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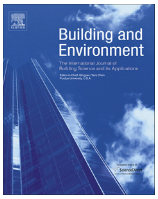

Detached eddy simulation of pedestrian-level wind and gust around an elevated building

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A B S T R A C T

Wind flow turbulence is known to have a major influence on the pedestrian-level wind (PLW) environments, particularly around a building. The elevated design of a building, as a special feature, proved to improve pedestrian-level weak wind conditions in high-density cities. The present study aims to assess three turbulence models, the detached eddy simulation (DES), the steady-state RANS (SRANS), and the unsteady-state RANS (URANS), in their simulation of the PLW flow turbulence concerning wind gust. The simulated mean wind velocities around isolated buildings with and without an elevated design were compared with those obtained from a wind tunnel experiment. The effects of mesh resolution and inflow fluctuating algorithm on the performance of the DES model were thoroughly evaluated. The DES model can better reproduce the mean flow fields than the other two models. Finally, the unsteady fluctuations of wind flow around the buildings with and without the elevated design are analyzed in terms of instantaneous wind velocity, lift coefficient, energy spectral density, and turbulence intensity. The predicted lift coefficient and Strouhal number are approximately 0.01 and 0.09, respectively, which is consistent with what are reported in the literature. Modifications of the frequency of vortex shedding, periodical wind flow pattern, and the normalized wind gust flow fields around the two types of buildings are compared in detail. The work reveals that transient turbulent flow pattern can be reasonably obtained with the DES model, indicating the potential of using the DES for PLW gust assessments in urban planning.

1. Introduction

Outdoor wind and thermal comfort in cities are significant for they are correlating to people's outdoor living conditions and recreational activities [1,2]. Some architectural features have been found to significantly modify the wind flow and thermal comfort conditions in buildings' surroundings at the pedestrian level. Various indices, such as wind velocity ratio, standard effective temperature (SET*) [3], physiological equivalent temperature (PET) [4], and universal thermal climate index (UTCI) [5] have been developed to evaluate pedestrians' outdoor wind and thermal comfort. Wind velocity is one of the important input parameters in these indices [2,6,7]; therefore, it is imperative that the turbulent flow fluctuations around buildings are reasonably predicted when assessing outdoor wind and thermal comfort [1,8,9] during the planning and design stages. Wind force is one of the main differences between outdoor and indoor, and is also a significant factor in outdoor air ventilation assessment (AVA) [10]. Researchers are working to explore differences in wind speed and the influence of this on pedestrians' comfort. Wind gustiness, the fluctuation of wind with time, is a transient and fluctuated process. It covers the smallest periods of time in which a person can effectively react, in seconds [11]. The analysis of gust wind speed is desirable in pedestrain-level wind (PLW) comfort assessments.

A building's elevated design (also called a lift-up) is a frequently-used architectural feature in subtropical cities in southeastern Asia and forms an open space underneath an elevated building, which provides shade and may function as a corridor for wind [2]. In particular, the open space underneath an elevated building was found to be more favorable and more thermally comfortable on a hot summer's day [2,12]. In recent studies [13–15], the ground pedestrian-level aerodynamics of several elevated building blocks were investigated via wind tunnel test and computational fluid dynamics (CFD) simulation. The area underneath an elevated

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building was found to have a higher wind amplification ratio than that of the building's surroundings. A combined method was provided to predict the outdoor thermal comfort in an elevated building's surroundings with simulated mean wind velocity and on-site measurement of air temperature, radiant temperature, and humidity [12]. However, only the mean flow results were preliminarily demonstrated in the authors' earlier study; limited turbulent flow fluctuations were focused on the flow around the elevated building. It is important that, in high-density cities, large recreational areas can be created with this design. In regard to the planning stage, the planners often desire to know the modifications of the instantaneous PLW flow field if this design is to be utilized. Therefore, a further study on turbulent flow fluctuations should be carried out to investigate the local variations of transient wind flow underneath an elevated building, due to the effect of turbulent flow modification.

PLW flow around buildings is mainly analyzed through three methods: field measurement, wind tunnel test, and CFD simulation. The main benefit of the field measurement is having no or little modeling to obtain the "real" flow physics in the urban environment, although it is influenced by many complicated aspects and becomes time-consuming in regard to the setup, measurement and capturing different outdoor weather conditions [16]. Wind tunnel test is generally conducted indoors and more easily controlled than the former method, while a well-equipped wind tunnel is expensive and the practitioners should have lots of preparations before conducting a measurement, which is the largest drawback [1]. One of the main advantages of CFD simulation is avoiding these time-consuming and high costs when obtaining an entire image of a flow field. As far as the performance of turbulence models in built environment studies is concerned, two practical factors have to be considered; namely, the computational time costs and the hardware requirements, which are directly dependent on the mesh resolutions required to obtain accurate results in accordance with the chosen turbulence model. In general, the steady-state RANS (SRANS) modeling approaches, such as the $k\!-\!\varepsilon$ family models, have the advantage of requiring shorter computing times and lower levels of hardware configuration, but it has been shown that only the mean flow pattern can be approximately provided [17]. It is also the case that the wake region size tends to be overestimated and a number of transient airflow features around an isolated building cannot be reproduced with SRANS models [18]. The unsteady-state RANS (URANS) approach can be an alternative choice when unsteadiness is pronounced with a low-turbulence approaching flow, such as the von Karman vortex shedding in the wake of a bluff body; but URANS models the turbulence by only resolving the unsteady "mean" flow structures [19]. The flow field around a single building has been assessed with URANS models by Tominaga [20], using unsteady RNG $k\!-\!\varepsilon$ model and $k\!-\!\omega$ SST model, and it was found that a better mean velocity field could be obtained with unsteady RNG $k\!-\!\varepsilon$ model. If the highly turbulent approaching flow with unsteady fluctuation is considered in the simulation of an urban wind environment, large eddy simulation (LES) or hybrid URANS/LES modeling approaches are recommended [19].

LES can provide a better prediction of the mean velocity field around a building than SRANS, but it requires more computation time and sensitive to many numerical parameters. For example, when the effects of Sub-grid scale models of LES were tested for the air flow around a benchmark single building, some deviations were observed among these models [21]. A typical hybrid URANS/LES approach, termed the detached eddy simulation (DES) modeling approach, was proposed to cut the computing time required and was first used by Spalart et al. [22]. Similarly, DES is also sensitive to many physical and numerical parameters, which should be further tested, particularly with regard to the switching modes between the URANS/LES [8,23]. In recent years, DES has been evaluated for its simulation of the wind flow and pollutant dispersion around both a single building block and a simple array of building blocks. The effects of the physical and numerical parameters, such as mesh resolution, discretization time-step, and sampling time in the DES were assessed by Liu and Niu [8] in regard to the flow around a single building, and it was shown that DES could provide similar simulation results as LES, but with a demand of lower mesh number and shorter computing time.

The inflow conditions of the LES and DES have to represent the random turbulence feature and must be compatible with the N-S equations [24]. Three sorts of inflow fluctuating algorithms are frequently used in outdoor wind simulations [25,26]. The first method, no perturbations method, ignores the inflow fluctuating components and only the streamwise wind velocity profile is embedded in the inlet of the computational domain. The other algorithm, the vortex method, has been used by some LES practitioners [8,27]. The vortex method inserts the perturbations into the mean flow velocity profile by randomly transporting certain numbers of 2D vortices on the computational domain inlet [28]. The third method, the spectral synthesizer method, generates the fluctuating velocity components by randomly synthesizing a divergence-free velocity field from the summation of the Fourier harmonics [29]. The impacts of the main inflow fluctuating generation algorithms on the performance of LES were evaluated for a single tall building [30] and the building interunit pollutant dispersion [21], respectively. However, the effects of these different algorithms are still not clear enough, particularly when used in conjunction with DES.

In the present study, the performances of SRANS, URANS, and DDES were assessed in reproducing the modified PLW flow fields around a building with and without elevation. The effects of mesh resolution and the inflow fluctuating algorithm on DDES were evaluated and the unsteady flow fluctuations in the building's surroundings were predicted. Additionally, the modifications made in regard to the mean wind and wind gust flow fields by the elevated design were investigated. With the potential of DDES to better simulate flow turbulence, periodical flow fluctuations are demonstrated.

2. Methodology

2.1. Turbulence models

The most widely-used turbulence models in CFD for the prediction of wind flow around buildings are those involved in RANS approaches. In the Reynolds averaging process, the solved variables in the instantaneous N-S equations are discretized into the time-averaged and fluctuating components. For the isothermal turbulent flow, the time-averaged RANS equations can be described as:

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho}{\partial x_i}(\rho u_i)=0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_j}(\rho u_i u_j)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\delta ij\frac{\partial u_l}{\partial x_l}\right)\right]+\frac{\partial}{\partial x_j}\left(-\rho\overline{u_i'u_j'}\right) \tag{2}$$

where u_i and u_j are the velocity components, μ is the viscosity, and $-\rho\overline{u_i'u_j'}$ is the Reynolds stress.