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Experimental study of wind load on tree using scaled fractal tree model

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Green urbanism has stimulated more research on the aerodynamics of tree in recent years. The insight gained in studying wind load on trees would mitigate risk of tree falling and enable sustainable landscape planning. However, deciphering the effect of wind on trees is a daunting task because trees come in various species, shapes and sizes. In this study, we aim at conducting wind tunnel tests on various species of trees, including measuring the respective drag coefficient and turbulent flow field using a force balance and particle image velocimetry system. The wind tunnel experiment is conducted using scaled down fractal tree model at 10 and 15 m/s. The 3D-printed tree model is grown based on the data collected on the species-specific tree parameters, such as the height, trunk diameters, crown box dimensions, etc. In this paper, the wind tunnel result of Yellow Flame (*Peltophorum pterocarpum*) is presented. Results show that the drag coefficient for this inflexible tree model is not sensitive to wind speed. The Reynolds shear stress and turbulence kinetic energy are observed to be the largest at the top and bottom of the crown where the velocity gradients are the highest.

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1. Introduction

Experimental study on wind load on trees is usually conducted using real trees in the field[1,2] or inside large testing facilities.[3–6] Alternatively, scaled down tree models are tested in wind tunnel[7–9] and water tunnel.[10–12] While real trees could yield more realistic results, but the cost is high. On the other hand, the success of scaled down tests lies heavily on the ability to reproduce a scaled down tree model that is accurate to the real trees' physical parameters. We aim to construct species specific scaled down fractal tree model based on real tree data, and conduct wind tunnel test to understand the effect of wind load to the tree and the downstream flow field. In this paper, a methodology to construct the tree model and wind tunnel test results of the Yellow Flame (*Peltophorum pterocarpum*) is presented.

2. The Tree Model

In this experiment, the tree model is built as a simple fractal tree based on the estimated[13] height, trunk diameters and crown box dimensions pertaining to the species found in Singapore. The fractal tree is formed by branches which are each recursively split into three child branches for three iterations. Figure 1 shows the Yellow Flame tree model. The crown or foliage volume is filled with interconnected elements to form a porous volume. As compared to crown construction using porous material like wool, fibers and foam as utilized in Refs. 8 and 9, our method allows the average frontal area ratio of dense tropical trees' foliage to be represented accurately. The frontal area ratio is the ratio between the frontal projected areas of the branches and leaves, and the crown shape. The whole tree merged into a single watertight model before sent for selective laser sintering (SLS) printing using polyamide PA2200.

The dimension of the 1:70 scaled tree model is 260.6 (L) $\times$ 259.5 (W) $\times$ 176 mm (H). Table 1 summarizes other parameters at different rotation angle clockwise about the trunk. Frontal area density (FAD), also known as foliage-element

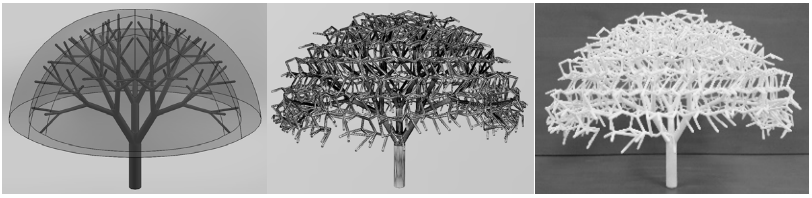

Fig. 1. The computer-aided design (CAD) model with defined crown volume (left), the CAD model with porous crown elements (middle) and the 3D-printed model (right) of the Yellow Flame tree.

Table 1. Tree crown frontal projected area and FAD.

Rotation angle, deg.	0	30	60
Frontal projected area of foliage (A), m^2	0.016569	0.013264	0.016386
FAD, m^{-1}	4.54151	3.63578	4.49151

area index in Refs. 14 and 15 is defined as the frontal area of the foliage (leaves and branches) divided by the volume of the crown. It can be interpreted as the reciprocal of the effective depth of the crown.

3. Experimental Setup

The wind tunnel experiment is conducted in a closed-loop low speed wind tunnel with a test section of 0.6 $(W) \times 0.6$ $(H) \times 2$ m (L). The tree model is mounted on the ATI Gamma force balance and the force measurement is taken for a duration of 5 s at 1000 Hz. The particle image velocimetry (PIV) system consists of a Phantom Miro M320s high speed camera, an LDY304 PIV laser, a high speed controller, a laser guiding arm and laser sheet optics. PIV data is taken at the streamwise centre plane for a duration of 4 s at 300 Hz.

4. Results and Discussions

4.1. *Drag and pressure loss coefficients*

The drag and pressure loss coefficients are plotted in Figs. 2 and 3. The definition of pressure loss coefficient (λ) is based on the description in Refs. 16 and 17. It is the pressure coefficient loss per unit depth of a porous media. In our case, it can be interpreted as the drag coefficient per unit depth of the tree crown. The coefficients are calculated using the mean force data and the frontal projected area of the crown. The pressure loss coefficient is the product of drag coefficient and FAD.

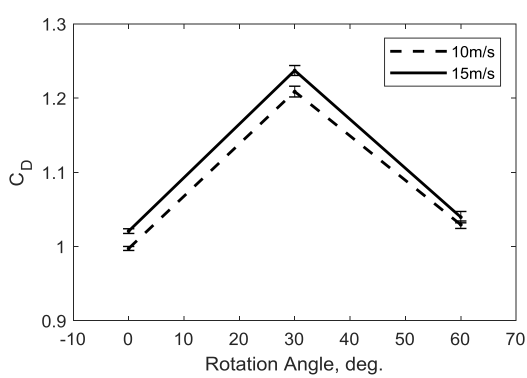

Fig. 2. Drag coefficient at different wind speeds and rotation angles.

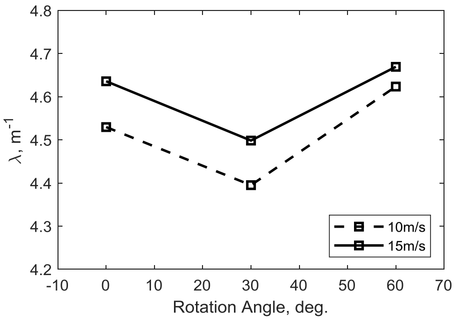

Fig. 3. Pressure loss coefficient at different wind speeds and rotation angles.

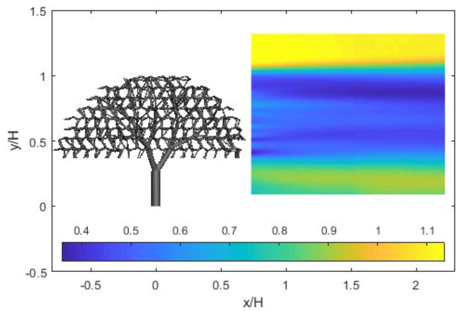

Fig. 4. (Color online) Downstream velocity field (m/s) at 10 m/s free stream wind speed and 0° rotation.

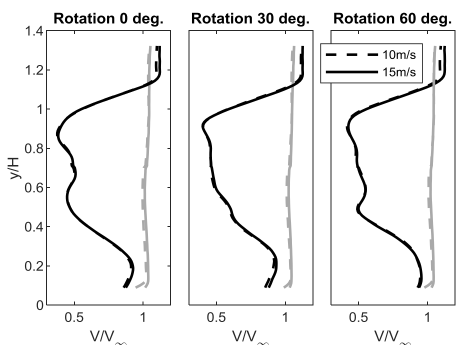

Fig. 5. Normalized wake profile at $1H$ upstream (grey) and $2H$ downstream (black).

As observed in Fig. 2, the drag coefficient at rotation angle of 30° is the highest albeit the smallest frontal projected area and slightly lesser drag force. It is likely due to its largest effective depth (smallest FAD). Using the largest streamwise dimension of the crown as an indication to the depth, from 0° to 60° rotation, the respective numbers are 260.6, 272.1 and 257.5 mm.

4.2. *PIV results*

Figure 4 shows the downstream velocity field of 10 m/s wind speed. Bleed flow can be clearly seen at the region close to the crown. From the PIV measurement, we extracted the flow field at $1H$ upstream and $2H$ downstream. As shown in Fig. 5, the incoming flow is uniform. The velocity deficit increases from the bottom to the top of the crown with deficit peaks at the top and bottom of the crown, except for the 30° case, which has the least deficit. This is well reflected in the drag force measurement of which the 30° case has the smallest drag. The wake profiles at 10 and 15 m/s wind speed are almost identical. This is consistent with the insensitivity of the drag coefficient to wind speed as seen in Fig. 2. Similar insensitivity of inflexible tree models is also mentioned in Refs. 7 and 8.

5. Conclusions

A methodology is derived to construct the tree model based on real tree parameters, and wind tunnel tests is conducted to assess the wind load on Yellow Flame tree at 10 and 15 m/s wind speed. The flow characteristics are analyzed and discussed in detail.

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