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Optimizing turbulent inflow conditions for large-eddy simulations of the atmospheric boundary layer

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ABSTRACT

Large-eddy simulations (LES) of the atmospheric boundary layer (ABL) require the specification of a turbulent inflow condition with appropriate turbulence intensities and length scales. When using a synthetic turbulence generator, the statistics obtained downstream of the inlet might deviate considerably from the intended values. In the present work we propose a fully automated approach to modify the input parameters for the turbulence generator such that the desired turbulence statistics are obtained at the downstream location of interest. The method employs a gradient-based optimization in combination with the divergence-free version of the digital filter method developed by Xie and Castro [1, 2]. A sensitivity analysis showed that the spanwise and vertical Reynolds stresses and length scales are the most influential input parameters. Hence, the optimization adjusts these parameters until the desired turbulence statistics are obtained downstream in the domain. The results demonstrate the promising capabilities of the method: the mean velocity profile is correctly maintained using an appropriate wall function, while the optimization results in Reynolds stresses, integral length-scales and turbulence spectra that compare well to ABL wind tunnel measurements.

1. Introduction

Computational fluid-dynamics (CFD) is increasingly employed in the wind engineering practice, and could, for example, represent a powerful tool for estimating mean and peak pressure distributions on buildings. An important challenge is that atmospheric boundary layer (ABL) simulations are influenced by uncertainties in the inflow boundary conditions and the turbulence model, which can strongly impact the accuracy of the results. For Reynolds-averaged Navier-Stokes (RANS) simulations, both these types of uncertainties have been shown to significantly affect the results (Gorlé et al., 2015; García-Sánchez et al., 2017). When using well-resolved large-eddy simulations (LES), which solve the filtered Navier-Stokes equations and only require a model for the subgrid-scale turbulence, the uncertainty related to the turbulence model can be reduced. However, the influence of the inflow boundary conditions is not eliminated. The remaining challenge is the definition of a turbulent inflow boundary condition that accurately represents the ABL flow in terms of the mean velocity, the turbulence intensities, and the turbulence length scales.

The methods to generate a turbulent inflow condition are generally classified in two categories: precursor methods and synthetic turbulence generators. Precursor or recycling methods employ either a separate simulation or a region upstream of the domain of interest to generate the turbulent inflow condition (Lund et al., 1998; Nozawa and Tamura, 2002; Liu and Pletcher, 2006; Tamura, 2008; Tabor and Baba-Ahmadi, 2010; Dagnew and Bitsuamlak, 2014; Wu, 2017). These methods resolve upstream roughness elements in the simulations to generate turbulence characteristic of an ABL. The computational cost of this approach presents a limitation for practical wind engineering applications. Moreover, the resulting boundary layer characteristics will depend on the chosen roughness configuration, providing only indirect control over the turbulence statistics. When the initial configuration does not provide the desired Reynolds stresses and integral length-scales, a time-consuming trial and error approach that involves modifying the roughness configuration and re-meshing the domain is required. Sensitivity or uncertainty quantification (UQ) studies to assess the influence of the inflow turbulence characteristics on the solution would require repeating this procedure for each inflow condition of interest.

Synthetic turbulence generators represent an efficient alternative, providing full control over the turbulence statistics near the inflow boundary at a lower computational cost. They can be further classified as digital filter methods, random field generation (RFG) methods, or

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synthetic eddy methods (SEM), which each have their strengths and weaknesses. Several variants of digital filter methods, which produce coherent structures in space and time by filtering a random velocity field, were specifically developed for ABL applications (Xie and Castro, 2008; Kim et al., 2013; Tabor and Baba-Ahmadi, 2010; Dagnew and Bitsuamlak, 2014; Wu, 2017; Daniels et al., 2013). Their main limitation is that they do not automatically generate a divergence-free velocity field; corrections need to be applied to avoid spurious pressure fluctuations in the domain (Kim et al., 2013). The RFG methods generate a turbulent flow field that is guaranteed to be divergence-free, but their drawback is that the resulting velocity field is characterized by Gaussian spectra and therefore not representative of an ABL (Dagnew and Bitsuamlak, 2014; Smirnov et al., 2001). As a result, modifications to provide desired turbulence spectra and correlations are required (Huang et al., 2010; Aboshosha et al., 2015). The SEM methods, which produce velocity fluctuations based on the superposition of eddies (Tabor and Baba-Ahmadi, 2010; Wu, 2017; Jarrin et al., 2006; Jarrin, 2008; Laraufie et al., 2011; Poletto et al., 2013), also do not guarantee a divergence-free velocity field. Finally, an important shared limitation of all digital filter methods is that the generated turbulent velocity field is not a solution of the system of equations being solved. As a result, the specified inflow statistics will develop towards an equilibrium condition downstream of the inlet, and the final result will depend on the subgrid model, the wall model, and the discretization used. It is not uncommon to observe a strong decrease in the turbulence intensity between the inlet and the downstream location of interest (Keating et al., 2004; Jarrin et al., 2009). The problem is similar to the horizontal inhomogeneity observed in RANS simulations of the ABL (Blocken et al., 2007; Parente et al., 2011), but the solution is more involved because of the complex interaction between the wall model, the subgrid model, and the numerics. For example, modifications to the wall function can improve the performance in terms of the mean velocity profile, but the decay in the turbulence intensity remains.

The objective of this study is to develop a method that efficiently overcomes this problem and enables simulations of wind loading on buildings in a variety of turbulent ABL conditions. We employ the divergence-free turbulent inflow condition developed by Xie and Castro (Kim et al., 2013), which uses the mean velocity profile, Reynolds stress profiles and turbulence length scales as input parameters. This boundary condition is combined with a gradient-based optimization algorithm to find the values for these input parameters that result in the desired turbulence statistics at our downstream location of interest. The approach was designed to not require the representation of any upstream roughness elements, such that the target ABL characteristics can be achieved with minimal user intervention.

The method is tested on an experiment performed in the ABL wind tunnel of the Polytechnic University of Milan (Amerio, 2014). We perform simulations of this neutral wind tunnel ABL, using the grid resolution, wall model, and subgrid model that will be employed in future simulations of a high-rise building. A baseline simulation, using the target turbulence statistics as input parameters, is used to demonstrate the turbulence decay. Subsequently, a sensitivity analysis is performed to inform the formulation of the objective function for the optimization algorithm. Finally, the performance of the optimization algorithm is tested, comparing the final results to the experimental data in terms of the mean velocity, Reynolds stress and length scale profiles, and in terms of power spectral densities.

In the following, the wind tunnel experiment used for validation is summarized first. In section 3, the LES set-up is presented, and section 4 presents the baseline simulation results and sensitivity analysis. In section 5 the formulation of the objective function and the results of the optimization are discussed. Conclusions and plans for future work are presented in section 7.

2. Wind tunnel experiment

The ABL facility of the Polytechnic University of Milan is a closed circuit wind tunnel with a 35 m long, 14 m wide and 4 m high test section. Spires and roughness elements are situated upstream in the test section to generate the desired neutral ABL (Fig. 1 on the left). The models are placed at a distance of 10 m from the inlet, in the center of a turntable of radius 6.5 m, to enable tests for different wind directions. Several tests were performed with the roughness configuration shown in Fig. 1. First, the ABL in absence of a building model was characterized on a plane normal to the ABL mean flow direction at the center of the turntable using 3D hot-wire measurements with a sampling frequency of 2000 Hz (Amerio and Zasso, 2017). Subsequently, several experiments to measure the wind pressure on a high-rise building model were performed (Amerio and Zasso, 2017).

In the present work we focus on the experiment performed without the model to test the capabilities of our inflow generation framework. The experimental data consists of 20 s time-series of the three components of velocity at 280 points distributed on a plane in the middle of the turntable. The spanwise resolution of the measurements is 0.6 m, while the vertical one is 43.7 mm below 0.75 m and 87.5 mm above (Fig. 1 on the right). The resulting mean velocity profiles obtained at five spanwise locations are shown in Fig. 2 (top-left). On average, they represent a neutral ABL log law with a friction velocity $u_\star$ of 0.49 m/s and a roughness height z_0 of 3.2 mm. The corresponding profiles for the streamwise Reynolds stress component $\overline{u'^2}$ and the streamwise turbulence length-scale ${}^{x}L_u$, are shown in Fig. 2 (top-right and bottom).

The plots show a spanwise variability in the profiles. Throughout the remainder of this paper, a polynomial fit to the average of the spanwise profiles is plotted using a dash-dotted line; the spanwise variability is represented using a gray shaded region defined by polynomial fits to the minimum and maximum values measured. The gray region will be used as the target region for the simulation results. Profiles for the other Reynolds stress components and length scales showed similar variability and are presented in the following sections for comparison to the data. In

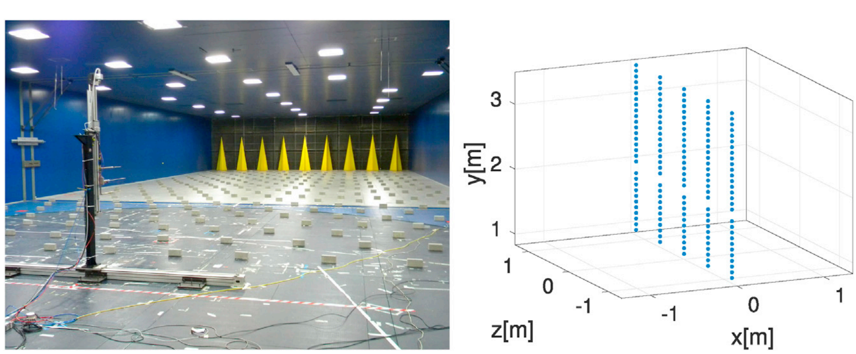

Fig. 1. Experimental setup of the ABL wind tunnel of the Polytechnic University of Milan (left); coordinates of the 280 measurement points on a spanwise-vertical plane at the center of the turntable (right).