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Sensitivity analysis of influential parameters for wind turbine noise

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Summary

Wind turbine noise is directly concerned by physical phenomena related to long-range sound propagation, i.e. ground effects (roughness, impedance), and micrometeorological effects (mean refraction, intermittency fluctuations, small-scale turbulence scattering).
In order to estimate the relative influence of these environmental and influence parameters on acoustic propagation, we present a sensitivity analysis based on a propagation model and on a specific numerical experiment design produced by a Morris screening method. The model used is a Parabolic Equation model (MW-WAPE) which takes into account ground effects (absorption through acoustic impedance diffusion through surface roughness) and micrometeorological effects (mean refraction through the vertical gradient of effective celerity atmospheric turbulence through the random Fourier modes technique).
The results allow the quantification of the global variability and uncertainties associated with main phenomena occurring in the emission-propagation-reception process. The results will allow quantifying the overall variability and uncertainties associated with the emission-propagation-reception sound chain. A better knowledge of these uncertainties will provide a better control of the quality of wind turbines noise prediction in an inhomogeneous outdoor environment.

1. Introduction

The noise emitted by wind turbines in operation can be the cause, in certain situations, of an annoyance reported by residents of wind farms. This sometimes leads to opposition against the development of these renewable energies, or to the implementation of degraded operating modes (acoustic curtailments) of the concerned wind farms, at the detriment of energy and environmental efficiency. Satisfactorily estimating the noise pollution potentially induced by wind turbines is a socio-economic and health challenge that requires the definition of reliable methods for predicting and estimating noise levels in the environment. Although the wind energy sound source has been the subject of many studies in recent years (sound emissions[9], directivity [24], sound power [1]), little work has focused on the influence of environmental parameters on the variability of the sound levels encountered. However, there is now a major challenge in estimating the accuracy and representativeness (spatial and temporal) of sound level measurements in non-homogeneous outdoor space. 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.

Predicting the variability (deterministic and random) of sound levels at the output of prediction models will therefore require both (i) refining the models, (ii) estimating fluctuations in all input data, (iii) performing an optimized numerical experiment design, and (iv) using advanced techniques for uncertainty propagation and sensitivity analysis of complex systems. The final objective is to develop a method that allows to more accurately assess the uncertainties of the entire modelling chain due to deterministic variability and random uncertainties in influential parameters: wind farm operating regime, micrometeorological conditions (atmospheric stability and turbulence), ground acoustic properties (acoustic impedance), surface roughness (spatial spectrum), etc.

The purpose of this paper is to present the relative influence of parameters known to be the most influential on acoustic propagation: ground effect through absorption and roughness, and atmospheric stratification effect through the wind and temperature gradient. It is organized as follows: Section 2 introduces the model used and describes how it takes into account the above-mentioned effects; Section 3 describes the sensitivity analysis method followed, the parameters analyzed, and presents the results of the numerical experimental design.

2. Parabolic Equation model

2.1. Principles of PE model

The propagation model considered is a parabolic equation model with fractional steps called split-step Padé, based on higher order Padé (2,2) approximants [12] and solved with the method of Collins [13]. The model assumes an inhomogeneous propagation medium without any overall motion (mean-wind). In this approach, the real moving atmosphere is replaced by hypothetical motionless medium with the effective sound speed $c_{eff} = c + v_x$, where v_x is the wind velocity component along the direction of sound propagation between the source and receiver, and c is the adiabatic sound speed. It is based on the Mean-Wind Wide-Angle Parabolic Equation (MW-WAPE) derived from the Helmholtz elliptic

equation for the sound pressure as described in [20]:

$$\left(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{\partial^2}{\partial z^2} + k^2\right) p(r,z) = 0 \tag{1}$$

with $k = \omega/c_0$. Then the pressure $p(r,z)$ is split in two components:

$$p(r,z) = u(r,z)H_0^{(1)}(kr) \approx \frac{1}{\sqrt{r}}u(r,z)e^{jkr} \tag{2}$$

where $u(r,z)$ is an envelope fuction that varies very little with distance, and $H_0^{(1)}$ is a propagative cylindrical wave represented by the asymptotic expression of the Bessel function of the 1st kind and of the order 0. The evolution of $u(r,z)$ is governed by the equation:

$$\frac{\partial u(r,z)}{\partial r} = jk\left(Q_{pd} - 1\right)u(r,z) \tag{3}$$

with Q_{pd} a pseudo-differential operator defined as:

$$Q_{pd}^2 = \frac{1}{k^2}\frac{\partial^2}{\partial z^2} + n^2 \tag{4}$$

and $n = c_0/c_{eff}$ is the index of refraction.

As the MW-WAPE equation is solved at each spatial step (chosen here as $\lambda/20$ along the longitudinal axis), it is possible to modify the propagation effects (*i. e.* ground impedance or the effective celerity profile) at each forward step. Thus, the model can solve acoustic propagation problem above a mixed ground in a refractive and turbulent atmosphere. This elements makes parabolic equation based methods particularly suitable and accurate for acoustic simulations in long-range outdoor sound propagation [14] [25] [4][5] [3] [18] [6]. Furthermore, recent work has made it possible to take into account soil roughness by using effective admittance as a boundary condition for the ground in our PE model.

2.2. Ground effects

Acoustic properties of the ground (porous absorption, impedance and diffusion) are described by an effective admittance model [10]:

$$\beta_{eff} = \beta + \beta_{rough} = \frac{1}{Z} + \beta_{rough} \tag{5}$$

The effective admittance can be seen as an additive correction to the normalized admittance $\beta = 1/Z$ with Z the impedance of the ground described by the Miki's impedance model in our code [21]:

$$Z = Z_0\left[1 + 5.50\left(\frac{f}{a_{fr}}\right)^{-0.632} + i8.43\left(\frac{f}{a_{fr}}\right)^{-0.632}\right] \tag{6}$$

$$k = k_0\left[1 + 7.81\left(\frac{f}{a_{fr}}\right)^{-0.618} + i11.41\left(\frac{f}{a_{fr}}\right)^{-0.618}\right] \tag{7}$$

where $Z_0 = \rho_0 c_0$ is the specific impedance of air, $k_0 = \omega / c_0$ the acoustic wavenumber, ρ_0 the density of air, c_0 the celerity of sound in the air, $\omega = 2\pi f$ with f the frequency, and a_{fr} the ground airflow resistivity.

β_{rough} gives the average effect of surface roughness on acoustic propagation and it is modeled by the following equation [11] [8]:

$$\beta_{rough} = \int_{-\infty}^{+\infty} \frac{\mathrm{d}\kappa'}{k_0 k_z(\kappa')} (k_0^2 - \kappa\kappa') W(\kappa\kappa') \tag{8}$$

with $\kappa = k_0 \sin\theta_i$ where θ_i is the incidence angle of the acoustic wave with the ground and $k_z(\kappa) = \sqrt{k_0^2 - \kappa^2}$. Considering that the probability density of the ground roughness heights follows a normal distribution, the roughness spectrum $W(\kappa\kappa')$ is defined in the wave numbers space by [8]:

$$W(k) = \frac{S_h^2 L_c}{2\sqrt{\pi}}^{-\frac{k^2 L_c^2}{4}} \tag{9}$$

with S_h the standard deviation of the ground roughness heights, and L_c the correlation length. S_h gives information on the vertical variations of the roughness, while the correlation length L_c reflects the horizontal variations of the roughness [11].

2.3. Atmospheric stratification effects

The atmospheric stratification effects on acoustic waves are taken into account *via* the assumption of effective celerity. In the case of a flat and clear ground, the atmosphere is considered homogeneous in the horizontal direction. It is then possible to neglect the evolution of the effective celerity according to distance. The average profile of effective celerity is then defined as follow :

$$\left\langle c_{eff}(z) \right\rangle = \sqrt{\gamma R \left\langle T(z) \right\rangle} + \left\langle V(z) \right\rangle \cos\theta \tag{10}$$

The vertical gradient of effective celerity is therefore expressed as:

$$\partial_z c_{eff} = \frac{1}{2}\sqrt{\frac{\gamma R}{T(z)}} \partial_z T(z) + \partial_z V(z) \cos\theta \tag{11}$$

$$\approx \frac{1}{2}\frac{\gamma R}{c_0} \partial_z T(z) + \partial_z V(z) \cos\theta \tag{12}$$

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 θ the angle between the wind direction and the direction of sound propagation. $V(z)$ and $T(z)$ are the vertical wind and temperature profiles, which are expressed as the sum of a mean part (symbol $\langle\ \rangle$) and a turbulent random part (symbol ')

$$V(z) = \langle V(z) \rangle + V'(z) \tag{13}$$

$$T(z) = \langle T(z) \rangle + T'(z) \tag{14}$$

$$\tag{15}$$

these micrometeorological profiles can be approached by logarithmic profiles defined as follows:

$$\langle V(z) \rangle \approx a_u \ln\left(\frac{z-d}{z_0}\right) \tag{16}$$

$$\langle T(z) \rangle \approx T_0 + a_T \ln\left(\frac{z-d}{z_0}\right) \tag{17}$$

and their derivatives by the expressions:

$$\partial_z V(z) \approx a_u \frac{1}{z-d} \tag{18}$$

$$\partial_z T(z) \approx a_T \frac{1}{z-d} \tag{19}$$

$$\tag{20}$$

where a_u and a_T are coefficients (unitless) that determine the shape of the profiles, d the displacement height and z_0 the roughness height of the flux profiles.

3. Sensitivity analysis

3.1. Morris method

Sensitivity analysis is the study of the relative influence of different input factors on the model output. The simplest and most common way to study the sensitivity of a model is to modify its inputs one by one ("One-At-a-Time": OAT), the others remaining fixed at a nominal value [19]. The induced effect on the output is then quantified and attributed to the parameter in question. The main problem with this method is that it does not take into account the effects induced by interactions between input parameters. To do so, a complete factorial design method can be follow. It consists in evaluating the calculation code for all combinations of input parameters, which allows the estimation of all input effects and their interactions. In practice, the number of simulations required makes this plan often unfeasible because it increases according to a power law in the number of input parameters. The experimental design becomes too expensive in terms of calculation costs.

Morris method [22] [26] makes it possible to overcome the limiting assumptions of the OAT plan while keeping a cost that increases linearly with the number of input parameters. Morris' method consists in repeating r times ($r = 5$ to 10) [27] [17] an OAT plan randomly in the input space, discretizing each input into a suitable number of levels (depending on the number r of repetitions to be performed) which leads to a number of $r(k+1)$ runs, where k is the number of input variables. The method starts by sampling a set of start values within the defined ranges of possible values for all input variables and calculating the subsequent model outcome. The second step changes the values for one variable (all other inputs remaining at their start values) and calculates the resulting change in model outcome compared to the first result. Next, the values for another variable are changed (the previous variable is kept at its changed value and all other ones kept at their start values) and the resulting change in

model outcome compared to the second run is calculated. This goes on until all input variables are changed. An example of the method is shown in figure 1 for $k = 2$ & $r = 2$.

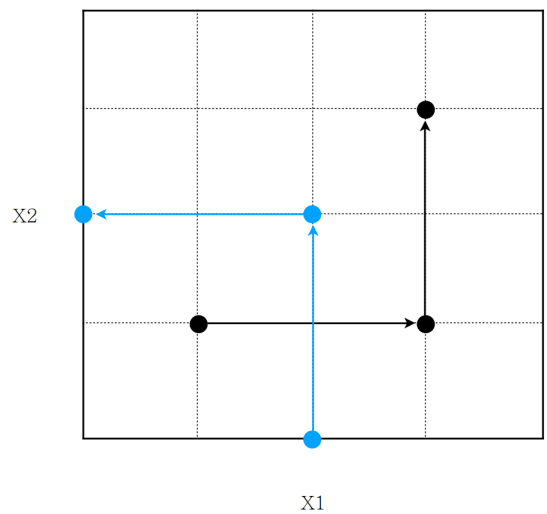

Fig. 1 Illustration of Morris' method with $k = 2$ and $r = 2$. The model has 2 inputs parameters X1 and X2 whose variation intervals are discretized into 5 levels. The calculations of the experimental design are represented by the points. The arrows represent the trajectories of the method (the value of a parameter is modified during a trajectory).

Each repetition i ($i = 1...r$) allows to evaluate an elementary effect (between 2 successive calculations) by input parameters. The entire experimental design provides a $r-$sample of effects for each input, from which the sensitivity indices are derived:

- μ^*, average of the absolute values of the effects,
- μ, average of the values of the effects,
- σ, standard deviation of the effects.

Thus, the more important μ^* is, the more the parameter contributes to the dispersion of the output. σ measures the linearity of the model: if the model output is linearly dependent on the X_n parameter studied, and X_n does not interact with other inputs, the effect of an elementary perturbation of X_n is the same regardless of its position in the input parameter space. In this case $\sigma = 0$. Therefore, the higher the σ is compared to μ^*, the less relevant is the assumption of linearity and non-interaction. Thence, Morris' method allows entries to be classified into 3 categories:

- inputs with negligible effects (low μ^* and σ)
- inputs with linear effects and no interaction (high μ^* and low σ)
- inputs with non-linear effects and/or interactions without distinction between the two (high σ compared to μ^*).

3.2. Study parameters

For this study we focus on the relative influence of the parameters known to be most influential in long-distance acoustic propagation: *i. e.* the ground effects (through roughness and absorption) and

atmospheric stratification (through vertical wind gradient and vertical temperature gradients). Future work will lead to more exhaustive conclusions by taking into consideration other parameters, such as air humidity or vegetation height (which has an influence on the displacement height of vertical flux profiles) for example.

The first step in the sensitivity analysis is to determine the influence parameters that we want to study and their ranges of variation. For the ground effects we have chosen 3 parameters: a_{fr} (airflow resistivity of the ground), L_c (correlation length of the roughness) and S_h (standard deviation of roughness height). Their variation intervals for natural ground are visible in the table 1 [16] [23] [7] [15] [2]. For the refraction we have taken into account 2 parameters: the coefficients a_u and a_T. These coefficients are used to calculate the logarithmic wind and temperature profiles, as well as their derivatives over the height z. The range of variation of the a_u coefficient has been determined with respect to the operating ranges of the wind turbines; i.e. the lower bound corresponds to a wind of $3m.s{-}1$ at the nacelle, and the upper bound corresponds to a wind of $25m.s{-}1$ at the nacelle. For the thermal coefficient, the bounds were determined in accordance with the different profiles possibly encountered outdoor.

Then we chose to set up the Morris method with $r = 10$, and 4 levels of discretization for the intervals of variation of the input parameters. These values correspond to the values typically encountered during sensitivity analysis with this method (good compromise between the number of calculations and the coverage of the input space) [27] [17]. The table 1 shows the values that can be taken by the parameters studied. For each calculation of the experimental design, each parameter will be assigned a value (according to the Morris method) indicated in this table.

Parameters	min value	case 2	case 3	max value	Description
a_{fr} $(kNsm^{-4})$	50	500	5000	50000	airflow resistivity of ground
L_c (m)	0.05	0.37	0.68	1	correlation length of rough ground
S_h (m)	0.01	0.23	0.037	0.05	standard deviation of roughness heights
a_u	0.25	0.78	1.32	1.85	aerodynamic refraction coefficient
a_T	-0.5	-0.25	0	0.25	thermal refraction coefficient

Table 1 Description and values that can be taken by the 5 parameters into the sensitivity analysis.

3.3. Results

The study was conducted for an omnidirectional point source located at $100m$ height. The propagation domain is $500m$ high and $1500m$ long. The relative influence of the parameters has been quantified at two specific points in this domain: microphone1($x = 500$,$z = 2$)m & microphone2($x = 1500$,$z = 2$)m. They correspond to a case of medium and long range sound propagation. The following figure shows an example of mapping obtained at $f = 50$Hz with the parabolic equation model, in the case of a fairly reflective ground (very marked interferences) and without refraction (unbent interference lobes).

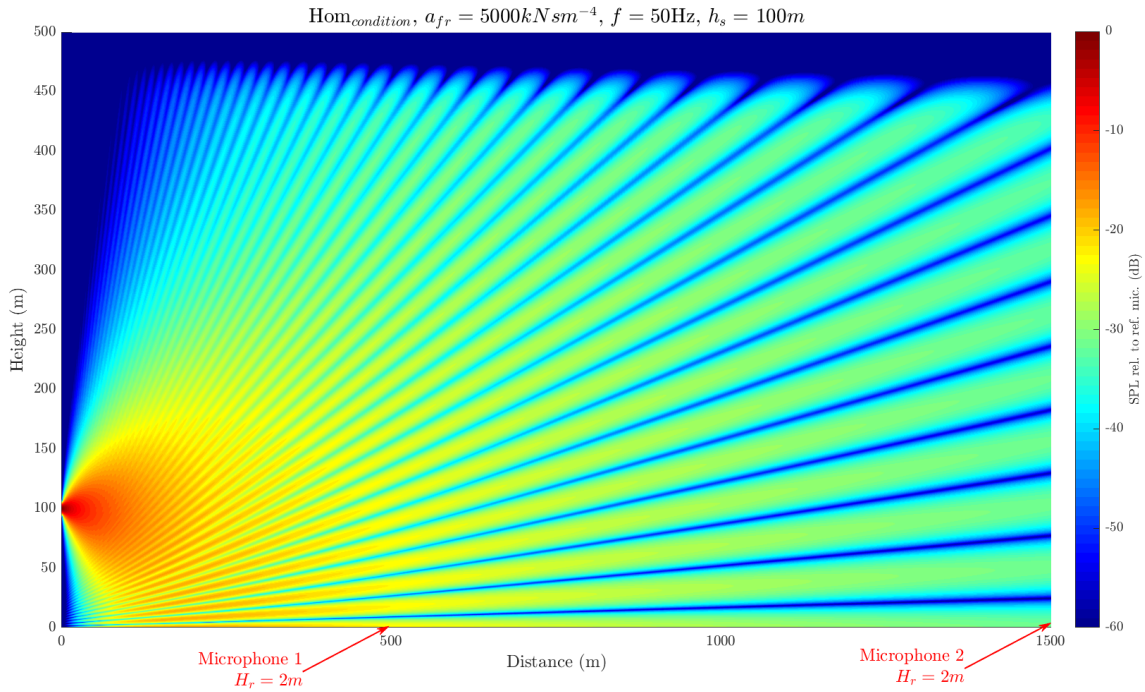

Fig. 2 Example of sound level mapping (attenuation) obtained with PE model.

The calculations of the experimental design will modify the mapping at the output of the model, and therefore the levels measured at microphones 1 and 2. As a result, the relative influence (μ, μ^* and σ) of each parameter is quantified. Some of the physical phenomena studied depend on frequency (i.e. absorption and roughness of the ground), so we carried out a sensitivity analysis per third octave band (50 to 1000Hz) in order to take this into account and not to bias the results. The figure 3 shows the results of the sensitivity analysis.

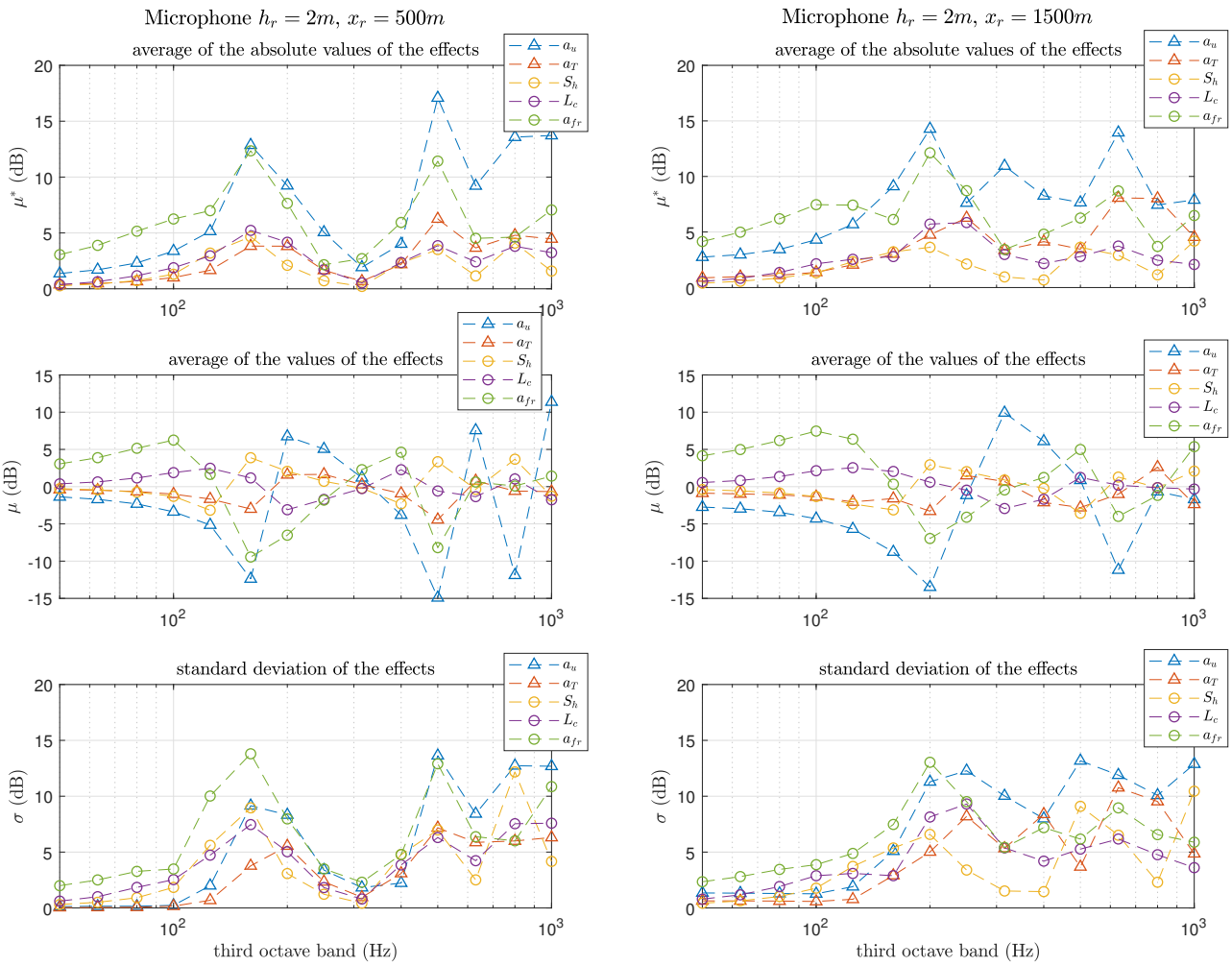

Fig. 3 Evolution of μ^*, μ and σ over the third octave band for: refraction effects (triangle) and ground effect (circle), in a medium range propagation case (left) and long range propagation case (right).

If we look at these figures as a whole, the wind profiles and airflow resistivity seem to be the most influential parameters (higher μ^* and σ) for almost all third octave bands. Nevertheless, the ground roughness and the temperature profile are not to be neglected regarding the values in dB of their respective μ and σ. These results are consistent because the 5 parameters studied are known to influence acoustic propagation.

If we look more closely at the phenomena at low frequencies (< 100Hz), it is ground absorption (a_{fr}) that emerges as the most influential parameters. In contrast roughness has little influence (< 2dB for μ^* and σ). This is due to the fact that ground variations are negligible compared to the wavelengths considered in this frequency range. It can also be noted that the effects for all the 5 parameters are more important at microphone 2 ($1500m$) than at microphone 1 ($500m$). This is in line with the physics

because the sound wave has propagated over a larger range and has therefore been more influenced by all the phenomena.

For frequencies above 100Hz, there is a fairly similar fluctuation of μ^* and σ for all parameters (whether at microphone 1 or 2): increase of the effects around the third octave band 200Hz and 630Hz. This fluctuation is related to the geometry of the system under study. Indeed, there are interference dips at the microphone position for the 200Hz and 630Hz third octaves band. As a result, when the environmental parameters are modified from one calculation to another, the interference patterns change. The microphones can alternatively be located in a minimum and maximum pressure, which leads to a very large dispersion of the results. This is why it is necessary to look at the relative influence of the parameters to conclude. In fact that doesn't mean that all the parameters are more influential at 200Hz and 630Hz third octave bands than at other frequencies, it is the system geometrical configuration that is more sensitive to effects at these measurement points.

Finally, when we consider the relative influence of the parameters, it therefore appears that above 100Hz, wind profile and ground resistivity are very influential parameters on acoustic propagation. The other parameters have also a non negligible influence on sound levels. Furthermore we note that μ^* and σ vary in a similar way regardless of the frequency and that σ is of the same order of magnitude than μ^*. This means that there are no interactions between variables and that the model's linearity assumption is valid for these 5 parameters.

4. Conclusion

In this study, the sensitivity analysis of a parabolic equation model was performed using the Morris method for a point source positioned 100m high above the ground. The relative influence of parameters known to have a strong influence on acoustic propagation (ground effects and atmospheric stratification) was determined at two points in space: a medium-range propagation case ($500m$) and a long-range propagation case ($1500m$) at $2m$ high. The conclusions of this paper are that wind profile and airflow resistivity are the most influential parameters for all third octave bands considered. Nevertheless, the influences of the other parameters (temperature vertical gradient and ground roughness) studied are even not negligible regarding the dispersion in SPL (dB).
Future work will allow other influence parameters to be taken into account, so that in the long term, the global variability and uncertainties associated with the emission-propagation-reception chain of sound will be quantified.

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