DRAG FORCE PREDICTION WITH CFD FULL CLOSURE MODEL SIMULATION ON SCALED FRACTAL TREE IN WIND TUNNEL

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Information on the wind load acting on an individual tree is essential to assess the risk of tree failures in urban landscapes. Numerical simulation is one of the approaches to predict the wind loads. Although a porous media approximation of the tree volume - with associated momentum sink and turbulence source terms - is known to simulate the impact of trees on the wind flow, a lack of knowledge exists when it comes to predicting the drag force on the trees. In this study, three-dimensional steady state Reynolds-Averaged Navier-Stokes simulations are performed of a scaled, procedurally grown L-System tree in a wind tunnel, represented in the simulations by a porous media zone. It is found that the influence of porous region geometry, i.e., ellipsoid or cuboid, on the drag force prediction is very small and can be neglected. The difference in using the leaf area density, plant area density and frontal silhouette area density of the scaled fractal tree model as a parameter to the porous-media model formulae is analyzed. In addition, the effect of a height-varying leaf area density is also analyzed and discussed, as well as the effect of including the tree-trunk in the model. Eventually, the simulation results exhibit a 19% over-prediction on the drag force; while a good match of the normalized velocity profiles is obtained at the tree leeward sides.

Keywords: CFD, full closure model, drag force, fractal tree, leaf area density.

1. Introduction

In modern cities, tree planting is one of the popular measures to improve outdoor environment for the cities. Tree failure risk management becomes an important priority for many tree owners. Information on the wind load acting on an individual tree is essential to assess the risk of tree failures in urban landscapes.[1] However, the interaction between wind

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and tree is often complex and dynamic, making it difficult to estimate the actual forces on a tree in a given location. In contrast with most rigid built structures, trees are slender, flexible structures that experience large deflections in the wind. Tree branches and leaves often bend leeward and reconfigure in a way that streamlines shape and reduces exposed area.

Numerical simulation is one of the approaches to predict the wind loads. There are three main ways to simulate the impact that trees have on the wind flow, in order of most to least complicated these are *1)* explicit resolution of the tree shape[2], *2) a* porous media approximation of the tree volume[3], and *3)* a roughness length approximation to the underlying ground[4].

The porous media approximation is a compromise between the other two methods in terms of accuracy and complexity. While the trees are not explicitly modelled, additional sink terms are introduced in the momentum equation that parametrize the shielding effects from the tree volume.[5,6] In this paper, we will extend the porous media approach to analyze the wind loads on a scaled, procedurally grown L-System tree with fractal geometry in wind tunnel.

2. Approach

2.1. *Tree canopy model*

The CFD code used for this modeling was OpenFOAM 2.4. The set of equations solved are the steady state three-dimensional (3D) Reynolds-Averaged Navier-Stokes (RANS) equations. The impact of tree is modeled by a porous media approximation of the tree volume. While the trees are not explicitly modelled, additional source terms are introduced in the momentum equations and k-ε turbulence model that parametrize the aerodynamic effects from the tree volume[7]:

$$S_u = -C_d a u_i U \tag{1}$$

$$S_k = C_d a \beta_p U^3 - C_d a \beta_d U k \tag{2}$$

$$S_\varepsilon = C_d a \alpha_p \beta_p \frac{\varepsilon}{k} U^3 - C_d a \alpha_d \beta_d \frac{\varepsilon}{k} U k \tag{3}$$

where S_u is the source term added to the momentum equations, which gives the effect of trees on velocity decrease. S_k and S_ε is the turbulence and dissipation source terms added to the transport equations of k and ε, respectively, which simulate the effects of trees on the amount of increase in turbulence and energy dissipation rate, respectively. C_d is the drag coefficient for tree canopy. a is leaf area density. u_i is velocity component. U is the velocity magnitude. α_p, and α_d, are model coefficients with typical values equal to 1.5. β_p, is fraction of mean flow kinetic energy being converted to wake generated energy by canopy drop, which has a typical value equal to 1. β_d, represents the magnitude of energy losses from interactions with obstacles, which has a typical value of 4.[8]

2.2. *Wind tunnel experiment*

A downscaled fractal tree based on L-system species models[9] is generated with 3D printing. Figure 1 shows a printed tree model example of Yellow Flame (*Peltophorum* *pterocarpum*). The wind tunnel test was done in Temasek Lab in National University of Singapore. The drag coefficient C_d is calculated based on the drag force from the load cell measurement. For a given incoming wind speed U_i, $C_d = 2F_d/(\rho U_i^2 A)$, where F_d is measured drag force, ρ is air density and A is the frontal area of the tree model.

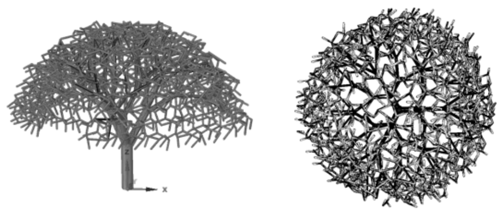

Fig. 1. Schematic of L-system fractal tree for Yellow Flame

2.3. *Numerical setup*

In the simulations, the cross section of wind tunnel is 0.6m x 0.6m, which is correspondence to the actual tunnel size. The porous tree region is modeled as cuboid shape, as shown in Figure 2. The whole domain is discretized with hexa-dominated grids with a total grid number around 4 million. “Non-slip” wall conditions are set on the tunnel walls. “Velocity inlet” conditions are applied at the tunnel with a constant incoming wind velocity. “Pressure” conditions with prescribed atmospheric pressure are imposed at the tunnel outlet.

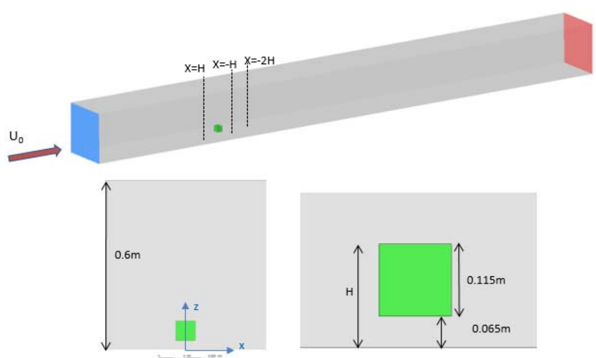

Fig. 2. Schematic of wind tunnel and tree geometry

3. Results and discussion

3.1. *Effect of canopy shape*

Though the actual crown shape of Yellow Flame tree model in wind tunnel test looks ellipsoid, it is common to simply the tree crown zone into a cuboid shape in CFD simulations. This would greatly reduce number of grids and save a large amount of the computational time, when the model is used in the applications for urban area including thousands of trees. The effect of geometry shapes, i.e., ellipsoid and cuboid, on the velocity profiles and drag force has been studied. In the simulation, the volume, frontal area and height of the two geometries were maintained the same. A constant leaf area density was used for both shapes. The drag forces predicted from the simulations were 2.860N and 2.885N for cuboid and ellipsoid, respectively. The difference between the two drag forces was only 0.8%, which was negligible. Hence, cuboid was adopted in all the following simulations

3.2. *Drag force based on frontal area density*

If parameter a in Eq. (1) – (3) used leaf area density calculated based on the single-side plant area of Yellow Flame tree model which was 11.3 m^{-1}, the drag force obtained from the simulation was 3.675 N, about 59% difference from the experimental data (2.313 N). From literature[10,11], it was found frontal area density (FAD) was adopted as parameter a in full closure model, which partly canceled through C_d. We hence proposed to use frontal silhouette area divide the tree crown volume for the calculation of FAD, which yielded a constant FAD=5.039. The drag force from the simulation based on FAD=5.039 was 2.809 N, which was only 20% discrepancy.

Effects of FAD varying with tree height which revealed the impact of vertical distribution of the foliage have been studied. The Yellow Flame tree model was divided into five horizontal layers and corresponding FAD value for each horizontal layer was calculated, as shown in Figure 3. Compared to constant FAD = 5.039, the FAD values in the middle layers were larger because of more leaf covered in the middle layers, which resulted in lower velocity magnitudes at those layer heights in the downstream (X=H), as shown in Figure 4. For the top layer where the FAD value was smaller than the constant FAD, the velocity magnitude was slighter bigger in the downstream (X=H). The predicted drag force was 2.784N, corresponding to 19.4% discrepancy to the wind tunnel data, which showed slightly closer prediction than the model with constant FAD.

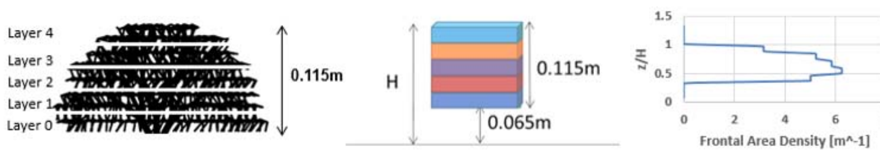

Fig. 3. Schematic of wind tunnel tree (left), CFD tree model (middle) and FAD profiles (right) for five horizontal layers

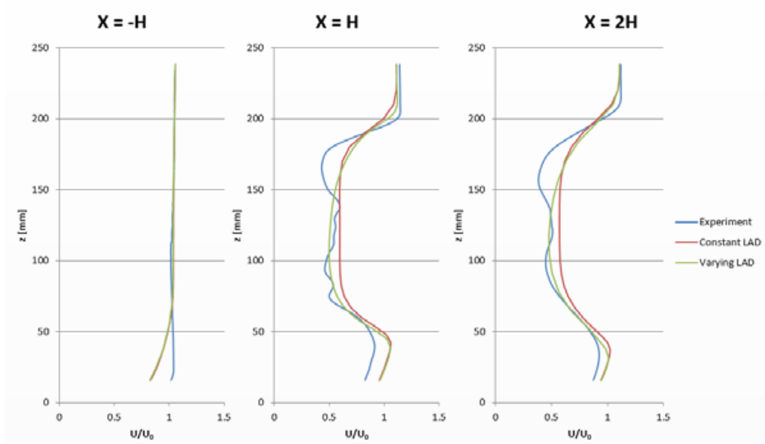

Fig. 4. Velocity profiles at upstream (X=-H) and downstream locations (X=H and X=2H) in the wind tunnel for FAD varying with tree height

3.3. *Model with trunk*

In this study, a trunk with a diameter 0.015m was explicitly modeled at the bottom of the porous cuboid tree zone to study the impact of trunk. As shown in Figure 5, the discrepancy of velocity profiles at the lower part tree height was reduced after the trunk was included in the model. However, the difference of predicted drag forces with and without tree was only 4%, which revealed that the majority of the drag force was from the tree canopy.

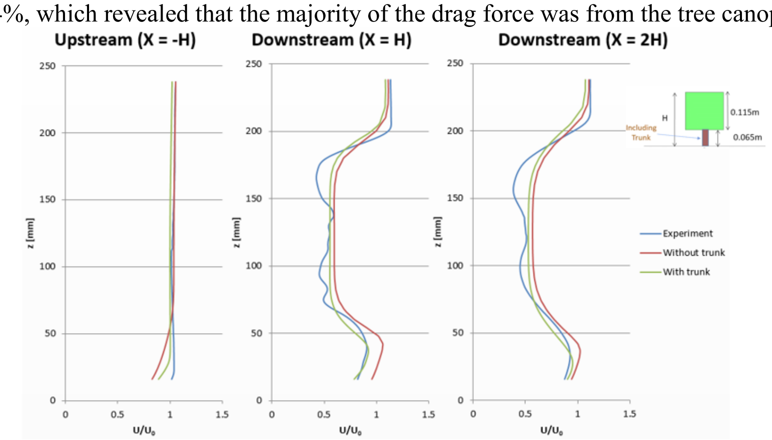

Fig. 5. Velocity profiles at upstream (X=-H) and downstream locations (X=H and X=2H) in the wind tunnel for model with trunk

4. Conclusions

A tree canopy model based on porous media approximation of tree volume developed for drag force prediction on scaled fractal tree in wind tunnel has been analyzed. Various sensitivity studies are implemented and the results demonstrate that: The influence of porous tree geometry, i.e., ellipsoid or cuboid, on the drag force prediction is found to be very small and can be neglected. Using frontal area density gives closer drag force prediction comparing to leaf area density for the full closure model. The variation of FAD with height impacts the velocity profiles and obtained slightly closer prediction of drag force than using constant FAD. With including the trunk in the model, the discrepancy of velocity profiles at the lower part tree height is reduced. Eventually, the simulation results exhibit about 19% over-prediction on the drag force; while a good match of the normalized velocity profiles is obtained at the tree leeward sides. As the project is still on-going, sensitivity studies with other tree species, e.g, *Khaya senegalensis* and *Hopea odorata*, will be carried out for model re-development and improvement.

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