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INVESTIGATING THE IMPACT OF ATMOSPHERIC BOUNDARY LAYER STRATIFICATION ON WIND FARM NOISE PROPAGATION

Jules Colas[1*] **Didier Dragna**[1] **Ariane Emmanuelli**[1]
Philippe Blanc-Benon[1] **Benjamin Cotté**[2] **Richard Stevens**[3]
[1] Univ Lyon, Ecole Centrale de Lyon, CNRS, Univ Claude Bernard Lyon 1, INSA Lyon, LMFA, UMR5509, 69130, Ecully, France
[2] Institute of Mechanical Sciences and Industrial Applications (IMSIA), ENSTA ParisTech, CNRS, CEA, EDF, Université Paris-Saclay
[3] Physics of Fluids Group, Max Planck Center Twente for Complex Fluid Dynamics, J. M. Burgers Center for Fluid Dynamics, University of Twente, Enschede, The Netherlands

ABSTRACT

The expansion of wind farm installations has been hindered by annoyance issues resulting from the noise emitted by wind turbines. Understanding the factors that affect sound propagation is crucial to mitigate the impact of noise. Atmospheric boundary layer (ABL) stratification strongly affects the noise propagation of isolated wind turbines. However, few studies have looked at the influence of atmospheric conditions on wind farm noise propagation. This study aims to investigate this through numerical simulations. Large eddy simulations (LES) are used to predict the mean flow inside and around the wind farm. The noise from each wind turbine is computed from an extended source model that determines the wind turbine sound production based on its geometry, and on the flow characteristics (wind speed and turbulence intensity). A model based on the parabolic equation is employed to compute the sound propagation based on the flow fields obtained from LES. Neutral, stable and unstable stability conditions are considered for an idealized wind farm layout. The results of this study provide insight into the influence of atmospheric conditions on wind farm sound propagation and can inform the development of effective noise mitigation strategies.

****Corresponding author***: *jules.colas@ec-lyon.fr.*

Keywords: *Wind farm, sound propagation, atmospheric boundary layer*

1. INTRODUCTION

The development of wind farms is essential to meet renewable energy targets and to reduce carbon emissions. However, the noise generated by wind turbines has become a significant issue, leading to annoyance and health concerns [1]. Wind turbine noise comes predominantly from aero-acoustic sound sources [2]. It is broadband, low-frequency and propagates over several kilometers. Furthermore, amplitude modulation, due to the blades' rotation, is identified as a significant cause of annoyance even at long-range distances. While the effect of atmospheric conditions on single wind turbines has been studied [3,4], research on wind farm noise propagation is generally limited to neutral cases [5,6]. However, both the interactions between wind turbines and the internal boundary layer that develops over a wind farm could be affected by varying atmospheric stratification. This study presents a methodology to predict these effects on wind farm noise propagation, including sound pressure level (SPL) and modulation of amplitude (AM). The aim is to develop a better understanding of the impact of ABL stratification on wind farm noise and to provide a foundation for developing effective noise mitigation strategies.

2. NUMERICAL METHOD

The methodology developed to predict wind farm noise is based on three different models, as described in Fig. 1. The first step is to compute a realistic flow in and around the wind farm using large eddy simulation (LES), with larger scales simulated, and smaller eddies modeled with a scale-dependent model [7]. An actuator disk model is used to simulate wind turbine-flow interactions. The simulation code has been validated for various stratification and wind farm layouts [8]. The mean 3D velocity and temperature fields are then fed into an extended source model [9] and a noise propagation model based on a 2D parabolic equation (PE) [10]. The SPL from each segment of the blade at each angular position is computed according to the moving monopole methodology described in [11]. This method allows one to compute the SPL variation by splitting each blade into several sources and computing the SPL for these uncorrelated sources at each angular position. Hence, overall sound pressure levels (OASPL) and AM can be predicted. Because the propagation method used in this study is 2D, several simulations must be performed for different propagation angles all around the turbine in order to obtain the whole SPL field around the wind farm.

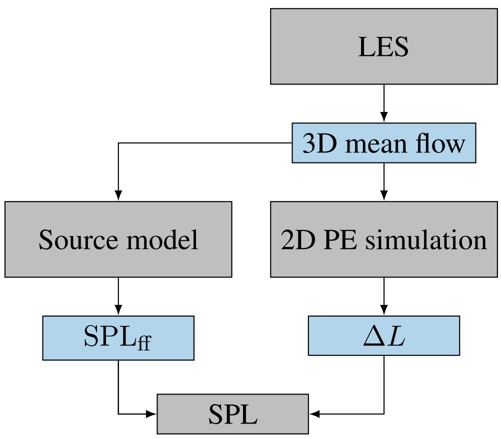

Figure 1. Diagram of the complete wind turbine noise prediction methodology

3. WIND FARM FLOW AND NOISE PROPAGATION

This section presents an illustration of the results attainable through the use of this methodology. Here the wind

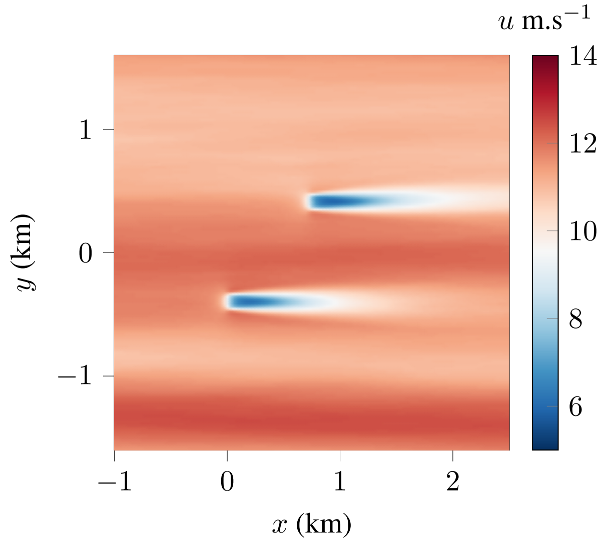

Figure 2. Streamwise velocity component at z = 100 m above the ground for a two-turbine case.

turbine geometry is the same as in Tian and Cotté [9] but with a diameter of 120 m and a hub height of 100 m. First, the flow for an idealized wind farm is simulated with 2 wind turbines as shown in Fig. 2. Results for a neutral ABL are presented here, stable and unstable stratification will also be considered in future studies. The wind speed at hub height is equal to 11.4 m.s^{-1}, and the rotational speed of the turbines is set to 12.1 rpm. The two wakes produced by the turbines are well visible in Fig. 2. Almost no interaction between the wake of the two turbines are visible in this scenario.

The averaged OASPL field, shown in Fig. 3, is obtained from the methodology described in Sec. 2. The dipolar characteristic of the source is well visible with two extinction zones crosswind. This was expected and is a result of the aeroacoustic source model employed. Downwind of both turbines, a small focusing effect can be observed. It is due to the wake of each turbine acting as a wave guide [12]. The wake focuses the sound wave propagating downwind, as the wake recovers the waves are then refracted downward by the ABL wind speed gradient. This focalization is expected to be increased with stable stratification because of stronger velocity gradient and longer wakes. Finally, a shadow zone appears around 500 m upwind of each turbine, due to the negative wind speed gradient [11]. In this scenario no interaction be-

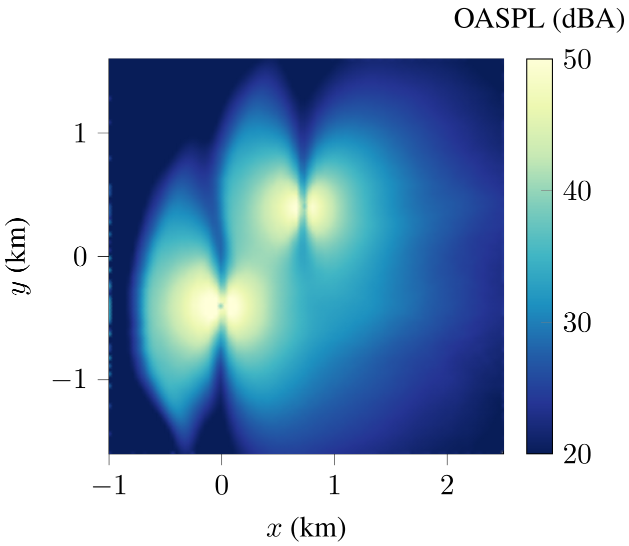

Figure 3. Averaged overall sound pressure level at 2 m height.

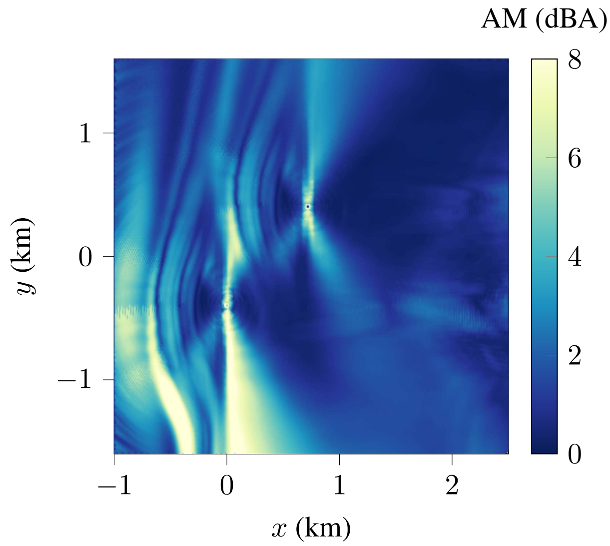

Figure 4. Amplitude modulation at 2 m height.

tween the two turbines are visible. The multi wake propagation in this case seems to be very close to the superposition of the solution for two isolated wind turbines.

The amplitude modulation (AM) is computed by taking the difference between the maximum and minimum OASPL during one rotation. The AM for the case studied is plotted Fig. 4 for a plane at 2 m height. Several phenomena can be described. First an increase in AM is visible crosswind for both turbines. This is directly due to the blade rotation. The source is coming closer and further from the receiver during one rotation. Because the SPL of the two turbines are summed the crosswind AM levels for the second turbines (at $x = 0.7$ km) are lower, due to the contribution of the first turbine (at $x = 0$ km) which reduces the difference between the minimum and maximum of the total SPL.

Another effect of the flow is the AM increase upwind of the two turbines. This increase corresponds to the frontier of the shadow zone, which moves back and forth as the sources move up and down [11]. For the second turbine the same phenomenon is visible with decreased AM due to the contribution of the first turbine. Finally, a very small increase in AM downwind can be attributed to the wake focalization. As the sources move up or down the focalization moves closer and further away from the turbine inducing variation in the SPL during one rotation.

4. CONCLUSION

In this work we developed a methodology to predict wind farm noise by means of numerical simulations. It can handle several ABL conditions, different noise source mechanisms and propagation effects. We show an example of the results obtained with this methodology. Several physical mechanisms of wind turbine noise propagation are captured by the method. Cross wind and upwind shadow regions, downwind focalization and different amplitude modulation phenomena are predicted. Beating effect were left out from this paper for conciseness. They are induced by the superposition of the SPL from two wind turbines rotating at different speed.

In the future, the effect of stable and unstable atmospheric conditions on OASPL and AM will be investigated. We also plan to extend this work for a full wind farm configuration, as the development of a wind farm internal boundary layer could also affect the downwind propagation.

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