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Letter

The steady and vibrating statuses of tulip tree leaves in wind

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HIGHLIGHTS

- 73 tulip leaves were tested in suspended condition and with front as well as back surface of the lamina facing wind.
- Three types of vibrating statuses, two types of steady statuses, and five critical wind speeds were observed in the range of wind speed 0–27 m/s.
- The probabilities of existence of the statuses and criticals, the probability density distributions in the test range of wind speed, and the expected values of the criticals were shown.

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ABSTRACT

The study of tree leaf aerodynamics is useful to tree protection, solar panel design and development of new power generation technology. 73 tulip leaves were tested in suspended condition and with front as well as back surface of the lamina facing wind. Three types of vibrating statuses, two types of steady statuses, and five critical wind speeds were observed. The existence probabilities of the statuses and criticals, the probability density distribution of every critical over the range of wind speed 0–27 m/s, and the expected values of the criticals were obtained by statistics. The critical Reynolds number, defined by critical wind speed and lamina length, shows an increasing trend with increasing the lamina area or length to width ratio of the lamina, but it shows no trend of increase or decrease with increasing the length ratio of petiole to lamina.

The study of aerodynamic behaviors of tree leaves has possible applications in many engineering aspects: A leaf-shaped flexible solar panel can endure much more severe wind than normal ones [1]. A power generation "tree" with artificial leaves connected by piezo-electric ceramic petioles can work at very low wind speeds [2]. Leaves may reconfigure themselves into different shapes at different wind speeds to minimize their resistance [3], which may help to conceive the future concept of vehicle and aircraft. The study of aerodynamic forces on single leaves and on crows is useful to the evaluation of trees' anti-wind ability [4].

Vogel [5] was the first researcher to observe the phenomenon of tree leaves' reconfiguration. He found that some kinds of leaves and leaf clusters in high winds could roll up into cones to protect themselves from damage. The following researchers have studied the reconfiguration of many kinds of plant leaves. Speck [6] studied the reconfiguration and frontal area reductions of giant reed leaves in high winds. Miller et al. [7] investigated the wakes of leaves of wild ginger Hexastylis Arifolia and wild violet Viola Papilionacea in water stream, and found that reconfiguring into conic structure was the key factor to the reduction of vortex-induced leaf vibration.

The aerodynamic resistances of plant leaves have also been studied. Albayrak et al. [8] investigated the influences of Reynolds number and leaf width on the hydrodynamic drags of Glyceria Fluitans leaf and stem. Speck [6] found that the drag of giant reed increased linearly with an increase of wind speed. Vogel [5] tested several kinds of broad leaves, found that the relation between leaf drag D and wind speed U was

$$D \sim U^{2+\alpha}, \tag{1}$$

where α was called Vogel coefficient, which indicated the degree of difference of the leaf from rigid body. Vogel found that most of the tested tree leaves had negative α values.

We should point out that, not all flexible bodies can do well in drag reduction. For example, the drag of a waving flag is much higher than that of an equal size rigid flat plate at 0° incidence [9].

In all the above-mentioned investigations, the leaves were so placed that their petioles and laminae were parallel to the stream, the influence of petiole bending and vibrating was negligibly small. It has been shown that the variation ranges of the latitude and

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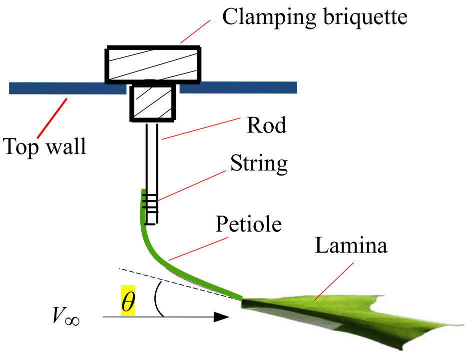

Fig. 1. Sketch of a tulip leaf tested in wind tunnel.

longitude angles of leaves around the truck of a tree are 0°–180° and 0°–360° respectively [10–12], so the incidence angle of wind to leaf varies in the extent of 0°–90°. For all possible incidences, the one the angle $\theta = 90°$ (the petiole and lamina surface vertical to the wind) is most different in aerodynamics from that the angle $\theta = 0°$ (the petiole and the lamina surface parallel to the wind) [13]. In the present study, attention will be paid to the incidence arrangement where $\theta = 90°$.

There are two different directions in the arrangement of $\theta = 90°$, one the leaf is vertically suspended, and the other the leaf is vertically erected. There are two conditions in each direction, one the front surface of the leaf facing wind (“F” for short), and the other the back surface facing wind (“B” for short).

Gravity is the sole reason to cause difference between the suspended and erected leaves. Deformation of the petiole and lamina may be induced by the leaf weight when it is erected, but no deformation is caused when it is freely suspended. Niklas [14] studied 2 species of simple leaves and 3 species of compound leaves, and found that the leaf weight per unit area was about 1 N/m^2. Scholes et al. [15] measured 16 species of desert tree leaves, and that found that the leaf weight per unit area changes within the range of 0.8–2.5 N/m^2. The total weight of a leaf is no higher than the drag force on the leaf induced by a wind of speed 1.5 m/s. The rigidity of the tulip petiole is relatively large, the deformation caused by gravity is small, and the aerodynamic difference between the suspended and erected directions can be neglected. We will solely investigate the suspended leaves in the following contents.

As shown in Fig. 1, the tulip tree leaf has a long and slightly tapered petiole of approximately circular cross-section, and the lamina shape is like a mandarin jacket, the upper part is much wider, and narrowed down rapidly at the waist, then changed the width slightly on the lower part.

The leaves were randomly collected from tulip trees growing on and around the campus of China Jiliang University in Hangzhou in early and middle May. The collected leaves were put in room temperature water to keep fresh. The test time for each leaf was less than 15 min, so that its mechanical behavior was not significantly changed during the test [5]. Total 73 leaves were tested, and the lamina area of the leaves varied in the range of 0.006–0.029 m^2. The lamina area probability density of the tested leaves was close to normal distribution.

The experiment was carried out in a wind tunnel in China Jiliang University. The test section of the tunnel was 2 m long, 0.6 m wide and 0.6 m high. It could provide uniform wind stream at speeds in the range of 0.6–35 m/s with turbulence intensity no higher than 0.4%.

As shown in Fig. 1, a clamping briquette was set on the top wall of the tunnel. A steel rod of length 0.2 m and diameter 7 mm was vertically placed in the tunnel and its upper end was tightly fixed by the clamping briquette. The petiole of the leaf was fastened on the lower end of the rod with a string, the lamina was freely suspended at the center of the cross-section, and its surface was perpendicular to the direction of wind stream. The aerodynamic status of the leaf in wind was recorded by a CCD camera with recording speed 50 frames per second.

Table 1
Probabilities of existence of critical wind speeds.

F-front surface facing wind, B-back surface facing wind					
Critical	1st	2nd	3rd	4th	5th
F	92.7%	91.4%	70%	88.6%	67.1%
B	13.7%	11%	87.7%	49.3%	30.1%

The changes of leaf status with wind speed V were first studied in condition “B”, the back surface of the lamina facing wind. The leaf was kept its vertical suspension position, and no distinct lamina deformation was observed if the wind speed V was less than 2.1 m/s (Fig. 2(a)). When the wind speed was increased to the first critical value V_1 (3.7 m/s), the lamina started abruptly to sway from one side to the other at a low frequency, which was accompanied by a rotary oscillation of the lamina around the petiole axis (Fig. 2(b)). The swing stopped and static lamina deformation was induced with the increase of V to the second critical value V (6.7 m/s), where the lobes on the left and right sides curled upwards like gliding wings (Fig. 2(c)), and the degree of upward bending of the lobes was amplifying with increasing V. The static deformation stopped and the 1st high frequency lamina vibration occurred abruptly as V increased to the 3rd critical value V_3 (8.3 m/s, Fig. 2(d)). The vibration stopped suddenly and the lamina rolled up into conic shape as V increased to the 4th critical value V_4 (11.4 m/s). A steady status of the leaf was formed and maintained in a horizontal position (Fig. 2(e)). The static conic shape was maintained in a relatively large range of wind speed $V_4 < V < V_5$. The stationary state was broken and the 2nd high frequency lamina vibration occurred at the 5th critical wind speed V_5.

In condition “F”, the front surface facing wind, and with the increase of V from 0 to higher values, the leaf went through a similar status changing process.

There were differences between conditions “B” and “F”. Firstly, two kinds of wing shape stationary status existed in condition “F”, one was the lobes curled upwards, and the other was the lobes curled downwards, but only one kind of wing shape existed in condition “B”. Secondly, in the conic shape stationary status, the midrib of the leaf could be on the upper or lower side of the horizontal cone in condition “F”, but it was solely on the lower side in condition “B”.

In the experiment, five critical wind speeds and five leaf statuses were observed. However, not all the criticals and statuses were observed in a specific leaf test. For example, in the test of a certain leaf in condition “B”, as the wind speed was increased step by step with increment $\Delta V = 0.5$ m/s, the petiole was bending downstream steadily, the left and right lobes curling upwards gradually, and finally the leaf reached the stationary status of gliding wings. No leaf swing was observed in the process, and the 1st and 2nd criticals did not exist in this test.

Table 1 shows the existence probabilities of the critical wind speeds obtained from the statistics of test results of the 73 leaves. We can see that for every critical speed, except the 3rd one, the probability of existence in condition “F” is much higher than that in condition “B”.

Table 2 shows the existence probabilities of the statuses. Each critical wind speed corresponds to the appearance of one status, but the existence probability of the critical is not necessarily equal to that of its corresponding status. For instance, in condition “B”, the probability of the 5th critical is 30.1%, the probability of 2nd