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Shelter effects of porous multi-scale fractal fences

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ABSTRACT

Rows of trees have been naturally used as wind and snow fences to reduce strong winds, to prevent soil erosion and mitigate snow/sand drifts. Trees, composed of multi-scale fractal structures, modify the airflow through and around them in a complicated manner. This research investigates how engineered porous fences, designed using a typical multi-scale fractal structure, would change the wake characteristics and subsequently reshape the wind shelter effects. A two-dimensional (2D) fractal fence composed of cross-grid type fractal struts, along with an one-dimensional (1D) fractal fence, were tested using a planar particle image velocimetry (PIV) method in a boundary-layer wind tunnel. Wakes and shelter effects of two fractal fences are compared to those of the non-fractal fence model of the same height, length, bottom gap and porosity of 50%. Results of the 2D fractal fence show a clear favorable shelter effect - the extended sheltered area of 1.5–4 times the fence height with the shelter parameter of 0.4, about 70% longer than that of the non-fractal fence provides. Multi-scale fractal fences may potentially be adopted to transform the porous fence design by allowing tuning of the arrangement of struts, an additional set of parameters besides fence height, length and porosity.

1. Introduction

Living plants, such as rows of trees and shrubs, have been widely used as natural wind and snow fences to reduce strong winds and provide shelter for crops and homes, or to prevent soil erosion and mitigate snow/sand drifts for centuries. As part of the ecosystem, vegetation is often self-sustained and cost-effective; but they may be constrained by available water resource, nutrients on site and rapidly changing environment. New living fences take several years to develop and established living fences require certain maintenance over time. The airflow around porous three-dimensional (3D) vegetation and the wind shelter effects of such vegetation are very complicated, which have been investigated by a few laboratory studies (e.g., Bitog et al., 2011; Lee and Lee, 2012; Lee et al., 2014). With different aerodynamic porosity levels of the model trees, wind-tunnel data show that highly 3D flow around a single tree is strongly related to its local geometry. Additionally, the shelter effects is correlated to the 3D wake characteristics in a complicated manner.

Alternative engineered porous wind and snow fences, such as horizontal and/or vertical slatted fences, are an established technique for achieving the same goal as that of the living fences. The design and installation of such fences are flexible, regardless of site condition and surrounding environment, compared with the living fences. The artificial fences serve as "drag or energy sinks" to extract momentum from the oncoming wind, thus reduce the wind speed to a certain extent and provide sheltering for specific purposes. Studies of engineered porous fences are reviewed by Li and Sherman (2015), Wang and Tackle (1995), and Tabler (2003) among others. Design of wind and snow fences to achieve desirable shelter effects requires to consider (1) geometric parameters such as the fence height (H), length, porosity, thickness, bottom gap ratio, fence shape, installation configuration (inclination angle and number of rows) and (2) the external environmental factors of predominant incoming wind speed, wind direction and the site landscape features. In particular, the fence porosity η, the ratio of opening area to the total front area, is one of the most important geometric parameters to determine the shelter effects (van Eimern et al., 1964; Heisler and DeWalle, 1988; Hagen et al., 1981; Wang and Takle, 1995; Wang et al., 2001). For fences constructed with a constant porosity, the design guideline recommends that a non-fractal wind and snow fence of 40–50% porosity and a bottom gap of 10–15% H would provide the optimized shelter effects over a flat terrain (Tabler, 1991, 1994, 2003).

Trees have complicated geometric structure, composed of a wide range of length scales that are organized into a hierarchical pattern (Critten, 1997; de Langre, 2008). These multi-scale elements can be seen as fractals – certain self-similar pattern repeated and superimposed at a range of scales (Debnath, 2006). Not only are fractals of very complex appearance, but found to excite different turbulence

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scales or generate vortices of different sizes at the same time. These turbulent scales interact with each other and exhibit remarkably different properties compared with previously documented turbulent flows, and they have been considered to form a "new class of turbulence" (Stresing et al., 2010; Hurst and Vassilicos, 2007). In the context of fractal structure, flows around trees have been studied using advanced numerical modeling and detailed laboratory experiments, for example, by Chester et al. (2007), Graham and Meneveau (2012) and Bai et al. (2012, 2013, 2015). As expected, the multi-scale fractal geometry of the tree leaves distinct footprint in the wake flow downstream. The coexistence of multiple length scales of the fractal trees and their induced highly heterogeneous flow fields (or multi-scale turbulence) are attributed to the transport of momentum and energy between the ambient flow and the ground surface covered by the trees.

It is of great interest to not only understand how turbulent flow is changed by multiscale forces imposed by fractal structures, but how to utilize such fractal objects as a flow manipulation strategy to achieve desired flow control effects. Practical applications of a variety of fractal design structures have been a very vibrant area. A series of workshops on "turbulent flows generated/designed in multiscale/fractal ways" have been organized at the Imperial College London since 2011. Typical fractal grid families, including the cross-grid, square grid and "I" grid, have been studied extensively in the past two decades. For example, fractal grids were used as air brakes or spoilers on planes to reduce noise level (Nedic et al., 2012). Fractal flanges were installed in front of flow meters for flow conditioning in a pipe (Manshoor et al., 2011). Furthermore, enhanced turbulent mixing of fractal structure was reported in combustion processes (Goh et al., 2013; Verbeek et al., 2015).

Adopting the idea of fractal grid to wind and snow fences, Keylock et al. (2012) examined a relatively simple 1D fractal wind fence, composed of three-generations of fractals in the vertical direction. The objective of their work is to explore a possibility of designing fractal fences that would affect the wake. They reported substantial differences of turbulence structure in the near wake, compared to that of its counterpart non-fractal fence with uniform construction of struts. The fractal wind fence introduced high turbulence intensities in the near wake that decayed rapidly downstream, which has also been reported on other fractal objects. It would be very insightful to further investigate how the fractal fences may influence the wind shelter effects, which is a central piece of information for design and optimization of wind/snow fences. If the introduction of multiscale fractal wind fences re-shapes the shelter effects in an encouraging way, such fractal fences could potentially revolutionize wind fence design by allowing tuning the arrangement of struts, while keeping the same height, length and porosity.

The present work aims to examine shelter effects of two typical multi-scale fractal wind fences using wind-tunnel experiments. Turbulent wake flows induced by the fractal wind fences under simulated atmospheric boundary-layer conditions are measured by a planar Particle Image Velocimetry (PIV) method. Shelter effects are quantified based on the velocity field up to x=7.5 H behind the fences, rather than the full-length of the wake. This wake region (x/H < 10) is coincident with that of the most remarkable shelter effects, very challenging to study analytically. The scope of this work only concerns the bulk turbulent flow characteristics, as wake aerodynamics is essential to inspect the influence of fractal fence structure on the shelter effects.

2. Experimental facility and measurement methods

2.1. Wind-tunnel simulation of an turbulent boundary-layer flow

Experiments were conducted in the fully turbulent flow region in a closed-type boundary-layer wind tunnel at the Pohang University of Science and Technology, South Korea. The wind tunnel has a test section of 6.75 m (L)×0.72 m (W)×0.48 m (H). A turbulent boundary layer (TBL) was established by installing spires of 0.28 m in height and artificial grass with a fetch of 0.5 m at the entrance region of the test section. Similar TBL simulations have been used in Park and Lee (2001), Zhang et al. (2008, 2015). The simulated TBL inflow under neutral thermal stability condition was examined at the mean free-stream speed U_0 of 5.53 m/s, yielding the Reynolds number of approximately 3.6×10^4, based on U_0 and the fence height H. This Re is lower than that of atmospheric flow by a factor of about 1000, which limits the direct scale-up application of the wind-tunnel results to the field scale. However, for flow studies over wind fences of sharp edges, flow always separates at the fence edge and wake structure therefore is not sensitive to the Reynolds number. By ensemble-averaging five hundred instantaneous velocity fields of the inflow, the vertical profiles of the mean streamwise velocity, streamwise turbulence intensity and Reynolds shear stress were obtained (Fig. 1).

The TBL depth δ is approximately 0.22 m, corresponding to the height of mean streamwise velocity reaching 0.99 U_0. The mean streamwise velocity profile in Fig. 1(a) is well represented by the power law as following:

$$U = U_0\left(\frac{y}{\delta}\right)^{a} \quad (1)$$

where the power-law exponent constant α=0.14, indicator of the

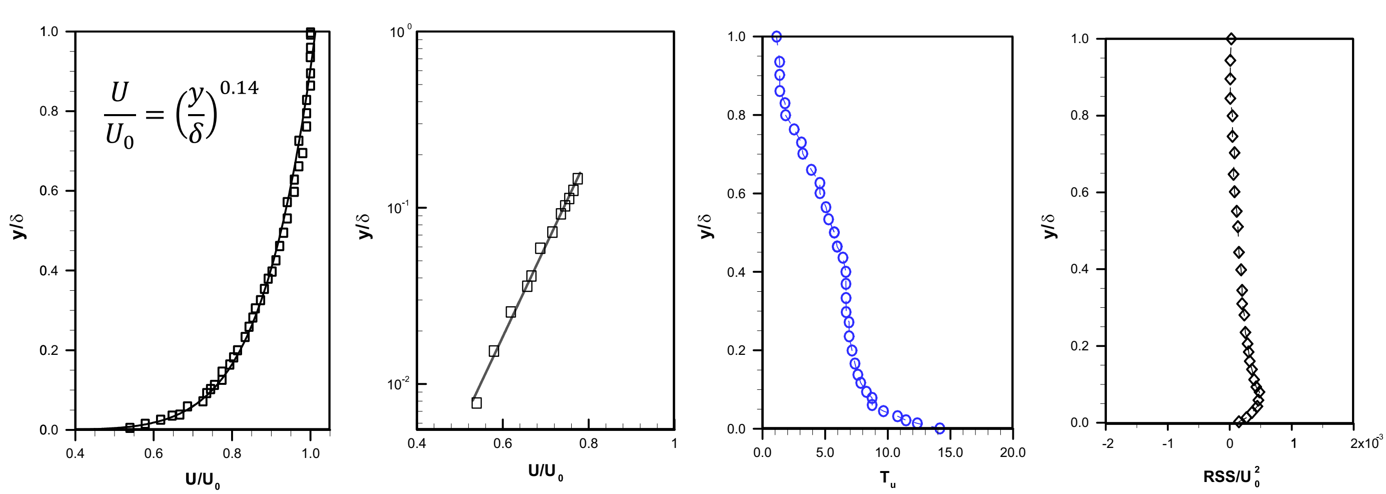

Fig. 1. Characteristics of the TBL inflow: vertical profiles of (a) mean streamwise velocity; (b) the surface-layer profile fitted with the M-O similarity theory; (c) streamwise turbulence intensity; (d) Reynolds shear stress.