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# INFLUENCE OF ENVIRONMENTAL PARAMETERS ON THE MODELING OF WIND TURBINE NOISE EMISSION AND PROPAGATION: A SENSITIVITY ANALYSIS

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## ABSTRACT

Reliable prediction of wind turbine noise involves taking into account environmental phenomena such as atmospheric conditions and ground properties, that are variable in time and space. Thus, it is essential to estimate the relative influence of those environmental parameters/variables on acoustic field calculations, in order to determine the parameters that will be the main source of uncertainties. To do so, we performed a sensitivity analysis based on the Morris' screening method using a wind turbine noise emission model coupled to a sound propagation model. The emission model is based on Amiet's theory and is coupled to a Wide Angle Parabolic Equation propagation model (WAPE). The whole simulation takes into account ground effects (absorption through acoustic impedance, and scattering through surface roughness) and micrometeorological effects (mean refraction through the vertical gradient of effective sound speed) for downwind conditions. The final results will help to quantify the overall variability and uncertainties associated with the emission-propagation-reception sound chain in order to provide a better control of the quality of wind turbine noise prediction in an inhomogeneous outdoor environment.

## 1. INTRODUCTION

Wind turbine noise can be the cause, in certain situations, of an annoyance reported by residents of wind farms. This sometimes leads to the implementation of degraded operating modes (acoustic curtailments) which has the consequence of slowing down the production and the development of this renewable source of energy. It appears crucial to estimate precisely the noise level induced by wind turbines in order to respond to the societal challenge that this technology raises. Although the wind energy sound source has been the subject of many studies in recent years (sound emissions [1], directivity [2], sound power [3]), few works have studied on the influence of environmental parameters on the variability of the sound levels encountered. As the propagation phenomena fluctuate over highly-variable time scales from seasonal trends to instantaneous fluctuations, as well as over space scales, this leads to tremen-

dous spread of sound pressure level (SPL) [4–6]. Estimating the global variability and uncertainties associated with the emission-propagation-reception chain thus appears essential for controlling the acoustic impacts of wind turbines in the environment. This requires to model accurately the dominant aeroacoustic sources for modern wind turbines [7, 8], and the propagation effects. A major step to obtain reliable prediction is to use statistical methods to quantify the model sensitivities and uncertainties [9–11].

The purpose of this paper is to present the relative influence of environmental parameters on both emission and propagation by using statistical techniques for sensitivity analysis. It is organized as follows: Section 2 introduces the model used and the environmental effects taken into account; Section 3 describes the sensitivity analysis method used, and presents the results of the study.

## 2. DESCRIPTION OF THE MODEL

### 2.1 Emission model

The emission model considers trailing edge noise and turbulent inflow noise and is based on Amiet's theory [12–14], as presented in [15]. Considering an airfoil of chord  $c$  and span  $L$  fixed relative to a far-field receiver, and considering an aspect ratio  $L/c$  greater than about 3, the power spectral densities (PSD) of the acoustic pressure can be written [16]:

$$S_{pp}^F(\mathbf{x}_R, \omega) = A(\mathbf{x}_R, \omega) \Pi(\mathbf{x}_R, \omega) |\mathcal{I}(\mathbf{x}_R, \omega)|^2, \quad (1)$$

with  $\mathbf{x}_R$  the far-field receiver position,  $A$  a coefficient that depends on the geometry and the angular frequency  $\omega$ ,  $F$  a superscript that refers to the *fixed* airfoil,  $\Pi$  a statistical function and  $\mathcal{I}$  an aeroacoustic transfer function. The main parameters of this model are the functions  $\Pi$  and  $\mathcal{I}$  that depend on the noise generation mechanism: turbulent inflow noise or trailing edge noise [14, 15].

For a rotating blade at the angular position  $\alpha$ , the PSD at a far-field receiver at angular frequency  $\omega$  is written [15, 17]:

$$S_{pp}^R(\mathbf{x}_R^T, \omega, \alpha) = \frac{\omega_e}{\omega} S_{pp}^F(\mathbf{x}_R^B, \omega_e, \alpha), \quad (2)$$

with  $\omega_e$  the emission angular frequency,  $\mathbf{x}_R^T$  the receiver coordinates in the wind turbine reference system, and  $\mathbf{x}_R^B$  the receiver coordinates in the blade reference system. The subscript  $R$  refers to the *rotating* airfoil, and the expression for the Doppler factor  $\omega/\omega_e$  is given in [17].

It should be noted that the incidence flow is not uniform along a wind turbine blade. In order to take this into account, a strip theory is used that consists in cutting each blade into  $D$  segments of variable chord  $c_d$  and span  $L_d$ , so as to respect the condition  $L_d/c_d \geq 3, d = 1..D$ , for which Eq. (1) is valid. Then a summation of each segments contributions is finally performed, assuming that the different segments are uncorrelated [15].

Since this analytical emission model is only valid in free field in a homogeneous atmosphere, a propagation model is needed to account for ground and meteorological effects. For this purpose, the moving monopoles approach is used (as detailed and validated in [18]). With this method, the sound pressure level (SPL) at a receiver is calculated for a blade segment  $S$  at an angular position  $\Phi$  (see Fig. (1)), using the point source approximation [19]:

$$\text{SPL}(\omega, \Phi) = \underbrace{\text{SWL}(\omega, \Phi)}_{\text{emission}} \underbrace{-10 \log(4\pi R_1^2)}_{\text{geometrical spreading}} + \underbrace{\Delta L(\omega, \Phi) - \alpha(\omega)R_1}_{\text{atmospheric and ground effects}}, \quad (3)$$

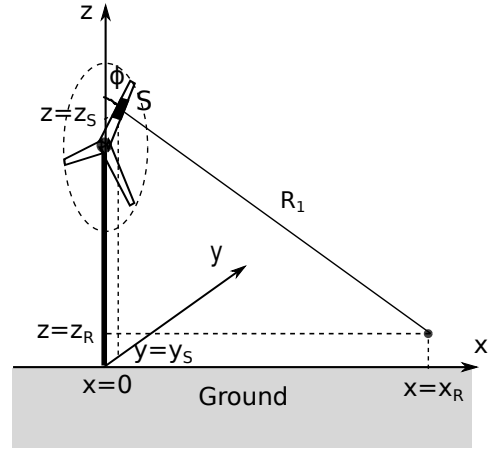
where  $\text{SWL}(\omega, \Phi)$  is the angle-dependent sound power level,  $R_1 = \sqrt{\mathbf{x}_R^2 + y_s^2 + (z_s - z_R)^2}$  is the distance between the segment at  $(0, y_s, z_s)$  and the receiver at  $(\mathbf{x}_R, 0, \mathbf{x}_R)$ ,  $\Delta L$  is the sound attenuation relative to the free field, and  $\alpha$  is the atmospheric absorption coefficient in dB/m. The angle-dependent  $\text{SWL}(\omega, \Phi)$  can be obtained from the free-field SPL calculated using Amiet's model [18]. The attenuation  $\Delta L(\omega, \Phi)$  can be calculated using any propagation model that can take into account meteorological effect and ground effect. In this study we are using a propagation model based on the parabolic approximation (see Sec. (2.2)). In order to limit the number of PE calculations to perform, a set of  $N_h = 7$  source heights  $H_n$  distributed along the rotor plane is considered:

$$H_n = H_{\min} + n\Delta H, \quad n = 0, \dots, N_h - 1, \quad (4)$$

with  $\Delta H$  the height step given by

$$\Delta H = \frac{H_{\max} - H_{\min}}{N_h - 1}, \quad (5)$$

where  $H_{\min}$  and  $H_{\max}$  are respectively the minimum height and the maximum height to consider. The attenuation  $\Delta L(\omega, \Phi)$  is then obtained using a nearest-neighbor interpolation for the source height. The maximum difference between the fictive position of the source and the exact source height is thus  $\Delta H/2$ . This fictive position is only used to calculate the  $\Delta L(\omega, \Phi)$ , since the variables  $\text{SWL}(\omega, \Phi)$  and  $R_1$  are calculated from the exact source positions.



**Figure 1.** Schematics of the moving monopoles approach with a receiver located at  $(\mathbf{x}_R, 0, z_R)$ .

## 2.2 Propagation model

The propagation model is a Wide-Angle Parabolic Equation (WAPE) method with a numerical scheme based on higher order Padé (2,2) approximants [20, 21] and solved with the method of Collins [22] called split-step Padé (2,2). The model assumes an inhomogeneous propagation medium modeled through the effective sound speed hypothesis  $c_{eff} = c + v_x$ , with  $v_x$  the wind velocity component along the direction of sound propagation between the source and receiver, and  $c$  the adiabatic sound speed. The WAPE model is derived from the Helmholtz elliptic equation for the sound pressure. The WAPE can be solved for the wave propagating in the positive  $x$  direction ( $\delta = +1$ ) or negative  $x$  direction ( $\delta = -1$ ):

$$\frac{\partial \phi(x, z)}{\partial x} = j k_0 \delta (\mathcal{Q}_{pd} - 1) \phi(x, z), \quad (6)$$

where  $\phi(x, z) = \sqrt{x} p_c e^{-j(\delta k_0 x)}$  is an envelope function that varies very little with distance,  $p_c$  the complex pressure,  $k_0 = \omega/c_0$  is the acoustic wave number, with  $c_0$  a reference sound speed, and  $\mathcal{Q}_{pd}$  is a pseudo-differential operator whose square is defined as:

$$\mathcal{Q}_{pd}^2 = \frac{1}{k_0^2} \frac{\partial^2}{\partial z^2} + \epsilon^2, \quad (7)$$

with  $\epsilon = c_0/c_{eff}$  the index of refraction.

The WAPE is solved at each spatial step, chosen here as  $\lambda/20$  with  $\lambda$  the wavelength. As methods based on the parabolic equation can solve acoustic propagation problems above a mixed ground in a refractive and scattering atmosphere, it makes them particularly suitable and accurate for acoustic simulations in long-range outdoor sound propagation [23].

### 2.2.1 Ground effects

Acoustic properties of the ground (porous absorption and scattering) are taken into account by an effective admittance model [24]. The implementation of this formulation

in the parabolic equation model considered here has been validated and detailed in [21]. The effective admittance  $\beta_{eff}$  is defined as follows:

$$\beta_{eff} = \beta + \beta_{rough} = \frac{1}{Z} + \beta_{rough}, \quad (8)$$

where  $Z$  is the acoustic impedance of the ground and  $\beta_{rough}$  the average effect of surface roughness on acoustic propagation. As a first approximation,  $Z$  is described in this study by the dimensionless notation of the Miki's impedance model [25]:

$$\frac{Z}{Z_0} = 1 + 6.17 \left( \frac{\rho_0 f}{a_{fr}} \right)^{-0.632} + i9.44 \left( \frac{\rho_0 f}{a_{fr}} \right)^{-0.632}, \quad (9)$$

$$\frac{k}{k_0} = 1 + 8.73 \left( \frac{\rho_0 f}{a_{fr}} \right)^{-0.618} + i12.76 \left( \frac{\rho_0 f}{a_{fr}} \right)^{-0.618}, \quad (10)$$

where  $Z_0 = \rho_0 c_0$  is the specific impedance of air,  $\rho_0$  the density of air,  $c_0$  the celerity of sound in the air,  $k_0 = \omega/c_0$  the acoustic wavenumber of air,  $k$  the wavenumber of the ground,  $\omega = 2\pi f$  with  $f$  the frequency and  $a_{fr}$  the ground airflow resistivity ( $\text{kN.s.m}^{-4}$ ).

The  $\beta_{rough}$  expression, corresponds to a 2D rough surface with a small and slowly-varying roughness [26], it is given by:

$$\beta_{rough} = \int_{-\infty}^{+\infty} \frac{d\kappa'}{k_0 k_z(\kappa')} (k_0^2 - \kappa \kappa') W(\kappa - \kappa'), \quad (11)$$

with  $\kappa = k_0 \sin \theta_i$  where  $k_z(\kappa) = \sqrt{k_0^2 - \kappa^2}$  and  $W$  the roughness spectrum of the ground. The roughness spectrum is the Fourier Transform of the autocorrelation function of the surface height profile (see [27] for more details). Considering that the probability density of the ground roughness heights is a normal distribution,  $W$  can be written as follows [28]:

$$W(k) = \frac{\sigma_h^2 l_c}{2\sqrt{\pi}} e^{-\frac{k^2 l_c^2}{4}}, \quad (12)$$

where  $\sigma_h$  is the standard deviation of the ground roughness heights, and  $l_c$  the correlation length of the horizontal variations of the ground.

### 2.2.2 Medium effects

In this study the ground presents an acoustic roughness, but the topography is considered as flat, so we assume that the atmosphere flux gradients are not range dependent in the horizontal direction  $x$ . It is then possible to neglect the evolution of the profiles according to distance. The average vertical profile of effective celerity is then defined as follows:

$$c_{eff}(z) = \sqrt{\gamma RT(z)} + U(z) \cos \theta, \quad (13)$$

with  $\gamma = C_p/C_v$  the heat capacity ratio of dry air at a constant pressure and volume,  $R$  the specific gas constant for dry air, and  $\theta$  the angle between the wind direction and the direction of sound propagation.  $U(z)$  and  $T(z)$  are the mean vertical wind speed and air temperature profiles. The shapes of these micrometeorological profiles can be approached according to different methods, such as the

Monin-Obukhov's similarity theory [29], or power laws for example. In this study the micrometeorological flux are assumed to have logarithmic profiles defined as follows:

$$U(z) = a_u \ln \left( \frac{z-d}{z_0} \right), \quad (14)$$

$$T(z) = T_0 + a_T \ln \left( \frac{z-d}{z_0} \right), \quad (15)$$

where  $T_0$  (K) is the ground surface temperature,  $a_u$  ( $\text{m.s}^{-1}$ ) and  $a_T$  ( $\text{K.m}^{-1}$ ) are coefficients that determine the shape of the profiles,  $d = 0.66h_v$  is the displacement height accounting for the influence of vegetation height  $h_v$  (m) on all vertical profile, and  $z_0 = 0.13h_v$  is the roughness height of the flux profiles [30]. Moreover, atmospheric absorption is taken into account in the model in accordance with the standard [31], which depends on air temperature  $T$  (K), atmospheric pressure  $p_{atm}$  (Pa) and the relative humidity of air  $h_r$  (%).

## 3. SENSITIVITY ANALYSIS

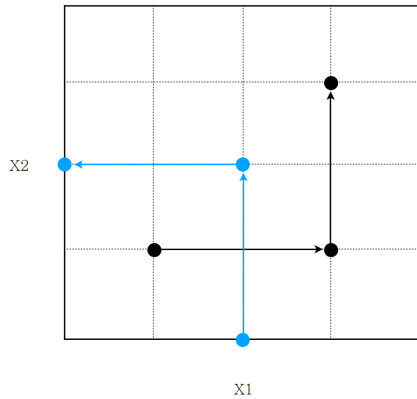
Sensitivity analysis of a model is the study of the relative influence of the different input parameters on the output. Usually, the sensitivity of a model to its input is obtained by performing a specific design of experiment. The induced effects on the output of each calculation of the design of experiment allows one to quantify the sensitivity of each input parameter. Two main categories of design of experiment exist: One-At-a-Time (OAT), which means that the value of a single parameter has changed between two calculations (this method does not take into account interactions between variables), and full factorial designs which tests all possible combinations of parameters (often impossible to implement because it is too expensive in terms of calculation time). As in [21], the Morris' method [32] is used because it overcomes the limitation of an OAT design, while keeping a cost that increases linearly with the number of input parameters.

### 3.1 Morris method

This method repeats  $n$  times ( $n = 5$  to  $10$ ) an OAT designs randomly in the input space [33], where each input variation interval is discretized into a suitable number of levels (depending on the number  $n$  of repetitions to be performed). This leads to  $n(m+1)$  runs, where  $m$  is the number of input variables. The Fig. 2 illustrates this method with  $n = 2$  designs of experiment, and  $m = 2$  parameters. Each repetition  $i$  ( $i = 1 \dots n$ ) of the design of experiment allows one to evaluate an elementary effect  $E_j^{(i)}$  (between 2 successive calculations) by input parameters  $X_j$ . The entire experimental design provides a  $n$ -sample of effects for each input, from which sensitivity indices are derived and expressed in dB : mean value of the effects  $\mu$ , mean absolute values of the effects  $\mu^*$  and standard deviation of the effects  $\sigma$ . In this study we focus on the  $\mu^*$  indice:

$$\mu^* = \frac{1}{n} \sum_{i=1}^n |E_j^{(i)}|. \quad (16)$$

Thus, the larger  $\mu^*$ , the more the parameter contributes to the spread of the output, because it means that the elementary effect  $E_j^{(i)}$  are important. It is therefore an influential parameter.



**Figure 2.** Illustration of Morris' method with  $n = 2$  designs of experiment represented by each colors, and  $m = 2$  parameters X1 and X2. The variation intervals of the parameters are discretized into 5 levels. The arrows represent the design of 2 specific experiment trajectories (the value of a parameter is modified during a trajectory), and the calculations are represented by the  $n(m + 1) = 6$  points.

### 3.2 Case study

The case study is a wind turbine of nominal power 2.3 MW and of diameter 93 m. The hub height is 80 m and the three blades of 45 m length are decomposed into 8 segments, as done in [15]. The rotational speed is supposed to increase linearly from 6 rpm at the cut-in wind speed of  $4 \text{ m.s}^{-1}$ , to 16 rpm at the rated wind speed of  $12 \text{ m.s}^{-1}$  [15]. As the physical phenomena studied depend on frequency, and considering the wind turbine sound power spectrum, we perform a sensitivity analysis at 14 different frequencies from 50 Hz to 1000 Hz. These frequencies correspond to the center frequencies of the third octave bands. The relative influence of the input parameters (see table 1) are then quantified at two points in the calculation domain : receiver 1 ( $x = 500, z = 2$ ) m and receiver 2 ( $x = 1500, z = 2$ ) m, which, in the case of wind turbine noise, can be considered respectively as medium and long range propagation cases.

### 3.3 Parameters

The prediction model (emission and propagation) depends on 9 parameters listed in Table 1. In order to build the Morris' design of experiments (see section 3.1), the intervals of variation of the 9 parameters considered are discretized into 4 values (see table 1). This study focuses on downwind propagation conditions because they usually represent the most detrimental conditions for neighbourhood, because the SPL is significantly lower in upwind and crosswind conditions at long range [34]. The atmospheric turbulence is not taken into account because its influence

on sound propagation is usually negligible for these conditions. Nevertheless, specific downwind conditions ( $\theta$  close to  $90^\circ$ ) combined with negative temperature gradients, see Eq. (13), can lead to the creation of shadow zone where turbulence can be not negligible. In order to avoid unrealistic SPL in the shadow zone in these rare situations (less than 8% for the  $(\theta, a_u, a_T)$  combinations considered here), following [35] the turbulence is accounted by introducing a limit of  $\Delta L \geq -25$  dB. The variation intervals of the ground parameters ( $a_{fr}, l_c$  and  $\sigma_h$ ) are chosen from values found in previous *in situ* experimental campaigns [5, 36, 37]. Also, we focus on low vegetation height so the  $h_v$  parameter has a maximum of 1 m. The  $h_r, T_0$  and  $a_T$  parameters are representative average values for temperate countries. The values of the wind profile coefficient  $a_u$  are chosen to cover the entire operating range of the wind turbine.

## 4. RESULTS

The method starts by performing  $n(m + 1) = 100$  calculations of the design of experiments for each of the 14 monochromatic calculations. It ends up with a total of 1400 noise maps. To obtain the sensitivity indices presented in Fig. 3, these maps are analyzed by the Morris' method (see Sec. 3.1). The figure 3 shows the evolution of  $\mu^*$ , which represents the absolute value of the mean effects (dB) of the 9 parameters over the 14 central frequencies of the third octave bands considered. The results are obtained at the two receivers (section 3.2) which are located at 500 m and 1500 m from the wind turbine, at 2 m above the ground.

We first notice that the wind coefficient  $a_u$  is the most influential parameter, with  $\mu^*$  values about 20 dB for all the frequencies and receivers, which means that the sound levels vary on average by 20 dB when the wind coefficient  $a_u$  varies within the range defined in Tab. 1. This is consistent with the physics because the wind gradient coefficient influences both noise emission and sound propagation : the wind influences the rotational speed of the blade (and so the acoustic emission), and also plays a role in refraction effects through atmospheric stratification. The wind and source-receiver angle  $\theta$  has also a high influence on SPL ( $6 < \mu^* < 14$  dB), which is explained by the important role of this parameter in acoustic emission through the source directivity, and in acoustic propagation through the acoustic refraction (see Eq. (13)). The vegetation height  $h_v$  is an important parameter with  $\mu^*$  values of several dB. These results are due to the role of  $h_v$  in the atmospheric flux profiles gradients (see Eq. (15) for wind vertical gradient and temperature vertical gradient) that influence both noise emission (through wind vertical gradient) and sound refraction (through both wind and temperature vertical gradient). The airflow resistivity of the ground  $a_{fr}$ , which accounts for the ground absorption impedance, has an important impact on SPL with  $\mu^*$  values of several dB. In this case study, the temperature profile coefficient  $a_T$  and the ground surface temperature  $T_0$  seem to have a marginal influence on SPL with  $\mu^*$  values about 2 dB. These pa-

Parameters	Description	Case 1	Case 2	Case 3	Case 4
$a_{fr}$ (kN.s.m <sup>-4</sup> )	airflow resistivity of the ground	50	500	1000	5000
$l_c$ (m)	correlation length of the rough ground	0.05	0.37	0.68	1
$\sigma_h$ (m)	standard deviation of the roughness height	0.01	0.023	0.037	0.05
$h_r$ (%)	relative humidity of air	40	60	80	100
$T_0$ (°C)	ground surface temperature	0	10	20	30
$a_T$ (K.m <sup>-1</sup> )	temperature profile coefficient	-0.5	-0.25	0	0.25
$a_u$ (m.s <sup>-1</sup> )	wind profile coefficient	0.67	0.98	1.33	1.67
$h_v$ (m)	vegetation height	0	0.33	0.66	1
$\theta$ (m)	wind and source-receiver angle	0	30	60	90

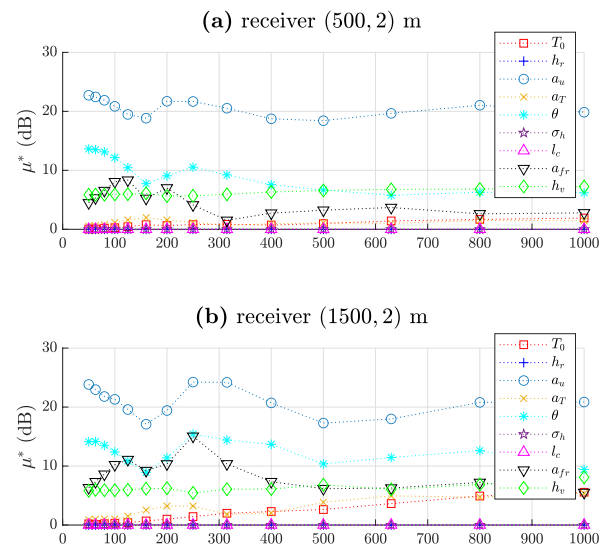
**Table 1.** Discretization of the variation intervals of the inputs parameters with 4 values for the Morris analysis. The study focuses on downwind conditions.

rameters influence the atmospheric stratification through the modification of temperature vertical gradient. Finally, compared to the other parameters, the ground roughness parameters  $l_c$  and  $\sigma_h$  seem to have a marginal influence on the variation of sound levels considering their  $\mu^*$  values in the order of one decibel. It should be noted that these observations related to ground roughness influence are only valid in the context of this study on wind turbine noise, which considers a high altitude and extended sound source with a spectrum that does not consider higher frequencies than 1000 Hz. Indeed, other studies have shown the importance of ground roughness on acoustic propagation [38], even for a non-grazing sound source [21] when no meteorological effects take place. The last parameter  $h_r$  also has a very low  $\mu^*$ . As the humidity mainly affects atmospheric absorption, which has only a significant impact on high frequencies, this result is not surprising given the frequency band considered here (50; 1000 Hz). Finally, it can be noticed that the effects of all the parameters seem to be higher at receiver 2 (1500 m) than at receiver 1 (500 m). This is simply due to the fact that the propagation effects are cumulative and logically increase with the distance.

## 5. CONCLUSION

This study presents a sensitivity analysis of a wind turbine noise propagation model. It classifies the environmental parameters by order of influence on SPL variability. Atmospheric conditions are considered through 6 parameters: the wind and temperature profile coefficients, the humidity of air, the angle between the wind and the source-receiver directions, the vegetation height and the ground surface temperature. Ground properties are taken into account through 3 parameters: the airflow resistivity of the ground, the standard deviation of the roughness height and the correlation length of the rough ground.

This study provides a quantitative (dB) classification of the parameters. The 4 most influential parameters are: the wind profile coefficient, the angle between the wind and the source-receiver directions, the vegetation height, and the airflow resistivity of the ground. The second order parameters are the temperature profile coefficient and the ground surface temperature which influence refraction through the modification of the temperature vertical profile. The non influential parameters are the two ground



**Figure 3.** Values of  $\mu^*$  for each frequency for the 9 varying environmental parameters with a receiver located at (500,2) m and (1500, 2) m. Emission and Propagative effects.

roughness parameters (correlation length and standard deviation of the roughness height), and the air humidity which is only influential at higher frequencies that the wind turbine spectrum considered here, through atmospheric absorption effect. Although the numerical value of sensitivity results are mainly valid for this study and could vary for another test configuration (for example with a grazing point source and/or other receiver positions), the results provide useful information on the order of magnitude of the influence of several parameters and on the relative influence between parameters. These conclusions will help to calculate uncertainties because it is then possible to "discard" non-influential parameters by considering them as constant, and so to reduce the complexity of the problem for further analysis (uncertainty quantification). A better knowledge of these variabilities and uncertainties will provide a better control of the quality of wind turbine noise prediction in an inhomogeneous outdoor environment.

This study could be further improved by the consideration of atmospheric turbulence, and by extending the anal-

ysis to upwind conditions. Also, it could be interesting to take into account several wind turbine sources to model a windfarm. Lastly the results could be compared with *in situ* measurements in order to verify the variability range of total SPL.

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