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Inflow turbulence generation methods with large eddy simulation for wind effects on tall buildings

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ABSTRACT

Generation of turbulent inflow conditions matching realistic wind flow characteristics in atmospheric boundary layer (ABL) is essential for accurate predictions of wind effects on buildings and structures using large eddy simulation (LES). It is thus necessary to evaluate the performances of different inflow turbulence generation techniques. In this study, four inflow turbulence generation methods (including three synthetic turbulence methods and the recycling method) were used to simulate wind flows in ABL for LES of wind loadings on a tall building. The advantages and limitations of these inflow turbulence generation methods were discussed through comparisons with available wind tunnel measurements and previous numerical simulation results. Several remedial measures were presented to improve the performances of these inflow turbulence generation methods. The findings of this paper are of use and interest to researchers and designers involved in the wind-resistant design of tall buildings, since one can follow the established procedure to predict the dynamic wind loadings on tall buildings by LES.

1. Introduction

With the rapid development of LES techniques and the drastic increase in computing power during the last decade, LES has become a powerful tool in computational wind engineering (CWE), which has been applied to numerical simulations of the wind effects on buildings and structures [1], topographic features of complex terrain [2], pollutant dispersion in urban environment [3] and so on. For the applications of LES in CWE, an important issue that affects the numerical accuracy is to generate appropriate inflow boundary conditions with limited information from experiments or field measurements [4]. If the specifications of the mean wind speed profiles and turbulence quantities are not proper, errors exist in fluctuating pressures on building surfaces; even the most basic flow physics are probably missing [5]. To overcome this difficulty, several inflow turbulence generation techniques have been developed for LES. Keating et al. [6], Tabor and Baha-Ahmadi [7], and Huang et al. [8] have comprehensively reviewed these techniques which can be classified into three major categories: synthetic turbulence methods, precursor dataset and recycling method [6].

For the synthetic methods, the main strategy is to superimpose the mean quantities with synthetic randomness. The random perturbations can be generated with several often-used types of methods. The first family is the spectral method. Kraichnan [9] first proposed to synthesize Fourier waves for homogeneous and isotropic turbulence. In the same spirit, Smirnov et al. [10] and Batten et al. [11] developed the spectral method to reproduce general inhomogeneous and anisotropic turbulence with a tensor scaling based on the Cholesky decomposition of the local Reynolds-stress tensor [11]. Furthermore, Huang et al. [8] modified the distribution strategy of the wave vector in Kraichnan's method and generated a spatially correlated turbulent flow field satisfying arbitrary prescribed spectrum. Within the same framework proposed by Huang et al. [8], Castro and Paz [12] included a dimensionless time scale parameter to establish the temporal correlation of the synthetic velocity fluctuations. One major advantage of the spectral method is to yield an "essentially" divergence-free turbulent flow field. Recently, Yu and Bai [13] discussed the solenoidal issue (divergence-free) in detail. They introduced a vector potential field into the method by Smirnov et al. [10] and generated a strictly divergence-free turbulent flow field. Another family of turbulence synthesis techniques is the digital filter method. Klein et al. [14] used the Gaussian filter to generate inflow turbulence with spatial and temporal correlations. The advantage of this method is to produce the inhomogeneous turbulence and suitable for complex inlet

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mesh. However, it may become computationally expensive if the inlet mesh is fine. Xie and Castro [15] introduced an exponential velocity correlation function rather than Gaussian one for LES of street-scale flows. Recently, they [16] modified the incompressible solver through the velocity–pressure coupling procedure to satisfy the divergence-free property. Alternative synthetic approach is based on proper orthogonal decomposition (POD) and linear stochastic estimation (LSE) with measured fluctuating velocity field from hot wire probes or stereoscopic particle image velocimetry (SPIV) [17–19]. The last family of the inflow generation methods derived from the idea that turbulence can be reproduced by a superimposition of coherent structures with given shape, length and time scales [20]. Mathey et al. [21] introduced a random two-dimensional vortex method to superpose Gaussian-shaped streamwise vortices on the specified mean velocity profile. Then, Jarrin et al. [22] further extended the method to arbitrary-shaped vortex. Nevertheless, the statistics of turbulence (such as the low-order moments and spectrum) are not explicitly specified in its procedure.

In order to diminish the upstream fetch as short as possible, Spalart [23] introduced the recycling method of using the periodic boundaries in the streamwise direction. Lund et al. [24] adopted the rescaling idea to specify a precise inlet profile following the prescribed shear stress and momentum thickness. Lund's method was originally developed for flat-plate boundary layer and a plane of data at several boundary layer thicknesses downstream from the inlet was scaled and reintroduced at the inlet with different similarity laws for the inner and outer layers of the velocity profiles. Liu and Pletcher [25] indicated that the improper position of the recycling and rescaling plane could result in longer recycling distance and execution time. They suggested using dynamically positioned recycling plane according to instantaneous flow properties. Nozawa and Tamura [26] further developed Lund's method to simulate turbulent boundary layer flow over a rough plate. This is similar to the common practice employed in wind tunnel tests to simulate the ABL flows. Kataoka [27] simplified Lund's rescaling method using constant boundary layer thickness and generalized similarity laws. Recently, Jiang et al. [28] applied the recycling method by Kataoka [27] to generate inflow conditions for the non-isothermal boundary layer flows. The coupling of the inflow and the recycling plane is usually referred to as pseudo-periodic or semi-periodic boundary conditions, which can be integrated into the main domain in a concurrent library generation fashion. Because the inflow condition is consistent with the solution of the Navier–Stokes equations, it is believed that the turbulent flow field could possess statistical characteristics of the realistic turbulence. However, the pre-computation of the recycling domain would demand additional computational resources and cost more execution time.

The precursor dataset is to generate a library of turbulent database by running a genuine turbulence simulation, and the dataset can be remapped into the main simulation. This method is particularly suitable for Direct Numerical Simulation (DNS) [10].

It is of utmost importance to properly impose time-dependent inlet boundary condition for accurate predictions with LES [4]. The wind effects on a standard tall building have been investigated with LES by Huang et al. [29] and Daniels et al. [30]. To generate the velocity fluctuations at the inlet, Huang et al. [29] used the method by Smirnov et al. [10] and Daniels adopted the methods by Xie and Castro [15] and Kim et al. [16]. However, to the best of the authors' knowledge, comprehensive evaluation of these methods has rarely been conducted before. This study aims to assess the performances of several turbulence generation methods for LES of wind effects on tall buildings.

In the present paper, four widely used methods, including the random flow generation method (RFG) [10], the Vortex method (VM) [21], the discretizing and synthesizing random flow generation method (DSRFG) [8] and the recycling method [26], are adopted to generate inflow turbulence for numerical simulations of wind loadings on the Commonwealth Advisory Aeronautical Council (CAARC) tall building. In this study, the computational procedure follows the workflow as illustrated in Fig. 1. Firstly, the numerical simulations in an empty computational domain are performed to check the equilibrium state of the simulated ABL using the different turbulence generation methods. Then, the simulations of the wind effects on the CAARC tall building are conducted and the performances of the turbulence generation methods are assessed through comparisons with available experimental results.

2. Inflow turbulence generation methods

This section presents a brief summary of the four turbulent inflow generation methods and their implementations. All the simulations reported in this paper are conducted with the finite volume method (FVM) based CFD code (Ansys/Fluent 14.0.0).

2.1. RFG method

The RFG method was modified by Smirnov et al. [10] on the basis of the random flow generation technique proposed by Kraichnan [9]. In this method, fluctuating velocity components are generated from the summation of Fourier harmonics. The scaling and orthogonal transformation is adopted to satisfy the divergence-free propriety and emulate inhomogeneous and anisotropic turbulence [10]. The RFG method has already been embedded into the Fluent code and is called Spectral Synthesizer. In the Fluent code formulation, the modeled spectrum, in which the wave vector and frequencies are sampled, is expressed as follows:

$$E(k) = 16(2/\pi)^{1/2} k^4 \exp(-2k^2) \tag{1}$$

where k is wave number and the number of Fourier harmonics is fixed to 100 [31]. In addition, it is required to provide the realistic inlet profiles including mean wind velocity (U), the turbulence

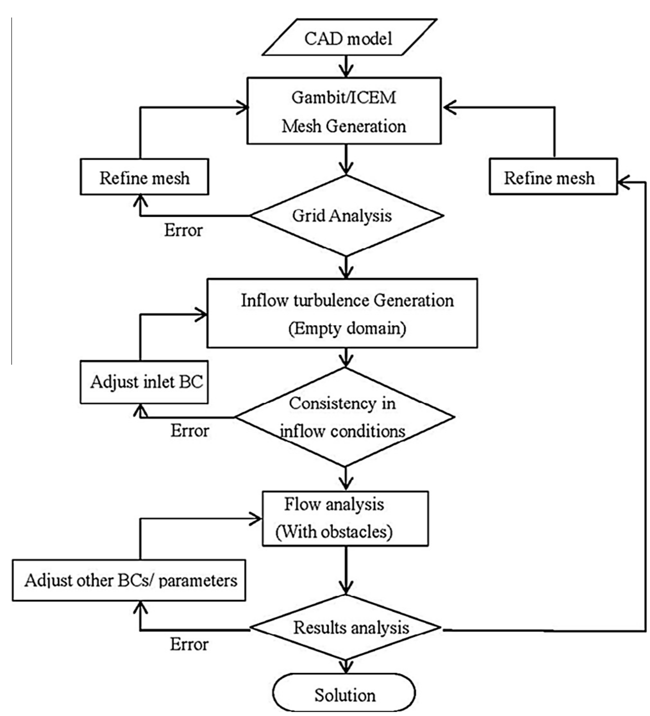

Fig. 1. Workflow diagram of CFD modeling in the present simulations.