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# 1 A wind tunnel study of the aerodynamic characteristics of a scaled, aeroelastic, model tree

2 Yanfeng Hao<sup>1</sup>, Gregory A. Kopp<sup>2,\*</sup>, Chieh-Hsun Wu<sup>2</sup>, Stefanie Gillmeier<sup>3</sup>

3 <sup>1</sup> Key Laboratory of Building Safety and Energy Efficiency of the Ministry of Education, Hunan  
4 University, Changsha, China, 410082

5 <sup>2</sup> Boundary Layer Wind Tunnel Laboratory, Faculty of Engineering, University of Western  
6 Ontario, London, ON, Canada, N6A 5B9

7 <sup>3</sup> Department of Civil Engineering, University of Birmingham, Birmingham, United Kingdom,  
8 B15 2TT

9 \* Correspondence: Gregory A. Kopp

10 Email: [gakopp@uwo.ca](mailto:gakopp@uwo.ca)

11 Tel: 519-661-2111

12 Fax: 519-661-3339

## 13 Abstract

14 Tree crowns, unlike most bluff bodies, are both porous and flexible, so frontal area and crown  
15 deflection vary with wind speed. The former leads to aerodynamic force characteristics that vary  
16 with frontal area and wind speed while the latter is related to energy transfer between wind and  
17 tree. In order to investigate aerodynamic force characteristics and energy transfer, an approach to  
18 constructing an aeroelastic model of a tree, which satisfies geometric similarity, dynamic  
19 similarity and dimensionless parameters including Froude number, Cauchy number and density  
20 ratio, was developed and wind tunnel tests were carried out. The model was designed with eight  
21 distinct crown configurations according to different quantities of leaves. Aerodynamic forces,  
22 wind speed and frontal area were measured synchronously. The results showed that crown  
23 sheltering effects effectively limited mean crown deflection, which limit the mean base  
24 overturning moment coefficient. In addition, the energy transfer of the model with different  
25 crown configurations were investigated, and the characteristics of energy transfer were identified.  
26 It was shown that the crown frequency effectively controls the response via mechanical  
27 admittance, which amplified the response at the crown frequency.

## 28 Keywords

29 Tree aerodynamics; wind loads; aeroelastic modeling; wind tunnel methods.

30 **Nomenclature**

31	$A_U$	wind-speed-specific frontal area of the aeroelastic model tree
32	C1	configuration 1: trunk
33	C2	configuration 2: trunk and branches
34	C3	configuration 3: trunk and branches with 1 set of 90 leaf clusters
35	C4	configuration 4: trunk and branches with 2 sets of 180 leaf clusters
36	C5	configuration 5: trunk and branches with 3 sets of 270 leaf clusters
37	C6	configuration 6: trunk and branches with 4 sets of 360 leaf clusters
38	C7	configuration 7: trunk and branches with 5 sets of 450 leaf clusters
39	C8	configuration 8: trunk and branches with 6 sets of 540 leaf clusters
40	Ca	Cauchy number
41	$C_M$	base overturning moment coefficient
42	$CS_{C_m U}$	normalized co-spectral density function between base overturning moment
43		coefficient and reference wind speed
44	$CS_{M U}$	normalized co-spectral density function between base overturning moment
45		measured by force balance and reference wind speed
46	$F_D$	measured drag force in the direction of the wind flow
47	Fr	Froude number
48	$d_{cc}$	crown center displacement
49	$D_{crown}$	diameter of the crown projected to the ground
50	E	elastic modulus
51	$f$	frequency
52	$f_{crown}$	crown frequency
53	Fr	Froude number
54	g	gravitational acceleration
55	H	height of the model or the prototype
56	$I_U$	turbulence intensity
57	L	characteristic length
58	$L_x$	integral scale
59	M	base overturning moment measured by force balance
60	$M_{qs}$	estimated base overturning moment based on quasi-steady assumption
61	Re	Reynolds number
62	real(•)	real part
63	$S_{aa}$	power spectral density function of acceleration at the top of the trunk derived from
64		free vibration decay tests
65	$S_{C_m C_m}$	power spectral density function of base overturning moment coefficient
66	$S_{d_{cc} d_{cc}}$	power spectral density function of crown center displacement
67	$S_{C_m U}$	cross spectral function between base overturning moment coefficient and
68		reference wind speed
69	$S_{MM}$	power spectral density function of base overturning moment measured by force
70		balance
71	$S_{M_{qs} M_{qs}}$	power spectral density function of estimated base overturning moment based on

72		quasi-steady assumption
73	$S_{MU}$	cross spectral function between base overturning moment measured by force
74		balance and reference wind speed
75	$S_{UU}$	power spectral density function of reference wind speed
76	T	terrain configuration
77	$U$	wind speed
78	$U_H$	wind speed at the top of tree
79	$U_{ref}$	reference wind speed at $z = 0.85\text{m}$
80	$Var(\bullet)$	variance
81	$z$	height above the wind tunnel floor
82	$z_{ref}$	reference height in model scale or full scale
83	$\delta_{\text{model}}$	damping ratio of the model
84	$\delta_{\text{prototype}}$	damping ratio of the prototype
85	$\theta$	momentum thickness of terrain configuration
86	$\nu$	kinematic viscosity of air
87	$\rho_{\text{air}}$	air density
88	$\rho_{\text{model}}$	model density
89	$H(f)$	mechanical admittance function

## 90 **1. Introduction**

91 The magnitude of wind load is known to have a significant effect on trees. For example, it is  
92 known that relatively small wind loads over relatively long durations affect tree growth, while  
93 larger wind loads over short durations bring leaf loss or branch fracture and extreme wind loads  
94 bring stem breakage or uprooting (Robertson 1987). Different species of trees can experience  
95 different magnitudes of wind load under nominally similar wind conditions. This is mainly  
96 because the details of the crown, such as frontal area and flexibility of branches, are critical in  
97 setting the aerodynamic characteristics (Gillies et al., 2002; Tanaka et al., 2011; Cao et al., 2012).  
98 There are two main methods to study aerodynamic characteristics of trees. One is field  
99 measurements, which have mainly focused on the aerodynamic force coefficients (Grant and  
100 Nickling, 1998; Kane and Smiley, 2006; Kitagawa et al., 2015; Koizumi et al., 2010, 2016;  
101 Borisevich and Vikhrenko, 2018; Gonzales et al., 2018) and overall capacity (Gillies et al., 2000;  
102 Kane et al., 2008). Estimated aerodynamic forces acting on tree crowns obtained from field  
103 measurements are of value; however, are rarely conducted because of the obvious challenge. An  
104 alternative method that tends to focus on determining aerodynamic force coefficients relies on  
105 experimental modeling in wind tunnels (Mayhead, 1973; Vogel, 1989; Stacey et al., 1994; Gillies  
106 et al., 2002; Guan et al., 2003; Rudnicki et al., 2004; Vollsinger et al., 2005; Gromke and Ruck,  
107 2008; Tanaka et al., 2011; Cao et al., 2012; Gromke, 2018). It is worth noting that Stacey et al.  
108 (1994) manufactured 12000 aeroelastic tree models to study wind flows and forces in a forest, in  
109 which the trees are somewhat simplified compared to full-scale prototype in order to achieve the  
110 objective of studying wind effects on a forest.

111 The two main wind tunnel approaches have been to use rigid models and dwarf potted trees.  
112 Rigid models cannot capture the shape changes due to branch and stem inflexibility. While dwarf  
113 potted trees capture flexibility effects; however these wind tunnel studies may not meet similarity

114 criteria because of mismatches between stem, branch and leaf sizes. This makes it challenging to  
115 transfer the measured results into full-scale dimensions for high wind speed ranges (Gromke and  
116 Ruck, 2008). A hybrid of the two aforementioned approaches is to use very large wind tunnels  
117 with small, but full-scale, trees. Some of these tests have ignored the effects of turbulence in the  
118 atmospheric boundary layer (Mayhead, 1973; Aly et al., 2013), which limits the usefulness of the  
119 results. However, more recent studies have also included gust effects (Miller et al., 2015;  
120 Giammanco et al., 2016). Therefore, the first objective of the study is to develop an approach to  
121 constructing an aeroelastic model of a tree with different crown configurations which satisfies the  
122 geometric similarity, dynamic similarity and dimensionless parameters including Froude number,  
123 Cauchy number and density ratio on the base of field measurement, and use multiple turbulence  
124 profiles in order to show their effects.

125 The classical formula for drag,  $F_D$ , in the direction of wind flow on a bluff body is

$$126 \quad F_D = \frac{1}{2} C_D \rho A U^2 \quad (1)$$

127 where  $C_D$  is the drag coefficient,  $\rho$  is the air density,  $A$  is the frontal area, and  $U$  is the wind  
128 speed. For a rigid bluff body, the frontal area does not vary with wind speed; however, this is not  
129 the case for trees, which change shape with wind speed, as discussed above. Crown streamlining  
130 is defined as the tendency of leaves and branches to align with the wind direction. Because this  
131 has the effect of decreasing the frontal area of the crown, the frontal area as a function of wind  
132 speed needs to be measured. Rudnicki et al. (2004) found that crown streamlining effects reduce  
133 the frontal area of conifer species by 36% to 54% at 20 m/s. Vollsinger et al. (2005) also found  
134 that this effect decreases the frontal area of hardwood species to about 20% to 37% of their initial  
135 values at 20 m/s. These results indicate that crown streamlining is a key factor for the frontal area  
136 under wind load.

137 Prior to the 21st century, frontal area measurements were mainly obtained via photography and  
138 tended to focus only on mean values or singular moments in time. Mayhead (1973) was the first  
139 to estimate frontal area through photography. Vogel (1989) used an area meter, which was a  
140 geometric figure of accurately known area, to measure leaf area. Since the beginning of the 21st  
141 century, digital photography has transformed the methods for identifying frontal area. With this  
142 technique, frontal area is calculated by counting pixels using gray scale images (Gillies et al.,  
143 2002; Rudnicki et al., 2004; Vollsinger et al., 2005; Cao et al., 2012; Gonzales et al., 2018).  
144 Although this research has provided significant contributions in estimating the frontal area, time  
145 dependent measurements are lacking, which limits the ability to model the gust effects caused by  
146 turbulence. Therefore, the second objective of the study is to use high frequency camera to record  
147 and analyze time histories of the frontal area and the crown deflection under wind load.

148 Aerodynamic force coefficients mainly depend on aerodynamic shape, surface roughness, and  
149 inflow turbulence. For flexible bodies, they also depend on the motion. For bluff bodies at high  
150 Reynolds numbers, aerodynamic force coefficients are usually fairly constant (Vogel, 1989).  
151 However, this does not appear to be the case for trees because of the porous structure and the  
152 changing geometry with wind speed due to crown streamlining. For example, Mayhead (1973)  
153 found that mean drag coefficients of trees decrease with increasing wind speed. This result has  
154 been validated by Rudnicki et al. (2004), Vollsinger et al. (2005) and Cao et al. (2012). Vogel  
155 (1989) found that drag coefficients of leaves decrease with increasing wind speed. Clearly, frontal  
156 area, wind speed and aerodynamic force coefficients affect each other. However, it is difficult to

157 measure fluctuations of these parameters synchronously, which limits accurate modeling of  
158 overall wind loads using dynamic models. Therefore, the third objective of the study is to  
159 measure the responses of the aeroelastic model tree including the frontal area, wind speed and  
160 aerodynamic forces simultaneously, and study the effects of numbers of branches and leaves on  
161 the mean and fluctuating values of aerodynamic forces, crown deflections, and the frequency  
162 content of these parameters.

163 Gardiner (1994) regarded the tree as a linear system and studied the transfer function between  
164 wind speed and tree displacement by field measurements. Moore and Maguire (2008) use finite  
165 element analysis to calculate the similar transfer function for trees. Such research has provided  
166 significant contributions regarding the energy transfer in trees. However, crown configurations  
167 for trees are always changing because of the seasonal effect on leaves. Therefore, the fourth  
168 objective of the study is to use the obtained data for different crown configurations to study the  
169 effects of different numbers of branches and leaves on energy transfer function.

170 The layout of this paper is as follows. The aeroelastic model tree, terrain simulation,  
171 measurements and instrumentation are described in Section 2. Section 3 presents the  
172 aerodynamics of the aeroelastic model tree, Section 4 presents the dynamic response of the  
173 aerodynamic model tree, while Section 5 presents energy transfer (mechanical admittance).  
174 Finally, conclusions are offered.

## 175 **2. Materials and methods**

### 176 ***2.1 Design of the aeroelastic model tree***

#### 177 ***2.1.1 Overview of dynamic similarity requirements***

178 The prototype for the study is a camphor tree (*Cinnamomum camphora*), which is broad-leaved  
179 and located widely in the south of China. Flexible structures, such as a tree, require matching  
180 several non-dimensional parameters in order to achieve dynamic similarity. These are  
181 summarized in Table 1. In addition to geometric similarity, an aeroelastic model should match the  
182 full-scale values of the following dimensionless parameters:

- 183 • Density ratio ( $\rho_{model}/\rho_{air}$ );
- 184 • Froude number ( $Fr = U^2/gL$ );
- 185 • Reynolds number ( $Re = UL/\nu$ );
- 186 • Cauchy number ( $Ca = \rho U^2/E$ );
- 187 • Damping ratio ( $\delta_{model}/\delta_{prototype}$ ) (Holmes, 2001).

188 The geometric scale of the aeroelastic model was chosen to be 1/6. This scale was mainly  
189 chosen to meet the requirement of the blockage ratio to be below about 5% while having a  
190 Reynolds number as large as possible because of the circular cross-sections of the branches and  
191 trunk, and noting that Reynolds number cannot typically be matched for scale model testing. The  
192 scale of the atmospheric boundary layer also needs to match this geometric scale, a point which is  
193 discussed further below.

194 Density ratio and length scale determine the model mass. Because of the use of a wind tunnel  
195 to simulate the natural wind, the air density of the prototype and the model are the same. This  
196 then leads to the requirement that the densities for the prototype and model components are the  
197 same. The current model had both the correct total mass and the distribution placed correctly.

198 The Froude number is a dimensionless parameter that represents the ratio of inertial to  
199 gravitational forces. Because of the importance of both gravitational and inertial loads on the

200 branches, crown, and trunk, matching the Froude number is required. This parameter is generally  
201 required in full aeroelastic model testing of long-span bridges and cable-suspended roofs  
202 (Holmes, 2001). Once the length scale is set, matching the Froude number leads to the velocity  
203 scale requirements, which becomes the square-root of the length scale (because the gravitational  
204 constant is fixed). Of course, once the length and velocity scales are fixed, the time (or  
205 frequency) scaling is also set.

206 On the other side, once the geometric and velocity scales are fixed in the wind tunnel, the  
207 Reynolds number is also set. Reynolds number similarity is not possible in most cases for  
208 boundary layer wind tunnels, as noted above. However, because the velocity scale is 1:2.45 and  
209 the length scale is 1:6, the model-scale Reynolds number is only a factor of 15 lower than full-  
210 scale. This may have some effect on the results, although the circular surfaces were roughened to  
211 minimize these.

212 The Cauchy number is a dimensionless parameter that represents the ratio of the inertia forces  
213 to the elastic forces. Here, we scaled the bending stiffness instead of the elastic modulus. Bending  
214 stiffness is the product of elastic modulus and second moment of area. Cauchy number is a  
215 difficult parameter to scale because of limitations in the availability of materials. In this case,  
216 modelling the stiffness of a branch or stem leads to significant challenges, which are discussed  
217 further below.

218 Finally, the damping ratio plays a key role in the dynamic response. The adjustment of the  
219 damping ratio is not straightforward to control in aeroelastic models generally and is difficult to  
220 determine in natural structures such as tree. This is mainly because collisions among branches  
221 and leaves contribute significantly to the damping of tree, and these random collisions cannot be  
222 controlled effectively and independently in the model tree with the approach to the numerous  
223 branches and leaves. The damping of the prototype is 5.4% based on modal measurements in the  
224 field, as described in Section 2.1.3. This damping, which is called “internal damping”, arises from  
225 two sources: the friction of the root-soil connection, and structural damping resulting from the  
226 movement of branches and the internal friction of the wood (Moore and Maguire, 2004).  
227 Although the damping of the aeroelastic model is about 2%, this discrepancy is not unexpected.  
228 In particular, it is reasonable that the damping of the model is smaller than the prototype because  
229 the model is fixed to the ground and the damping does not include the contribution from the  
230 friction of the root-soil connection. However, it is difficult to determine how much the friction of  
231 the root-soil connection of the prototype contributes to the damping. This mismatch will cause  
232 some discrepancy of the swaying behavior.

### 233 ***2.1.2 Description of the aeroelastic model tree***

234 Camphor trees are widely used as raw materials for medicine and furniture (Hu et al., 2012). A  
235 transplanted camphor tree (which was transplanted 2 years prior to analysis) was selected as the  
236 prototype of the aeroelastic model tree. The main dimensions, including trunk height, trunk  
237 diameters at different heights, crown height, crown diameter, diameters and inclinations of main  
238 branches, and leaves, were measured by gradienter, vernier caliper and laser range finder. Based  
239 on these sizes, the tree skeleton (Figure 1b) was extracted from the prototype (Figure 1a) and the  
240 physical model (Figure 1c) recovered. The dynamic characteristics of the prototype were  
241 measured in field, which are discussed further in Section 2.1.3. The physical parameters of the  
242 trunk and branches of the prototype, including density and elastic modulus, were derived from the

243 method of Jiang and Peng (2001). The resulting designs of each component of the model tree are  
244 described below.

245 The trunk model borrows from the method of full aeroelastic model of long-span bridges. The  
246 structural skeleton of the trunk is made of a high-strength aluminum rod ( $\rho = 2700\text{kg/m}^3$ ,  $E =$   
247  $6.91 \times 10^{10}\text{Pa/m}^2$ ) of circular cross section, which is 0.5m long. In addition to diameter at  
248 breast height (DBH = 0.15m), the diameters at 15 distinct heights of the prototype trunk were  
249 also measured. Based on these sizes, the aluminum spine was machined so that the variation of  
250 trunk diameter on the model stiffness was modelled. Such variation is important in modelling the  
251 bending responses. The connection at the top of the trunk was designed to provide a fixed joint  
252 for branches. In order to simulate the aerodynamic shape of the trunk, 15 segments of “cladding  
253 components” were attached to the trunk spine. Adjacent segments were separated by a 0.8 mm  
254 gap in order to prevent their contacting each other with a subsequent contribution to the trunk  
255 stiffness. These were 3D printed to have the correct mass by adjusting the “wall” thickness.

256 There were 10 main “first-class” branches and 102 “higher-class” branches to support the  
257 crown frame. The method used to build the trunk was not suitable for making aeroelastic  
258 branches because the diameters of the branches are too small at a scale of 1:6 (ranging from 0.003  
259 - 0.009 m). As an alternative, a combination of aluminum wire ( $\rho = 2700\text{kg/m}^3$ ,  $E = 6.91 \times$   
260  $10^{10}\text{Pa/m}^2$ ) and rigid hollow rods ( $\rho = 930\text{kg/m}^3$ ) was used, based on the principle of  
261 equivalent mass and displacement. To describe the concept of equivalent displacement, the true  
262 deformation of an aeroelastic branch (Figure 2a) is replaced by the alternative model (Figure 2b).  
263 One obvious distinction is that the aeroelastic branch deformation is curved while the alternative  
264 deformation is a combination of curve and linear. Although it may affect local displacements of  
265 branches, crown streamlining of branches of two models would be consistent, because the free  
266 ends of the branches of the two models have the same displacement under the same load. Based  
267 on this, the stiffnesses of the two models are the same. The appropriate mass of the model is  
268 obtained by altering wall thickness of the hollow rod, so that the resulting natural frequencies  
269 match those of the prototype.

270 The range of leaf mass was determined by comparison between natural frequency of the  
271 prototype measured in field and that of a finite element model in which leaf weight can be  
272 adjusted to match the natural frequency. Because the field measurements happened during  
273 autumn, considering the seasonal effect on leaves, this mass range was altered suitably so that the  
274 natural frequency and crown area of the model were in the range of the prototype over the course  
275 of a year. There were 540 leaf clusters in total added to the model, which is much smaller than for  
276 the prototype over much of the year. Based on the fact that the typical leaf cluster of the prototype  
277 usually includes 5 leaves (Figure 3a), model leaf clusters (Figure 3c) were made according to a  
278 computer-based 3D model of a leaf cluster (Figure 3b).

279 Leaves are made of lamina and petiole. Lamina determines leaf deformation while petiole  
280 determines leaf direction (Vogel, 1989). Dynamic characteristics of leaves were neglected  
281 because of material limitations: sheet plastic and steel piano wire were used to model the lamina  
282 and petiole, respectively. Because the clusters are made of steel piano wire and sheet plastic, the  
283 stiffness of man-made cluster is larger than the prototype, which causes different deformations  
284 and directions of the leaves between the prototype and the model under wind load. This is a  
285 limitation of the model, which needs to be addressed in the interpretation of the results.

286 Eight crown configurations of the aeroelastic model were designed by assembling different



287 quantities of branches and leaf clusters. These include the trunk portion of the model tree, which  
288 is named as case C1 (Figure 4a). Case C2 (Figure 4b) includes both trunk and branches. Case C3  
289 is formed by adding one leaf cluster to each of the branches in case C2 (Figure 4b). Following the  
290 same way, the branches were incrementally added with clusters for cases C4 to C8 shown in  
291 Figures 4d-h, respectively. Six sets of clusters were incrementally increased in order from free-  
292 ends to fixed-ends of branches to simulate the growth sequence of leaves in reality. The  
293 dimensions and mass of eight configurations of the aeroelastic model tree are listed in Table 2.

### 294 **2.1.3 Dynamic characteristics of the aeroelastic model tree**

295 For the accurate identification of the natural frequencies of the aeroelastic model tree, a modal  
296 analysis using a finite element model (FEM), along with experimental displacement tests of the  
297 model tree were conducted. The former was accomplished using the ANSYS finite element  
298 software package according to the dimensions and material properties of the aeroelastic model  
299 tree (Figure 5a). The latter was completed by free vibration decay tests of the trunk. For the  
300 experiments, the crown was released from a relatively large displacement within the elastic range  
301 of the materials in order to increase collisions among branches and leaves as much as possible in  
302 the process of free vibration. Then, the free vibration decay time history was recorded by a high  
303 sensitivity accelerometer attached to the top of the trunk. Figure 5(b) illustrates the overall mode  
304 shape at  $f = 2.0$  Hz for case C8, in which all branches sway in phase, but without trunk  
305 swaying. This frequency is close to the frequency range where the first peaks are identified in the  
306 power spectral density functions of the acceleration atop the trunk (Figures 5d, e). Based on these  
307 characteristics, this frequency range is defined as the “crown frequency”. In addition, based on  
308 case C1 (just the trunk without the crown; Figure 4a), and the continuity of frequency variation of  
309 the trunk (from cases C1 to C8) shown in Figure 5(d) and (e), this frequency range is defined as  
310 the “trunk frequency”. Figure 5(c) illustrates the overall mode shape at the trunk frequency range  
311 ( $f = 12.2$  Hz) for case C8, in which trunk sways out of phase with crown.

312 Figure 5(f) shows frequencies of the aeroelastic model for the eight crown configurations in the  
313 two orthogonal directions. The crown frequency, which is far smaller than trunk frequency, as  
314 shown in the Figure 5(f), indicates that the crown with a spreading canopy and no central trunk  
315 sways as a whole (James, 2010). The collisions among branches and leaves are key factors in this  
316 process. In addition, crown frequency is also governed by the stiffness and mass of branches,  
317 along with the leaf mass. The crown vibration is more obvious than trunk vibration in this  
318 frequency range (Figure 5b). Crown frequencies in the along-wind direction are almost the same  
319 as those in the across-wind direction, which indicates the symmetry of the model. Crown  
320 frequencies decrease with increasing numbers of leaf clusters (Figure 5f) because of the added  
321 mass.

322 On the other hand, trunk frequency depends on the stiffness and mass of the trunk and crown.  
323 The trunk frequency of the prototype camphor tree was identified by modal measurement method  
324 of Single Input Single Output (SISO). This method measures response at one fixed point of the  
325 trunk while lightly hitting different points along the height of the trunk with a force hammer  
326 (Reynders et al., 2010). The trunk frequency of the prototype is found to be 5.18 Hz. Based on  
327 the frequency scale of 2.45:1, the target frequency of the model trunk is 12.68 Hz. Trunk  
328 frequency of C6 is 12.70 Hz (Figure 5f), which is reasonably close to the target trunk frequency  
329 (i.e., 0.2% higher).

330 The ratio between the crown and trunk frequencies for different crown configurations is about  
 331 1:3 to 1:4. Serigo et al. (2008) found that the ratio of the first two frequencies of an olive tree  
 332 with a spreading canopy and no central trunk is about 1:2. Schindler et al. (2010) found that the  
 333 ratio for a plantation-grown Scots tree with a central trunk is about 1:3. These indicate that the  
 334 first two frequencies of the aeroelastic model tree are reasonable.

## 335 2.2 Terrain simulation

336 The turbulent atmospheric boundary layer (ABL) flows were simulated in the high-speed  
 337 section of the Boundary Layer Wind Tunnel Laboratory (BLWTL) II at University of Western  
 338 Ontario (UWO), Canada. It has a fetch of 39 m for flow development. The cross section at the  
 339 test location is 3.36 m wide and 2.05 m high. Three spires with 1.22m height and 0.1 m base  
 340 width were placed at the upstream inlet. Sets of roughness blocks are distributed along the fetch  
 341 between the inlet and the test location. By altering the heights of roughness blocks and barriers,  
 342 four different ABL flows (T1-T4) were generated.

343 Mean wind speed profiles were measured using a Cobra Probe (TFI, Model no. 900, 311) at a  
 344 sampling frequency of 625 Hz. In what follows, the ABL flow conditions to which the aeroelastic  
 345 model tree was exposed are described in detail. Therefore, mean wind speeds and turbulence  
 346 intensities of the ABL flows simulated with terrains T1-T4 are analyzed. Vertical profiles of the  
 347 aforementioned ABL flows are shown in Figure 6. In addition, ESDU 85020 (2008a) guideline is  
 348 used to illustrate flow characteristics of two full-scale ABL flows which develop as a result of  
 349 “open” (T5) and “suburban” (T6) terrains. While the mean velocity profiles of T1, T2 and T3 are  
 350 similar to that of T5 for heights similar to the crown height, the velocity profile of T4 differs at all  
 351 heights investigated, which indicates that wind tunnel terrains provide realistic bounds on full-  
 352 scale terrains in the mean flow sense. There is a clear increase in turbulence intensities ( $I_{U,T1} <$   
 353  $I_{U,T2} < I_{U,T3} < I_{U,T4}$ ) from terrain T1 to terrain T4. While turbulence intensities of T4 are similar  
 354 to those obtained for terrain T5, turbulence intensities of terrain T6 are the largest among the  
 355 different ABL flows investigated. This finding may suggest that gust effects are underestimated  
 356 for measurements conducted for terrains T1-T3. Table 3 provides turbulence intensities at the  
 357 reference height ( $z_{ref} = 0.85H$ ) for all terrain types investigated.

358 Figure 7 shows plots of power spectral density functions of streamwise velocities for all six  
 359 ABL flows at corresponding measurement heights, namely, at  $z_{ref} = 0.85m$  for terrains T1 - T4  
 360 and at  $z_{ref} = 5.1m$  for terrains T5 and T6. The power spectra of terrains T1-T4 illustrated in  
 361 Figure 7 shows that the magnitudes of the measured power spectra seem to be primarily  
 362 dependent on the turbulence intensity; the magnitude increases with increasing turbulence  
 363 intensity. Figure 7 furthermore illustrates the power spectral density functions of terrains T5 and  
 364 T6, and thereby highlights large differences between the power spectra of terrains T1-T4 and T5-  
 365 T6. Table 3 shows that the dimensionless integral length scale ( $L_x/D_{crown}$ ) of terrains T5 and T6  
 366 are significantly larger compared to those obtained for terrains T1-T4, which is caused by the  
 367 primary issue when using relatively large scale models in typical boundary layer wind tunnels.  
 368 The mismatch of integral length scales causes the tree's crown to miss the response caused by  
 369 relatively large scale wind gusts. As a result, investigations conducted with terrains T1-T4 will  
 370 likely underestimate the tree's response compared to full-scale. Momentum thicknesses

371 normalized by the height of the model tree,  $\theta/H, \theta = \int_0^H \frac{U}{U_H} \left(1 - \frac{U}{U_H}\right) dz$ , are shown in Table 3.

372 The momentum thicknesses of terrains T5 and T6 lie within a similar range as terrains T1-T4,  
373 which indicates that the analyzed terrains will not miss the effects caused by momentum  
374 thickness.

### 375 ***2.3 Measurements and instrumentation***

376 The wind tunnel tests were carried out in BLWTL II at UWO. The set-up of the wind tunnel  
377 tests and coordinate system definition are shown in Figure 8. Aerodynamic forces, wind speed,  
378 and crown area were measured synchronously to determine characteristics of aerodynamic forces,  
379 aerodynamic force coefficients and crown deflections, and energy transfer functions.

380 Aerodynamic forces were measured by a six-component force balance (JR3, Model no. 5640).  
381 Background noise of the force balance is typically less than 4% of the measured coefficients of  
382 variations (COV) with the wind. Because aerodynamic forces caused by the crown dominate the  
383 total aerodynamic forces of the tree, four cobra probes are used to measure the local wind speed  
384 around the crown. The locations of the four cobra probes are shown in Figure 8. Cobra probe 1  
385 was used as reference wind speed to calculate aerodynamic force coefficients. The data for  
386 aerodynamic forces and wind speeds were collected synchronously at a sampling rate of 625 Hz  
387 for a duration of 245 s, which relates to approximately 10 minutes in full-scale.

388 Two 1 Mb Photron FASTCAM-1024 PCI CMOS cameras (maximum sampling frequency:  
389 1000 Hz) were used to record digital images of the aeroelastic model. A more detailed description  
390 of the cameras can be found in Taylor et al. (2010). Two digital cameras were installed: one  
391 downstream of the aeroelastic model and the other one at the side of the model, as can be seen in  
392 Figure 8. These cameras were used to capture images to calculate frontal area and crown  
393 deflection during each run at a sampling rate of 60 Hz for 20 s, which is sufficient to resolve all  
394 dynamic effects. Images from both cameras were synchronized in time with the aerodynamic  
395 force and wind speed measurements.

396 Figure 9(a) shows that compared to the dark wind tunnel background, the model tree is shown  
397 white on the gray-scale images. For the digital image processing, first, a threshold was defined by  
398 means of which a program could determine whether pixels in the gray-scale image are counted as  
399 white (tree) or black (no tree). Within this process, all “tree pixels” were assigned a bright white  
400 color, as shown in Figure 9(b). The frontal area of the tree was then estimated by counting the  
401 number of white pixels in the processed image. In this processing, the reference scale ( $6.818 \times$   
402  $10^{-7}$  m<sup>2</sup>/pixel) between pixel size and length was determined by a calibration block in the  
403 image. In order to enhance the accuracy of determining the frontal area, the contrast between tree  
404 and background was increased by covering components that reflected light in black tape and  
405 lighting only the test section of the wind tunnel while turning off all other lights.

406 The identification of crown deflection follows a similar method as described for the frontal  
407 area. Firstly, the crown center, which is defined as the center of mass of all white pixels, was  
408 identified. The reference crown center was calculated without wind, and by subtracting the  
409 location of the reference crown center from the location of the deflected crown center (due to  
410 wind), the crown's displacement due to wind was obtained.

411 The process for recording data is described as follows. Still images of the aeroelastic model  
412 were first captured from both cameras to calculate the frontal area and the original position in still  
413 air. Then, the wind speed was increased to the desired level and the measurements of images,  
414 wind speeds, and base reactions were conducted synchronously. The aeroelastic model tree was

415 subjected to six different average reference wind speeds (nominally about 3.7, 4.6, 5.6, 6.7, 7.8  
416 and 8.8m/s). The Reynolds numbers based on the average trunk diameter and these wind speeds  
417 range from 6,200 to 14,700.

### 418 **3. Aerodynamics of the aeroelastic model tree**

#### 419 **3.1 Mean base overturning moments**

420 The trunk is usually described as a cantilever fixed perpendicularly to the ground. Trunk  
421 breakage is usually caused by large tensile stresses that occur when the bending moment and self-  
422 weight exceed the tensile strength of the trunk. In this failure mode, the bending moment plays a  
423 key role. The base overturning moment caused by crown mass and crown displacement is  
424 separated to obtain the purely aerodynamic moment. The corresponding base overturning  
425 moment coefficient is defined as

$$426 \quad C_M = \frac{M - m_{crown} * d_{cc}}{0.5 \rho U_{ref}^2 A_U H} \quad (2)$$

427 where  $C_M$  is the base overturning moment coefficient,  $M$  is the base overturning moment  
428 measured by the force balance,  $m_{crown}$  is the crown mass corresponding to the different  
429 configurations,  $d_{cc}$  is the crown center displacement,  $\rho$  is the air density,  $A_U$  is the wind-  
430 speed-specific frontal area, which is defined as frontal area corresponding to mean reference wind  
431 speed and crown configuration,  $U_{ref}$  is the reference wind speed, and  $H$  is the height of the  
432 aeroelastic model tree. For the mean base overturning moment coefficient,  $\bar{C}_M$ , mean values are  
433 used for all time-varying quantities in equation (2). For time-varying analyses of  $C_M$ ,  
434 simultaneously measured time-varying quantities are used in equation (2).

435 Figure 10(a) shows the relationships between frontal area and reference wind speed in terrain  
436 T1. For the different crown configurations, frontal areas are essentially constant with wind speed  
437 and depend on the number of leaves included in the crown configurations, ranging from 0.05 to  
438 0.14 m<sup>2</sup> (model scale) for cases C2 to C8, which indicates that it has little effect on base  
439 overturning moment coefficient. Thus, crown streamlining effects are not observed directly with  
440 this model. We attribute this to the excess stiffness of the model lamina and petiole, as indicated  
441 in Section 2.1.2.

442 The effects of crown configuration and wind speed on the mean base overturning moment  
443 coefficient in terrain T1 are shown in Figure 10(b). The different values along the abscissa in the  
444 Figure 10(b) are determined by different crown configurations. The mean base overturning  
445 moment coefficients increase with increased numbers of leaf clusters and tend to be steady when  
446 there are relatively more leaf clusters (for case C8). This is mainly because the initial increased  
447 number of leaves significantly change the aerodynamics of the model tree. This leads to increased  
448 base overturning moment coefficients. The steady trends are mainly caused by crown deflection,  
449 and not by frontal area, because frontal areas are basically constant with wind speed (Figure 10a),  
450 and crown center displacements are consistent with the increasing trends followed by steady  
451 trends for base overturning moment coefficients, which are discussed later in the paper (Figure  
452 15a). At the same time, the mean base overturning moment coefficients decrease for larger wind  
453 speeds, which is discussed further in Section 3.2. This result is also found in wind tunnel tests of  
454 broad-leaved species (Cao, et al., 2012; Vollsinger, et al., 2005) and field measurements of broad-  
455 leaved species (Kitagawa, et al., 2015; Koizumi, et al., 2010).

456 Figure 11 shows the effects of the ABL momentum thickness on the mean base overturning

457 moment coefficient. For a specific crown configuration, it can be seen that the mean base  
458 overturning moment coefficients are basically constant in the range of momentum thickness from  
459 0.07 to 0.10, associated with the smoother terrain T1, T2 and T3, and then decrease for 0.17,  
460 which represents the rougher terrain T4. This is mainly because momentum thickness is a  
461 parameter which reflects the differences in the mean wind speed profile. Increased momentum  
462 thickness corresponds to reduced mean wind speeds in the profile, which reduces the  
463 aerodynamic forces acting on the tree.

### 464 **3.2 Fluctuating base overturning moments**

465 In order to determine fluctuating characteristics of base overturning moments and moment  
466 coefficients, various statistical parameters were investigated for cases C2 to C8. Table 4 provides  
467 the mean values, standard deviations (SD) and COV of reference wind speeds, base overturning  
468 moments, and moment coefficients in terrain T1. The COV for the base overturning moments  
469 decrease from 12% to 8% for the increased numbers of leaves (for cases C2 to C8), with  
470 turbulence intensities hold constant at about 6%, even though both the mean and fluctuating (SD)  
471 of the base overturning moments increase substantially with increased numbers of leaves. It is not  
472 clear what causes this, because there is no apparent correlation between COV of base overturning  
473 moments and damping (including both structural and aerodynamic damping; Table 4), which is  
474 derived from crown deflection calculated by both the random decrement method and the  
475 logarithmic decrement method (James, 2010). In contrast, the COV for the base overturning  
476 moment coefficients fluctuate around the average value about 14% for the different crown  
477 configurations (with turbulence intensities hold constant at about 6%). Further analyses will be  
478 presented below and in the following sections.

479 Figures 12(a) and (b) show the effects of turbulence intensity (in terrain T1, T2, T3 and T4) on  
480 the COV for the base overturning moments and moment coefficients, respectively. The COV for  
481 the base overturning moments increase linearly with larger values of turbulence intensity (Figure  
482 12a). It is worth noting that the increased numbers of leaf clusters tend to slightly mitigate the  
483 fluctuations of base overturning moments. The COV for the moment coefficients as a function of  
484 turbulence intensity exhibit similar trends, although the frontal area has some effect on the  
485 normalized response.

486 The characteristics in frequency domain about base overturning moment are described in  
487 Figure 13. Figure 13(a) illustrates the power spectral density functions of the base overturning  
488 moments for cases C2 to C8 in the along-wind direction at the reference wind speed of 8.8 m/s in  
489 terrain T1. The broad peaks for base overturning moments are identified to be close to the crown  
490 frequency. The secondary peaks, which are relatively smaller in magnitude and narrower in  
491 bandwidth, are identified to be in the range of the trunk frequency (Figure 5f). These indicate that  
492 crown frequencies dominate the fluctuations of the base overturning moments. Figure 13(b) show  
493 the similar results for the base overturning moment coefficients. Figure 13(c) illustrates the power  
494 spectral density functions of the base overturning moment coefficients for case C8 at the  
495 reference wind speeds of 3.7 to 8.8 m/s at same conditions. The broad peaks for different wind  
496 speeds are constant and identified to be close to the crown frequency, which indicates that the  
497 base response is determined by crown frequency and not related to a possible vortex induced  
498 vibration.

499 The normalized co-spectral density function in the along-wind direction is defined as (Holmes,

500 2001)

$$501 \quad CS_{MU} = \text{real}(S_{MU}/\sqrt{S_{MM} * S_{UU}}) \quad (3)$$

$$502 \quad CS_{C_mU} = \text{real}(S_{C_mU}/\sqrt{S_{C_mC_m} * S_{UU}}) \quad (4)$$

503 where  $CS_{MU}$  is the normalized co-spectral density function between the base overturning  
504 moment (measured by the force balance) and the reference wind speed, while  $CS_{C_mU}$  is the  
505 normalized co-spectral density function between base overturning moment coefficient and  
506 reference wind speed.  $S_{MU}$  is the cross spectral function between the base overturning moment  
507 (measured by the force balance) and the reference wind speed,  $S_{C_mU}$  is the cross spectral  
508 function between the base overturning moment coefficient and the reference wind speed,  $S_{MM}$ ,  
509  $S_{C_mC_m}$ ,  $S_{UU}$  are the power spectral density functions of the base overturning moment (measured

510 by the force balance), base overturning moment coefficient and reference wind speed,  
511 respectively, and  $\text{real}(\bullet)$  is real part. The time history of the base overturning moment  
512 coefficient is calculated by equation (2), which is determined by the fluctuations of the base  
513 overturning moment (measured by the force balance), reference wind speed and frontal area.

514 The details of the correlation between the wind speed fluctuation and the base overturning  
515 moment are described in Figure 14. Subplot (a) in Figure 14 shows a 3-sec time segment of the  
516 normalized velocities and base overturning moment fluctuations (i.e.,  $(U(t + \tau) - \bar{U})/(U'^2)^{0.5}$   
517 and  $(M(t) - \bar{M})/(M'^2)^{0.5}$ ) in terrain T1. Because the velocity probe is placed a short distance  
518 upstream of tree model (Figure 8), the velocity signal shown in Figure 14(a) is delayed by a lag  
519 time,  $\tau$ , for better visual comparison with the moments. Figures 14(b) shows the corresponding  
520 base overturning moment coefficients by using the two quantities in Figure 14(a), i.e.,  $C_M(t) =$

521  $(M(t) - m_{crown} * d_{cc})/(0.5 * \rho * U_{ref}(t + \tau)^2 * A_U(t) * H)$ . Figure 14(c) further shows the co-  
522 spectra to quantify the correlation (in the frequency domain) between velocity and base  
523 overturning moment, while Figure 14(d) shows the co-spectra for the velocity and moment  
524 coefficients.

525 From Figure 14(a), it is clear that the large-scale turbulence (i.e., slowly varying wind speed  
526 traces) correlates well with base overturning moment responses, while the pattern of the small-  
527 scale turbulence (i.e., fast-changing velocities) are not found in the base overturning moments.  
528 This observation is consistent with the co-spectral plot shown in Figure 14(c), in which the  
529 correlation coefficients reach a maximum (of about 0.5) at frequencies lower than the crown  
530 frequency, and decay to zero for frequencies larger than crown frequency. This is mainly because,  
531 at frequencies lower than the crown frequency, the base overturning moment of the model is  
532 basically determined by the large-scale gust, and the model is behaving in quasi-steady manner.  
533 The sudden drop of the co-spectra at the crown frequency is thought to be induced by the  
534 mismatch of random turbulent fluctuations and the regularized crown vibration.

535 From the co-spectra plot shown in Figure 14(d), however, negative correlations can be found  
536 between the velocity fluctuations and the base overturning moment coefficients. Because the  
537 moments are nearly unresponsive to small-scale turbulence (i.e., for  $f > f_{crown}$ ), as already

538 shown in Figures 14(a) and (c), a positive small-scale gust means a direct increase of the  
539 denominator in Eq. (2), and, hence, a direct decrease of moment coefficient. The examples of  
540 these situations are labeled as blue boxes in Figures 14(a) and (b), which provides the explanation  
541 for the negative correlation between small-scale gusts and moment coefficients. On the other  
542 side, Figure 14(d) implies a negative correlation between the large-scale gust (i.e.,  $f < f_{\text{crown}}$ )  
543 and base overturning moment coefficients. This is further asserted by looking at the yellow-  
544 circled region of the time histories shown in Figures 14(a) and (b), in which the stronger gust is  
545 associated with lower moment coefficient, and vice versa. Note that this observation also echoes  
546 the negative correlation between mean velocity and mean base moment coefficients in Figure  
547 10(b).

548 To explain the negative correlation between the (large-scale) gust and the base overturning  
549 moment coefficient, the side-view snapshot of the tree model taken at a time,  $\tau$ , after the peak  
550 positive gust is shown in Figure 14(e) and compared to that corresponding to a negative gust  
551 shown in Figure 14(f). It is clear that the crown is displaced more into the stream direction for the  
552 positive gust. Such an instantaneous shape is thought to be more aerodynamic than the shape  
553 associated with the negative gust, and, hence, reduces the base moment coefficients for the  
554 positive gust. This mechanism is postulated to explain the negative correlation between the large-  
555 scale turbulence and the base overturning moment coefficient.

## 556 **4. Dynamic response of the aeroelastic model tree**

### 557 **4.1 Mean crown deflections**

558 The crown center displacement is a primary parameter to evaluate crown deflection. The  
559 effects of crown configuration and wind speed on mean crown center displacements in the along-  
560 wind and across-wind directions in terrain T1 are shown in Figures 15(a) and (b). Figure 15(c)  
561 depicts the relationships between mean crown center displacements and mean base overturning  
562 moment coefficients for different reference wind speeds in terrain T1. The monotonically  
563 increasing trends for crown center displacements in the along-wind direction cease at about  
564  $\bar{A}_Y^{0.5}/H \approx 0.34$ , which are followed by stable trends for  $\bar{A}_Y^{0.5}/H \approx 0.37$ . This is mainly because,  
565 as the number of leaves is increased from zero, the area that the wind can act on directly is also  
566 increased, which leads to increased aerodynamic forces. This causes increased crown center  
567 displacement. However, for crown configurations with larger numbers of leaves and branches,  
568 sheltering effects play an important role in reducing the relative importance of further increased  
569 quantities of leaves and branches such that the crown center displacement tends to level off with  
570 increased area, which indicates that some branches and leaves are sheltered from each other  
571 under wind load. In fact, the current study indicates that up to 33% of the leaves (relative to case  
572 C8) can be removed without affecting the crown center displacement. The crown center  
573 displacements in the along-wind direction clearly increase with increasing the reference wind  
574 speed, as expected. The relationships between mean crown center displacements and mean base  
575 overturning moment coefficients present similar changes. These can be explained by the crown  
576 sheltering effects. The crown center displacements in the across-wind direction are far less than  
577 these in the along-wind direction, which indicates that the crown response in the along-wind  
578 direction dominates crown behavior in windy conditions.

### 579 **4.2 Fluctuating crown deflections**

580 In order to determine fluctuating characteristics of the crown center displacements, the COV

581 and power spectral density functions were obtained from the time histories of crown center  
 582 displacements in the along-wind and across-wind directions for cases C2 to C8.

583 Table 4 shows the mean values, SD and COV of reference wind speeds and crown center  
 584 displacements in the along-wind and cross-wind directions in terrain T1. There is a decreasing  
 585 trend of the COV of crown center displacements in the along-wind direction from 10% to 6% for  
 586 increased numbers of leaves, with turbulence intensities hold constant at about 6%. However, the  
 587 COV of crown center displacements in the across-wind direction are much larger than those in  
 588 the along-wind direction. This is mainly because the crown center displacements in the across-  
 589 wind direction fluctuate about zero, and noting that the variance is about two thirds of that for the  
 590 along-wind direction. This is likely a reflection of the differences between the longitudinal and  
 591 lateral turbulence intensities.

592 Figure 16 shows the effects of turbulence intensity (in terrain T1, T2, T3 and T4) on the COV  
 593 for the crown center displacements in the along-wind direction. The relationships are observed to  
 594 be similar as those between the base overturning moments and turbulence intensity. There is a  
 595 similar slight reduction in the COV for the crown center displacements with larger numbers of  
 596 leaf clusters.

597 The vibration characteristics in frequency domain about crown center displacement in  
 598 orthogonal directions are described in Figure 17. Figures 17(a) and (b) show the power spectral  
 599 density functions of the crown center displacements in the along-wind and across-wind directions  
 600 for cases C2 to C8 at reference wind speed of 8.8 m/s in terrain T1. The frequency range where  
 601 the main peaks for the crown center displacements in both two directions are located is close to  
 602 the crown frequency range. The secondary peaks in the trunk frequency range are less significant,  
 603 indicating that the crown frequencies dominate the fluctuations of the crown center displacements  
 604 and not the trunk fluctuations. Figures 17(c) and (d) show power spectral density functions of the  
 605 crown center displacements in the two directions for case C8 at reference wind speeds of 3.7 to  
 606 8.8 m/s at same conditions. The constant frequency where the main peaks are located indicates  
 607 crown deflection is not related to a possible frequency of vortex shedding.

## 608 **5. Energy transfer (mechanical admittance)**

609 Based on quasi-steady assumption, the base overturning moment is estimated:

$$610 \quad M_{qs} = 0.5\rho\bar{C}_M U_{ref}^2 \bar{A}_U H \quad (5)$$

611 The mechanical admittance function in the along-wind direction is defined (Davenport, 1963)

$$612 \quad S_{MM}(f) = |H(f)|^2 S_{M_{qs}M_{qs}}(f) \quad (6)$$

613 Where  $M_{qs}$  is estimated base overturning moment based on the quasi-steady assumption,  
 614  $S_{MM}(f)$  is the power spectral density function of base overturning moment measured by the  
 615 force balance,  $S_{M_{qs}M_{qs}}(f)$  is the power spectral density function of estimated base overturning  
 616 moment based on the quasi-steady assumption, and  $H(f)$  is the mechanical admittance function.

617 In fact, the mechanical admittance based on the quasi-steady assumption that aerodynamic  
 618 force fluctuations are determined by the turbulent fluctuations of the wind is the combination of  
 619 aerodynamic and mechanical admittance. To separate the aerodynamic admittance, wind tunnel  
 620 tests with a rigid model would be necessary. Therefore, a general experimental formula for



621 aerodynamic admittance,  $\chi(f) = 1/(1 + \left[\frac{2f\sqrt{AU}}{U_{ref}}\right]^{4/3})$  (Holmes, 2001), is included to provide a  
622 reference for “typical” characteristics (Figure 18). It is generally accepted that for large-scale  
623 gusts, that the aerodynamic admittance is 1 since quasi-steady theory will tend to hold for these  
624 relatively slowly changing wind speeds. In contrast, the overall loads are not affected  
625 significantly by the smaller-scale turbulence so the admittance falls off rapidly at high  
626 frequencies. However, body-generated turbulence (such as that caused by periodic vortex  
627 shedding) increases the aerodynamic admittance. Holmes (2001) model is provided in Figure 18,  
628 which accounts for only the usually large-scale and small-scale effects.

629 Figure 18 shows the measured mechanical admittance functions in the along-wind direction for  
630 different crown configurations in terrain T1. The mechanical admittance functions reflect  
631 background parts caused by the wind and resonant parts caused by the aeroelastic model tree at  
632 low and relatively higher frequency, respectively. For  $f/f_{crown} < 1$ , the admittance is almost  
633 constant with values of about 1. This is mainly because there is a highly positive correlation  
634 between base overturning moments and wind speeds in the same frequency range, as shown in  
635 Figure 14(a). This is the quasi-steady range, where large-scale gusts control the response,  
636 consistent with aerodynamic admittance model included in the figure. Here “large-scale” implies  
637 gusts larger than  $U_{ref}/f_{crown}$ , rather than a typical dimension proportional to a physical  
638 dimension. The first peaks appear near the crown natural frequency, while the secondary peaks,  
639 which are smaller in magnitude (except for case C2) and narrower in bandwidth, appear near the  
640 trunk frequency. This indicates that the crown frequency effectively controls the response via  
641 mechanical admittance, which amplifies the response at the crown frequency. However, this  
642 effect is slightly reduced as more leaves or branches are added to the tree because of a reduction  
643 of peak values in the admittance at  $f/f_{crown} = 1$ . For smaller scale gusts, with  $f/f_{crown} > 1$ ,  
644 the admittance falls off rapidly (except for an increase in values at the trunk frequency), as these  
645 smaller gusts do not coherently act on the crown. The fall-off is more rapid than Holmes’ model  
646 for  $f/f_{crown} > 1.5$  which may be due to branches moving out of phase with the bulk of the  
647 crown.

## 648 **6. Conclusions**

649 In this study, the characteristics of base overturning moments, base overturning moment  
650 coefficients, and crown deflections were investigated for the aeroelastic model of a tree with eight  
651 distinct crown configurations in four terrain conditions. The energy transfer functions for  
652 different crown configurations were also examined. The main findings are as follows:

- 653 (i) An approach to constructing an aeroelastic model of a tree which satisfies geometric  
654 similarity, dynamic similarity and dimensionless parameters including Froude number,  
655 Cauchy number and density ratio was developed. Although the model could not include  
656 leaf deformation, it captured the major aerodynamic characteristics related to the branch  
657 structure.
- 658 (ii) Crown sheltering effects of leaves, which effectively limit the increases of crown  
659 deflections with increased crown area, occur when there are more than 67% of the leaves  
660 (relative to the case C8). Then crown deflections limit the increases of base overturning  
661 moment coefficients with increased crown area. In addition, the base overturning moment  
662 coefficients decrease with increased wind speeds and increased ABL momentum

- 663 thickness, respectively.
- 664 (iii) The COV for base overturning moments, moment coefficients and crown deflection in the  
665 along-wind direction are determined by turbulence intensity of the wind. Crown  
666 frequencies dominate the fluctuations of base overturning moments, moment coefficients,  
667 and both crown deflections in the along-wind and across-wind directions for different  
668 crown configurations (i.e., number of leaves and branches).
- 669 (iv) The energy transfer functions for different crown configurations in the along-wind  
670 direction indicate that mechanical admittance presents obvious peaks in the crown  
671 frequency, with much smaller peaks in the trunk frequency. The crown responds to large-  
672 scale gusts in a quasi-steady manner for gusts larger than  $U_{ref}/f_{crown}$ , with dynamic  
673 amplification at the crown frequency, and a rapid drop for gusts smaller than  
674  $U_{ref}/f_{crown}$ . Increased numbers of branches and leaves reduce the dynamic amplification  
675 effect in the crown frequency.

676 The primary limitations of the current model tree are as follows:

- 677 (i) The inflexible leaves clearly affect the streamlining of the crown. Material limitations  
678 restrict the accurate simulation of the bending stiffness of lamina and petiole. These  
679 limitations should be a focus of future work, although they will remain a challenge.
- 680 (ii) The mismatch about integral length scale between wind tunnel terrains and theoretical  
681 full-scale terrains causes the discrepancy on swaying behavior between the aeroelastic  
682 model tree and the prototype. It would be useful to know if the quasi-steady behavior is  
683 maintained for larger integral scales.
- 684 (iii) The mismatch on internal damping between the aeroelastic model tree and the prototype  
685 also causes the discrepancy on swaying behavior, which affects the application of the  
686 results in full scale.

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## Figures

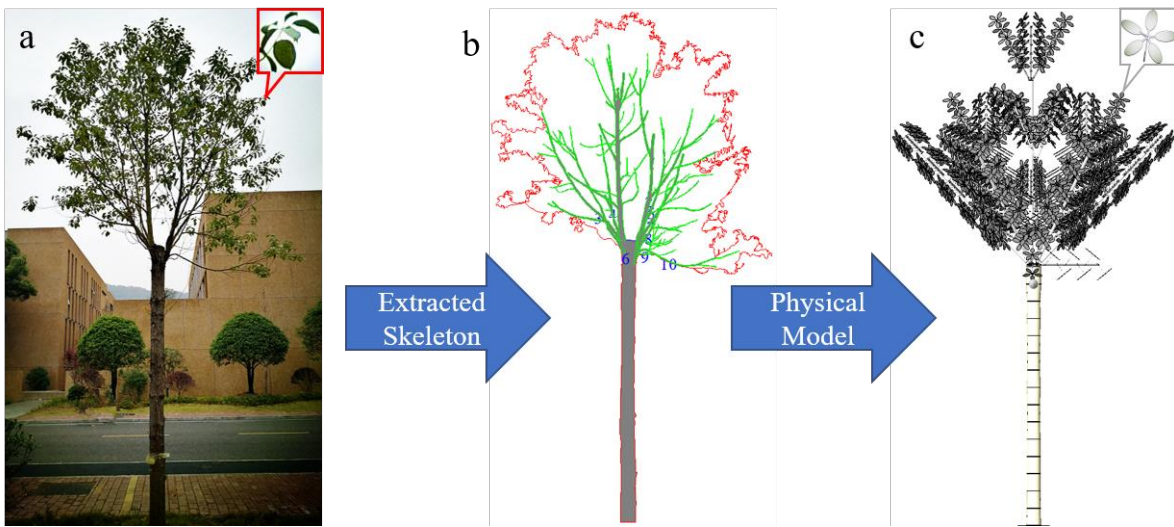


Figure 1: Schematic of the aeroelastic model tree: (a) prototype, (b) skeleton and (c) model.

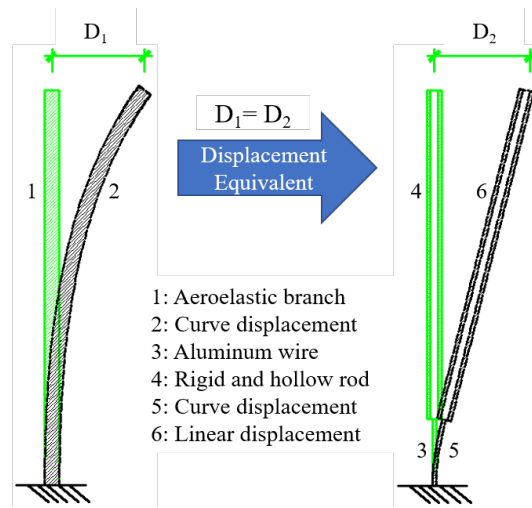


Figure 2: Schematic of equivalent displacement for the free ends of branches

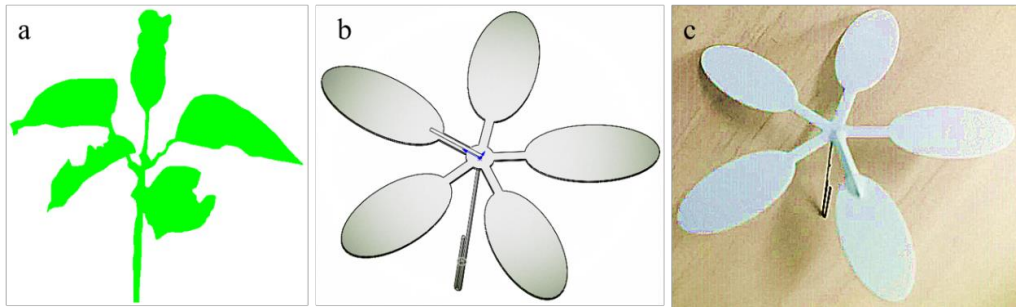


Figure 3: Leaf cluster: (a) prototype, (b) 3D computer model and (c) actual model.



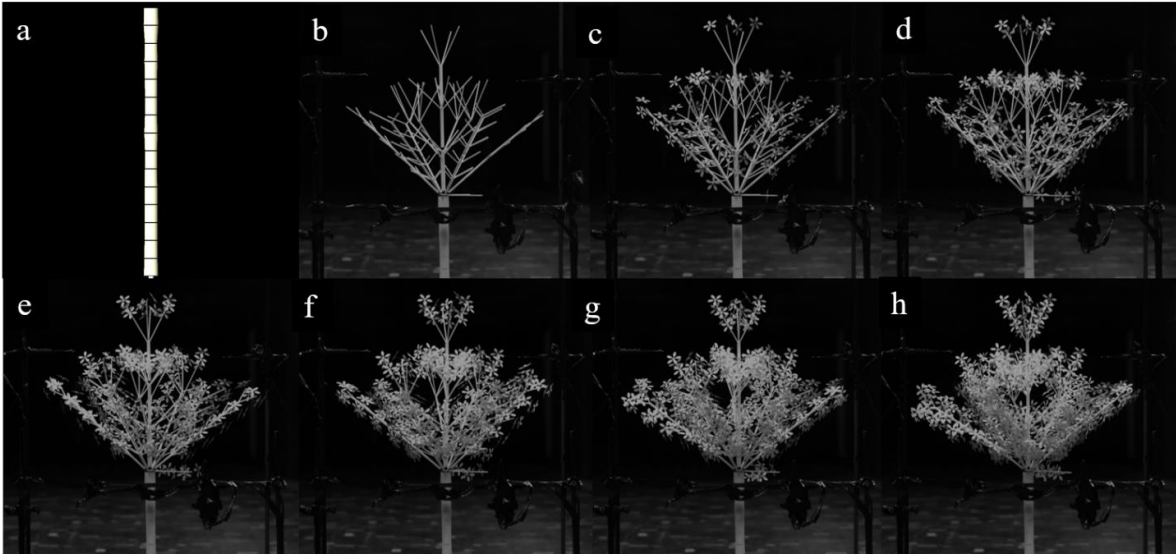


Figure 4: Eight configurations, C1 (a), C2 (b), C3 (c), C4 (d), C5 (e), C6 (f), C7 (g) and C8 (h).

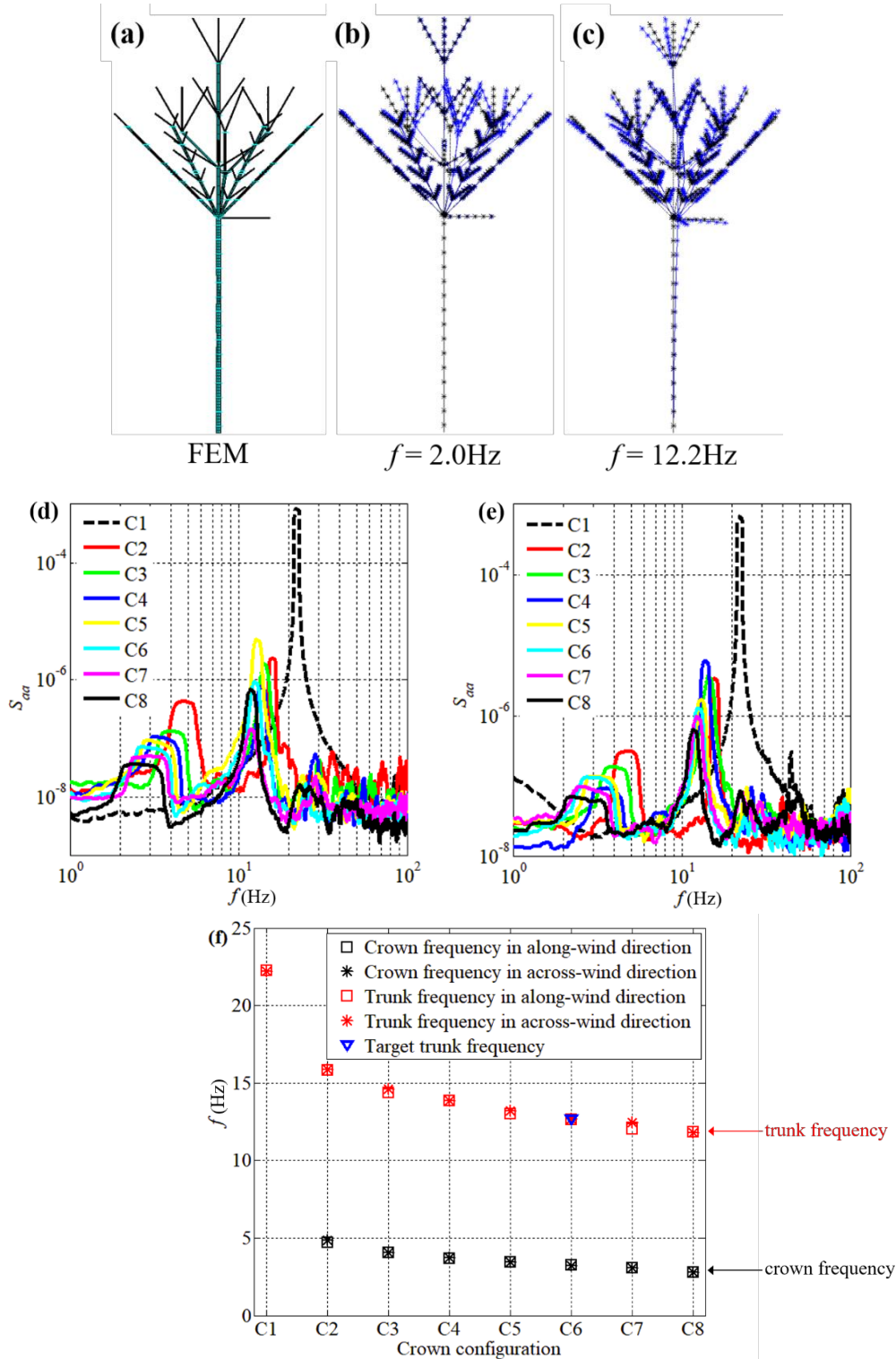


Figure 5: (a) FEM of the aeroelastic model tree, mode shapes corresponding to (b) crown and (c) trunk frequencies for case C8, power spectral density functions of accelerations at the top of the trunk for different configurations in the (d) along-wind and (e) across-wind directions derived from free vibration decay tests, and (f) frequencies of the aeroelastic model tree in the along-wind and across-wind directions.

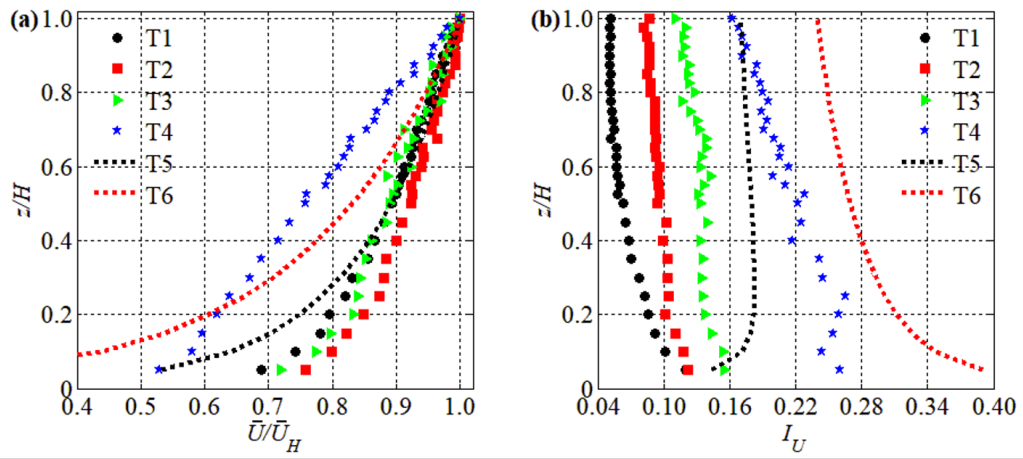


Figure 6: (a) Non-dimensional mean velocity profiles normalized by the mean velocity at the top of tree and (b) turbulence intensity profiles for four wind tunnel terrains (T1, T2, T3, T4), and two theoretical full-scale terrains named as “Open” and “Suburban” (T5, T6).

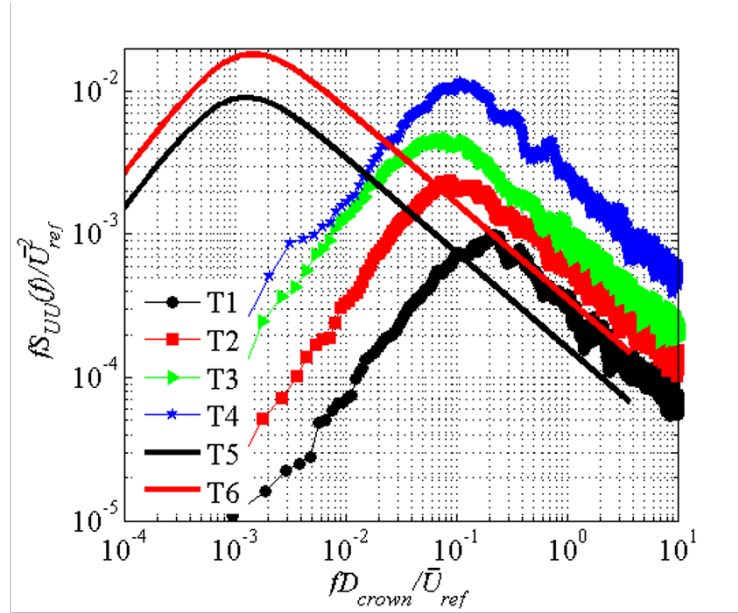


Figure 7: Power spectral density functions of streamwise velocities at reference height in four wind tunnel terrains (T1, T2, T3, T4,  $z_{ref} = 0.85\text{m}$ ), and two theoretical full-scale terrains named as “Open” and “Suburban” (T5, T6,  $z_{ref} = 5.1\text{m}$ ).

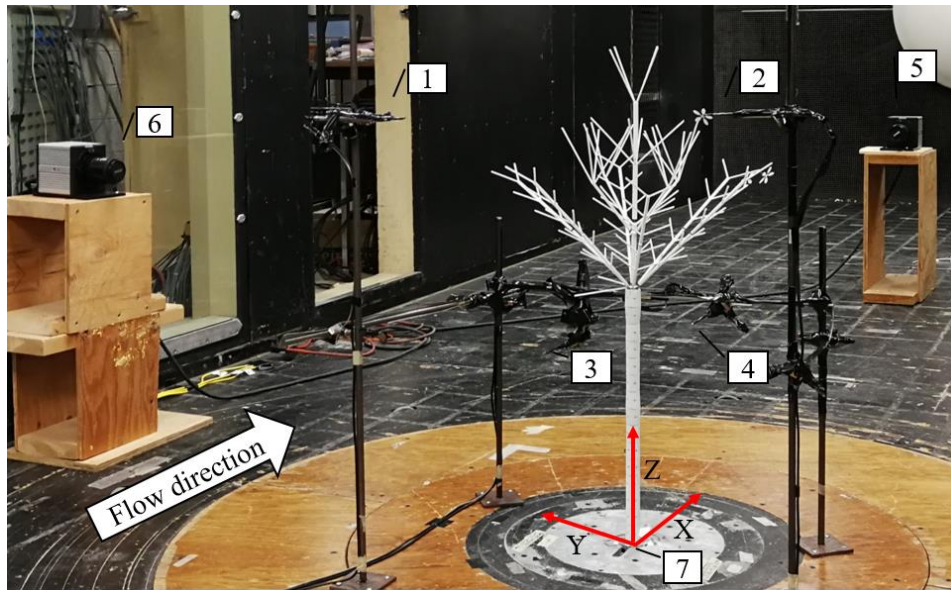


Figure 8: The set-up of the wind tunnel tests: 1 cobra probe 1  $(-0.22, 0.36, 0.85)$ , 2 cobra probe 2  $(-0.22, -0.25, 0.85)$ , 3 cobra probe 3  $(-0.075, 0.15, 0.35)$ , 4 cobra probe 4  $(-0.075, -0.15, 0.35)$ , 5 downstream camera  $(2.8, 0, 0.65)$ , 6 lateral camera  $(0.05, 1.35, 0.65)$ , 7 JR3 force balance  $(0, 0, -0.025)$ . (X, Y, Z), unit: m.

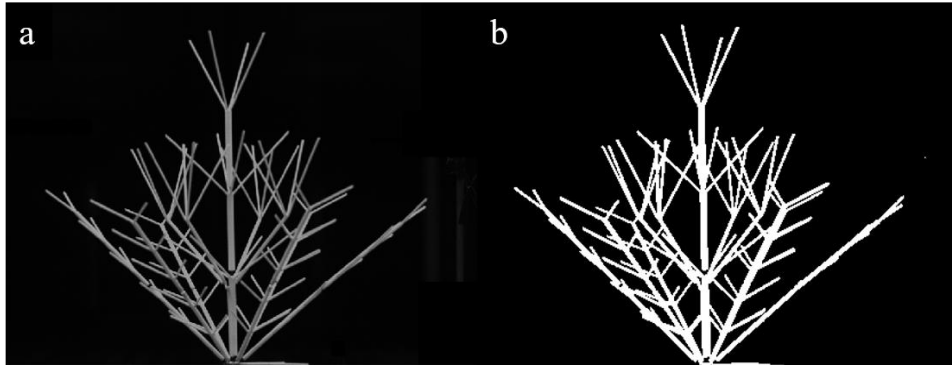


Figure 9: Frontal area of the aeroelastic model tree, (a) cropped image, (b) spatially discretized image.

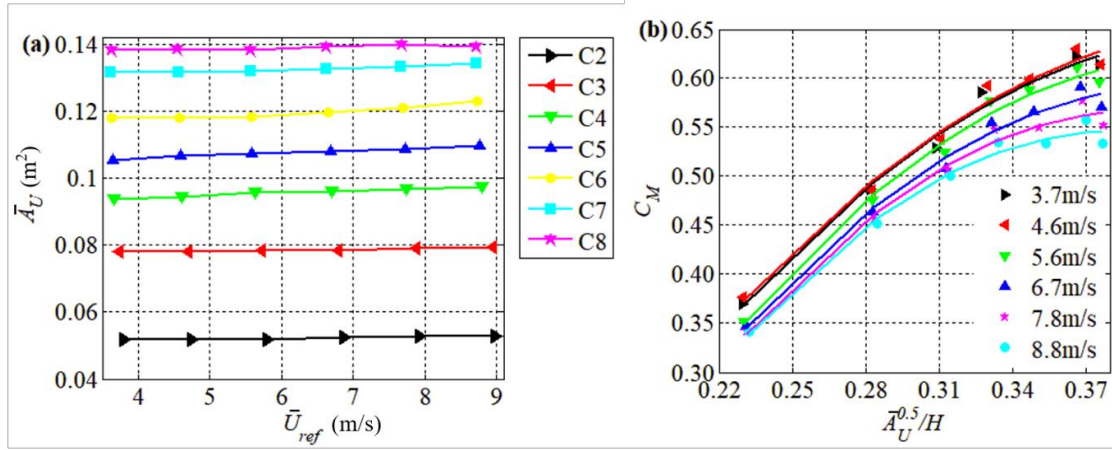


Figure 10: (a) Variations of mean frontal areas ( $\bar{A}_U$ ) versus mean reference wind speeds ( $\bar{U}_{ref}$ ) for cases C2 to C8, (b) variations of mean base overturning moment coefficients ( $\bar{C}_M$ ) versus square roots of mean frontal areas divided by the height of the model tree ( $\bar{A}_U^{0.5}/H$ ) at reference wind speeds of 3.7 m/s to 8.8 m/s in T1.

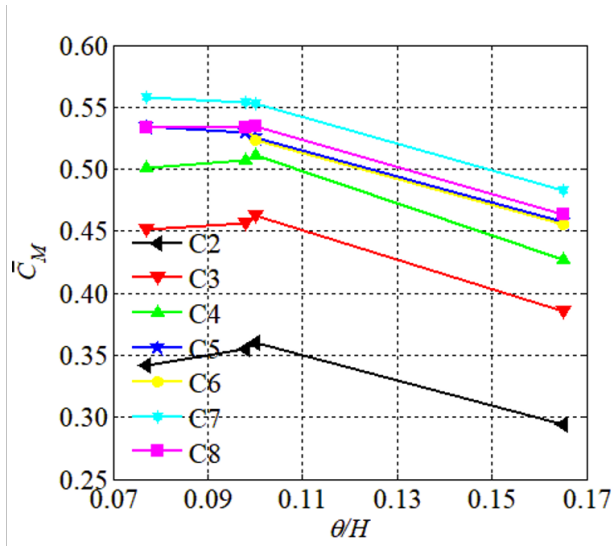


Figure 11: Variations of mean base overturning moment coefficients ( $\bar{C}_M$ ) versus momentum thickness normalized by the height of the model tree ( $\theta/H$ ) for cases C2 to C8 at a reference wind speed of 8.8 m/s, for terrains T1, T2, T3 and T4.



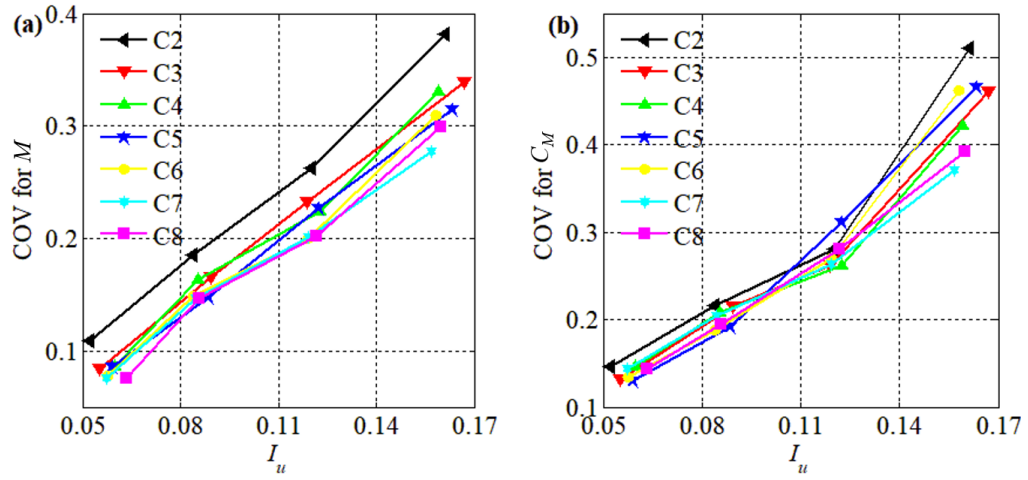


Figure 12: Variations of COV for (a) base overturning moment ( $M$ ) and (b) moment coefficients ( $C_M$ ) versus turbulence intensity ( $I_u$ ) for cases C2 to C8 at a reference wind speed of 8.8 m/s, for terrains T1, T2, T3 and T4.

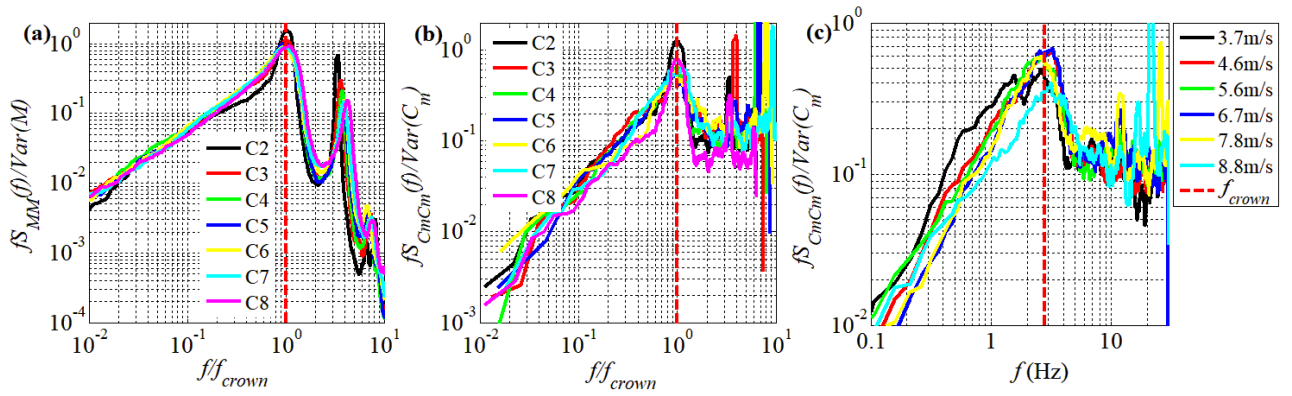


Figure 13: Power spectral density functions of (a) base overturning moments and (b) base overturning moment coefficients versus frequency normalized by crown frequency ( $f/f_{crown}$ ) for cases C2 to C8 in the along-wind direction at reference wind speed of 8.8 m/s, and (c) base overturning moment coefficients versus frequency for case C8 in the along-wind direction at reference wind speeds of 3.7 m/s to 8.8 m/s in T1.

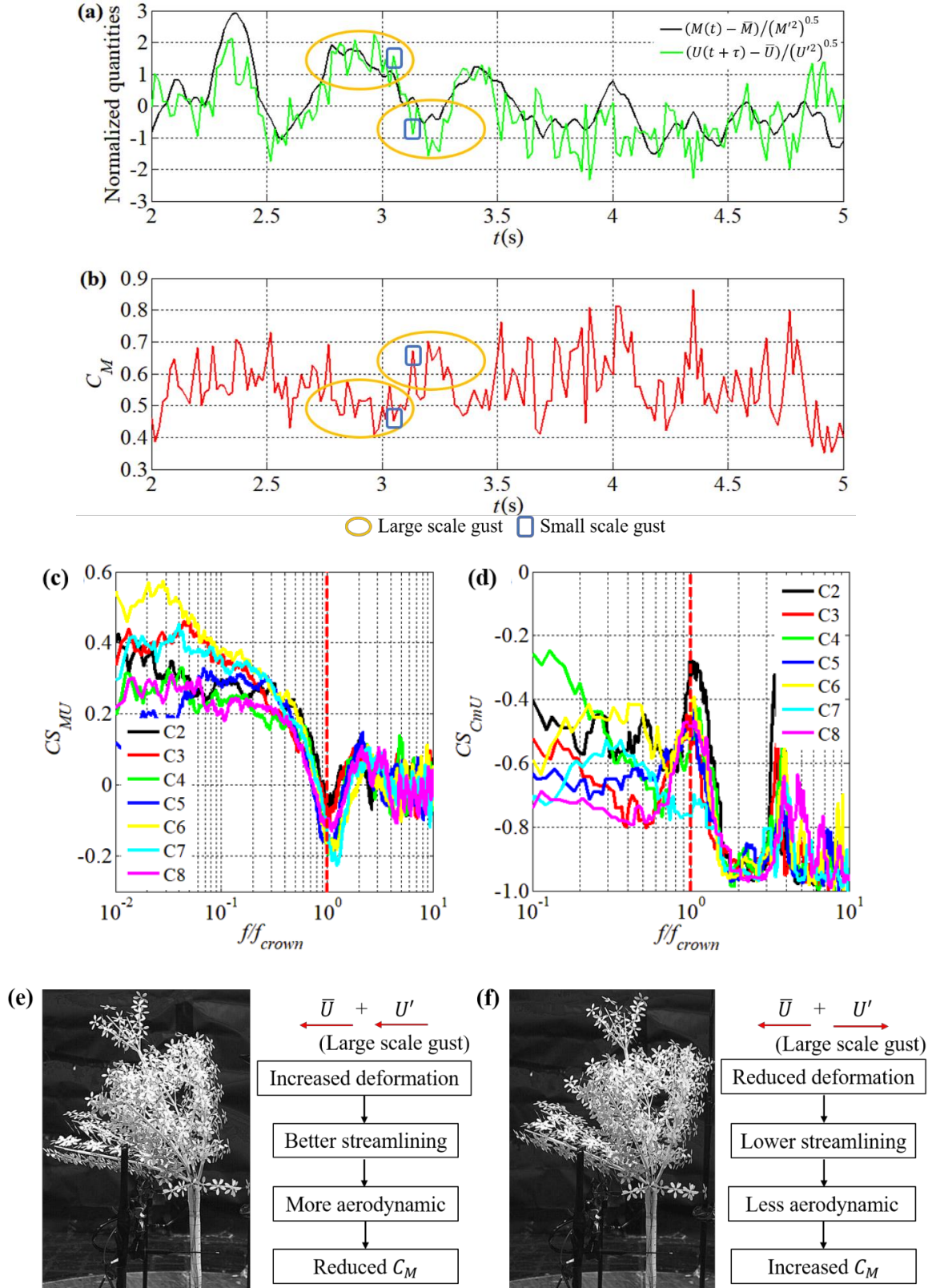


Figure 14: Time history of (a) normalized base overturning moment  $((M(t) - \bar{M}) / (M'^2)^{0.5})$  and normalized reference wind speed  $((U(t + \tau) - \bar{U}) / (U'^2)^{0.5})$ , and (b) base overturning moment coefficient  $(C_M(t) =$

$(M(t) - m_{crown} * d_{cc}) / (0.5 * \rho * U_{ref}(t + \tau)^2 * A_U(t) * H)$  for case C8, normalized co-spectral density functions between (c) base overturning moments and reference wind speeds, and (d) base overturning moment coefficients and reference wind speeds versus frequency normalized by crown frequency ( $f/f_{crown}$ ) for cases C2 to C8, and crown deformation with (e) positive and (f) negative large scale gusts for case C8, at reference wind speed of 8.8 m/s in T1.

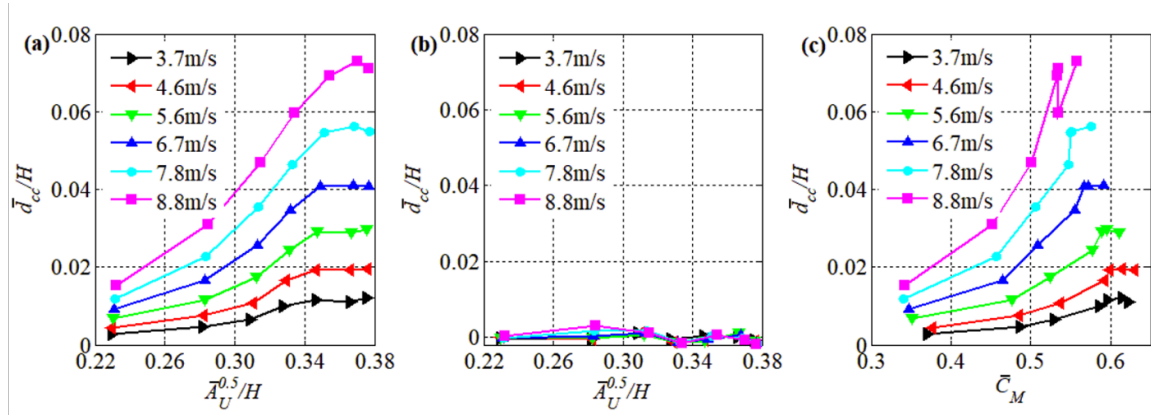


Figure 15: Variations of mean crown center displacements ( $\bar{d}_{cc}/H$ ) in the (a) along-wind and (b) across-wind directions versus square roots of mean frontal areas divided by the height of the model tree ( $\bar{A}_U^{0.5}/H$ ), and (c) mean crown center displacements ( $\bar{d}_{cc}/H$ ) in the along-wind direction versus base overturning moment coefficients ( $\bar{C}_M$ ) at reference wind speeds of 3.7 m/s to 8.8 m/s in T1.

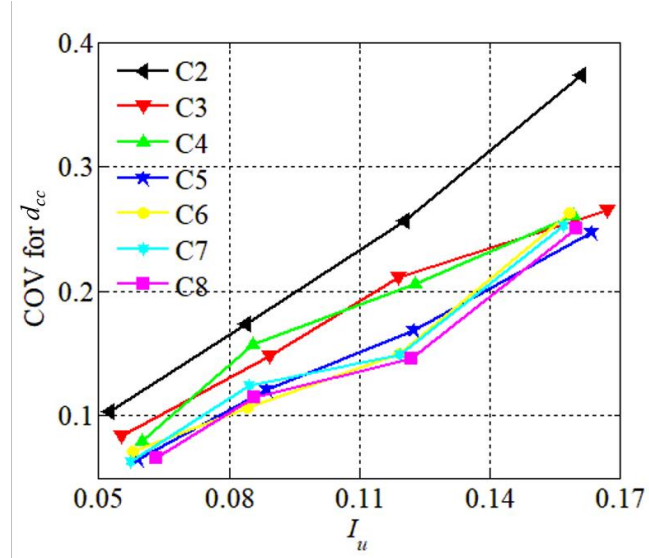


Figure 16: Variations of COV for crown center displacement ( $d_{cc}$ ) in the along-wind direction versus turbulence intensity ( $I_u$ ) for cases C2 to C8 at a reference wind speed of 8.8 m/s, for terrains T1, T2, T3 and T4.

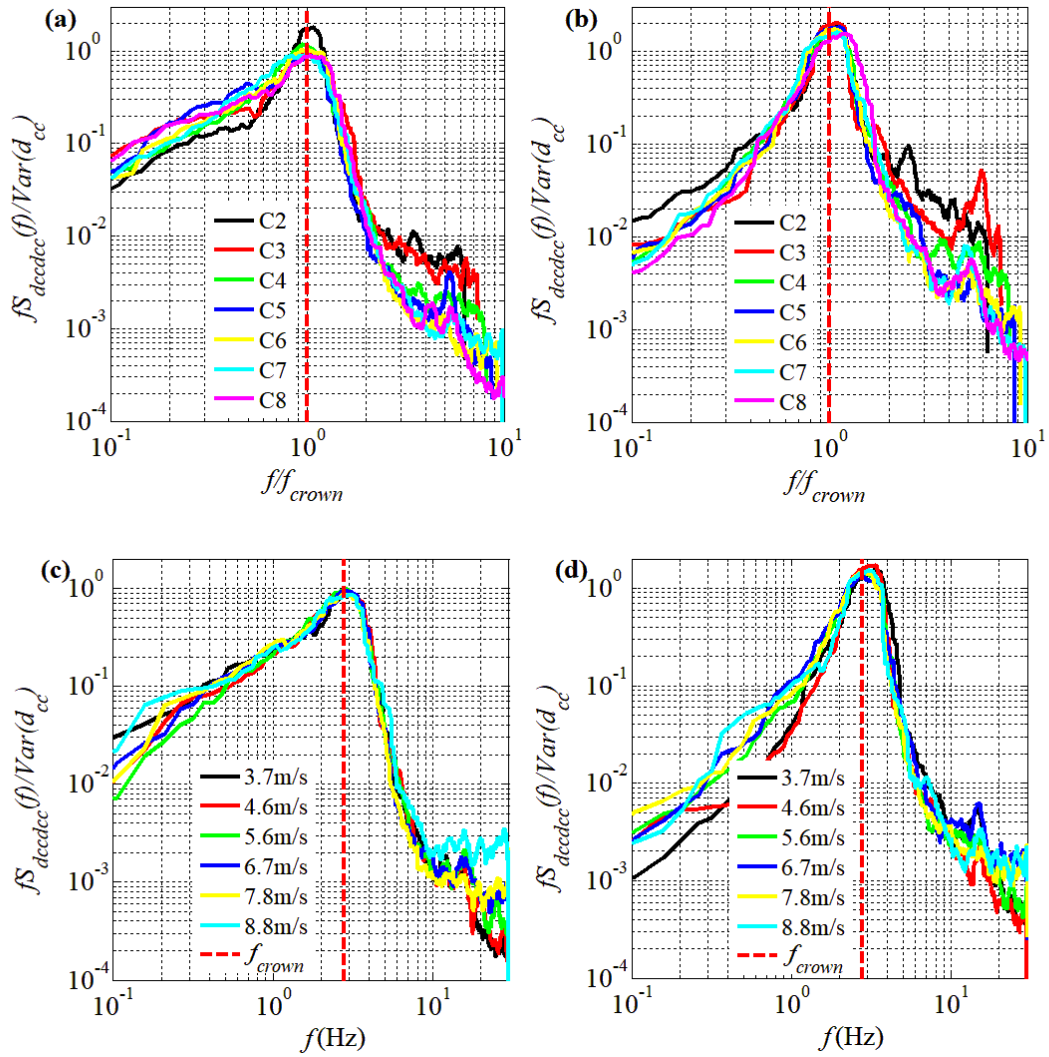


Figure 17: Power spectral density functions of crown center displacements in the (a) along-wind and (b) across-wind directions versus frequency normalized by crown frequency ( $f/f_{crown}$ ) for cases C2 to C8 at reference wind speed of 8.8 m/s, and in the (c) along-wind and (d) across-wind directions versus frequency for case C8 at reference wind speeds of 3.7 to 8.8 m/s in T1.

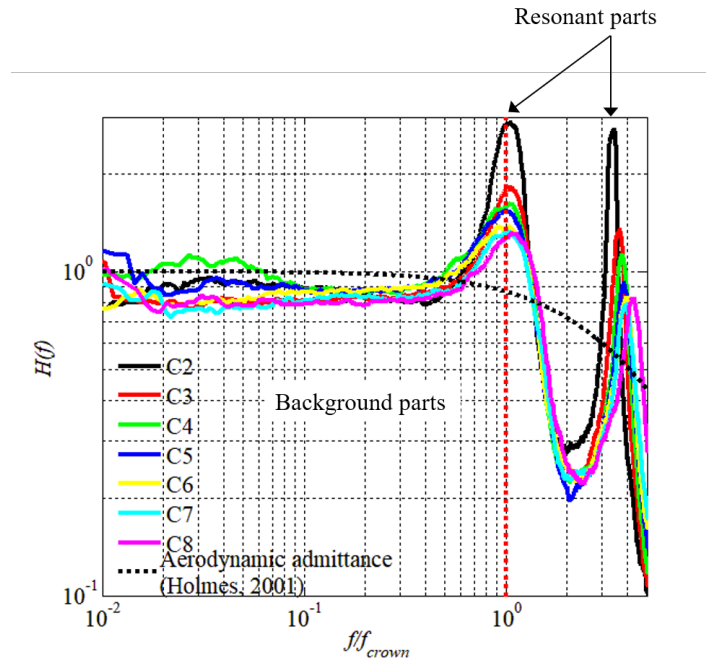


Figure 18: Mechanical admittance functions versus frequency normalized by crown frequency ( $f/f_{crown}$ ) for cases C2 to C8 in the along-wind direction at reference wind speed of 8.8 m/s in T1.



## Tables

Table 1: Aeroelastic scaling parameters

Parameter	Unit	Reduced ratio	Similarity requirement
Length	m	$\lambda_L = 1:6$	Wind tunnel scale
Velocity	m/s	$\lambda_U = 1:2.45$	Froude number
Density	kg/m <sup>3</sup>	$\lambda_\rho = 1:1$	$\lambda_\rho = \rho_m/\rho_p$
Frequency	Hz	$\lambda_f = 2.45:1$	$\lambda_f = \lambda_U/\lambda_L$
Time	s	$\lambda_t = 1:2.45$	$\lambda_t = \lambda_L/\lambda_U$
Mass per meter	kg/m	$\lambda_m = 1:6^2$	$\lambda_m = \lambda_\rho \lambda_L^2$
Mass Moment of Inertia per meter	kg · m <sup>2</sup> /m	$\lambda_j = 1:6^4$	$\lambda_j = \lambda_m \lambda_L^2$
Bending Stiffness	N · m <sup>2</sup>	$\lambda_{EI} = 1:(2.45^2 \cdot 6^4)$	$\lambda_{EI} = \lambda_U^2 \lambda_L^4$ Cauchy number

Table 2: Dimensions and mass for the aeroelastic model tree without wind

<b>Configuration</b>	<b>Tree height(m)</b>	<b>Crown height(m)</b>	<b>Tree mass(kg)</b>	<b>Frontal area(m<sup>2</sup>)</b>	<b>Crown area(m<sup>2</sup>)</b>
C1	0.50	0.00	0.1568	0.0135	0.0000
C2	0.96	0.46	0.2587	0.0516	0.0381
C3	0.99	0.49	0.2759	0.0775	0.0640
C4	0.99	0.49	0.2941	0.0924	0.0789
C5	0.99	0.49	0.3122	0.1035	0.0900
C6	0.99	0.49	0.3297	0.1162	0.1027
C7	0.99	0.49	0.3470	0.1310	0.1175
C8	0.99	0.49	0.3657	0.1366	0.1231

Table 3: Characteristics of the four wind tunnel terrains and two theoretical full-scale terrains

Terrain	Turbulence intensity, $I_u$	Integral scale, $L_x$	Momentum thickness, $\theta$
	$z_{ref} = 0.85H$	$L_x/D_{crown}$ $z_{ref} = 0.85H$	$\theta/H$
T1	0.051	0.76	0.100
T2	0.088	1.68	0.077
T3	0.12	2.02	0.098
T4	0.19	1.35	0.165
T5	0.17	19.58	0.107
T6	0.25	16.93	0.136

Table 4: Characteristics of reference wind speeds, base overturning moments, damping, base overturning moment coefficients and crown deflections for cases C2 to C8 at reference wind speed of 8.8 m/s in T1.

Configuration		C2	C3	C4	C5	C6	C7	C8
Reference wind speed in the along-wind direction $U_{ref}$ (m/s)	mean	8.98	8.95	8.80	8.76	8.73	8.72	8.73
	SD	0.47	0.49	0.53	0.52	0.50	0.50	0.55
	COV	0.053	0.055	0.060	0.059	0.058	0.057	0.063
Base overturning moment in the along-wind direction $M$ (N.m)	mean	0.8698	1.7119	2.2463	2.6855	2.9822	3.3976	3.3775
	SD	0.1035	0.1541	0.2065	0.2468	0.2502	0.2751	0.2743
	COV	0.1190	0.0900	0.0919	0.0919	0.0839	0.0810	0.0812
Damping in the along-wind direction (%)	structural and aerodynamic damping	6.1	5.6	6.3	5.0	4.0	6.1	3.2
Base overturning moment coefficient in the along-wind direction $C_M$	mean	0.3416	0.4513	0.5007	0.5348	0.5337	0.5579	0.5339
	SD	0.0532	0.0609	0.0761	0.0723	0.0732	0.083	0.0797
	COV	0.1557	0.1349	0.1520	0.1352	0.1372	0.1488	0.1493
Crown deflection in the along-wind direction $d_{cc}$ (m)	mean	0.0150	0.0305	0.0464	0.0590	0.0685	0.0721	0.0704
	SD	0.0016	0.0026	0.0037	0.0039	0.0049	0.0045	0.0046
	COV	0.1067	0.0852	0.0797	0.0661	0.0715	0.0624	0.0653
Crown deflection in the across-wind direction $d_{cc}$ (m)	mean	0.0003	0.0029	0.0011	0.0016	0.0007	0.0006	0.0018
	SD	0.0010	0.0015	0.0020	0.0029	0.0027	0.0033	0.0035
	COV	3.3333	0.5172	1.8182	1.8125	3.8571	5.5000	1.9444

SD is standard deviation, COV is coefficient of variation, mean = mean ( $\bullet$ ), SD = std ( $\bullet$ ), and COV = SD / mean.