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SENSITIVITY ANALYSIS OF WIND TURBINE BROADBAND NOISE ESTIMATION TO SEMI-EMPIRICAL MODELS PARAMETERS

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ABSTRACT

The continuous increase of energy demand and the rising concerns on climate change, are pushing the European Union decarbonization strategies and transition toward renewable based energy systems, with wind energy playing a leading role. It is therefore necessary to have a better understanding of how wind turbines (WTs) interact together and with their surroundings, including maximum noise emissions. Among the different methods to compute aeroacoustic emissions of WTs, semi-empirical models are a valid choice to have a-priori estimations of noise spectra and sound pressure levels. These models are based on correlation laws for different physical mechanisms that contribute to the noise generation. Popular models for dominant noise sources are the Amiet approach for turbulent inflow and the Lowson model for turbulent boundary layer-trailing edge noise. In this work we carry out a sensitivity analysis of the models to the selection of different parameters. The turbulent intensity and dissipation, boundary layer displacement thickness, and the tuning coefficients are randomly varied to assess the major contributions to model sensitivity taking as a test case a reference multi-MW horizontal axis wind turbine.

Keywords: *Wind turbine rotor noise, semi-empirical noise models, Trailing edge noise, Inflow noise*

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1. INTRODUCTION

The increasing penetration of wind turbines and farms in human populated areas rises concerns regarding their impacts on environment and population. In particular, the noise emissions generated by rotors may negatively interfere with local human activities [1]. Even if some authors agree that most of the rotor aerodynamic noise is masked by environmental background noise [2], the researches from Bakker et al. have found psychological distress and sleep disturbances in populations leaving in close proximity of wind turbines [3]. In addition, noise emissions from wind farms and turbines must compel with regional and national regulaments [4].
However, noise prediction of wind turbines may result, in complex and computationally expensive numerical campaigns. Numerical simulations based on medium- and high-fidelity approaches require demanding HPC efforts. Few experimental data are available, and numerical simulations based on medium- and high-fidelity approaches require demanding HPC efforts. Semi-empirical acoustic models (SAMs) are able to estimate the acoustic spectrum and sound pressure level (SPL) by setting a few parameters and operating conditions of the turbine. For istance, Leloudas et al. [5] combined Blade-Element Momentum (BEM) method and semi-empirical models with measurements to estimate noise emissions from a wind turbine test site. A similar approach can be found in Zhu et al. [6] for a small-sized wind turbine. De Girolamo et al. [7] combined the actuator line method with SAMs to have an accurate estimation of WT self-noise.

In SAMs, the predicted SPL may be strongly affected by the modeler's assumption. For example, the Amiet model [8] for turbulent inflow noise, is based on the choice of a proper turbulent length scale and turbulent intensity, that are often difficult to measure or simulate. In this work, we aim to analyze the sensitivity of the broadband noise estimation given by semi-empirical models, to typical model input parameters.

2. SEMI-EMPIRICAL MODELLING OF ROTOR NOISE

Noise emissions in wind turbines as well as in ducted turbomachineries can be ascribed to mechanical and aerodynamic noise, with the latter being predominant. Among the various mechanisms that concur to the noise level, the two dominant sources come from (i) the interaction between WT blades and turbulent inflow, *i.e. inflow-turbulence noise* and (ii) between the sharp edges of the trailing edges and the turbulent vorticity in the boundary layer, *i.e. turbulent boundary layer-trailing edge noise* [6]. The two mechanisms can be estimated using semi-empirical models. The overall sound pressure level (SPL) can therefore computed as:

$$\mathrm{SPL}_{overall} = 10\log_{10}\left(10^{0.1\cdot \mathrm{SPL}_{TI}} + 10^{0.1\cdot \mathrm{SPL}_{TE}}\right) \quad (1)$$

The formulation for inflow-turbulence noise follows the approach of Amiet [9], that expresses the SPL as one-third octave bands at a given frequency as:

$$SPL_{TI} = 10\log_{10}\left(\rho^2 c^4 \frac{L_\epsilon d}{2{r_e}^2} M^5 I^2 \frac{\hat{k}^3}{\left(1+\hat{k}^2\right)^{\frac{7}{3}}}\overline{D}\right) + 78.4 \quad (2)$$

where ρ is the air density, c is the wind velocity, L_ϵ is the dissipation length scale, d is the blade span, r_e is the distance between receiver and source, M the local Mach number, I the turbulent intensity. $\overline{D}$ is a directivity term that keeps in account the position of the receiver, whereas the wavelength $\hat{k}$ can be computed as:

$$\hat{k} = \frac{4}{3}\cdot\frac{2\pi f L_\epsilon}{U} \quad (3)$$

The model has been additionally modified to improve its accuracy at lower frequencies, according to [9].

Based on the Lowson model [10], the SPL due to trailing-edge noise can be estimated as:

$$SPL_{TE} = 10\log_{10}\left(\frac{\delta M^5 d}{{r_e}^2} G(f)\right) + 128.5 \quad (4)$$

where the function $G(f)$ reads as:

$$G(f) = \frac{4\left(\frac{f}{f_p}\right)^{2.5}}{\left[\left(\frac{f}{f_p}\right)^{2.5} + 1\right]^2} \quad (5)$$

The Strouhal peak frequency f_p is a function of the Mach number , the boundary layer thickness δ and boundary layer displacement thickness δ^*, such as:

$$f_p = \frac{0.02 M^{-0.6}}{\delta^*} \quad (6)$$

In the original formulation, the two thicknesses are estimated based on the flat plate theory.

3. METHODOLOGY

The two semi-empirical models have been implemented within a Python framework and tested on the state-of-art Neg-Micon NM80 wind turbine, which has a power capacity of 2.75 MW [11]. These acoustic models specifically rely on the radius, chord, span, and twist parameters of the blade elements used to discretize the 40.04 m long blade, which has been divided into 28 elements. Boundary layer thickness δ, turbulent intensity I, dissipation length L_ϵ, and temperature T were varied as indicated in Table 1, for a total of 28,336 trials.

The parameter limits were determined based on previous investigations. Specifically, the boundary layer thickness limits were obtained using a panel method [12] for Reynolds numbers and angles of attack specific to the analyzed wind turbine, considering operational conditions outlined in [13]. The turbulent intensity and temperature were selected within a range of typical environmental conditions for wind turbine operation. The temperature directly impacts the calculation of density ρ and speed of sound c, which are computed assuming standard atmospheric pressure (101325 Pa). The minimum value of the dissipation length considered is 10 m, as the semi-empirical acoustic models require the assumption of a compact acoustic source, which is valid when the atmospheric dissipation length significantly exceeds the characteristic chord dimensions of the blade (with a maximum value of approximately 3 m in this case).

4. RESULTS

A multi-dimensional map for the overall SPL was built based on the results from parametric analysis. Some of

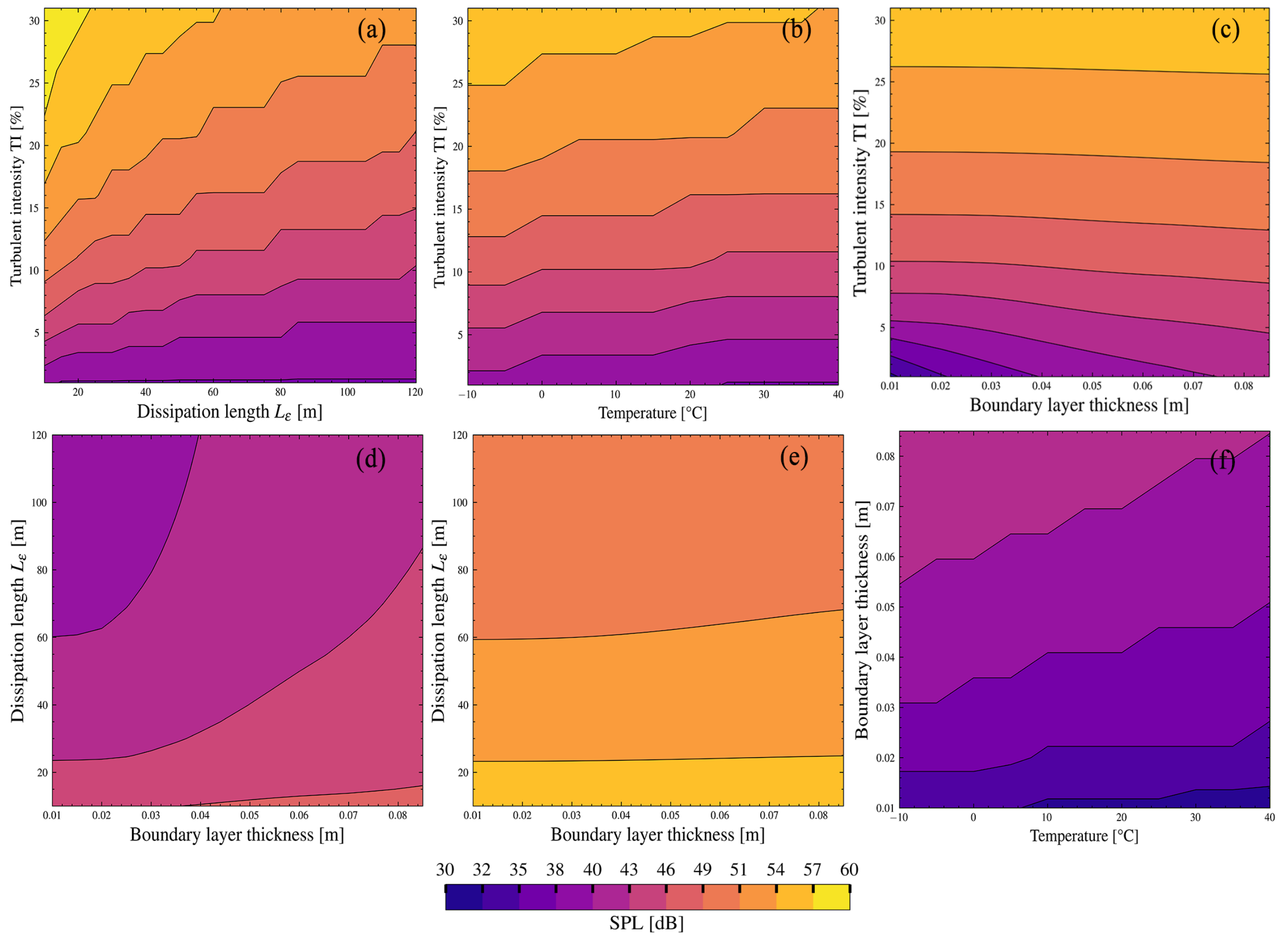

Figure 1. Overall SPL variability for fixed combination of parameters: (a) $L_\epsilon - I$, $\delta = 0.02m$, $T = 20°C$ (b) $T - I$, $\delta = 0.02m$, $L_\epsilon = 40m$ (c) $\delta - I$, $T = 20°C$, $L_\epsilon = 40m$ (d) $\delta - L_\epsilon$, $T = 20°C$, $I = 6\%$ (e) $\delta - L_\epsilon$, $T = 20°C$, $I = 6\%$ (f) $T - \delta$, $I = 1\%$, $L_\epsilon = 40m$.

Table 1. Variability range of the factors included in the analysis.

Variable	Min value	Max value	Step
δ [m]	0.01	0.08	0.005
I $[\%]$	1	31	5
T $[°C]$	-10	40	5
L_ϵ $[m]$	10	120	5

the significant combination and their effects on the overall SPL is reported in Figure 1. The different subplots illustrate the SPL as a function of two variables, with fixed combinations of the remaining factors. The analysis of results suggests that some factors have a drastic impact on the predicted SPL, while large variation of other do not affect the outcome significantly. In particular:

- Dissipation rate and turbulent intensity play a significant role, as small variations lead to peak increases of SPL. This can be observed in (a), where SPL drops from 60 dB to 30 dB. This may seriously impair SAM applicability to case where no reliable data on inflow turbulence are available.
- As a consequence of the Amiet formulation, the SPL increases drastically for high values of turbulent intensity, and it is predominant in the SPL pre-

diction with respect to temperature (b) and δ for $I > 5\%$ (c)

- Temperature has a mild influence on the SPL, as evident from (b) and (f), with a noticeable effect only at extremal values (-10/40 $^{\circ}C$)
- The boundary layer thickness δ shows a certain degree of correlation with the dissipation length selection (d), resulting in an intermediate variation of the SPL from 38 dB (low δ and $L_s > 90m$) to 45-50 dB ($L_s < 5m$). Nevertheless, such correlation can be totally neglected for high values of turbulent intensity ($I > 20\%$)

5. CONCLUSIONS

The implementation of Amiet and Lowson formulations for inflow-turbulence and turbulent boundary layer-trailing edge noise was exploited to carry out the sensitivity analysis of the overall SPL to the selection of parameters. The analysis was performed using the geometry of the Neg-Micon NM80 wind turbine. Turbulent intensity, ambient temperature, dissipation length scale and boundary layer thickness were chosen as factors. Among the variables, the model is strongly dependent on the selection of turbulent intensity and dissipation length, whereas ambient temperature and boundary layer thickness become relevant only in extremal ranges. In particular, temperature plays a marginal role only for the extrema of the considered range. From this analysis we can conclude that the predominant factors are the turbulent intensity and the dissipation length, also suggesting that their estimation must be close to real values to accurately assess the noise emissions from a WT.

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