In this paper, we propose a workable Geometrical-Wind Tunnel-Computational (GWTC) approach to model the wind effect on single tree. Firstly, L-System models based on tree species-specific growth and branching process is developed to process the laser-scanned point cloud model and reconstruct biologically and visually representative fractal tree for wind tree modelling. Subsequently, a scaled down fractal tree is generated with 3D printing and subjected to tunnel testing with load cell and PIV measurement data under the wind speed of 10 and 15 m/s. Lastly, CFD Reynolds-Average Navier Stokes (RANS) simulation with Full Closure Model and Large Eddy Simulation (LES) using appropriate momentum sink and turbulence source terms for the volumetric tree is carried out. Yellow flame (Peltophorum pterocarpum) tree is tested; and reasonable agreement of drag force prediction and velocity profiles is obtained when comparing the CFD simulation results with wind tunnel data. The RANS modelled drag force results exhibit 20% of over-prediction; while the normalized velocity profiles display good match of velocity decay at the tree leeward sides. On the other hands, LES simulation produce better results with only 3% discrepancy with experimental results. Preliminary experimental result comparison between yellow flame and Khaya senegalensis (to be subsequently referred as Khaya in this paper) is also carried out. Due to actual random wind direction, current methodology still has limitation for validation with urban on site measurement. Nonetheless, this GWTC approach is the first step in establishing modelling tool applicability to examine the effect of forest structure and composition on wind loads. In future, sensitivity analysis with CFD parametric study associated with other tree species (e.g. Hopea odorata) for model improvement will be carried.

Keywords: fractal tree, point cloud model, wind tree modelling, geometry reconstruction, CFD, urban greenery, Virtual Singapore
1. **Introduction**

Trees provide numerous environmental, economic, and social benefits: they improve the microclimate via shading and evaporative cooling; they improve air quality via pollutant deposition and carbon sequestration; and they improve road safety in stormy periods by water runoff reduction. However, trees can fail when an externally applied force exceeds the load-bearing capacity of the structure, and these failures may occur under a variety of conditions by trunk or branch fracture or by the loss of mechanical support in the root system. Tree failures can have severe consequences when they occur around valuable property, infrastructure, and people. Although these events are rare, many seek to avoid unfortunate outcomes by carefully managing their trees to reduce the inherent risk.

Therefore, it is important to understand the complex and dynamic wind-tree interaction phenomena, in order to estimate the aerodynamic force that tree can endure in given locations. However, wind tree modelling over complex shape of tree branches and leaves systems poses tremendous challenges on both geometrical reconstruction\(^1\) and tree aerodynamics\(^3,4\) simulation. Although it is important to include the irregular tree branches and leaves geometry for wind load prediction on urban greenery, the computational resource and cost for meshing and CFD simulation would make it prohibitive to model every single geometrical detail.

To circumvent the above challenge, we propose a practical approach, namely Geometrical-Wind Tunnel-Computational (GWTC) methodology to model the wind effect on single tree. Subsequently, we would extend it to model individual tree in town area (about 1km x 1km site area with few thousand of trees). This GWTC approach would involve following three work scopes

1. 3D Fractal Modelling with L-system to generate tree species models found in Singapore from laser-scanned point cloud of actual trees\(^5\). The finite element surface mesh model of the tree would also be produced.
2. 3D Printing and Parameter Extraction from Fractal Tree Model to produce the fractal porous media models; based on the wind tunnel experimental results to establish relation between fractal parameters and drag coefficient, \(C_d\)\(^6\). A 3-D printing technique will be considered to construct the tree model with complicated geometries; and detailed wake survey of the flow over the tree model will be carried out by particle image velocimetry.
3. 3D CFD wind tree modelling at wind tunnel and urban landscape to develop, simulate, validate and implement the CFD large scale wind-tree study using tree-fractal approach; with momentum sink terms\(^7\) being modelled as functions of the tree anisotropy Leaf Area Density (LAD) properties and reflecting the realistic directional effects from tree heterogeneity. CFD analysis of flow over single fractal tree with high fidelity LES grid-filtering turbulence model will also be investigated\(^8\).
2. Approach

2.1. Tree Geometrical Fractal Modelling

Firstly, based on isolated point cloud data for individual trees, algorithms have been developed to segregate tree point data into woody structure (trunk, branches) and foliage. The filtering process takes in two parameters; an intensity cut-off limit and a neighbourhood distance limit. Figure 1 shows the filtering process with intensity threshold separation method.

Although a general outline of the tree branches can be extracted, the segregation process at this stage is not a clean separation and still contains many small clusters of points that represent leafy structures. Hence, the next extraction process involves a distance-based clustering process. A set of points is first defined to be the base “root” of the tree. A shortest path algorithm based on Dijkstra’s algorithm is used to find the distance of each point to the base root. As can be seen in Figure 2, each distance interval can be seen distinctively with the alternate colouring scheme. Points located in each distance interval are clustered together to form a “node”. Following that, nodes can be easily connected up based on the adjacency to each other. A skeletonisation of the branches is then formed. The thickness of each branch can also be estimated, and represented by a cylindrical geometry.

The process of point filtering & skeletonisation of tree point cloud allow us to derive some parameter values, such as trunk height, branching angle, number of first or higher order branching, etc. The parameter data are subsequently used to form species statistics and constraints to procedurally generate similar 3D species models that represent actual trees. The species models are procedurally generated based on a set of L-system growth
rules. We formulated the rules with respect to tree architecture that identifies various species in terms of growth process, branching pattern, and axis morphology. Secondly, we generated fractal models to represent certain tree species in Singapore by adopting above L-system models with typical/average species profiles based on known species architecture (e.g. growth process, branching patterns, axis morphology), field measurements, and observations. In essence, the fractal model is a branch skeleton representing a tree without leaves, flowers, fruits, and other seasonal components. The L-system fractal models provide information of tree branch segments, specifically their locations, orientations, and (branch) diameters. Figure 3 show the L-system fractal models for yellow flame tree species, with corresponding species-average parameter values.

Fig 3: *Peltophorum pterocarpum* (yellow flame). L-system tree model based on the average parameters collected of the species

Finally, we developed a methodology to convert L-system fractal models into finite element surface mesh models. The skin surface tree joint model is adopted. For each tree branch joint, the direction of the branches is used as a basis for constructing the model, with each direction using a ball as a representation. The merged surface of the balls is then generated in a triangle mesh format (see Figure 4).

Fig 4: Meshed Skin Surface for modelling the joint of the tree branches

Based on the information from the L-system, a set of cylindrical and ball joint component is created separately. From the simple ball joint mode, to fully remove the half-sphere, a series of critical points are first inserted onto the surface of the ball joint. Using the critical points as junctures, a mesh-walk traverse algorithm is used to connect the critical points up before the half-sphere can be removed cleanly. The result is that the opening is much smoother for the Final Ball Joint Component Mesh. The final merged tree model extracted from the L-system model can be seen in Figure 5.
2.2. Tree Wind tunnel Modelling

Scaled down 3D printed fractal tree with model height of 0.15m and minimum branch diameter of 2mm (model size ratio is about 0.01 when comparing to actual tree) is produced for wind tunnel testing. The fabricated tree model is then mounted in the wind tunnel for PIV and drag measurement. The load cell that measures drag force is mounted underneath the tree model. The wind tunnel tests were conducted in two wind speeds: 10m/s and 15m/s, and different rotation angles (hence different frontal projected area). The wind tunnel experimental setup and testing parameters are shown in Figure 6.

Fig 6: Experimental setup for PIV and drag measurement with different testing conditions

The laser arm fires laser sheet at the centre plane of the tree, allowing the visualization of the flow field of the plane. Figure 7 shows the typical velocity field and wake profile results for 15m/s and 0 degree rotation for yellow flame tree species.

2.3. Tree CFD Modelling

Both CFD Reynolds-Average Navier Stokes (RANS) simulation with Full Closure Model porous media formulation and Large Eddy Simulation (LES) with Wall-adapting Local Eddy-viscosity (WALE) subgrid scale model are carried out for wind-tree modelling of single tree in wind tunnel. OpenFOAM is used for both simulation analysis. The volumetric tree canopy is modelled using appropriate momentum sink and turbulence source terms. Momentum sink \( S_u = -C_d (LAD) u U \) is added to the momentum equation, in which \( C_d \) is the drag coefficient for tree canopy, \( LAD \) is leaf area density \( (m^2/m^3) \), \( u \) is velocity component \( (m/s) \) and \( U \) is the velocity magnitude. For tree modelling, the product of \( C_d \) and \( LAD \) is termed as pressure loss coefficient, \( \lambda^3 \). It is the static pressure loss \( \Delta p_{stat} \) per material thickness normalized by the dynamic pressure \( p_{dyn} \) (see Figure 8).

\[
\lambda = \frac{\Delta p_{stat}}{p_{dyn}} = \frac{p_{stat} - p_{stat}}{p_{dyn}} \frac{d}{(1/2) p u^2 d} 
\]
$u$ mean velocity component in streamwise direction
$d$ obstacle’s streamwise depth
$p_{\text{luw}}$ static pressure windward of the obstacle
$p_{\text{lee}}$ static pressure leeward of the obstacle
$\rho$ density of fluid

Essentially, the pressure loss coefficient $\lambda$ is a parameter depending on the internal structure of the obstacle and describes integrally the permeability.

Fig 7: PIV result for (a) average velocity field and (b) mean wake profile at 15m/s and 0 degree rotation

Fig 8: Measurement for pressure loss coefficient $\lambda$ in tree modelling

3. Results and discussion

3.1. CFD Modelling results with RANS and LES

Typically for drag force calculation over solid body, it is the sum of normal force resulting from form drag and shear force from friction on surface. However for porous tree model,
it is important to consider that drag force calculation also needs to take into account the additional components due to net momentum flux. Figure 9 shows the fundamental difference for drag force calculation between solid body and porous medium.

We found that most prior literature has used the Leaf Area Density (LAD) calculation based on the plant area density of the tree model in the wind tunnel test, and this results in wrong calculation, most often over-predicting drag force by more than 50%. Instead, we made the correction and proposed frontal silhouette area of the tree model for calculation of frontal area density (FAD) to represent the leaf area density for the full closure model. This has resulted in tremendous improvement to the CFD drag force comparison with experimental results. With $\text{FAD} = 4.375$, $C_d = 0.98$ and free stream velocity of 15m/s, RANS simulation produces the drag force calculation with about +21% error. However, drastic improvement can be obtained with LES simulation result, as it yield only +2.95% error when comparing with experiment data. In addition, LES gives about 14% uncertainty when comparing average velocity at H downstream; better than RANS simulation (23%). The result can be illustrated in Figure 10 and Table 1 below.

![Drag force calculation for solid body and porous medium](image)

**Fig 9:** Drag force calculation for solid body and porous medium

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![Velocity profiles at different locations in the wind tunnel](image)

**Fig 10:** Velocity profiles at different locations in the wind tunnel for 0-degree rotation for (a) RANS simulation and (b) LES simulation

**Table 1:** CFD results comparison with experimental data on drag force for case study with $FAD = 4.375$, $C_d = 0.98$ and free stream velocity of 15m/s

<table>
<thead>
<tr>
<th>Wind tunnel load cell measured drag force (N)</th>
<th>Calculated drag force with RANS simulation (N)</th>
<th>% error</th>
<th>Calculated drag force with LES simulation (N)</th>
<th>% error</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.314</td>
<td>2.797</td>
<td>+20.9%</td>
<td>2.382</td>
<td>+2.95%</td>
</tr>
</tbody>
</table>
3.2. Experimental results comparison between two different tree species, Yellow Flame and Khaya

Figure 11 shows the 3D printed model for both yellow flame and Khaya tree.

![3D printed tree model for (a) yellow flame and (b) Khaya](image)

Table 1 below shows the result comparison on frontal projected area ratio of both Yellow Flame and Khaya tree.

<table>
<thead>
<tr>
<th>Tree</th>
<th>Rotation Angle, deg.</th>
<th>0</th>
<th>30</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frontal Projected Area, m²</td>
<td>0.16569</td>
<td>0.13264</td>
<td>0.16386</td>
</tr>
<tr>
<td></td>
<td>Crown Volume, m³</td>
<td>0.0036483</td>
<td>0.0036483</td>
<td>0.0036483</td>
</tr>
<tr>
<td></td>
<td>FAD, m⁻¹</td>
<td>4.54151</td>
<td>3.63878</td>
<td>4.49151</td>
</tr>
<tr>
<td>Yellow Flame</td>
<td>Rotation Angle, deg.</td>
<td>0</td>
<td>45</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>Frontal Projected Area, m²</td>
<td>0.014299</td>
<td>0.015667</td>
<td>0.013929</td>
</tr>
<tr>
<td></td>
<td>Crown Volume, m³</td>
<td>0.0021468</td>
<td>0.0021468</td>
<td>0.0021468</td>
</tr>
<tr>
<td></td>
<td>FAD, m⁻¹</td>
<td>6.66052</td>
<td>7.29771</td>
<td>6.4880</td>
</tr>
</tbody>
</table>

From the above results, it is found that frontal silhouette area for Khaya is generally lower than yellow flame tree. However, due to smaller crown volume, Khaya would give higher FAD. Figure 12 shows the $C_D$ result comparisons for both yellow flame and Khaya.

![$C_D$ result comparisons for both yellow flame and Khaya](image)

Interestingly, it is found that Khaya tree gives lower $C_D$ value despite the higher FAD geometrical data. Further analysis need to be evaluated to look into the correlation between
4. Conclusions

A practical Geometrical-Wind Tunnel-Computational (GWTC) approach to model the wind effect on single tree and predict the tree drag force has been proposed and analyzed. This methodology uses L-System for species-specific tree growth and branching process to generate tree fractal models, which were printed scaled down (100:1) for wind tunnel PIV and drag force measurement, and employ both RANS and LES simulation for CFD flow modelling and drag calculation for further validation. Testing has been carried out for yellow flame tree; and RANS produce reasonable prediction of 80% accuracy for drag force prediction. The higher fidelity of LES turbulence modelling gives much better 97% accuracy, albeit at the expenses of computational cost. In addition, it is found that Frontal Area Density (FAD) value using the frontal silhouette area of the tree model is of paramount importance for CFD tree modelling and give the insightful information about tree permeability and pressure loss coefficient. Preliminary experimental results for yellow flame and Khaya tree also reveals that there could be intrinsic correlation between pressure loss coefficient ($\lambda$) with drag force and velocity decay downstream for wind effect on tree and vegetation.

Acknowledgments

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References