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Simulation of turbulent flows around a prism in suburban terrain inflow based on random flow generation method simulation

Yi-Chao Li [a,*], Chii-Ming Cheng [b], Yuan-Lung Lo [b], Fuh-Min Fang [c], De-qian Zheng [d]

[a] Wind Engineering Research Center, Tamkang University, New Taipei City, Taiwan
[b] Civil Engineering, Tamkang University, New Taipei City, Taiwan
[c] Civil Engineering, National Chung-Hsing University, Taichung, Taiwan
[d] School of Civil Engineering and Architecture, Henan University of Technology, Henan, China

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ABSTRACT

In the study, the modified discretizing and synthesizing random flow generation (MDSRFG) was adopted to generate an anisotropic boundary layer inlet for large-eddy simulation. The mean velocity, turbulence intensity and turbulence length scale distributions at inlet, were defined according to the measurements at TKU wind tunnel. The von Kármán model was used as the target spectrum. Wind tunnel pressure measurements on a square prism model with aspect ratio of 3 was used for validation of numerical simulation. Results show that turbulence energy is well maintained from the inlet to the downstream. The relative differences between the measurement and predicted results are 3.4% (mean drag coefficient), 11% (fluctuating drag coefficient), 25.6% (fluctuating side force coefficient) and 4.7% (Strouhal number). The simulated mean and fluctuating pressure distributions showed good agreements with the experiments. The averaged differences between measurement and predicted results are 14.49% (mean pressure coefficient) and 13.74% (fluctuating pressure coefficient). This indicates that the adoption of a reasonable process based on the MDSRFG method is an effective tool to generate a spatially correlated atmospheric boundary layer flow field.

1. Introduction

The aerodynamic behavior of a prism in an atmospheric boundary layer has been a typical problem in wind engineering. To analyze the problem numerically, an appropriate turbulent inlet flow should not only maintain its mean wind speed and the turbulence characteristics to the downstream, but also result in reliable wind force on the structure. There are several reasons to develop an appropriate procedure to generate random flow field as an inflow boundary condition in large-eddy simulations (LES). Firstly, LES has become an attractive approach due to the improvement of computational power. Secondly, the turbulence behavior within the domain is dominated by the inlet condition. Moreover, when the inlet condition is not properly prescribed, even for stationary turbulent flows, LES method could consume large execution time, such as adding artificial shear stresses or the roughness elements to obtain a target flow with fully developed turbulence.

To successfully execute this technique, several methods are available for the generation of inlet turbulence boundary-layer flow conditions. They can be classified into two general categories: precursor simulation methods and synthesis methods (Tabor and Baba-Ahmedi, 2010). Both approaches present advantages and drawbacks and can be implemented in many different ways.

Precursor simulation methods involve the generation of turbulence by conducting a pre-computation of the flow in order to generate a ‘library’ or database, before or in concurrency with the main LES calculation. Then, the generated fluctuations are introduced into the inlet boundary of the computational domain. Examples of this kind of approach are the methods based on cyclic domains (Liu and Pletcher, 2006; Lund et al., 1998) or those using a pre-prepared library. In particular, Lund et al. (1998) applied a modified Spalart method (Spalart and Leonard, 1985), in a concurrent library generation fashion, to sample the data as the simulation proceeds. All the above-mentioned precursor methodologies can be integrated into the main domain, sampling the turbulence in a downstream section of the inlet and then mapping it back into the inlet. In summary, the precursor simulation methods set the conditions for the LES implementation from a ‘real’ simulation of turbulence, it is therefore expected that the

* Corresponding author.
E-mail address: Liyichao223@gmail.com (Y.-C. Li).

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velocity fluctuation field could possess many of the required statistical characteristics, including temporal and spatial correlation and energy spectrum.

Another widely used methodology is the so-called synthesized turbulence method, in which a pseudo-random coherent field of fluctuating velocities with spatial and time scales is superimposed on a predefined mean flow. The random perturbations can be generated in several different ways, such as the Fourier techniques (with its variants), the digital filter based method and the proper orthogonal decomposition (POD) analysis. An example of the Fourier approaches is the random flow generation (RFG) technique proposed by Smirnov et al. (2001) and developed on the basis of the work of Kraichnan (1970), which involves scaling and orthogonal transformations applied to a continuous flow field. This transient flow field is generated in a three-dimensional domain as a superposition of harmonic functions with random coefficients. This method can generate an isotropic divergence-free fluctuating velocity field satisfying the Gaussian' s spectral model as well as an inhomogeneous and anisotropic turbulence flow, provided that an anisotropic velocity correlation tensor is given. Smirnov et al. (2001) used their approach to set inlet boundary conditions to LES methods in the simulation of turbulent fluctuations in a ship wake as well as initial conditions in the simulation of turbulent flow around a ship-hull. Another successful application was the particle dynamics modeling by Smirnov et al. (2005). By adopting the concepts of the RFG method, Huang et al. (2010) made further improvements and proposed the discretizing and synthesizing random flow generation (DSRFG) method to produce an inlet fluctuating velocity field that meet specific spectrum. Castro et al. (2011) then modified the DSRFG to MDSRFG by preserving the statistical quantities at the inlet part of the computation domain and keeping independence of number of points for simulating target spectrum. However, few studies investigated and successfully maintained statistical quantities of the turbulence boundary layer from inlet to the downstream in the computation domain. Therefore, there are still some technical and theoretical problems, such as the adjustment of spatial correlation and the definitions of anisotropic turbulence intensity and turbulence length scale, to be overcome.

Accordingly, this paper attempts to generate the suburban terrain inlet by MDSRFG. The related parameters, such as the mean wind speed, turbulence intensity, turbulence integral scale and power spectra from the suburban turbulent boundary layer flow are provided from Tamkang University BLWT-1(TKU BL-1) wind tunnel tests. A prism model with an aspect ratio of 3 was built; and pressure data was measured in a suburban terrain flow field to validate the numerical results.

2. Method

2.1. Wind tunnel experiment

In order to assure the reliability of the turbulence boundary inlet based on MDSRFG for large-eddy simulations, a prism model (see Fig. 1) with a characteristic length D=0.1 m is set and tested in a wind tunnel with a test section of 18 m(L) × 2 m(W) × 1.5 m (H). The turbulent boundary layer inlet flow with a power-law α value of 0.25 is generated to represent wind profiles over a suburban terrain. The freestream velocity (U_δ) of the approach flow is 8.85 m/s. The boundary layer thickness (δ) is 1 m. The corresponding Reynolds number ($U_\delta D/\nu$) is 5.9×10^4. The aspect ratio (h/D) of the square pressure model is 3. The total measurement period is 280 s with a sampling rate of 200 Hz.

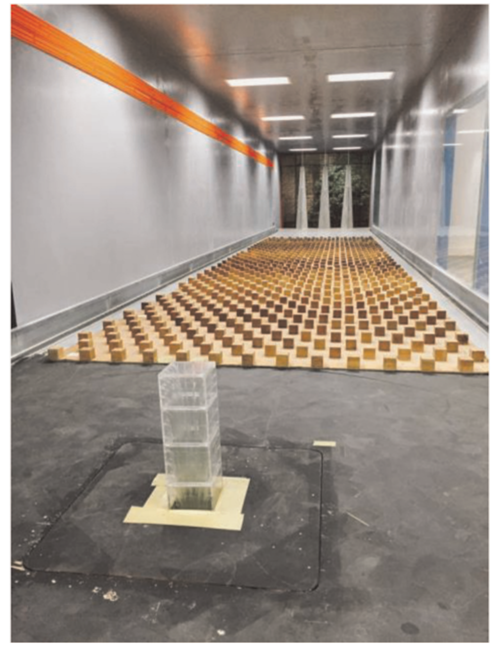

Fig. 1. Pressure model in TKU BL-1 with suburban terrain.

2.2. Numerical method

The simulation adopts the weakly-compressible-flow method (Song and Yuan, 1988). The continuity and momentum equations are

$$\frac{\partial p}{\partial t} + \nabla\cdot\left(k\vec{V}\right) = 0 \tag{1}$$

$$\frac{\partial \vec{V}}{\partial t} + \vec{V}\cdot\nabla\vec{V} = -\nabla\frac{p}{\rho} + \nabla\cdot\left[(\nu+\nu_t)\nabla\vec{V}\right] \tag{2}$$

where p, $\overrightarrow{V}$ and t denote respectively pressure, velocity and time; k is the bulk modulus of elasticity of air; ν and ν_t are respectively the laminar and turbulent viscosities. The turbulent viscosity (ν_t) is determined based on a subgrid-scale turbulence model as

$$\nu_t = C_S \Delta^2 \left(\frac{S_{ij}^2}{2}\right)^{0.5} \tag{3}$$

where C_S is the Smagorinsky coefficient; Δ denotes the characteristic length of the computational grid and $S_{ij} = (\partial u_j/\partial x_i + \partial u_i/\partial x_j)$. Based on a concept of dynamic model proposed by Germano et al. (1991), two grid systems, corresponding respectively to a grid filter and a test filter, are used in the flow calculations. The test filter width is selected as twice of the grid filter width. By comparing the resulting differential turbulent shear stresses associated with the two filter systems at a certain time step in the computation, the C_S value at the next time step is then obtained. The dynamically determined C_S is clipped at zero and 0.23.

A finite-volume method is adopted to calculate and then update the fluxes within each elapsed time based on an explicit predictor-corrector scheme (MacCormack, 1969). Second-order accuracy in space is used in the discretized equations of Eqs. (1) and (2), and the Crank–Nicolson scheme is used in time integration. During the computation process, the time increment is limited by the Courant–Friedrichs–Lewy (CFL) criterion (Courant et al., 1967).