolio, H. Aa Madsen, and A. Fischer. A combined aeroelastic-aeroacoustic model for wind turbine noise: verification and analysis of field measurements. *Wind Energy*, 20(8):1331–1348, 2017.

[4] Vadim Zouboff, Yves Brunet, Michel Bérengier, and E Sechet. A qualitative approach of atmospheric effects on long range sound propagation. Ottawa, Canada, 1994. 6th Inter. Symp. On Long Range Sound Prop.

[5] D. Keith Wilson. The sound-speed gradient and refraction in the near-ground atmosphere. *The Journal of the Acoustical Society of America*, 113(2):750–757, January 2003.

[6] Benoit Gauvreau. Long-term experimental database for environmental acoustics. *Applied Acoustics*, 74(7):958–967, July 2013.

[7] Sylvain Cheinet, Matthias Cosnefroy, Florian Königstein, Winfried Rickert, Marcus Christoph, Sandra L. Collier, Adrien Dagallier, Loïc Ehrhardt, Vladimir E. Ostashev, Alexandre Stefanovic, Thomas Wessling, and D. Keith Wilson. An experimental study of the atmospheric-driven variability of impulse sounds. *The Journal of the Acoustical Society of America*, 144(2):822–840, August 2018.

[8] Chris L. Pettit and D. Keith Wilson. Proper orthogonal decomposition and cluster weighted modeling for sensitivity analysis of sound propagation in the atmospheric surface layer. *The Journal of the Acoustical Society of America*, 122(3):1374–1390, September 2007.

[9] Olivia Leroy, Benoit Gauvreau, Fabrice Junker, Etienne De Rocquigny, and Michel Bérengier. Uncertainty assessment for outdoor sound propagation. 20th International Congress on Acoustics (ICA), 2010.

[10] D. Keith Wilson, Chris L. Pettit, Vladimir E. Ostashev, and Sergey N. Vecherin. Description and quantification of uncertainty in outdoor sound propagation calculations. *The Journal of the Acoustical Society of America*, 136(3):1013–1028, September 2014.

[11] T. Van Renterghem and D. Botteldooren. Variability due to short-distance favorable sound propagation and its consequences for immission assessment. *The Journal of the Acoustical Society of America*, 143(6):3406, June 2018.

[12] Bill Kayser, Benoit Gauvreau, and David Ecotière. Sensitivity analysis of influential parameters for wind turbine noise. In *8th International meeting on Wind Turbine Noise conference*, Lisbon, Portugal, June 2019.

[13] Bill Kayser, Benjamin Cotté, David Ecotière, and Benoit Gauvreau. Environmental parameters sensitivity analysis for the modeling of wind turbine noise in downwind conditions. *The Journal*

*of the Acoustical Society of America*, 148(6):3623–3632, December 2020. Publisher: Acoustical Society of America.

[14] Bill Kayser, Benoit Gauvreau, David Écotière, and Vivien Mallet. Wind turbine noise uncertainty quantification for downwind conditions using metamodeling. *The Journal of the Acoustical Society of America*, 151(1):390–401, January 2022.

[15] B. Cotté. Extended source models for wind turbine noise propagation. *The Journal of the Acoustical Society of America*, 145(3):1363–1371, March 2019.

[16] Yuan Tian and Benjamin Cotté. Wind turbine noise modeling based on Amiet's theory: Effects of wind shear and atmospheric turbulence. *Acta Acustica united with Acustica*, 102(4):626–639, August 2016.

[17] Vladimir E. Ostashev, D. Keith Wilson, and Michael B. Muhlestein. Wave and extra-wide-angle parabolic equations for sound propagation in a moving atmosphere. *The Journal of the Acoustical Society of America*, 147(6):3969–3984, June 2020.

[18] J. Christophe, J. Anthoine, and S. Moreau. Amiet's Theory in Spanwise-Varying Flow Conditions. *AIAA Journal*, 47(3):788–790, 2009.

[19] ISO9613-1:1993. Acoustics — Sound attenuation in free field — Part 1: atmospheric absorption calculation, 1993.

[20] P. Chevret, Ph. Blanc-Benon, and D. Juvé. A numerical model for sound propagation through a turbulent atmosphere near the ground. *The Journal of the Acoustical Society of America*, 100(6):3587–3599, December 1996.

[21] Dirk van Maercke and Jérôme Defrance. Development of an Analytical Model for Outdoor Sound Propagation Within the Harmonoise Project. *Acta Acustica united with Acustica*, 93(2):201–212, March 2007.

[22] Erik Salomons, Dirk van Maercke, Jérôme Defrance, and Foort de Roo. The Harmonoise Sound Propagation Model. *Acta Acustica united with Acustica*, 97(1):62–74, January 2011.

[23] F. G. Bass and I. M. Fuks. *Wave Scattering from Statistically Rough Surfaces: International Series in Natural Philosophy*. Elsevier, 1979. Google-Books-ID: aLM3BQAAQBAJ.

[24] Yasushi Miki. Acoustical properties of porous materials-Modifications of Delany-Bazley models-. *Journal of the Acoustical Society of Japan (E)*, 11(1):19–24, 1990.

[25] Ray Kirby. On the modification of Delany and Bazley fomulae. *Applied Acoustics*, 86:47–49, December 2014.

[26] M. D. McKay, R. J. Beckman, and W. J. Conover. Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code. *Technometrics*, 21(2):239–245, May 1979.

[27] I. T. Jolliffe. Principal Components in Regression Analysis. In I. T. Jolliffe, editor, *Principal Component Analysis*, Springer Series in Statistics, pages 129–155. Springer, New York, NY, 1986.

[28] Georges Matheron. *Les variables régionalisées et leur estimation: une application de la théorie des fonctions aléatoires aux sciences de la nature.* Masson et CIE, 1965.

[29] Ilya Sobol. On the distribution of points in a cube and the approximate evaluation of integrals. *USSR Computational Mathematics and Mathematical Physics*, 7(4):86–112, January 1967.

[30] Andrea Saltelli, Marco Ratto, Terry Andres, Francesca Campolongo, Jessica Cariboni, Debora Gatelli, Michaela Saisana, and Stefano Tarantola. *Global Sensitivity Analysis: The Primer*. John Wiley & Sons, February 2008.