Aerodynamic characteristics of trees for green roofing systems

Jinxin Cao a, Yukio Tamura b, Akihito Yoshida c

aTokyo Polytechnic University, Kanagawa, Japan, jinxin@arch.t-kougei.ac.jp
bTokyo Polytechnic University, Kanagawa, Japan, yukio@arch.t-kougei.ac.jp
cTokyo Polytechnic University, Kanagawa, Japan, yoshida@arch.t-kougei.ac.jp

ABSTRACT: Three tree species appropriate for intensive green roofs with different aerodynamic forms were tested through a boundary layer wind tunnel experiment, including one deciduous tree, one coniferous tree and one broadleaf evergreen tree. Drags and over-turning moments under different wind speeds were measured; wind-speed-specific frontal areas and tip displacements were recorded. Even considering frontal area reduction due to increasing wind speeds, drag coefficients decrease with increase in wind speed for deciduous and coniferous trees. The effect of crown porosity varies among tree species.

KEYWORDS: tree; drag coefficient; over-turning moment coefficient; wind-speed-specific frontal area; wind tunnel experiment.

1 INTRODUCTION

Green roofing systems are lightweight, engineered roofing systems that allow for the propagation of rooftop vegetation while protecting the integrity of the underlying roof (Earth Pledge Foundation, 2004). There are two main classifications of green roofs: extensive and intensive. Extensive green roofs have a thin substrate layer with low-level planting, typically sedum or lawn, and can be very lightweight in structure. Intensive green roofs have a deeper substrate layer to allow deeper rooting plants such as shrubs and trees to survive (Castleton, 2010). The likelihood of tree failure in green roofing systems is high since trees on the tops of buildings are exposed to higher wind velocities than those on the ground. Therefore, wind loads on trees and their mitigation is an important issue in the design and maintenance of green roofing systems.

During past decades, the effects of wind forces on trees have been studied from the viewpoint of forest stability. Mayhead (1973) was among the first to systematically present drag coefficients for various British forest tree species based on through wind tunnel measurements. Rudnicki et al. (2004) and Vollsinger et al. (2005) also studied the relationship between crown streamlining and drag in a wind tunnel for several young hardwood species and juvenile conifers. Of these studies, Rudnicki et al. (2004) was the first to identify wind speed specific crown frontal area simultaneously with crown drag, while crown frontal areas in still air were used before. Recently, researches relating to wind forces on real urban trees were conducted through wind tunnel experiments (Ishikawa, 2006) and field measurements (Takamori et al, 2003; Kane and Smiley, 2006; Kane et al, 2008; Koizumi et al, 2010) to determine how to prevent wind damage to them. Although field measurements tended to overcome the size restriction of wind tunnel testing, it was difficult to record the reconfigurations of trees.

The goal of this study was to evaluate drag and over-turning moment coefficients, reconfigurations and deflections of different trees. Drag coefficients based on frontal areas in still air and wind-speed-specific frontal areas were both determined; Over-turning moment coefficients based on frontal areas in still air and aerodynamic centers were provided. Other parameter considered was crown porosity as affected by crown pruning.
2 METHODS AND MATERIALS

2.1 Trees

Three trees including one deciduous tree, Rose of Sharon (*Hibiscus syriacus*) (HS); one coniferous tree, Emerald Cedar (*Thuja occidentalis 'Smaragd'* (TO); and one evergreen tree, Japanese Holly (*Ilex crenata*) (IC), were chosen, as shown in Figure 1. The criteria for choice of tree species were: (1) suitable for green roofs and (2) representatives of different types of trees, especially from the aerodynamic viewpoint. Table 1 summarizes morphometric data for each species, including tree geometries, main characteristics of branching habits and foliage textures. Trees were cut just above the root flare and mounted to the five-component force balance. Rotation of the bottom of stems was not allowed after the mounting.

2.2 Measurements

Wind tunnel experiments were carried out in a Boundary Layer Wind Tunnel at Tokyo Polytechnic University, Japan. The test section was 2.2m wide by 1.8m high. Drag and over-turning moment data measured through a five-component commercial force balance where the tree was mounted and the reference wind pressure recorded at 1.2m above the wind tunnel floor were simultaneously collected at 500Hz and the sampling time for each run was 10 minutes. Two digital cameras were installed, one downstream of the tree and the other outside the wind tunnel, to capture the frontal areas and deformations after each run for each intended wind speed respectively.

![Figure 1. Experimental trees](image)

![Figure 2. Uniformity of mean wind speed (U=10 m/s)](image)

Table 1. Tree geometries and tree forms

<table>
<thead>
<tr>
<th>Item</th>
<th>HS</th>
<th>TO</th>
<th>IC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (<em>H</em>: m)</td>
<td>1.24</td>
<td>0.98</td>
<td>0.40</td>
</tr>
<tr>
<td>Width (<em>B</em>: m)</td>
<td>0.53</td>
<td>0.45</td>
<td>0.42</td>
</tr>
<tr>
<td>Caliper (<em>b</em>: cm)</td>
<td>2.3</td>
<td>3.7</td>
<td>3.3</td>
</tr>
<tr>
<td>Fractal area (<em>A</em>: m²)</td>
<td>0.15</td>
<td>0.33</td>
<td>0.11</td>
</tr>
<tr>
<td>Volume (<em>V₀</em>: cm³)</td>
<td>555</td>
<td>2280</td>
<td>930</td>
</tr>
<tr>
<td>Porosity (VP: %)</td>
<td>/</td>
<td>97.1</td>
<td>96.6</td>
</tr>
<tr>
<td>Branching habit</td>
<td>upright</td>
<td>pyramidal</td>
<td>round</td>
</tr>
<tr>
<td>Crown shape</td>
<td>multi-trunked</td>
<td>with a single leader</td>
<td>clumping stems</td>
</tr>
<tr>
<td>Trunk and Branches</td>
<td>rhomboid</td>
<td>scale-like</td>
<td>obovate</td>
</tr>
<tr>
<td>Foliage texture</td>
<td>dentate</td>
<td>entire</td>
<td>serrulate</td>
</tr>
</tbody>
</table>
Uniform flow fields were adopted. Wind speeds ranged from 5m/s to 15m/s, the maximum wind speed in this wind tunnel, with 1m/s interval. The uniformity of the wind speed at the measurement position is shown in Figure 2 and a 30cm-high end plate was used to compensate for the non-uniform wind flows near the wind tunnel floor. The exposed part of force balance was covered by the wooden cover with a streamlined shape attached to the end plate.

2.3 Variation in crown porosity

The original crown porosities were reduced by pruning the branches several times using thinning pruning method (ANSI, 2001) which only removed small-diameter branches along the outside of the crown and almost kept the post-pruning crown dimensions. Four pruning for TO (Fig. 3) and three pruning for IC (Fig. 4) were conducted. The pruning dose (volumes of pruned branches and leaves) were measured using a water-displacement method after each tree pruning.

The original volume of each tree was $V_0$, and the volume after each pruning was $V_i$, ($i$ was the times of pruning) and pruning dose (PD) (Table 2) was performed using:

$$PD = \frac{V_0 - V_i}{V_0} (i = 1, 2, ..., N)$$

(1)

The imaginary solid volumes $V_E$ (gross volume) formed by the boundary of the tree structure were estimated by the special software “Tree analyzer 1.20” (Phattaralerphong and Sinouquet, 2005) through eight photos of the tree structure taken from 8 directions. The 3D crown porosity (VP) (Table 1, 2) was defined by the ratio between the volume of the trees and $V_E$:

$$VP = \frac{V_E - V_i}{V_E} (i = 0, 1, ..., N)$$

(2)
2.4 Calculations

$E$ value, an alternative measure of crown reconfiguration suggested by Vogel (1984), represents the exponent to which the wind speed must be raised to be directly proportional to either the drag coefficient or the drag divided by the square of wind speed:

$$\frac{F_D}{U^2} \propto U^E$$  \hspace{1cm} (3)

where $F_D$ is measured mean drag and $U$ is measured mean wind speed.

Two sets of results for mean drag coefficients (Fig. 7) for each tree ($C_{D,U}$ and $C_{D,S}$) were calculated based on wind-speed-specific frontal areas and frontal areas in still air.

$$C_{D,U} = \frac{F_D}{0.5 \rho U^2 A_U}$$  \hspace{1cm} (4)

$$C_{D,S} = \frac{F_D}{0.5 \rho U^2 A_S}$$  \hspace{1cm} (5)

where $\rho$ is air density calculated using readings from a barometer and thermometer before each experimental run; $A_U$ and $A_S$ are wind-speed-specific frontal areas of trees and frontal areas of trees in still air, respectively.

Overturning moment coefficients $C_M$ at the bottom of tree stems were calculated based on frontal areas in still air as follows:

$$C_M = \frac{M_{OT}}{0.5 \rho U^2 A_S H}$$  \hspace{1cm} (6)

where $M_{OT}$ is measured mean overturning moment and $H$ is the height of tree in still air.

The distance between stem base and the height of aerodynamic center of trees ($H_C$) can be identified based on:

$$H_C = \frac{M_{OT}}{F_D} = \frac{0.5 \rho U^2 A_S H \cdot C_M}{C_D S} = \frac{C_M H}{C_D S}$$  \hspace{1cm} (7)

and the non-dimensional height of the aerodynamic center of the trees ($\alpha_C$) were normalized by the height of the tree in still air:

$$\alpha_C = \frac{H_C}{H} = \frac{C_M}{C_D S}$$  \hspace{1cm} (8)
3 RESULTS AND DISCUSSIONS

3.1 Force and wind speed relationship

Fig. 5 shows the relationship between drag force and wind speed for the three trees, including the experimental data and curve fit using power function. $E$ values are -0.36, -0.29 and -0.01 for HS, TO and IC respectively.

Although the aerodynamic forms of HS and TO are totally different, including branching habit and leaf texture as indicated in Table 1, their $E$ values do not show a large difference. However, the $E$ value for IC, close to 0, is different from the previous two trees. This is mainly due to higher branch stiffness of IC and its reconfiguration is limited compared to HS and TO. It can be concluded that other than morphological differences among species, $E$ values, which reflects the ability of reconfiguration, are mainly affected by the branch stiffness.

3.2 Frontal area and wind speed relationship

The wind-speed-specific frontal areas of the three trees and corresponding curve fits are shown in Fig. 6. The high capacity for reconfiguration of HS showed the largest exponent -0.20, while the exponent was -0.07 for TO. IC presented a positive power exponent of 0.04, which indicates that the frontal area slightly increased with increase in wind speed. This is mainly because the high frequency movements of branches and leaves at large wind speeds cannot be identified by the relatively low-frequency digital camera and overlapping in photographs was available.

When the wind speed increased from 5m/s to 15m/s, frontal areas decreased by 20% for HS from 0.15m$^2$ to 0.12m$^2$, and 10% for TO from 0.33m$^2$ to 0.30m$^2$, and the values kept constant for IC. Unlike HS and TO, the reconfiguration of both branches and leaves of IC was not obvious because of the smaller size of the crown; the less flexible branches and leaves do not easily change their shapes.

3.3 Deflection of tree

The tip displacements normalized by the tree height as well as the fitted curves are presented in Figure 7. The maximum relative displacement $x_{top}/H$ for HS was the largest among the three species, 0.3 when the wind speed was 15m/s and the values for TO and IC were 0.17 and 0.03, respectively. Although the quantity of the wind-speed-specific tip displacement for HS was around twice that of TO, the exponents for the curve fitting were almost the same: 1.58 and 1.57. Moreover, since the power exponent for IC was 3.78, which was close to 4, pure bending theory for a rigid body in which the second-order derivative of the deformation was proportional to horizontal force seemed to be appropriate for it.

3.4 Drag coefficient

Two sets of results for mean drag coefficients (Fig. 8) for each tree were calculated. For HS and TO, it can be seen that even drag coefficients based on wind-speed-specific frontal area also decreased with increase in wind speed. This indicates that wind-speed-specific frontal area is not the only parameter to affecting drag coefficients, but that there are other factors caused by reconfiguration of trees.
As expected, drag coefficients for HS and TO based on frontal area in still air decreased more rapidly with increase in wind speed and were consistently smaller than those calculated based on wind-speed-specific frontal area. For wind speeds from 5m/s to 15m/s, for HS, the drag coefficients based on wind-speed-specific frontal area decreased by 20% from 0.61 to 0.49, while those based on frontal area in still air decreased by 36% from 0.59 to 0.38; for TO, the
values based on wind-speed-specific frontal area decreased by 12% from 0.83 to 0.73, while those based on frontal area in still air decreased by 19% from 0.83 to 0.67. For IC, drag coefficients keep constant around 0.79.

Figure 7. Variation of tip displacements due to mean wind speeds

Figure 8. Mean drag coefficients

wind speeds
The exponents for the fitted curves using $C_{D,U}$ values based on wind-speed-specific frontal area of the three trees were -0.19, -0.12 and -0.05. Since the only difference between the two sets of drag force coefficients was the area used for calculation, the discrepancy in the exponents of the curve fitting for the two sets of data can be reflected by the exponents of the curve fitting for wind-speed-specific frontal area. The exponents for wind-speed-specific frontal area were -0.20, -0.07 and 0.04; thus, the exponents for $C_{D,S}$ values based on still air area were -0.39, -0.19 and -0.01.

Drag coefficients of HS and TO have been compared with those obtained from similar researches on real trees. Two deciduous trees, Blackcotton wood (Vollinger, 2005) and Japanese zelkova (Takamori, 2003), and two coniferous trees, Lodgepole pine (Rudnicki, 2004) and Dawn redwood (Takamori, 2003), in a similar wind speed range were chosen for comparison. The results showed that the present data for both HS and TO were comparable to the previous data. For HS, the values ranged from 0.49 to 0.61 were between the reported range from 0.51 to 0.85; and the range from 0.73 to 0.83 for TO was also located in the range for previous data from 0.66 to 1.05, which validate the reasonableness of the present data.

![Figure 9. Mean overturning moment coefficients](image)

![Figure 10. Relative height of aerodynamic centers](image)

![Figure 11. Effect of crown porosity on mean drag coefficients](image)
3.5 Aerodynamic center
Results of overturning moment coefficients calculated based on frontal area in still air and relative height of the aerodynamic center are shown in Figures 9 and 10, respectively. The relationships between overturning moment coefficients and wind speeds for the three species were similar to the results for drag coefficients.

Aerodynamic center was mainly affected by the distribution of the crown structures and differed among tree species. Among the three experimental trees, the maximum value of $a_c$, 0.62, was recorded for IC, since the main crown was located at the upper part of the tree and left trunk only at half the bottom. TO has the smallest value of aerodynamic center, 0.45, since the crown has a conical shape and the main crown was distributed at the lower part of the crown. For HS which has a relatively uniform distribution in branch and leaves from top to bottom compared with the previous two species, the values ranged from 0.53 to 0.57.

3.6 Effect of crown porosity
Figure 11 shows the effect of crown porosity on drag coefficients of the tree in terms of the crown porosities and the values for the wind speeds of 5m/s, 10m/s and 15m/s were chosen. For TO, when the wind speed was low (5m/s), the drag coefficients first increased with increase in crown porosity and then decreased. This tendency never took place and drag coefficients gradually decreased with increase in crown porosity for high wind speed (10m/s and 15m/s). For IC, although the values at different wind speeds slightly changed, values for the same wind speed did not differ with change in crown porosity.

4 CONCLUDING REMARKS
Aerodynamic characteristics including drag and over-turning moment coefficients and plant forms of three trees, suitable for green roofing system were investigated through wind tunnel experiments. Variations of drag, frontal area, tip displacement and drag and over-turning moment coefficient due to mean wind speed were mainly discussed. The effect of crown porosity, view angle and turbulence intensity were investigated. The main conclusions are summarized as follows:

(1) The Vogel exponents were -0.36 and -0.29 for HS and TO, and -0.01 for IC. The power exponents fitting the relationship between wind-specific frontal areas and wind speed were -0.20, -0.07 for HS and TO, and 0 for IC. The discrepancy between Vogel exponents and power exponents for frontal areas indicated that there were parameters other than area reduction due to reconfiguration that affected the reduction of drag forces. The power exponents for the curve fitting of tip displacements of the three trees were 1.58, 1.57 and 3.78, respectively. Pure bending theory for a rigid body seems to be appropriate for IC since the value was close to 4.

(2) Even considering area reduction due to wind speed, mean drag coefficients decreased with increase in wind speed from 0.61 to 0.49 for HS, from 0.83 to 0.73 for TO, which were comparable to those of previous researches. Values for IC kept constant at around 0.79. The aerodynamic center was mainly affected by the distribution of the crown structures and differed among tree species.

(3) The effect of crown porosity differed among tree species and wind speeds. For TO, unfavorable porosity occurs with maximum drag coefficients with low wind speed while porosity has little effect on IC.
5 ACKNOWLEDGEMENTS

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6 REFERENCES