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Wind tunnel numerical modeling for wind farm control strategies

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SUMMARY:
In wind energy and wind engineering research it is of fundamental importance to reproduce correctly the Atmospheric Boundary Layer (ABL). During wind tunnel testing various techniques are utilized, and the resulting ABL is borne out of the interaction of the peculiar chamber configuration with the incoming flow. Correctly reproducing this interaction in a numerical setting it is important to be able to validate the codes' performance through the experimental measurements performed in the wind tunnel. This study aims to reproduce numerically the Politecnico di Milano wind tunnel (GVPM) by comparing the performance of the numerical model with complete experimental mapping obtained through 3D hot-wire anemometer measurements. Subsequently, the results achieved by a numerical wind turbine model immersed in the wind tunnel simulation will be compared to the ones obtained with a standard precursor ABL simulation and to experimental data.

Keywords: Atmospheric boundary layer, Wind tunnel numerical modeling, Large eddy simulation, Actuator line model, Wake recovery

1. INTRODUCTION

To study the action of the wind on man-made structures in the lower part of the atmosphere (wind turbines, buildings, etc.) ad-hoc wind tunnels have been developed to reproduce the peculiar characteristics of the Atmospheric Boundary Layer (ABL). Engineering codes prescribe the characteristics of the ABL to be taken into account depending on the location of the structure. Correctly representing the wind characteristics during wind tunnel testing is a fundamental aspect of the craft (Blocken, 2018; Wu, 2017), both from an experimental and a numerical point of view. During wind tunnel testing it is thus necessary to reproduce a target boundary layer, through the use of turbulence-generating geometrical objects, such as spires and blocks, arranged in various configurations (Irwin, 1981). The resulting ABL is a product of the configuration chosen and the flow entering the test section, which depends on a lot of factors. It is often discounted, but the inlet flow at the beginning of the test section is affected by the objects inside the chamber, depending on their blockage ratio.

In the context of numerical simulations that have as objective the reproduction of the ABL with its unsteady characteristics, multiple approaches have been proposed (Yan and Li, 2015). Recycling methods and synthetic turbulence are very useful for reducing computational costs by replacing the physical modeling of the wind tunnel. Nevertheless, they are not usually able to fully capture the behavior of the flow that actually impinges on the object during the experiments. This is why, for validating numerical codes for wind energy applications, such as the Actuator Line Models (ALM) developed in-house (Cioffi et al., 2020; Muscari et al., 2023; Sanvito et al., 2023), with experiments performed in the wind tunnel, the correct representation of the behavior of the flow actually acting on the wind turbine cannot be discounted. This is especially true for wind farm control, due to the relevant impact of the length scales of the flow (Hodgson et al., 2023).

It is thus important for a facility such as GVPM to be able to reproduce with fidelity, through the means of Large Eddy Simulations (LES), the behavior of the flow inside its test section under multiple ABL configurations. The GVPM facility is an interesting example, characterized by the presence of two test sections arranged in a vertical layout, as shown in Fig. 1. Moreover, the entrance of the ABL section comes after a pressure drop due to the presence of the heat exchanger, resulting in a background turbulence in the order of 2% throughout all the section. The numerical results will be validated against the experimental measurements performed during the CL-Windcon test campaigns, in which the mapping of the chamber through the use of 3D-hotwire anemometers has been carried out at 2 plane locations, in different roughness configurations.

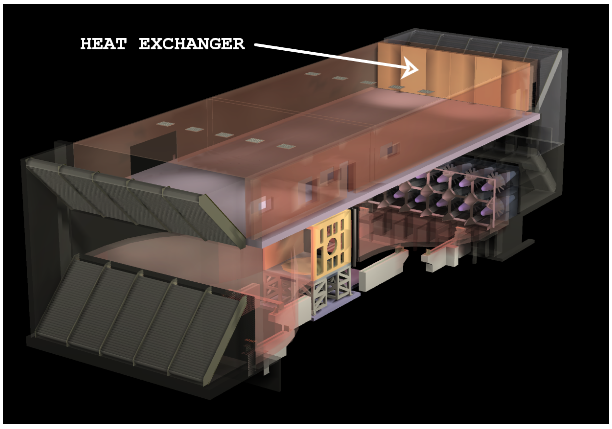

Figure 1. GVPM Wind tunnel rendering

In the context of wake control strategies, a complete numerical model of the GVPM wind tunnel will then allow us to compare the results obtained by the ALM codes with the experiments that will be performed in the GVPM wind tunnel. We will be able to quantify more accurately the impact of the length scales of the actual flow on the wake recovery behavior, by comparing the results with the ones obtained through more conventional practices, such as precursor-successor simulations or synthetic generation. Moreover, for what concerns synthetic turbulence generation for ABL, a numerical model of the GVPM wind tunnel will help us validate such methods by offering a complete insight into the wind to be matched at the test location. Lastly, such a model will also be able to inform the test engineers on the complete wind behavior varying the turbulence-generating objects configuration, to develop new ones more representative of the wind behavior at real scale.

2. METHODOLOGY

2.1. Part 1: GVPM numerical model

The first part of the work aims to accurately reproduce numerically the flow inside the test section of GVPM. Therefore, wall-modeled Large Eddy Simulations will be employed, describing as accurately as possible the wind tunnel geometry. The peculiar characteristics of the GVPM wind tunnel pose some challenges from the numerical point of view. It is incorrect to reproduce the flow impinging on the initial spires as a uniform zero-turbulence flow. The flow entering the chamber presents a background turbulence of 2%, and the presence of the spires close to the entrance generates a vertically non-uniform blockage, thus a non-uniform wind velocity profile. Initially, it is fundamental to reproduce the flow condition due to the simultaneous contribution of both spires and the porous media, representing the heat exchanger. To model the heat exchanger without resolving its geometry a Darcy-Forchaimer model will be employed. A first analysis will be carried out to evaluate the length of the upstream fetch, shown in Fig. 2, necessary to correctly reproduce the interaction of the flow with the spires and the porous media. The validation will be performed with the two configurations mapped during CL_Windcon, one off-shore low-turbulence, and the other on-shore high-turbulence. Since the high-turbulence configuration presents some brick elements, computationally expensive to mesh accurately, the results' dependency on grid refinement will be analyzed. To assess the predictive performances of the model, simulations of other different configurations will be carried out. For these, the model's performance will be evaluated on the wind profiles obtained at the test table location.

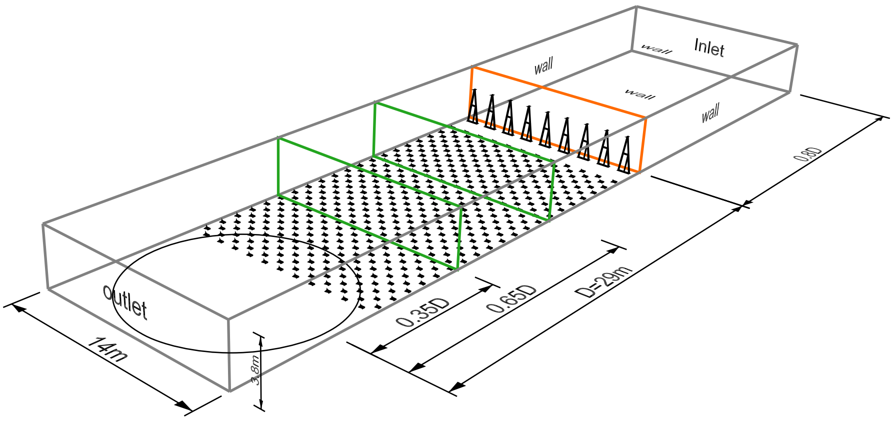

Figure 2. Scheme of the CFD model in the on-shore configuration. The orange plane indicates the heat exchanger, while the green planes represent the mapping made by 3D-hotwire anemometers. D indicates the distance between the center of the rotating test table and the heat exchanger.

2.2. PART 2: Validation of ALM codes in ABL flow

Once the GVPM numerical model has been validated, it will be possible to assess the results obtained with the in-house ALM codes. Extensive testing campaigns have already been carried out (Bayati et al., 2018), and others will be in the near future in which a Particle Image Velocimetry (PIV) mapping of the wind turbine wake will be produced in different tilt/yaw configurations. The ALM will be implemented in the simulations through the use of the SOWFA OpenFOAM open-source module. Comparing the results obtained through the use of precursor-successor simulations, the numerical wind tunnel simulations and experimental tests will offer insights into the wake recovery mechanisms for wind turbines immersed in the ABL, as well as a method to validate more accurately the ALM models.

3. PRELIMINARY RESULTS

The presentation of results will first focus on the performance of the GVPM model compared to the measurements performed during the CL_Windcon testing campaign. The impact of the most important modeling choices, i.e. the antecedent fetch, the modeling of the porous layer, and the mesh refinement, will be investigated. Some preliminary results in terms of velocity and turbulence intensity profiles are shown in Fig.3, at different distances from the entrance of the chamber. The simulated profiles show a good agreement with the experimental ones, specifically at the location near the rotating table. Moreover, the velocity profiles present a knee

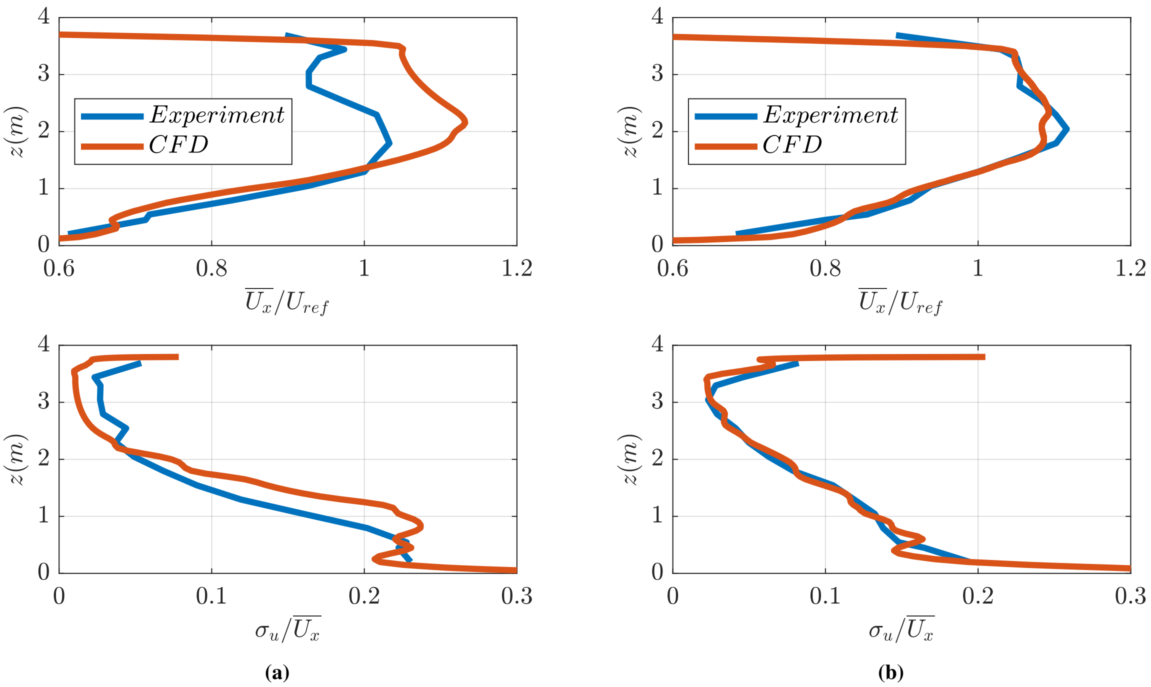

Figure 3. Normalized wind velocity (with respect to the velocity at z=1.3m) and longitudinal turbulence intensity profiles comparison for the on-shore configuration at **(a)** 0.65D and **(b)** 0.35D before the center of the test table, where D is defined in fig. 2.

at around 2m height, which could have a potential impact on the wake recovery mechanisms.

Subsequently, the results obtained by placing the modeled wind turbine in the numerical GVPM flow will be compared to the ones derived using a standard precursor-successor approach. Their performance with respect to experimental PIV data will be assessed in terms of wake recovery behavior.

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