Industrial application of large-eddy simulation for wind resource assessment in complex terrain

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Introduction

The urgent need for renewable energies encourages a growing exploitation of wind energy and forces the wind industry to consider wind parks with increasing terrain complexity. At the same time, the industrial research assessment uses Computational Fluid Dynamics (CFD) in order to predict energy productions, optimize layout or turbine designs. However, the application of CFD for atmospheric flows in complex terrain is a very difficult task. Linearized models and Reynolds-Averaged Navier–Stokes (RANS) models are certainly the most popular models for industrial wind resource assessment because of their relatively small computational cost. However, they model all turbulent scales and they are known to be deficient in presence of complex flows. In opposition, Large Eddy Simulation (LES) models resolve the largest scales and model only the smallest scales. They promise thus an increased accuracy in complex flow. The main objective of this project is the direct and industrial application of LES for wind resource assessment in complex terrain.

![Figure 1: Example of complex site. Elevation map of computational terrain height $z_0$.](image1)

Software

In this project, a new software called E-PALM is developed. The software is based on PALM model (e4777) [1] and follows the results of Assisi project [2]. In this context, a Python wrapper around PALM together with a specific configuration of PALM are developed. E-PALM is optimized for computational efficiency and industrial applications. Also, a precursor simulation library, a nesting option and specific user-interface and pre/post-processing capabilities are developed. Especially, the pre-process providing automatically the computational topography in order to fit the prescribed wind direction and numerical configuration. In addition, the post-processing provide automatically useful results such as vertical profiles (mean and variance), time series, histograms, spectra and 2D slices. An example of E-PALM pre/post-processing outputs are shown in figures 1 and 2.

![Figure 2: Example of complex site. Top: Slice of non-dimensional filtered wind speed $u_*/u_0$. Bottom: Slice of non-dimensional mean wind speed $u_*/u_0$.](image2)

Numerical method

The model considers the LES of the 3D incompressible Navier-Stokes equations in Cartesian coordinates with Coriolis but without Buoyancy and Moisture. The numerical discretization is based on high-order finite difference methods and the continuity and momentum equations are coupled through the projection method. The LES modelling is based on implicit filtering, Boussinesq approximation and a static SGS-TKE model. The flow is driven by the geostrophic wind and a constant flux boundary condition is imposed at the bottom boundary following Monin-Obukhov Similarity Theory (MOST). The topography is represented by a Cartesian topography following the computational grid. The inflow boundary condition is defined with a fixed mean profile and superposed turbulence taken from a recycling plane located inside the domain. The simulation procedure is based on a two steps methodology with a precursor simulation and a main simulation. In this context, the precursor simulation is defined with a simplified configuration and is used in order to provide the initial flow and the mean inflow profile of the main simulation. This procedure allows to reduce the total computational time.

![Figure 3: Flat terrain. Right: Graph of non-dimensional mean streamwise velocity $u_*/u_0$ against non-dimensional mean spanwise velocity $v_*/u_0$. Profile of non-dimensional mean wind speed $u_*/u_0$.](image3)

Flat terrain

The model is first validated against theory on flat terrain. This simplified case is the first necessary step to more complex cases and allows a rigorous characterization of the model behavior. It is found that the results are very consistent with the theory. Especially, the Ekman spiral and the theoretical wind speed profile are very well reproduced, e.g. figure 3. However, a mismatch very near the ground can be observed. This mismatch is very classical for LES of atmospheric flows. Indeed, it is impossible to resolve the turbulence in the very-near ground region because of the very large Reynolds number and the roughness of the terrain and wall models must be used. It found that the results near the ground can be much improved by using a finer resolution.

![Figure 4: Bolund hill. Top: Slice of non-dimensional filtered wind speed $u_*/u_0$. Bottom: Slice of non-dimensional mean wind speed $u_*/u_0$.](image4)

Bolund hill

The model is then validated against experimental data on Bolund hill [3]. This case is currently the most popular validation case for atmospheric flows in complex terrain and is known to be very challenging due to the high complexity of the terrain. It is found that the general behavior of the flow is very well reproduced with a strong blockage in front of the hill, a very strong acceleration at the top of the cliff, a relatively constant flow on the top of the hill and a large wake after the hill, cf. figure 4. However, it is found that the flow shows very sharp gradients very close to the ground which are not captured accurately by the numerical model, e.g. figure 5. In this context, it is found that the resolution must be very fine in order to capture accurately the near wall behavior and the results can be much improved by using a finer resolution.

![Figure 5: Bolund hill. Left: Profile of non-dimensional mean wind speed $u_*/u_0$. Center-left: Profile of mean wind deviation angle $\beta$. Center-right: Profile of mean wind inclination angle $\beta$. Right: Profile of non-dimensional mean turbulent kinetic energy $k/u_0^2$.](image5)

Conclusion

A new software has been implemented in order to allow an industrial application of LES for wind resource assessment in complex terrain. The model has been validated against theory on flat terrain and experimental data on Bolund hill. It is found that the model is capable of giving accurate results. A resolution study has been performed and guidelines for the resolution were provided. In addition, a comparison with ENERCON in-house software E-WIND [4] has been performed and it is found that E-PALM allows more accurate results, especially in complex flow regions. Finally, the software has been tested on several ENERCON sites and the software proved to be technically reliable and computationally very efficient. In the future, further sensitivity and validation studies should be performed and many improvements could be implemented in order to increase the physical modeling, e.g. nesting with larger-scale models.


