Sustainable Cities and Society 19 (2015) 46–60

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

# LES of ABL flow in the built-environment using roughness modeled by fractal surfaces

Haitham Aboshosha [a], Girma Bitsuamlak [b,*], Ashraf El Damatty [b]

[a] Boundary Layer Wind Tunnel Laboratory (BLWTL), Western University, London, ON, Canada
[b] Department of Civil and Environmental Engineering/WindEEE Research Institute, Western University, London, ON, Canada

ARTICLE INFO

*Article history:*
Received 13 February 2015
Received in revised form 22 June 2015
Accepted 4 July 2015
Available online 18 July 2015

*Keywords:*
Large eddy simulation (LES)
Ground roughness
Atmospheric boundary layer (ABL)
Aerodynamic roughness
Wind profile
Inflow turbulence
Wind spectra
Fractal surface

ABSTRACT

The available methods to model ground roughness are not suitable for practical unsteady flow simulations in built-environment, or are limited to slightly rough terrains, or do not provide enough details on the flow structure close to the ground. In the current study, a robust model that simulates rough terrains and provides reasonable transient flow details close to the ground is proposed. The model can handle wide variety of rough exposure encountered in the built-environment. It is based on coupling two existing models in the literature; (i) surface gradient drag-based and (ii) canopy models. In this study the terrains are represented by equivalent fractal surfaces generated from random Fourier modes (RFM). Further, in a boundary layer wind tunnel testing, it is a common practice to use code-based prescribed aerodynamic roughness, $z_0$, to define the terrain exposure type and to select the inflow mean velocity profiles and turbulent intensity levels. For a similar numerical application, there is no guidance on how to simulate turbulent flow corresponding to a specific prescribed $z_0$. For such applications a new scaling technique is developed to scale arbitrary fractal surfaces in order to produce the prescribed $z_0$. ABL flow, over three types of terrain exposures, is investigated using LES employing the new model. It is observed that the resulting ABL flow characteristics in terms of mean and fluctuating velocity profiles as well as velocity spectra match very well with the target engineering data, which validates the proposed method.



## 1. Introduction

Urban flow characteristics are significantly affected by the ground roughness. For example, flow over urban exposure exhibits different flow characteristics compared to open exposure in terms of mean flow profiles, turbulence intensity and turbulence spectrum. While some applications such as pedestrian level wind comfort studies in urban area may only require mean flow characteristics that can be extracted from steady Computational Fluid Dynamics (CFD) simulation. Others, such as mass transport (pollution dispersion, wind driven rain, wind driven snow), wind effect on structures (wind load, wind induced vibration etc.) require unsteady flow simulations using Large Eddy Simulation (LES) (Dagnew & Bitsuamlak, 2013). Proper modeling of the ground roughness is vital for accurate unsteady flow simulations. Modeling approaches used to assess the effect of ground roughness can be classified into three categories. In the first category, an explicit modeling of the roughness is used, where the topology of the ground elements is modeled as part of the simulation. The explicit modeling of urban roughness can be applied at different level of approximation. As described in Fig. 1, the roughness can be modeled either by representing the roughness using approximate uniform blocks in uniform or staggered arrangement that take advantage of symmetry, or by using multiple roughness patches (as it is typically achieved in boundary layer wind tunnels), or semi idealized approximate urban topology, or accurate urban topology derived from LIDAR or GIS measurements.

Explicit modeling of ground roughness can be further classified into two groups. In the first group, each roughness element (i.e. obstacle) is geometrically represented and a wall boundary condition is applied to each surface of the element as indicated in Fig. 2a. This approach is computationally costly, thus only suitable for steady flow simulations and it is not practical for unsteady simulations (Abdi & Bitsuamlak, 2014).

In the second group, the immersed boundary method (Iaccarino & Verzicco, 2003; Mittal & Iaccarino, 2005) is employed to model the roughness elements. As indicated in Fig. 2b, drag forces are introduced in the governing flow equations at the cells that are partially or fully immersed within the roughness elements. Although, this method is computationally less intense compared to the first

* Corresponding author. Tel.: +1 519 661 1211x88028; fax: +1 519 661 3339.
*E-mail address:* gbitsuam@uwo.ca (G. Bitsuamlak).

http://dx.doi.org/10.1016/j.scs.2015.07.003
2210-6707/

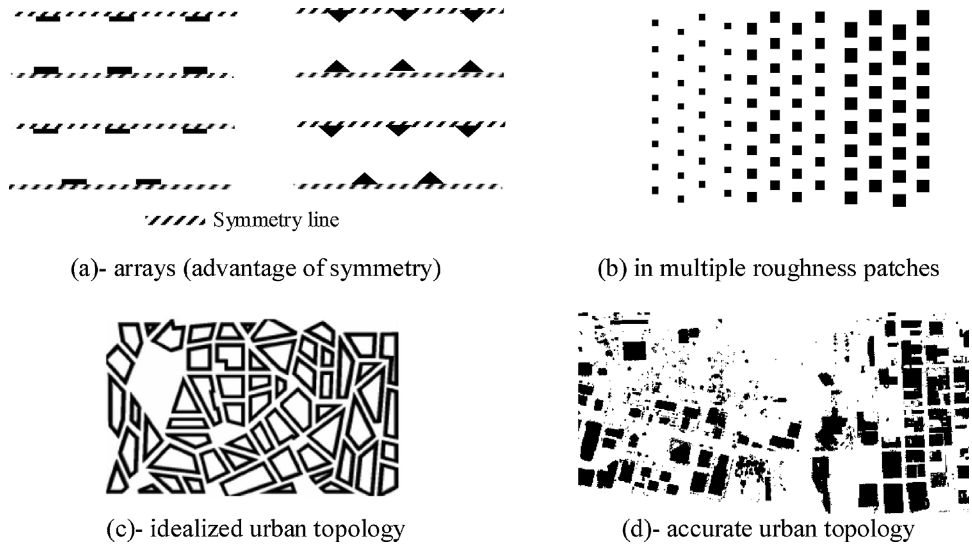


**Fig. 1.** explicit roughness modeling.

group, it still requires significant computational resources making it practically not suitable for unsteady urban flow simulation.

The second category of modeling the ground roughness employs the implicit modeling, for example, using wall functions. Several variations of wall functions are widely used in LES such as those by Businger, Wynagaard, Izumi, and Bradley (1971), Schumann (1975), Thomas and Williams (1999) and Xie, Voke, Hayden, and Robins (2004). The main advantage of using wall functions is the simplicity of simulating a terrain exposure with a prescribed aerodynamic roughness $z_0$, which is of a great importance in building and wind engineering applications. However, wall functions have a drawback as they are only suitable for smooth to slightly rough terrains with an aerodynamic roughness, $z_0$, constrained by the practical grid size, $\Delta_z$. The reasons behind this limitation can be summarized as follows: (i) In wall functions, drag forces induced by the terrain are typically introduced in a single grid layer using the velocity extracted at the mid-level of the layer height, $z_p = 0.5\cdot\Delta_z$, and the target roughness $z_0$, as indicated in Fig. 3; (ii) The level where the velocity is extracted (i.e. $z_p = 0.5\cdot\Delta_z$) has to be placed in the logarithmic flow region, which is usually located above the physical roughness height, $k_s$ or $\sim 30\cdot z_0$ (Richards & Hoxey, 1993; Franke, 2006; Fluent Inc., 2005; Blocken, Stathopoulos, & Carmeliet, 2007). That is because wall functions relate the shear stress induced by the ground roughness to the velocity $U_p$ inside the logarithmic law region. If the level of the velocity extraction, $z_p$, is placed below the physical roughness height, $k_s$ or $\sim 30\cdot z_0$, it means that the velocity is extracted from the canopy layer and wall functions in this case estimate erroneous shear stress. Although in such a case the shifted version of the logarithmic law may be used (Vermeire, Orf, & Savory, 2011), this approach is uncertain and can easily lead to inaccurate results as indicated by Tsai and Tsuang (2005). The above mentioned reasons introduce a constraint on the maximum terrain roughness, $z_0$, that can be simulated by wall functions while employing a specific grid with a height $\Delta_z$ as $60\cdot z_0 < \Delta_z$. Such a constraint becomes very critical for rough terrains such as suburban ($z_0 = 0.3$ m) and urban ($z_0 = 0.7$ m) terrain exposures, where the height of the first grid has to be 18 and 42 m, respectively. This limits the usability of the resulting flow in built-environment flow applications as most of the important flow details near the ground are wiped out.

The third category of modeling the roughness is neither fully implicit nor fully explicit, here referred as "in-between" methods. This includes canopy models used for urban and vegetation canopies (Shaw & Schumann, 1992; Su, Shaw, Paw, Moeng, & Sullivan, 1998; Katul & Albertson, 1998; Albertson, Katul, & Wiberg, 2001; Katul, Mahrt, Poggi, & Sanz, 2004; Shiguang & Weim, 2004; Yang, Raupach, Shaw, Paw, & Morse, 2006a; Yang, Morse, Shaw, & Paw, 2006b; Cassiani, Katul, & Albertson, 2008).

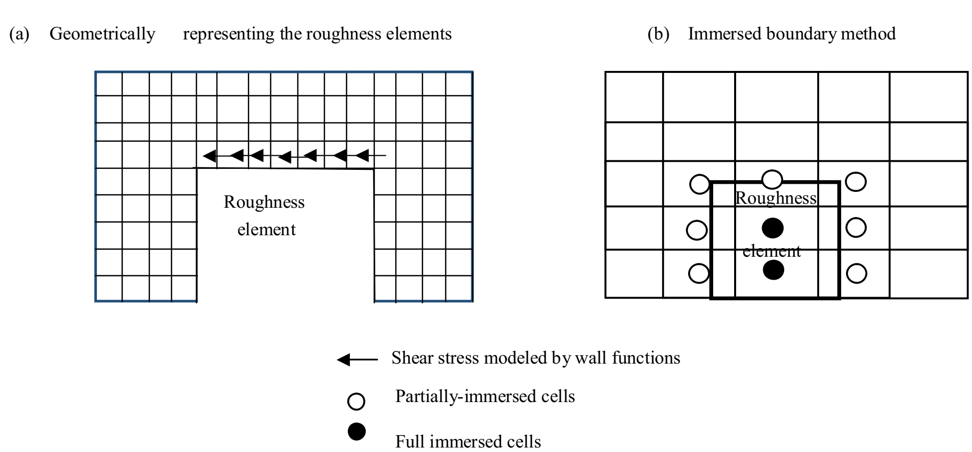


**Fig. 2.** Methods of explicit roughness modeling in CFD.