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Mechanical Response of Young Canes of Wind-Blown Kiwifruit Vines

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Abstract : Kiwifruit vines with broad leaves are easily torn or shed by high-speed wind. In this study, the threshold wind speed at which a cane is broken was investigated experimentally with varying physical parameters of a kiwifruit vine under two different ABL (atmospheric boundary layer) conditions. In addition, the temporal variation of wind-blown young canes was visualized using a high-speed camera. The average threshold wind speeds for ABL types A and B are about 20.5 m/s and 18.9 m/s, respectively. A wind-blown young cane takes periodic up-and-down motion when it is broken off. The mean fluttering frequency of young canes of the kiwifruit vines was found to be about 4.5 Hz.

Keywords : Kiwifruit cane, Temporal variation, Threshold wind speed, Wind damage, Fluttering frequency.

1. Introduction

Some direct mechanical effects of strong wind on plants include bending of branches, uprooting, and physical leaf damages arising from leaf tearing, stripping, and abrasion. (Cleugh et al., 1998). Plants respond in a variety of ways to these mechanical impacts. However, their main response is to change their growth rate for the whole plant or for some parts of the plant, to modify morphology, and finally, to reduce grain yields. Many responses of plants, from changes in plant morphology to lodging, depend less on the mean wind speed than the intermittent and turbulent features of the oncoming wind (Nobel, 1981; van Gardingen and Grace, 1991).

Strong winds lead to the burial of newly emerged crops, young seedlings being pulled out of the soil, or partial expose of the roots (Komlev, 1960; Woodruff et al., 1972). As the crop grows taller, the wind force can lodge the crop either by breaking its stems or by collapsing the roots.

Plants frequently exposed to strong wind have different anatomical and morphological characteristics such as increased leaf thickness, decreased leaf size, and decreased height (Nobel, 1981; Grace, 1988). This kind of morphological modification is a direct response to the mechanical stresses caused by violent plant motion such as shaking or stroking of branches, which reduces the extension growth (Rees and Grace, 1980; Grace et al., 1982). At high-speed wind, the allocation of assimilates is shifted from the production of leaf materials to the production of stems and roots, leading to the reduction of the leaf area (Grace, 1988). Russell and Grace (1978) mentioned that the tillering rate of grasses was markedly reduced at high-speed wind.

Among horticultural fruit crops, the kiwifruit (Actinidia deliciosa Planch.) is largely affected by wind, especially during the spring season. Because the tillering young canes of kiwifruit vines are very tender, the vegetative canes carrying next season's fruiting buds have been known to be broken at a gentle breeze of 8-12 m/s. The leaves of kiwifruit vines are easily torn or shed by wind due to their broad leaf size and shortage of elasticity. The wind-broken canes and torn leaves would delay the growth of kiwifruit vines and reduce the production yield of kiwifruits. Therefore, it is important to minimize wind damage to kiwifruits.

McAneney et al. (1984) evaluated the performance of windbreak and trellis on harvest of kiwifruits at two orchards. The wind damage of kiwifruits was increased with the increase in distance from windbreaks. The field evaluation was carried out for standard "T-bar" trellised vines during a particular windy season, and shelter spacing was selected to reduce wind speed adequately. McAneney and Judd (1987) explained the shelter strategies for kiwifruits based on wind damage measurements. As mentioned, most previous studies on physical wind damage to the kiwifruit have been focused on the performance of windbreaks.

As far as we have surveyed, there is no previous experimental study on the physical wind damage of kiwifruit canes in the fluid mechanical point of view. In this study, we measured the threshold wind speed at which the physical wind damage occurs for a total of 140 samples of kiwifruit canes. The effect of atmospheric boundary layer (ABL) configuration on the physical damage of kiwifruit canes was investigated using two different ABL configurations. In addition, the temporal variation of wind-blown kiwifruit canes was analyzed by capturing dynamic consecutive images with a high-speed camera.

2. Experimental Methods

2.1 Atmospheric Boundary Layer (ABL)

The surface boundary layer is commonly formed as a consequence of interactions between the atmospheric wind and the underlying ground surface over time scales of one day or less. The present experiments were conducted in a closed-return type subsonic wind tunnel of which the test section is 6.75 $m^L \times$ 0.72 $m^W \times$ 0.6 m^H in size. A toothed barrier (Cook, 1978) spanning the floor of the test section was installed at the leading edge of the test section and a biplanar wooden-type grid was followed across the entire test section to yield a logarithmic velocity profile over a significant portion of the test section. Figure 1 shows photographs of the toothed barrier and the wooden-type grid installed in the wind-tunnel test section. The turbulence stresses and power spectra were also tried to satisfy the prerequisites of the neutrally stable atmospheric boundary layers. In particular, in order to establish strong turbulence intensity for ABL type B, an artificial grass with height 10 mm and length 6 m was glued on the bottom surface of the test section. For comparison, the same experiment was repeated for ABL type A over the original wind tunnel test section surface without the upstream barrier, mixing grid, and artificial grass.

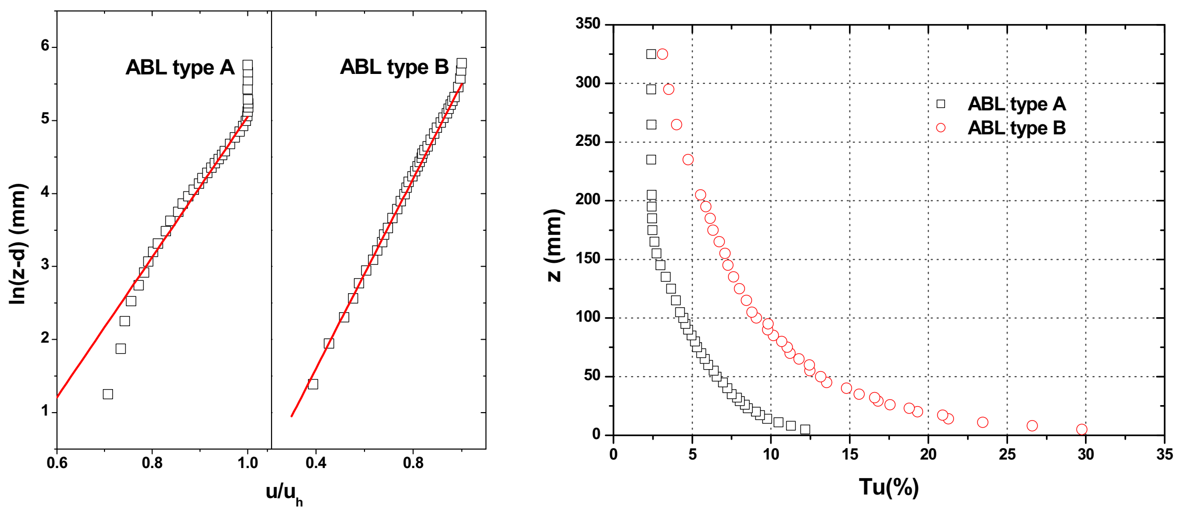
The mean velocity and turbulence intensity profiles of the simulated ABLs were measured

(a) Toothed barrier (b) Wooden-type grid

Fig. 1. Photographs of a toothed barrier and a wooden-type grid installed in the wind-tunnel test section.

using a hot-wire anemometer (TSI IFA-100) at the location of the experimental sample, 4.5 m downstream from the leading edge of the test section. For this, gold-coated X-wire probes (DANTEC 55P51) were used, and the effective cosine-law method was employed to calibrate the X-wire (Perry et al., 1987; Lim et al., 2007). At each measurement point, 16,300 velocity data were acquired at a sampling rate of 2-10 kHz after low-pass filtering at 800 Hz. The streamwise pressure gradient was nearly negligible due to the presence of corner fillets and small adjustable breathers located between the wind tunnel test section and the first diffuser.

Figure 2 shows the streamwise mean velocity and turbulence intensity profiles measured at the location of test sample fixation. Thickness of the ABL (δ) simulated in this study is about 0.26 m (ABL type A) and 0.33 m (ABL type B), respectively. The roughness lengths z_0 were found to be 0.01 mm (ABL type A) and 0.37 mm (ABL type B). They were determined by fitting the measured velocity profiles near the ground surface to the logarithmic law $u = u_* / \kappa \cdot \log((z-d)/z_0)$, where u is the mean streamwise velocity, u_* and d are the friction velocity ($\sqrt{\tau_{wall} / \rho}$) and the zero-plane displacement, respectively. The friction velocity u_* was determined directly by extrapolating Reynolds shear stress ($\overline{u'w'}$) measurements to the wall. Then the measured mean velocity data were fit to the logarithmic law to ensure the correct u_* with varying d appropriately. The mean velocities are nondimensionalized with the wind velocity (u_h) at the height of test sample. A straight line of slope u_* / k was superimposed on the logarithmic velocity profiles with a von Kármán constant of $k = 0.40$, as shown in Fig. 2(a). The turbulence intensity profiles shown in Fig. 2(b) seem to reflect real ABL appropriately the ABL in the real site. The local turbulence intensity ($\sqrt{u'^2} / U_0 \times 100$) on the ground surface for ABL types A and B was about 13 % and 30 %, respectively.



(a) Streamwise mean velocity (b) Turbulence intensity

Fig. 2. Streamwise mean velocity and turbulence intensity profiles of the two ABLs simulated in the wind tunnel.

2.2 Wind Tunnel Test

The samples of kiwifruit canes tested in this study were grown following the standard cultural practices in open orchards, receiving full sunlight on the pergola system. Young canes of 0.25-0.30 m in length, newly sprout from one-year old canes of kiwifruit vines, were collected in late April. Figure

3 shows a typical test sample of a young kiwifruit cane with large-size leaves L and D indicate the length and diameter of the young cane, respectively. Meanwhile, the symbol θ represent the shoot angle between a young cane and a one-year old cane.

The test sample of a young cane was placed horizontally inside the wind tunnel test section to simulate the real growth environment of a kiwifruit vine. To increase the wind load acting on the test sample, the windward side of the test sample was determined to have a shoot angle θ of a young cane less than 90°. The test sample was fixed to the ground surface of the test section using holders which can adjust the height of the test sample easily.

To record the critical wind speed at which the test cane is just broken, the movement of the test

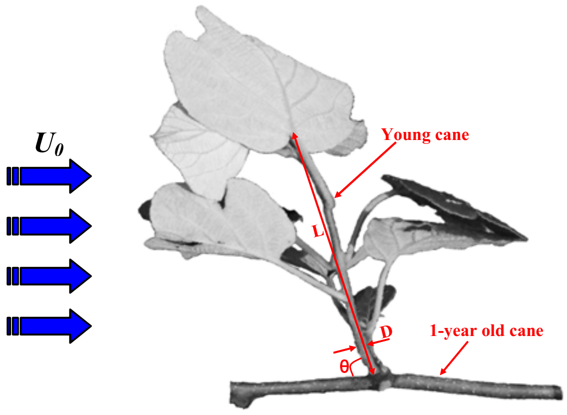


Fig. 3. Main parameters for a typical test sample.

cane was recorded using a digital video camera. In addition, to investigate the temporal variations of the wind-blown kiwifruit canes, the dynamic images were captured consecutively using a high-speed CMOS camera (Photron FASTCAM-APX) with a spatial resolution of 1024 × 1024 pixels at a frame rate of 2000 fps (Nagayama and Tanaka, 2006; Zhang et al., 2007).

3. Results and Discussion

3.1 Threshold Wind Speed

McAneney and Judd (1987) classified the wind damages of kiwifruit vines into three categories. The first is the cosmetic fruit damage, the second is the damage to young cane growth, and the third falls in the category of general response. In this study, we focused on the wind-blown breaks of young canes of kiwifruit vines, which belong to the second category.

Figure 4 shows these representative wind-blown break configurations of kiwifruit canes. In general, most young canes were broken at the joint between a young cane and a one-year old cane

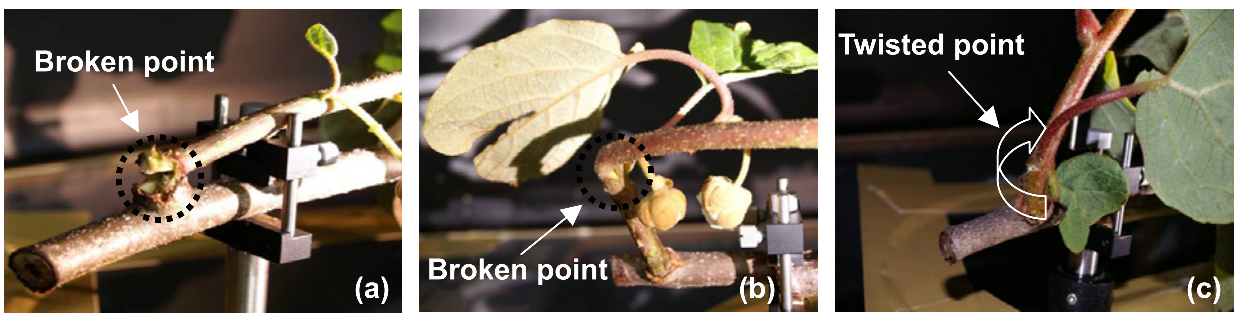


Fig. 4. Three different wind-blown break configurations of kiwifruit canes.

(Fig. 4(a)). The samples of relatively long-stemmed young cane were usually broken at 3-6 cm upper part of the joint (Fig. 4(b)). Some samples were not broken off but were instead twisted (Fig. 4(c)). In this case, the external appearance has no difference from the original sample since the internal xylem vessels were only broken. In this study, all the above three cases were categorized into "broken cane."

To investigate the threshold wind speed, the flow velocity at which a young cane was broken off from the one-year old cane was recorded. Figure 5 represents the threshold wind speed of the wind-broken canes for two ABL configurations. The test number in Fig. 5 represents the accumulated number of young cane samples tested in this study. As shown in Fig. 5, the threshold wind speed is evenly distributed from 11 m/s to 27 m/s. In the range of 11-17 m/s, the effect of ABL configuration on wind-broken speed is not significant. About half of the 140 test samples were broken in the wind speed range of 18-22 m/s. In this range, the threshold wind speed at which young canes were broken has different values with respect to ABL configuration. For the case of ABL type B, the young canes newly sprout were broken at 5-10 % lower wind speed, compared to ABL type A. This is attributed to the fact that young canes with large-size leave sway more severely under a wind of strong turbulent velocity fluctuations. On average, the threshold wind speeds for the case of ABL types A and B are about 20.5 m/s and 18.9 m/s, respectively. These threshold wind speeds are similar to the previous results (16.7-29.6 m/s) of Vogel (1989) tested for other plants with broad leaves. From these results, we can see that the turbulent flow characteristics of the oncoming wind have a noticeable influence on the wind-broken physical damage of the young canes of kiwifruit vines.

Recently, Kang and Lee (2008) mentioned that as the L/D increases (longer thinner shoots), the threshold wind speed at which the young shoot was broken is decreased, regardless of the ABL configuration. The shoot angle seems to have noticeable influence on the threshold wind speed.

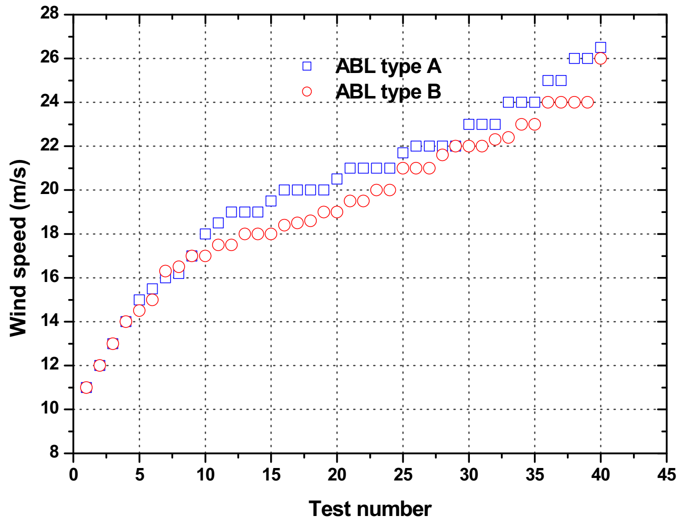


Fig. 5. Threshold wind speed of the wind-broken canes with respect to ABL configuration.

3.2 Temporal Variation of a Wind-Blown Young Cane

The dynamic response of a wind-blown young cane for the oncoming ABL wind was captured using a high-speed camera at a frame rate of 2000 fps. Figures 6 and 7 show the sequential motion images for both cases of unbroken cane and wind-broken cane, respectively.

Vogel (1989) mentioned that broad leaves were reconfigured into a cone shape, and the cone angle became increasingly acute with the increase of wind speed. The wind-blown reconfiguration of unfold leaves into a cone shape seems to be caused by long petioles and bilaterally lobed or heart-shaped leaf configuration.

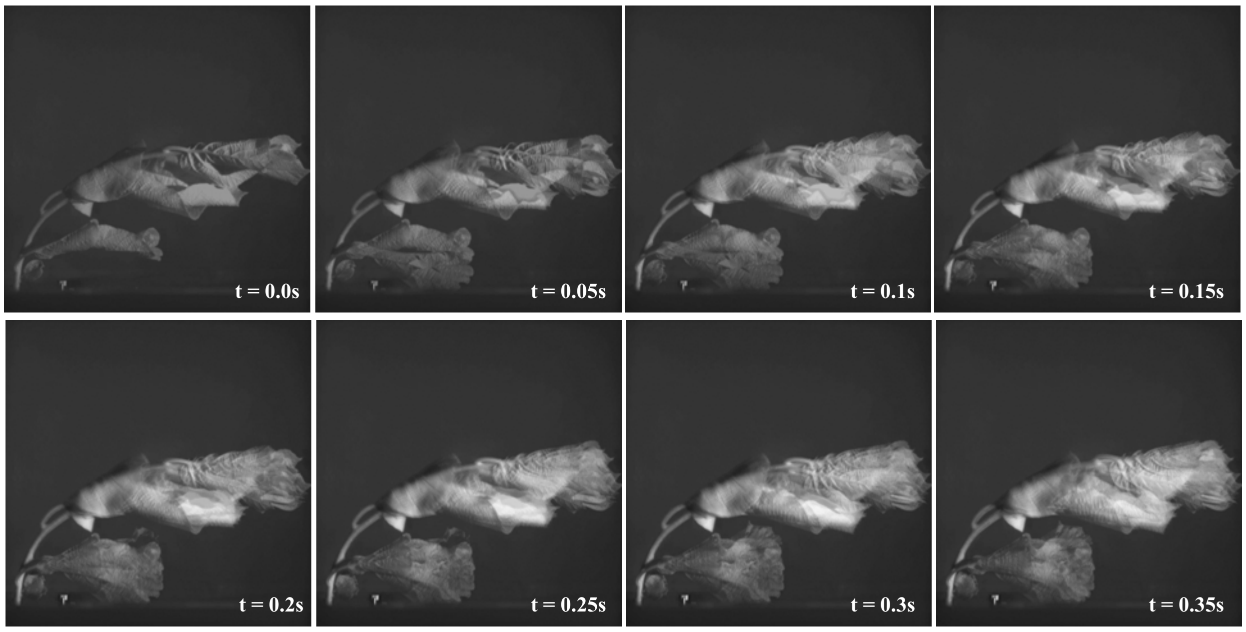


Fig. 6. Temporal variation of a young cane unbroken by the wind of ABL type B (U_0 = 23 m/s).

For the unbroken cane (Fig. 6), large-scale affixed at the upper part of the young cane were wrapped together and reconfigured into a cone shape. With the lapse of time, the cone shape of the wrapped leaves around the young twig was maintained without noticeable fluctuations for a long time. Therefore, the young cane is almost locked and its motion frequency is nearly zero. Due to reconfiguration into a cone shape and mutual sheltering, the windward surface exposed to the wind is largely reduced. Therefore, the drag coefficient of the young cane is smaller even at a high wind speed as compared to that of wind-broken canes at a low speed. From these results, we can see that the wind load on unbroken young canes is small and the corresponding bending moment acting on the joint between the young cane and the one-year old cane is also consequently small.

However, for the case of wind-broken canes, even though each leaf was reconfigured into a cone shape, the nearby leaves did not wrap together around the young twig and flutter irregularly as

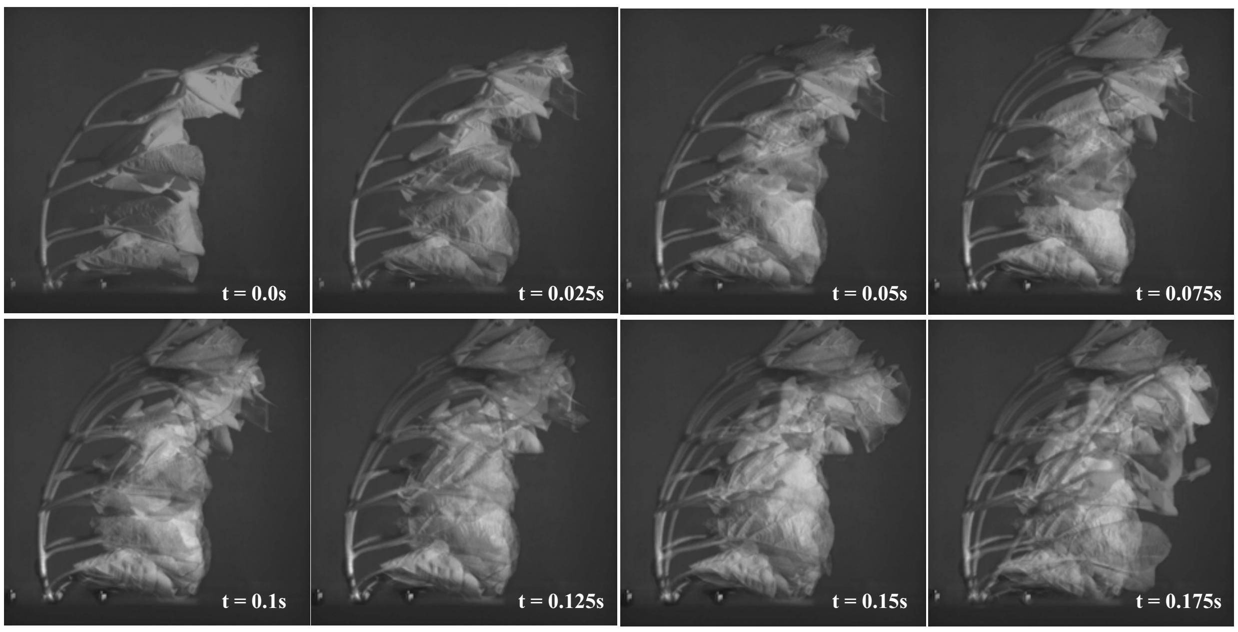


Fig. 7. Temporal variation of a young cane broken by the wind of ABL type B (U_0 = 23 m/s).

shown in Fig. 7. In this case, the length of young canes used to be long, and the shoot angle θ is relatively small. This kind of morphological features seem to prevent the wrapping of affixed leaves. The drag coefficient of the wind-broken cane would be much larger than that of unbroken canes, because the windward area of the young cane with fluttering leaves increases largely. The young cane deflected down by the wind was raised due to the lift force generated by the flutter of large leaves. Then it was deflected down again as the magnitude of drag force was increased more than the lift force. This up-and-down motion of the wind-broken cane repeated periodically up to the instant of its falling apart from the one-year cane.

In order to investigate the morphological aspect of wind-broken young canes, we measured their fluttering frequency as functions of length (L), and diameter (D) of the wind-broken young canes under ABL condition of type B. The fluttering frequency represents the averaged number of fluttering events occurred in a second. As shown in Fig. 8, the critical L/D value of wind-broken young canes is in inverse proportion to the characteristic frequency of fluttering motion. The characteristic frequencies of the wind-broken young kiwifruit canes have a mean value of about 4.5Hz. The fatigue load due to this periodic up-and-down motion seems to make the young cane finally be broken by the wind. From these results, we can see that a young cane can be easily broken as the large-scale leaves affixed at the upper part are fluttered individually without wrapping altogether into a cone shape and it takes a periodic up-and-down fatigue motion.

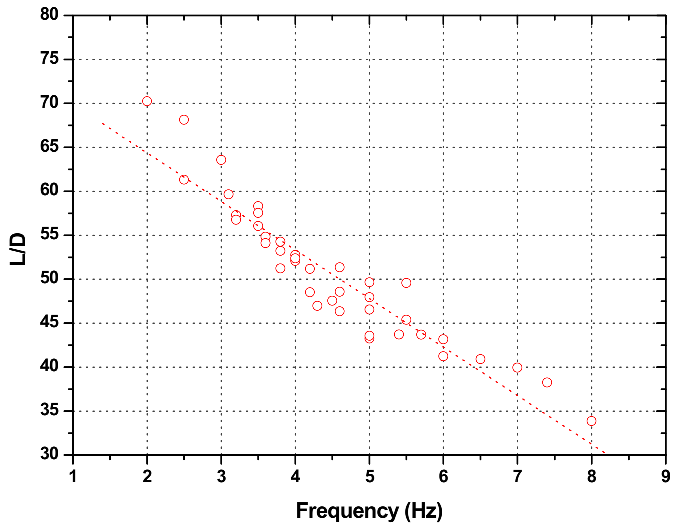


Fig. 8. Fluttering frequency of wind-broken young canes as a function of L/D (ABL type B).

4. Conclusion

Fluid mechanical characteristics of wind-blown young canes of kiwifruit vines were investigated through wind tunnel experiments.

The threshold wind speed at which a young cane was broken off was found to start at 11 m/s. About half of the tested 140 samples were broken in the wind speed range of 18-22 m/s. On average, the threshold wind speeds for ABL types A and B are about 20.5 m/s and 18.9 m/s, respectively. However, in the smaller wind speed range of 11-17 m/s, the ABL configuration does not show significant influence on the threshold wind speed.

For the unbroken-canes, as a section to the on-coming wind, large leaves affixed at the upper part of the young cane were wrapped together and reconfigured into a cone shape. The acute cone shape of the wrapped leaves around the young twig was maintained for a long time without noticeable fluttering motion. On the other hand, for the case of wind-broken canes, each leaf was reconfigured into a cone shape. However, adjacent leaves did not wrap altogether around the twig and flutter independently in irregular pattern. In this case, the drag acting on the young cane would be much larger than that of unbroken-canes because the windward area of the young cane with fluttering large leaves increases. The wind-broken young canes show periodic up-and-down motion. The young cane was finally broken by the continued fatigue motion. The mean value of fluttering frequency of the wind-blown young canes was about 4.5 Hz.

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References

Brundell, D. J., Flower Development of the Chinese Gooseberry (*Actinidia chinensis* Planch). I. Development of the Flowering Shoot, New Zealand Journal of Botany, 13 (1975), 473-483.

Cleugh, H. A., Miller, J. M. and Böhm, M., Direct Mechanical Effects of Wind on Crops, Agroforestry Systems, 41 (1998), 85-112.

Cook, N. J., Wind-tunnel Simulation of the Adiabatic Atmospheric Boundary Layer by Roughness, Barrier and Mixing Device Method, Journal of Wind Engineering and Industrial Aerodynamics, 3 (1978), 157-176.

van Gardingen, P. and Grace, J., Plants and Wind, Advances in Botanical Research, 18 (1991), 189-253.

Grace, J., Pitcairn, C. E. R., Russell, G. and Dixon, M., The Effect of Shaking on the Growth and Water Relations of *Festuca arundinacea* Schreb, Annals of Botany, 69 (1982), 217-225.

Grace, J., Plant Response to Wind, Agriculture, Ecosystems and Environment, 22/23 (1988), 71-88.

Kang, J. H. and Lee, S. J., Experimental study on wind breakage of kiwifruit shoots (*Actinidia deliciosa* Planch.), Journal of Horticultural Science & Biotechnology, 83 (2008) (in press).

Komlev, A. A., Field-protective Afforestation and the Increase in Financial Yield of Agriculture, Selsk Khoz Povolzhya, 6 (1960), 43-45.

Lim, H. C., Castro, P. I. and Hoxey, R.P., Bluff Bodies in Deep Turbulent Boundary Layers: Reynolds-number Issues, Journal of Fluid Mechanics, 571 (2007), 97-118.

McAneney, K. J., Judd, M. J. and Trought, M. C. T., Wind Damage to Kiwifruit (*Actinidia chinensis* Planch.) in Relation to Windbreak Performance, New Zealand Journal of Agricultural Research, 27 (1984), 255-263.

McAneney, K. J. and Judd, M. J., Comparative Shelter Strategies for Kiwifruit: A Mechanistic Interpretation of Wind Damage Measurements, Agricultural and Forest Meteorology, 39 (1987), 225-240.

Nagayama, K. and Tanaka, K., 2D-PIV Analysis of Loach Motion and Flow Field, Journal of Visualization, 9-4 (2006), 393-401.

Nobel, P. S., Wind as an Ecological Factor. In: Lange OL, Nobel PS, Osmond CB, Ziegler H, eds. Physiological Plant Ecology I: Response to the Physical Eenvironment, (1981), 475-500, Springer-Verlag, Berlin.

Perry, A. E., Lim, K. L. and Henbest, S. M., An Experimental Study of the Turbulence Structure in Smooth and Rough Wall Turbulent Boundary Layers, Journal of Fluid Mechanics, 177 (1987), 437-466.

Rees, D. J. and Grace, J., The Effect of Wind on the Extension Growth of *Pinus contorta* Douglas, Forestry, 53 (1980), 145-153.

Russell, G. and Grace, J., The Effect of Wind Speed on the Growth of Grasses, Journal of Applied Ecology, 16 (1978), 507-514.

Snowball, A. M., Flower Development in *Actinidia deliciosa* (A. Chev.) C.F. Liang et A.R. Ferguson, (kiwifruit), (1985),149, MSc (Botany) thesis, University of Auckland (New Zealand).

Vogel, S., Drag and Reconfiguration of Broad Leaves in High Wind, Journal of Experimental Botany, 40 (1989), 941-948.

Woodruff, N. P., Lyles, L., Siddoway, F. H. and Fryrear, D.W., How to Control Wind Erosion, Agriculture Information Bulletin, 354 (1972), 22.

Zhang, W., Kang, J. H. and Lee, S. J., Visualization of Saltating Sand Particle Movement near a Flat Ground Surface, Journal of Visualization, 10-1 (2007), 39-46.

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