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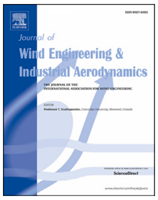

Large eddy simulation of the neutral atmospheric boundary layer: performance evaluation of three inflow methods for terrains with different roughness

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ABSTRACT

In large eddy simulations (LES) of the atmospheric boundary layer (ABL), the choice of inflow method and the specification of surface roughness are crucial for obtaining accurate results. The consistency between inflow conditions and wall boundary condition has been investigated in depth for the RANS approach, whereas it needs further analysis for LES. This paper investigates the combined effect of inflow method and aerodynamic roughness length for LES of the neutral ABL. Three basic inflow generators in combination with three terrain types are evaluated in terms of streamwise homogeneity of the vertical profiles of mean velocity and turbulence kinetic energy. The results show that the precursor method best preserves the homogeneity of the profiles for all roughness lengths considered, with mean absolute deviations up to 0.7% for mean velocity and 3.5% for turbulence kinetic energy at the outlet of the computational domain. Among the synthetic methods, the Vortex Method performs satisfactorily for mean velocity and, to a lesser extent, turbulence kinetic energy, whereas the random flow generation (RFG) method leads to the largest deviations from the target profiles. Finally, the value of the aerodynamic roughness length is found to only weakly influence the performance of the inflow methods considered.

1. Introduction

Large eddy simulation (LES) is increasingly used for a wide range of topics in wind engineering, such as pollutant dispersion (Bazdidi-Tehrani et al., 2016; Gousseau et al., 2011; Moonen et al., 2013; Salim et al., 2011a, 2011b; Tomas et al., 2015; Tominaga and Stathopoulos, 2011; Xie and Castro, 2009), natural ventilation (Blocken, 2014; Jiang et al., 2003), vegetation effects (Kanda and Hino, 1994; Shaw and Schumann, 1992; Tamura et al., 2007; Watanabe, 2004), wind energy (Calaf et al., 2010; Porté-Agel et al., 2011) and wind effects on buildings (Aboshosha et al., 2015a; Dagnew and Bitsuamlak, 2014; Daniels et al., 2013; Huang et al., 2010; Li et al., 2015; Nozawa and Tamura, 2002; Tamura and Ono, 2003; Yan and Li, 2015).

In the past much attention has been paid to the accurate CFD modeling of the atmospheric boundary layer (ABL), both using Reynolds-averaged Navier-Stokes (RANS) and LES approaches, with particular regard to the correct implementation of boundary conditions. Specifically, inconsistencies between inlet conditions and wall treatment for RANS modeling of the ABL have been investigated by many authors (Blocken et al., 2007a, 2007b; Gorlé et al., 2009; Hargreaves and Wright, 2007; Parente et al., 2011; Richards and Hoxey, 1993). Such inconsistencies can lead to unintended streamwise gradients in the vertical profiles of mean wind speed and turbulence quantities. As a consequence the incident profiles, defined as the vertical profiles of mean velocity and turbulence quantities detected in an empty computational domain at the position where the obstacle(s) would be placed in a non-empty domain, might differ from those prescribed at the inlet boundary. Since these incident profiles may have a considerable impact on the results of numerical simulations of flow around buildings or other obstacles, it is nowadays considered best practice to verify the homogeneity of the vertical profiles of the ABL in an empty computational domain (Blocken et al., 2007a, 2007b; Blocken, 2015; Franke et al., 2007) before running

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the main simulation including the objects of interest.

In case LES is chosen to resolve the flow, a time-varying velocity field has to be specified at the inflow boundary using an appropriate inflow generator; in addition, a suitable model that accounts for surface roughness needs to be employed.

With respect to the inflow methods, the generated unsteady flow should faithfully represent the mean wind speed and turbulence characteristics of the flow field (Tabor and Baba-Ahmadi, 2010; Tamura, 2008; Wu, 2017). Comprehensive reviews of the topic exist in the literature (Keating et al., 2004; Tabor and Baba-Ahmadi, 2010; Wu, 2017). According to Tabor and Baba-Ahmadi (2010) the inflow methods can be classified in two main families: precursor simulation methods and synthetic methods.

With regard to the roughness modeling, in LES three categories of methods exist (Rodi et al., 2013). One approach is to explicitly model the roughness elements, whose walls are treated as no-slip walls in the CFD code. An alternative approach consists of applying momentum forcing terms, which is commonly used to model the effect of vegetation on the flow field. The third approach takes into account the ground roughness through prescription of shear stresses at the wall.

Although comparative studies have been performed in the past in order to assess the separate impact of inflow turbulence generation methods (Sections 2.1–2.3) and aerodynamic roughness length (Section 2.4), to the best of our knowledge no comparative studies that take into account changes of both inflow methods and aerodynamic roughness length have yet been performed. Hence, the main focus and novelty of this paper concerns the combined effect of different inflow generators and different terrain roughness lengths.

In the simulations reported in this manuscript the performance of a precursor method is compared to that of two basic but well-known synthetic methods, i.e. the Vortex Method (Mathey et al., 2003, 2006; Sergent, 2002) and the RFG method (Kraichnan, 1970; Smirnov et al., 2001), for the LES of the neutral atmospheric boundary layer in an empty domain above three different terrain types: rural, suburban and urban. The above-mentioned synthetic methods are selected for the present study since they are frequently employed for comparative studies (e.g. Bazdidi-Tehrani et al., 2016; García et al., 2015; Poletto et al., 2013; Yan and Li, 2015) and in recent studies concerning ABL flows (e.g. Gousseau et al., 2013; Iousef et al., 2017). In order to model the terrain roughness, a prescribed wall shear stress is applied to the wall, since this approach is commonly adopted for ABL flows (Rodi et al., 2013). In particular, the model proposed by Thomas and Williams (1999) is used due to its effectiveness in modeling roughness effects and ease of implementation. In order to assess the effect of the aerodynamic roughness length on the performance of the inflow methods, the streamwise homogeneity of the vertical profiles of mean velocity and turbulence kinetic energy is evaluated.

In the following section, an overview of inflow methods and roughness treatments is provided. In Section 3, computational domain and numerical settings of the CFD simulations are described, including the chosen inflow methods and wall shear stress boundary condition. In Section 4, the results of the numerical simulations are presented: first a quality check of the flow in the precursor domain is performed, then the profile homogeneity of mean velocity and turbulence kinetic energy is discussed along with an analysis of turbulence statistics. Finally, the main points of this work are discussed and summarized in Section 5.

2. Overview of inflow methods and roughness treatments

2.1. Precursor methods

An effective method to obtain inflow data is to simulate a precursor domain with periodic boundary conditions driven by a forcing term (e.g. a pressure gradient) and, once the flow is fully developed, sample velocity data in a cross-sectional plane and store them in a database. In this way a library is created that can be used to provide inflow boundary conditions for the main simulation domain (successor domain). Note that in this way a periodicity is introduced in the successor domain due to the limited extent of the precursor domain. Chung and Sung (1997) compared different procedures to map data from a precursor domain including phase and amplitude jittering (Lee et al., 1992), which are two different ways to manipulate the data from a precomputed library in order to remove the periodicity from the stored velocity signal. However, important limitations were found for all methods considered. Data from previously stored databases can be rescaled (e.g. Schlüter et al., 2004) in order to match prescribed statistical properties. Lund et al. (1998) proposed a method through which the inner and outer layer velocities, sampled in a plane downstream of the inlet, are rescaled according to similarity laws and reintroduced at the inlet of the precursor domain. Velocity data are sampled from a cross-sectional plane between the inlet and the recycling plane, and can be either stored to generate a library or directly mapped to the inlet of the successor domain (e.g. Stevens et al., 2014). Nozawa and Tamura (2002) and recently Yang and Meneveau (2016) extended Lund's method for flows over rough surfaces. Another sub-category of precursor methods is the internal mapping (see Tabor and Baba-Ahmadi, 2010), in which precursor and successor domain are combined in a single computational volume. Similar to Lund's method, recycling and rescaling from a sampling plane located downstream of the inlet are applied to generate the new inlet boundary condition; the successor domain is the part of the domain downstream of the sampling plane.

2.2. Synthetic methods

The family of synthetic methods can be divided in several groups. The first one is the group of Fourier methods, in which turbulence is generated through a summation of harmonic functions. The random flow generation (RFG) method by Smirnov et al. (2001), who modified the original method by Kraichnan (1970), falls in this category and is divergence-free for homogeneous turbulence and nearly divergence-free for inhomogeneous turbulence. Huang et al. (2010) modified Smirnov's method, so that any assigned energy spectrum could be reproduced; they termed this method the discretizing and synthesizing random flow generation (DSRFG) method. Castro et al. (2011) proposed a further modification of the DSRFG, which was successfully tested in an empty domain and then applied by Li et al. (2015) for LES of flow around a square prism with a focus on pressure and force coefficients. Aboshosha et al. (2015a) also proposed a modification of DSRFG, termed consistent discrete random flow generation (CDRFG), in order to overcome some limitations of the method employed by Huang et al. (2010) and improve reproduction of target spectra and coherence in the flow.

Another relevant group is that of digital filter methods whose aim is to generate velocity fluctuations starting from a set of random data (with zero mean and variance equal to one) using a digital filter based on a correlation function (for instance, Gaussian or exponential). In this method correlations are therefore imposed directly, not through a prescribed energy spectrum (Wu, 2017). Some examples of digital filter methods are described by di Mare et al. (2006), Klein et al. (2003), Veloudis et al. (2007), and Xie and Castro (2008). Kim et al. (2013) proposed a modified version of Xie and Castro's method, which has the important property of being divergence-free. Okaze and Mochida (2017), starting from the work of Xie and Castro (2008), developed a synthetic method based on the Cholesky decompositions of the turbulence flux tensor to generate turbulent fluctuations of both velocity components and a scalar, with prescribed temporal and spatial correlations.

Among the remaining synthetic methods, it is worthwhile to mention