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CFD Analyses of the Wind Drags on *Khaya Senegalensis* and *Eugenia Grandis*

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CFD Analyses of the Wind Drags on *Khaya Senegalensis* and *Eugenia Grandis*

Abstract

The drag coefficients of one mature *Khaya Senegalensis* tree and one *Eugenia Grandis* tree in Singapore were analysed using computational fluid dynamics (CFD) modelling and validated with field measurements. For the numerical method, an innovative laser scanning approach was used to generate the tree geometries and to calculate the *three-dimensional* (3D) leaf area density distribution within the canopies. The canopies were represented by multiple porous domains and the turbulent effect of leaves was simulated by source and sink terms as a function of the calculated leaf area density. Computational fluid dynamics analyses using ANSYS 17.2 software were carried out on both leafless and leafed tree models. Three turbulent models, the Realizable k- ϵ model, Transition Shear Stress Transport model and Reynolds Stress Model were compared, and it was found that the differences in the drag forces among the turbulent models were negligible when they were meshed appropriately based on the grid independence study. The computed drag coefficient of the *Khaya Senegalensis* tree and the *Eugenia Grandis* tree from CFD modelling were similar within the range between 0.6 and 0.7. From field monitoring including the wind velocity and stem strains, the drag coefficients of both trees were calculated to be 0.51 and 0.4. Possible reasons causing the difference and limitations of the numerical method are discussed.

Keywords: CFD, Drag Coefficient, Laser Scanning, Urban Tree, Wind

1. Introduction

1.1 Wind and Tree Failures

Tree failure is not only a loss to the environment. It also poses a public safety risk and can lead to property damage in urban areas (Duryea et al., 2007; Lopes et al., 2009; Schmidlin, 2009).

Tree stability is particularly important in Singapore, given its planning policy that embraces the city in a garden philosophy. In fact, Singapore was recently identified as the most treed city in the world based on remote sensing of canopy cover in a study done by MIT Senseable City Lab (Li et al., 2015; Seiferling et al., 2017; Yuen, 1996). Wind storms in tropical areas are considered as the major cause of failures for healthy trees. Wind causes a tree to deform or fail and wind drag is used to describe the net force on a tree in the direction of the wind flow. The drag force consists of both pressure drag and viscous drag. Pressure drag is related to the flow separations produced when the air flows through the tree while viscous drag is generated from the turbulent shear stresses on the tree surfaces. In most cases of tree failures, it can be expected that pressure drag would dominate for tree failures since trees are typically bluff bodies and flow separations would occur when air passes trees. However, at small velocities, viscous drag could also be dominant even for a bluff body like trees. As illustrated in Figure 1, wind velocity also affects the dominant drag on trees. At lower wind velocities, the viscous drag may dominate due to the friction between air and leaves. As wind velocity increases, pressure drag will increase and viscous drag will decrease. Therefore, the viscous drag dominates at lower wind velocities and pressure drag dominates at higher velocities in general.

Drag coefficient is used to describe the wind drag on tree in a dimensionless way and can be calculated as:

$$C_d = 2F/(\rho A u^2) \quad \text{Equation 1}$$

where F is the drag force in the wind direction, C_d is the drag coefficient, ρ is the air density, A is the projected canopy area perpendicular to the wind direction and u is the mean wind velocity.

The drag coefficient of a tree is an important parameter when estimating the critical wind velocity that could lead to a tree failure and it has been a useful tool for arborists to manage

trees (Cullen, 2005). The drag coefficient can be measured in the field (Koizumi et al., 2010) or through wind tunnel experiments with proper scaling. It can also be calculated through numerical simulations. Endalew et al. (2009) compared the results of wind tunnel experiments and numerical simulations for two 1:10 scaled tree models with an average height of 24 cm. The inlet velocity was scaled 10 times up to 10 m/s, in order to maintain the same turbulent properties with a 1 m/s wind flowing through a tree height of 2.4 m in the field. However, this scaling requirement makes the wind tunnel experiment difficult for a tree height of 20 m at high wind velocities. Therefore, the wind tunnel experiment may not be appropriate since it limits the size of tree and the corresponding wind velocity that could be represented from the field. The objective of this study is to obtain the drag coefficient for mature trees through CFD analyses and to validate the analyses using field measurements.

1.2 Turbulent Flow

Reynolds number is an important dimensionless value to differentiate the characteristics of the fluid flow regimes into laminar flows and turbulent flows (Reynolds, 1883):

$$Re = \rho u D / \mu \quad \text{Equation 2}$$

where Re is the Reynolds number of the flow, D is the average characteristic width of the tree canopy and μ is the dynamic viscosity of air.

As described in Figure 1, at low Reynolds number, when the wind velocity is small, the friction between air and tree is important and the viscous drag is large compared to the pressure drag. However, as the wind velocity increases, pressure drag becomes dominant. Laminar viscous drag is only important at very low wind velocities. For a tree with a canopy width of 20 m, the Reynolds number is about 7×10^6 at a wind velocity of 5 m/s. Hence, the flow can be characterized as in the turbulent regime which the pressure and flow velocity fluctuate chaotically, usually irregular and random.

The flow velocity at the solid boundary, such as ground and tree trunk, is held at zero due to the physical no-slip condition. Since the flow velocity far from the boundary is the freestream wind velocity, a boundary layer region will develop and it is used to describe the layer near the solid boundary when the flow velocity increases from zero to the mainstream velocity. A turbulent boundary layer consists of an inner layer and an outer layer. For numerical representation, wall functions can be used to reproduce the effects of near wall turbulence in the turbulent boundary layer in an efficient manner to avoid the extremely fine meshes (Zhang et al., 2017). The first thin layer adjacent to the wall is known as the viscous sublayer within which turbulence does not exist and the viscous shear dominates (Franzini et al., 1997). The thickness of this sublayer could be as thin as a few hundredths of a millimetre, and the mean velocity is linearly proportional to the wall distance (Franzini et al., 1997). Further from the viscous sublayer is the log-layer where the mean velocity becomes proportional to the logarithm of the wall distance. The outer layer is the region when the turbulence affects the shear stress distribution.

1.3 Computational Fluid Dynamics Modelling

Computational fluid dynamics (CFD) modelling describes the use of numerical methods and turbulent models to solve fluid equations. Airflow is considered as an incompressible flow if the calculated Mach number is less than 0.3 (Franzini et al., 1997) :

$$M = u/c \quad \text{Equation 3}$$

where M is the Mach number and c is the speed of sound.

Airflow through trees typically belongs to the incompressible flow regime unless the wind velocity approaches 100 m/s and the Mach number therefore exceeds 0.3. Navier-Stokes Equations for incompressible flow can thus be used to investigate the steady-state drag forces

on trees. The equations include the continuity equation and momentum equations derived from the conservation law of mass and momentum (Franzini et al., 1997):

$$\partial \mathbf{u}_i / \partial x_i = 0 \quad \text{Equation 4}$$

$$\rho \partial (\mathbf{u}_i \mathbf{u}_j) / \partial x_j = -\partial p / \partial x_i + \partial [\mu (\partial \mathbf{u}_i / \partial x_j + \partial \mathbf{u}_j / \partial x_i + 2/3 \delta_{ij} \partial \mathbf{u}_l / \partial x_l)] / \partial x_j$$

$$\text{Equation 5}$$

where $i, j = 1, 2, 3$, $\mathbf{u}_i$ is the i^{th} component of the velocity, x_i is the Cartesian coordinate and p is the pressure.

Taking the time average, the Reynolds Averaged Navier Stokes (RANS) equations can be obtained as (Fluent, 2011):

$$\partial \overline{\mathbf{u}_i} / \partial x_i = 0 \quad \text{Equation 6}$$

$$\rho \partial (\overline{\mathbf{u}_j \mathbf{u}_i}) / \partial x_j = -\partial \overline{p} / \partial x_i + \partial [\mu (\partial \overline{\mathbf{u}_i} / \partial x_j + \partial \overline{\mathbf{u}_j} / \partial x_i + 2/3 \delta_{ij} \partial \overline{\mathbf{u}_l} / \partial x_l)] / \partial x_j + \partial (-\rho \overline{\mathbf{u}_i' \mathbf{u}_j'}) / \partial x_j \quad \text{Equation 7}$$

Where $\overline{\mathbf{u}_i} = \mathbf{u}_i - \mathbf{u}_i'$, $\mathbf{u}_i'$ is the i^{th} component of the fluctuating velocity, $\overline{\mathbf{u}_i}$ is the i^{th} component of the averaged velocity and $\overline{p}$ is the average pressure.

In the RANS equations, the velocity is decomposed into its mean and fluctuating components. However, one more unknown term, the turbulent Reynolds stress tensor $\overline{\mathbf{u}_i \mathbf{u}_j}$, is introduced and needs to be solved by turbulent models. Turbulent models include both Eddy Viscosity Models and Reynolds Stress Model (RSM). Eddy Viscosity Models are most commonly used due to faster convergence and good performance in many engineering problems, and the Boussinesq Hypothesis is used by assuming an isotropic value for the turbulent viscosity to calculate the Reynolds stresses (Fluent, 2011). However, the isotropic assumption is not appropriate if the turbulence is strongly anisotropic. Instead, RSM solves the six separate Reynolds stress components directly without any assumption, and hence could be more

accurate in these cases but require a longer run time to solve the extra equations (Fluent, 2011). The Realizable k- ϵ model and Transition Shear Stress Transport (SST) are two other eddy viscosity models to incorporate additional equations to solve the set of RANS equations. The Realizable k- ϵ model is the most widely used model given its lower computational cost and accuracy for most flow requirements (Fluent, 2011). However, the Realizable k- ϵ model may also not perform well when dealing with flows that have large pressure gradients near the wall. The Transition SST can be applied to solve the flow near the wall as well as further from the wall (Fluent, 2011).

Researchers have conducted studies on airflow through trees using various Eddy Viscosity Models. Gan and Salim (2014) performed numerical simulations based on the RSM scheme. Five porous cuboids were used to represent the canopy of a tree. The effect of leaves was simulated by a pressure loss coefficient within the canopy. However, the pressure loss coefficient was assumed, and the simulations results were not validated by any experiments. Note that it may not be reliable enough to represent the effect of leaves by only pressure or momentum loss without considering the turbulence created. The change in the turbulence of leaves should also be consider. Endalew et al. (2009) applied the k- ϵ model to simulate the airflow within a complex three-dimensional (3D) canopy architecture. They suggested that the leaves could be represented by the porous domains around the solid branches as illustrated in Figure 2.

The air flow is modified by the presence of the leaf region. A possible approach is to simulate by source and sink terms in the RANS equations as a function of the leaf area density (LAD) (Sanz, 2003; Endalew et al., 2009). LAD is defined as the total leaf area of one side per unit volume and the unit is m^{-1} . It can be calculated in various manner, for example from a set of photographs using the gap fraction method as suggested by Phattaralerphong et al. (2006).

However, the LAD distribution used in the study of Endalew et al. (2009) only varied with tree height instead of 3D coordinates.

2. Material and Methods

2.1 Geometry model from point cloud laser scanning

In this study, the laser scanner V-Line 3D Terrestrial Scanner RIEGL VZ-400 was used to generate the point clouds of the selected trees. One *Khaya Senegalensis* tree and one *Eugenia Grandis* tree in the Chua Chu Kang area of Singapore were chosen in this study as *Khaya Senegalensis* and *Eugenia Grandis* are two species that are commonly planted in Singapore. The height of the *Khaya Senegalensis* tree was about 30 m and the width of the canopy was about 25 m. The height of the *Eugenia Grandis* tree was about 25 m and the width of the canopy was about 16 m. The leaves and wooden parts in the point cloud were differentiated by reflectance. The point clouds were then post-processed in CANUPO and AutoCAD to generate the 3D tree model simulated in the ANSYS 17.2 analysis design software. The point clouds and 3D models are shown in Figure 3 and Figure 4, for the *Khaya Senegalensis* tree and the *Eugenia Grandis* tree respectively.

2.2 Leaf Area Density (LAD) Calculation

LAD was computed from the point cloud data within each 0.2 m voxel cube based on an optimal voxel dimension study done by Béland et al. (2014). Figure 5 plots the LAD profile of the *Khaya Senegalensis* tree and the *Eugenia Grandis* tree in MATLAB and the colour represents the LAD value of each 0.2 m voxel cube. The 3D distribution of LAD also describes the 3D canopy architecture when Figure 5 and Figure 3 or Figure 4 are compared.

Since each tree canopy is represented by multiple porous domains, the average LAD for each porous domain is the total leaf area in the domain divided by the volume of the domain and could be calculated from (Endalew et al., 2009):

$$A_{LAD} = 1/V \sum A_{LAD_i} V_i \quad \text{Equation 8}$$

Where A_{LAD} is the average leaf area density of the porous domain in the canopy, A_{LAD_i} and V_i are the leaf area density and the volume of the voxel respectively, V is the volume of the porous domain.

2.3 Airflow through leafless models

Airflow through the leafless *Khaya Senegalensis* tree and the *Eugenia Grandis* tree were simulated in ANSYS 17.2 to obtain the drag forces and drag coefficients. A grid independence study was carried out first to determine the necessary meshing scheme, which provides the desired accuracy. Figure 6 shows the *Khaya Senegalensis* tree geometry with the boundary conditions.

Richards and Hoxey (1993) suggested the vertical profile for fully developed Atmosphere Boundary Layer (ABL) profile as:

$$u(z) = u_{ABL}^* / \kappa \ln[(z + z_0)/z_0] \quad \text{Equation 9}$$

$$k(z) = u_{ABL}^{*2} / \sqrt{C_\mu} \quad \text{Equation 10}$$

$$\varepsilon(z) = u_{ABL}^{*3} / \{\kappa \ln[(z + z_0)/z_0]\} \quad \text{Equation 11}$$

where z is the height coordinate, $u(z)$ is the wind speed at height z , u_{ABL}^* is the ABL friction velocity, $\kappa = 0.41$ is the von Karman constant, z_0 is the aerodynamic roughness length and C_μ is a turbulent model constant equal to 0.09. ABL friction velocity was calculated from (Chiu et al., 2017):

$$u_{ABL}^* = u_{ref} \kappa / \ln[(z + z_0)/z_0] \quad \text{Equation 12}$$

where u_{ref} is the wind velocity at the reference height h .

Aerodynamic roughness length represents the roughness of the ground surface and a roughness length of 0.25 m was used in this study since some scattered high obstacles such as trees existed in the field (WMO, 2008). ABL friction velocity was estimated at 0.55 m/s for a wind velocity of 5 m/s at the reference height of 10 m. The wind velocity inlet profile is shown in Figure 7 as calculated from Equation 9.

The ground, the tree trunk and the branches were assigned with no-slip wall boundary conditions while the top and two side boundaries were set as slip symmetry boundary conditions. A pressure boundary was imposed at the outlet to enable the air to flow out of the domain.

Table 1 illustrates the settings for the meshing schemes. Meshing Scheme 1 is the coarsest while Meshing Scheme 3 is the finest. Three turbulence models, Realizable k- ϵ model, Transition SST model and RSM model were compared to investigate the influences of the different turbulent models on the drag force and drag coefficient. The convergence criteria for all parameters were set to 1×10^{-6} . For the solution method, the Semi-Implicit Method for Pressure-linked Equations (SIMPLE) scheme and the 2nd order upwind scheme were employed. The drag coefficient and the lift coefficient were computed as well in each iteration. The calculation was terminated when the residuals, the drag coefficient and the lift coefficient became stable.

2.4 Airflow through leafed models

The boundary conditions applied for the leafed *Khaya Senegalensis* tree and the leafed *Eugenia Grandis* tree were the same as the boundary conditions applied for the leafless trees.

Momentum sink terms, turbulent kinetic energy sink terms and dissipation rate source terms were used as described in Equations 13, 14 and 15 in each porous domain of the canopy to consider the effect of leaves. When wind passes the tree canopy, there will be a loss in the momentum and the turbulent kinetic energy, and an increase in the eddy dissipation rate. If the viscous drag is much smaller than the pressure drag, it can be ignored and the momentum sink term S_u derived based on this condition given by Sanz (2003):

$$S_u = -\rho C_d A_{LAD} u^2 \quad \text{Equation 13}$$

The turbulent kinetic energy sink term S_k for dense canopies is modified from Walklate et al. (1996):

$$S_k = -\rho C_d A_{LAD} k u \quad \text{Equation 14}$$

where k is the turbulence kinetic energy. The dissipation rate source term S_ε is based on the studies by Katul et al. (2004):

$$S_\varepsilon = \rho C_d A_{LAD} C_{\varepsilon 4} \varepsilon u \quad \text{Equation 15}$$

where ε is the eddy dissipation rate and $C_{\varepsilon 4} = 1.5$ is a constant obtained from mixing length anisotropy (Sanz, 2003).

2.5 Drag coefficients from field instrumentations

For field instrumentations, weather station and Linear Variable Differential Transducer (LVDT) as shown in Figure 8 were installed to monitor the wind velocity and stem strains, respectively. Previously, Koizumi et al. (2010) also evaluated the drag coefficients of tree with the field test method by monitoring the wind velocity and the stem strains at the same time.

Two LVDTs measured the tree strains in the North-South direction and East-West direction. They were installed on each tree from 1 m above the ground. The total strains could be

calculated based on these two strains at two perpendicular directions. The drag coefficients were calculated from Equation 1. Bending stress could be related to drag force through:

$$\sigma = FL_c y / I \quad \text{Equation 16}$$

where F is the drag force, L_c is the distance from the centre of pressure on the tree to the LVDT measuring point, y is the radius of the trunk at the LVDT attachment point and I is the second moment of area of the cross section at the LVDT attachment point. Figure 9 sketches the position of LVDTs and the centre of wind pressure on a tree and illustrates the lever arm L_c used to calculate the bending stress in Equation 16.

Bending stress could be calculated from the total strain of LVDTs:

$$\sigma = E \sqrt{(\Delta L_1 / L_0)^2 + (\Delta L_2 / L_0)^2} \quad \text{Equation 17}$$

where E is the Young's Modulus of the respective tree, ΔL_1 and ΔL_2 are the deformations of the two LVDTs at two directions and L_0 is the original length of the LVDT.

Static pulling tests were conducted by some researchers to obtain the modulus of elasticity and the modulus of rupture of the tree (Peltola et al., 2000). The average stiffness of the tree-root-soil system could be measured by recording the pulling forces and the respective stem strains or deflections together. To pull a tree, a winch positioned on another tree was used for the anchorage. The winch was connected to a load cell by a cable and then connected to the tree. The angle between the trees and the cable were measured. The height of the anchoring point was recorded as well. The tree was pulled by a displacement of 5 cm at each step until a cumulative displacement of 30 cm was reached within the elastic range. The resisting force and the corresponding displacement were recorded. A high-resolution video camera was used to record the lateral deflection as well. After the static pulling test, branches were cut with a chainsaw and three-point bending tests were conducted to measure the modulus of the branches. The tree stem was assumed to have a tapered shape. The tapered ratios were calculated from

the measurements of the diameters at the trunk top and trunk bottom. Then the overall stiffness of the tree was estimated as:

$$E = T_r^3 PL^3 \delta / (3I) \quad \text{Equation 18}$$

where P is lateral force acting on the attachment, L is the height of attachment point, δ is the displacement of the tree at the attachment point and T_r is the tapered ratio. Using this equation, the calculated average Young's Modulus of *Khaya Senegalensis* was 0.9 GPa and the average Young's Modulus of *Eugenia Grandis* was 1.23 GPa based on the static pulling tests on other *Khaya Senegalensis* trees and *Eugenia Grandis* trees in Singapore (NParks & NTU, 2017).

From Equation 1, Equation 16 and Equation 17, drag force and drag coefficient could be calculated as follows:

$$F = EI \sqrt{(\Delta L_1/L_0)^2 + (\Delta L_2/L_0)^2} / (L_c y) \quad \text{Equation 19}$$

$$C_d = 2EI \sqrt{(\Delta L_1/L_0)^2 + (\Delta L_2/L_0)^2} / (L_c y \rho A u^2) \quad \text{Equation 20}$$

The mean velocity u could be calculated as:

$$u = \int_0^H u(z) dz / H \quad \text{Equation 21}$$

where H is the height of tree.

Substituting Equation 9 and Equation 12 into Equation 21 gives:

$$u = u_{ref} [-H + Hh (4H + 1) + 0.25 \ln(4H + 1)] / \{\ln[(z + z_0)/z_0] H\} \quad \text{Equation 22}$$

When $u_{ref} = 5$ m/s at a reference height of 10 m, the mean velocity was 5.2 m/s for the 30-metre-high *Khaya Senegalensis* tree and 4.9 m/s for the 25-metre-high *Eugenia Grandis* tree as calculated from Equation 22. From Equation 22, it can also be observed that the mean velocity varies proportionally with the reference velocity u_{ref} .

3. Results and Discussion

3.1 Airflow through leafless models

Simulations on models meshed with Meshing Scheme 1 required about 3 hours on 4 parallel processors to reach converged results. Simulations with Meshing Schemes 2 and 3 required 4 hours instead. With finer meshes, although the time to calculate each iteration increased, the number of iterations computed to the converged solution decreased, which explained why Meshing Schemes 2 and 3 with different meshing densities had the same computing time. Figure 10 and Table 2 describe the computed drag coefficient with different meshing number of nodes in the three meshing schemes using the Realizable k- ϵ model, the Transition SST model and the RSM model. To allow for grid independent drag results, the mesh resolution was increased for each tree model until the change in drag became less than 2% between the successive meshing schemes.

For all three turbulent models, Meshing Scheme 3 was found to be appropriate with the drag difference reducing to be less than 2%. Therefore, Meshing Scheme 3 was used to simulate the airflow through the *Eugenia Grandis* tree. Table 3 describes the wind drags on the *Eugenia Grandis* tree using the Realizable k- ϵ model, the Transition SST model and the RSM model. The drag differences among the three turbulent models were less than 2% for the *Khaya Senegalensis* tree or the *Eugenia Grandis* tree. The drag force applied to the *Khaya Senegalensis* tree was larger than the drag force applied to the *Eugenia Grandis* tree. The reason is that the larger projected area of the *Khaya Senegalensis* leads to a higher drag force. In addition, the *Khaya Senegalensis* tree is 5 m higher than the *Eugenia Grandis* tree, hence experiences a larger average velocity. However, the drag coefficient of the *Eugenia Grandis* tree is higher than the *Khaya Senegalensis* tree. The reason could be due to the denser

distribution of branches of the *Eugenia Grandis* tree, resulting in a higher drag coefficient with less projected area.

Since the results of the three turbulent models did not differ much, only the pressure contours using the Realizable k- ϵ model are presented in Figure 11. Figure 11 plots the pressure contour on the *Khaya Senegalensis* tree and on the *Eugenia Grandis* tree. The wind direction is perpendicularly into the paper. The higher pressure is experienced on the part of tree facing the wind and the lower pressure is observed at the back of the tree.

3.2 Airflow through leafed models

Tables 2 and Table 3 show that wind drags on leafless trees among the different turbulent models are small. Therefore, when estimating the drag on leafed trees, only the realizable k- ϵ model was used.

Figures 12 and 13 plot the velocity contour and the velocity streamline around the *Khaya Senegalensis* tree and the *Eugenia Grandis* tree on x-z plane, where x-direction is the wind direction. The cavity zone could be observed at the back of canopy from Figure 12 or Figure 13. Although the canopy is porous, the air still tends to flow through the voids around the canopy with less resistance and momentum loss.

Figure 14 plots the pressure contour on the *Khaya Senegalensis* tree and on the *Eugenia Grandis* tree. The wind direction is perpendicularly into the paper. The higher pressure is experienced at the part of tree facing the wind and the lower pressure is observed at the back of the tree. The difference in leaf area density leads to the different gradient of pressure transitions from high pressure to low pressure though each porous domain.

The drag related results are summarized in Tables 4 and 5, for the *Khaya Senegalensis* tree and the *Eugenia Grandis* tree, respectively.

The total projected area is smaller than the summation of canopy and trunk area due to the overlapped projected area. The total area is smaller by 8% for the *Khaya Senegalensis* tree and 12% for the *Eugenia Grandis* tree. The reduction in the total area of the *Eugenia Grandis* tree is higher because the ratio of the trunk covered by the canopy is higher for the *Eugenia Grandis* tree than that for the *Khaya Senegalensis* tree. Furthermore, the ratio of the drag force on canopy to the total drag force is 0.97 for the *Eugenia Grandis* tree and 0.92 for the *Khaya Senegalensis* tree and the ratio of the drag force on trunk to the total drag force is 0.03 for the *Eugenia Grandis* tree and 0.08 for the *Khaya Senegalensis* tree since more trunk area is covered by the canopy on the *Eugenia Grandis* tree. For both trees, the drag forces on the trunk of leafed models are higher than those on the trunk of leafless models since the leaves surrounding and covering the trunk reduces the drag applied on the trunk.

The drag coefficients of the leafed models are higher than those of the leafless models. For the *Khaya Senegalensis* tree, the drag coefficient of the leafed tree is 8.8% higher than a tree without canopy. For the *Eugenia Grandis* tree, the drag coefficient of a leafed tree is 6.4% higher. In other words, compared to a solid geometry, the porosity that leaves create could increase the drag coefficient of the tree.

Generally, the drag coefficients of the *Khaya Senegalensis* tree is 0.64 and the drag coefficients of the *Eugenia Grandis* tree is 0.68. It is noted as well that the centres of pressure on the two trees are at a similar ratio of the respective tree height. The centre of pressure on the *Khaya Senegalensis* tree is 18.54 m, at about 0.618 of the tree height and the centre of pressure on the *Eugenia Grandis* tree is 14.87 m, at about 0.595 of the tree height. The similar drag coefficients and the small difference in the centres of pressure as ratios of the total heights could result from the similar geometries of the two trees. The drag coefficient is slightly higher on the *Eugenia Grandis* tree due to a higher canopy coverage. The centre of pressure as a ratio of total height on the *Eugenia Grandis* tree is lower due to a lower centroid of canopy.

3.3 Drag coefficients from field instrumentations

The drag coefficient of the *Khaya Senegalensis* tree and the *Eugenia Grandis* tree versus the mean wind velocity are plotted in Figure 15. The best fit of mean drag coefficients calculated for each 0.2 m/s interval for the two trees are plotted in Figure 15 as well. The starting threshold is 1 m/s according to the specification of the mounted weather station. The standard deviation of the drag coefficient is 0.05 for the *Khaya Senegalensis* tree and 0.12 for the *Eugenia Grandis* tree.

The mean drag coefficients of other trees based on the field work from Koizumi et al. (2010) are plotted together with the mean drag coefficients of the two trees in this study (Figure 16). The drag coefficients calculated from wind tunnel studies are not included because the variation could be large due to the different scales of Reynolds number and modulus. It has been pointed out that the drag coefficients of dwarf trees are greater than those of large trees at the same wind velocity (Koizumi et al., 2010; Mayhead, 1973). This is because the lower Reynolds number of the dwarf tree corresponds to a higher drag coefficient. The trees analysed in the study of Koizumi et al. (2010) were smaller, resulting in a larger drag coefficient at the same wind velocity.

As observed, drag coefficient varies with wind velocities. Mayhead (1973) pointed out that the wind drag could increase linearly with the wind velocity instead of square of the wind velocity. This implies that the drag coefficient calculated from Equation 1 might decrease linearly with wind velocity instead of being constant. It is observed as well from Figure 15 that the drag coefficient decreases as wind velocity increases, approaching constant after certain wind velocity. In most published studies, the decrease in drag coefficient was attributed to the reconfiguration of trees (Mayhead, 1973; Rudnicki et al., 2004; Koizumi et al., 2010). While flexible bodies will behave differently from rigid bodies this behaviour needs to be examined

carefully based on the Cauchy number that can show how much the flexibility affects the drag coefficient. Cauchy number is defined as a dimensionless number to describe the relative importance of fluid drag compared to the elastic counterpart:

$$C = \rho u^2 / E \quad \text{Equation 23}$$

where C is the Cauchy number.

The Cauchy number was modified by Niklas (1992) to incorporate the effect of slenderness:

$$C_y = \rho u^2 S^3 / E \quad \text{Equation 24}$$

where S is the slenderness ratio.

It has been found that the effect of reconfiguration is negligible when C_y is less than 1 (de Langre, 2008). When the Cauchy number exceeds 1, the drag coefficient drops significantly.

In this study, the average modulus of the mature trees was around 1 GPa, and the slenderness ratio was about 30 for a height of 30 m and a diameter of 1 m. Hence, the calculated Cauchy number is about 8×10^{-4} at a wind velocity of 5 m/s. Although the Cauchy number increases as wind velocity increases, it will be less than 1 if the wind velocity is below 173 m/s. As such, the effect of the tree deflection can be neglected.

If an individual branch is considered, the slenderness ratio may become higher and the respective Cauchy number may increase as well. The Branch modulus is around 1 GPa (NParks & NTU, 2017) based on the three-point bending experiments. Figure 17 shows the relationship between Cauchy number and slenderness ratio at various wind velocities. The Cauchy number increases as the slenderness ratio increases and reaches 1 when the slenderness ratio increases to 310 at a wind speed of 5 m/s. Therefore, the deflection of an individual branch can be neglected at low wind velocities when calculating wind drags. However, as wind velocity increases and the Cauchy number exceeds 1, the deflection starts to affect the wind drags. In

addition, an integral canopy could behave very differently from an individual branch. As illustrated in Figure 18, the wind velocity increases and the canopy in the windward side will tend to deflect towards the vertical direction and hence the overall projected area increases. The deflection of the canopy in the leeward side will be much smaller resulting from the blockage of the canopy on the windward side. As wind velocity further increases, the canopy on the windward side may bend to the leeward side and the overall projected area will decrease. Hence, the streamlining effect of the canopy leads to a significant reduction in the drag coefficient as the viscous drag becomes dominant instead of the pressure drag.

We might consider why the drag coefficient decreases at low wind velocity range when the effect of reconfiguration mainly occurs at high wind velocities. Often, another important factor to be considered is the dominance of the skin friction drag at low wind velocity range. Even for a stiff body that does not undergo reconfiguration as wind velocity changes, the drag also decreases as velocity increases. The reason is that the frictional drag or the viscous drag is dominant at low velocity. Moreover, if the flow is laminar, the drag force on the stiff body also varies linearly with the wind velocity (Franzini et al., 1997). Here, we propose that the decrease in drag coefficient at low wind velocity range for mature trees is mainly due to the dominance of the viscous drag instead of the change in the projected area. At high wind velocities, a large decrease in the projected area and the streamlining effect lead to a considerable decrease in drag coefficient.

Figure 19(a) proposes the general variation of drag coefficient as wind velocity increases. The drag coefficient tends to decrease first as wind velocity increases. Figure 19(b) represents the tree under no wind condition. Figure 19(c) represents the tree under small wind condition. The viscous drag is dominant and the drag coefficient reduces as wind velocity increases. As shown in Figure 1, the viscous drag decreases but the pressure drag increases simultaneously. Since the viscous drag is dominant, the overall drag coefficient decreases. However, it is assumed

that the change in overall projected area due to the fluttering of leaves on mature trees is small and could be neglected. Figure 19(d) represents the tree under higher wind velocity, when pressure drag becomes dominant and the drag coefficient does not decrease significantly. This is the range when the numerical approach in this paper can be applied. Figure 19(e) represents a tree that starts to experience streamlining and this results in a significant decrease in drag coefficient. However, the drop in drag coefficient at this stage is rarely found in the previous field measurements. The reason could be that obvious streamlining only occurs at very large wind velocities for mature trees and the tree is hardly stable at that large lean angle.

The numerical method is only applicable when the viscous drag is small and negligible compared to the pressure drag, so that the source and sink terms can be used. At this stage, the drag coefficient does not change significantly. The numerical approach should not be applied when the wind velocity is below or beyond this range. Nevertheless, the range could vary for different trees because their size will affect the Reynolds number and the slenderness ratio, as well as the modulus which affects the flexibility. For a very flexible or very slender vegetation, the numerical approach is not applicable as reconfiguration and streamlining would occur much easily, resulting in a large gradient of drop in drag coefficient starting from a very low wind velocity and the pressure drag is small compared to the viscous drag. In this case, the drag force may vary linearly with the wind velocity.

From the field monitoring results in Figure 15, it is shown that the pressure drag dominant range is beyond 2m/s for both the *Khaya Senegalensis* tree and the *Eugenia Grandis* tree. Therefore, the numerical analyses were conducted from a wind velocity of 2 m/s for the two trees and compared with the field calculations of drag coefficients. Hence the pressure drag would be dominant and the source and sink terms could be applied.

Table 6 summarizes the drag coefficients of both trees computed from numerical modelling and the curve fit of the mean from instrumented site data at a reference wind velocity of 2 m/s. The values are in the reliable range of drag coefficients for actual trees, i.e. 0.29-0.88 (Koizumi et al., 2010). The drag coefficients calculated from numerical analyses are higher than those from field instrumented results. Errors could come from both numerical analyses and field calculations. In addition, the error also could come from the estimates of the wind log profile in the atmosphere boundary layer. For numerical analyses, errors could come from the estimates of the generated geometries, LAD calculations, or numerical errors such as computer round-off error and discretization error. These errors commonly exist and may have negligible effects in the final results. Moreover, when applying source and sink terms, the estimates of pressure dominate range when viscous drag can be neglected may lead to errors. The range could be better estimated with more data from the field at larger wind velocities. For field measurements, errors could come from the instrument accuracy, time lag, limited data at higher wind velocity and estimate of modulus. The accuracy is 0.3 m/s for the wind velocity measurements and is 0.2% linearity for the LVDTs. Moreover, the errors due to time lag could occur between the time when the wind velocity was registered and the time when the corresponding tree displacement was recorded. The monitored data were mainly located in the low wind velocity range. In addition, error could come from the modulus estimates when assuming the same modulus for the same species. Although the geometries are similar, the soil conditions could vary and water content inside the tree could be different. As from Equation 20, the drag coefficient computed from site data was linearly proportional to the Young's Modulus of the tree. The Young's Modulus could be underestimated, resulting in an underestimation of drag coefficients compared to the numerical results. When estimating the Young's Modulus, the obtained strains are larger during the static pulling compared to those

strains from field monitoring data. Since the modulus is higher at low strains than at large strains, the Young's Modulus could be underestimated.

Furthermore, there are some assumptions that influence the drag coefficients calculated but do not affect the comparison between the field results and numerical results. It is assumed that the wind velocity is only averaged by height and the effect of changes in projected area with height is not incorporated into the calculation. This may lead to errors in drag coefficients as the canopy area is larger and experiences a higher wind velocity compared to the trunk area. In addition, the lever arm used to calculate the drag coefficients in the field is assumed to be the same as the lever arm calculated from the numerical analyses, which may lead to errors in drag coefficients. However, these assumptions do not affect the comparison between numerical analyses and field calculations, which is the objective of this study. The numerical analyses can be validated through the comparison between the bending moments. Moreover, the numerical approach can be validated through the comparison between the dimensionless drag coefficients. To explain this, the bending moments from the field can be calculated by:

$$M = EI\sqrt{(\Delta L_1/L_0)^2 + (\Delta L_2/L_0)^2}/y \quad \text{Equation 25}$$

After multiplying a constant $2/L_c \gamma \rho A u^2$ to the bending moments from both the numerical analyses and field calculations, a dimensionless number C_d as in Equation 20 can be obtained and compared. Since the values of $2/L_c \gamma \rho A u^2$ are the same for both methods, the numerical analyses could be validated by the comparison between drag coefficients from numerical analyses and field calculations.

4. Conclusion

The drag coefficients for the mature *Khaya Senegalensis* tree and *Eugenia Grandis* tree were in the range between 0.6 and 0.7 based on CFD modelling. The numerical approach takes

520 advantage of laser scanning to generate the geometry and to calculate the leaf area density
521 distribution based on 3D coordinates, as well as the application of CFD simulations with source
522 and sink terms as a function of leaf area density to represent leaves. The similarity in the drag
523 coefficients between the two trees could result from the similar overall geometries.

524 The drag coefficients from field measurements were smaller than those from numerical
525 analyses, being about 0.51 for the *Khaya Senegalensis* tree and 0.4 for the *Eugenia Grandis*
526 tree. The differences can be attributed to the possible uncertainties in the numerical modelling
527 and field measurements.

528 This numerical approach is a useful method to obtain the drag coefficient of trees, however,
529 some limitations need to be noted. This method is only applicable when the wind speed is
530 within a range that viscous drag can be neglected compared to the pressure drag. The drag
531 coefficient may be lower for trees experiencing small wind speeds or higher for trees that could
532 deform significantly at high wind speeds. The wind velocity range when pressure drag is
533 dominant can be estimated from field measurements but could vary by tree size and flexibility.

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Figures

Figure 1. Variations between total drag, pressure drag, viscous drag and wind

Figure 2. Porous domain around the branches to model the effect of leaves using sink and source terms

(Endalew et al., 2009).

Figure 3. (a) Scanned *Khaya Senegalensis* tree point clouds and (b) post-processed 3D model simulated in ANSYS.

Figure 4. (a) Scanned *Eugenia Grandis* tree point clouds and (b) post-processed 3D model simulated in ANSYS.

Figure 5. Leaf Area Density distribution of (a) *Khaya Senegalensis* tree and (b) *Eugenia Grandis* tree in MATLAB.

Figure 6. Boundary conditions in CFD modelling.

Figure 7. Velocity inlet profile.

Figure 8. (a) Weather Station and (b) LVDT installed.

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Figure 9. Illustration of the lever arm used to calculate the bending stress.

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(a)

(b)

Figure 11. Pressure contour on (a) the *Khaya Senegalensis* tree and (b) the *Eugenia Grandis* tree.

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Figure 12. Velocity contour around (a) the *Khaya Senegalensis* tree and (b) the *Eugenia Grandis* tree.

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(a)

(b)

Figure 13. Velocity streamline around (a) the *Khaya Senegalensis* tree and (b) the *Eugenia Grandis* tree.

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(a)

(b)

Figure 14. Pressure contour on (a) the *Khaya Senegalensis* tree and (b) the *Eugenia Grandis* tree.

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(b)

(a)

Figure 15. Drag coefficients and best fit of the mean drag coefficients from site instrumented data of
(a) the *Khaya Senegalensis* tree and (b) the *Eugenia Grandis* tree

Figure 16. Comparison of best fit of mean drag coefficients from field instrumented data for trees in this study and other trees (Koizumi et al., 2010).

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Figure 17. Relationship between Cauchy number and slenderness ratio.

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Figure 18. Deflected tree at different wind velocities.

(a)

Figure 19. A proposed relationship between drag coefficient and wind velocity for mature and stiff trees and tree geometries under different wind velocities (Akagi & Kitajima, 2006).

648 Table 1. Settings in different meshing schemes.

Meshing Scheme	Relevance	Relevance Centre	Smoothing	Span Angle Centre	Growth Rate	Nodes (million)
1	0	Medium	Medium	Medium	1.2	0.8
2	50	Medium	Medium	Medium	1.2	1.9
3	100	Medium	Medium	Medium	1.1	3.5

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650 Table 2. Drag coefficient of the *Khaya Senegalensis* tree.

Turbulent Model	Meshing Scheme	Drag Force (N)	Projected Area (m²)	Drag Coefficient	Change in Drag
Realizable k-epsilon	Meshing Scheme 1	539.9	47.3	0.675	-
	Meshing Scheme 2	473.4	47.3	0.592	12.3%
	Meshing Scheme 3	470.3	47.3	0.588	0.7%
Transition SST	Meshing Scheme 1	527.3	47.3	0.659	-
	Meshing Scheme 2	482.2	47.3	0.603	8.6%

	Meshing Scheme 3	478.2	47.3	0.598	0.8%
	Meshing Scheme 1	520.9	47.3	0.651	-
RSM	Meshing Scheme 2	476.9	47.3	0.596	8.4%
	Meshing Scheme 3	467.7	47.3	0.585	1.9%

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Table 3. Drag coefficient of the *Eugenia Grandis* tree.

Turbulent Model	Drag Force (N)	Projected Area (m²)	Drag Coefficient
Realizable k- epsilon	260.2	27	0.642
Transition SST	261.7	27	0.646
RSM	259.1	27	0.639

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Table 4. Summarized results of CFD modelling for the *Khaya Senegalensis* tree.

<i>Khaya Senegalensis</i>	Drag Force (N)	Ratio of the Total Drag	Projected Area (m²)	Drag Coefficient	Center of Pressure (m)	Ratio of Tree Height (Tree Height = 30 m)
Canopy	3990	0.92	392	0.615	19.0	0.633

Trunk	326	0.08	47.3	0.401	13.4	0.445
Total	4316	1	407	0.640	18.5	0.618

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656 Table 5. Summarized results of CFD modelling for the *Eugenia Grandis* tree.

<i>Eugenia Grandis</i>	Drag Force (N)	Ratio of the Total Drag	Projected Area (m²)	Drag Coefficient	Center of Pressure (m)	Ratio of Tree Height (Tree Height = 25 m)
Canopy	1917	0.97	192	0.679	15.1	0.606
Trunk	51	0.03	27	0.129	4.7	0.186
Total	1968	1	196	0.683	14.9	0.595

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658 Table 6. Comparison between drag coefficients computed from numerical modelling and site
659 instrumented data.

<i>Drag Coefficients from</i>	<i>Khaya Senegalensis</i>	<i>Eugenia Grandis</i>
Numerical Modelling	0.64	0.69
Site Instrumented Data	0.51	0.40

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