

PAPER

Estimation of water stress of plant by vibration measurement of leaf using acoustic radiation force

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Abstract: In order to estimate the water stress of a plant, the natural frequency of the leaf-stalk system was investigated. As a means of vibrating the leaf, acoustic radiation force was utilized, and the successive measurement of the natural frequency of “komatsuna”, which was cultivated in a pot of soil, was performed for a week until wilting after stopping irrigation. As a result, it was found that the natural frequency is decreased drastically by the wilting of the leaf before the drooping occurs. In addition, daily variation was also observed in the early days, but it was gradually suppressed as the day went on. These behaviors were discussed referring to a simple cantilever beam model. In conclusion, it was ascertained that the acoustic radiation force is efficient for vibrating a leaf-stalk system. Furthermore, it was confirmed that measuring the natural frequency of the leaf-stalk system is effective for the early detection of water stress of a plant.

Keywords: Water stress of plant, Vibration measurement of leaf, Acoustic radiation force

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1. INTRODUCTION

The saving of agricultural water is one of the most important subjects for solving the forthcoming “water problem”, because water use in agriculture now makes up 70% of the total water use in the world. Therefore, various efforts have been made so far, for example, water reuse or recycling technologies in plant factories have markedly progressed, and the water-use efficiency of a closed-type plant factory with artificial light has reached more than 98% [1]. On the other hand, unique intelligent green-house horticulture [2,3] and phytotechnology [4–7], which includes the reduction technique of water, have also been developed. These techniques are based on the “speaking plant approach (SPA)”, which is the idea of obtaining various kinds of information about the plant noninvasively by “listening” to the plant as if it were really speaking.

In particular, noninvasive detection of the “water stress of a plant” or the “crop needs for water” has been studied by various approaches, such as optical spectroscopy

of the blue shift of the red edge [8,9] or near-infrared (NIR) spectroscopy [10]. Another approach is image processing such as the observation of the closing of the stomata [11], or the total cross section of leaves from a top or side view [12]. Although the leaf’s shape (*e.g.*, wilting) is the most sensitive sign of water stress of the plant, it is too difficult to analyze using the current image processing techniques.

In order to develop a more sensitive detection technique for water stress of the plant, we have focused on the stiffness of the leaf, which is related to wilting, and confirmed that the natural frequency of a leaf decreases with the reduction of water content in the leaf [13]. In addition, Young’s modulus was estimated and compared with the reported value [14].

On the other hand, we have also attempted the visualization of the water distribution in soil by measuring the sound velocity using a scanning laser Doppler vibrometer (SLDV) [15–20]. By using these techniques, we are aiming to perform the most suitable irrigation control to save water in soil culture by adopting “negative-pressure-difference irrigation”, which is reported to be

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effective for cultivating plants as well as saving water [21]. Acoustic techniques are also applied to the measurement of environmental conditions, such as temperature, humidity, and wind velocity [22–24].

Although the vibration measurement of the leaf is expected to be a new technique for detecting the water stress of plants, the automation of the measurement system is essential to realize successive observation. Thus, we attempted to utilize a loudspeaker instead of the manual air gun to vibrate the leaf automatically. Nevertheless, this method was not efficient for the vibration of leaf.

In such a situation, we came up with the idea of using acoustic radiation force from a high-power ultrasonic speaker (i.e., parametric speaker) to vibrate a leaf.

Thus, in this study, we investigated whether the ultrasonic speaker would be suitable for vibrating a leaf. We also performed the long-time measurement of natural frequency of a leaf-stalk system cultivated in soil in order to observe water stress of the plant.

2. VIBRATION MEASUREMENT WITH ACOUSTIC RADIATION FORCE

2.1. Acoustic Radiation Force

As is known well, strong ultrasound generates the acoustic radiation pressure P [Pa]. With the acoustic pressure of the ultrasound p [Pa], P is given as

$$P = \alpha \frac{p^2}{\rho_0 c_0^2}, \quad (1)$$

where ρ_0 [kg/m³] and c_0 [m/s] are the density and sound velocity of air, respectively. The factor α is between 1 (total absorption) and 2 (total reflection) [25].

In order to confirm whether the vibration force received by the leaf from the ultrasonic speaker is indeed the acoustic radiation force, we compared the experimental value with the theoretical one obtained using Eq. (1).

First, for confirmation, we estimated the transmittance T of the ultrasound of frequency $f = 40$ kHz against a leaf of thickness $d = 0.3$ mm in air as a premise of Eq. (1). Let the acoustic characteristic impedances of air and the leaf be Z_0 [Pa·s/m] and Z , respectively. Then, the transmittance T of the sound wave irradiated perpendicularly to the leaf is given by

$$T = \frac{1}{1 + 0.25(Z/Z_0 - Z_0/Z)^2 \sin^2(2\pi d/\lambda)}, \quad (2)$$

where λ [m] is the wavelength of sound in the leaf. Assuming that the sound velocity in the leaf is $c = 1,500$ m/s as with water, λ is estimated as

$$\lambda = c/f = 0.0375 \text{ m} = 37.5 \text{ mm}. \quad (3)$$

Because this value is much larger than the leaf thickness d , the sound wave seems to pass through the

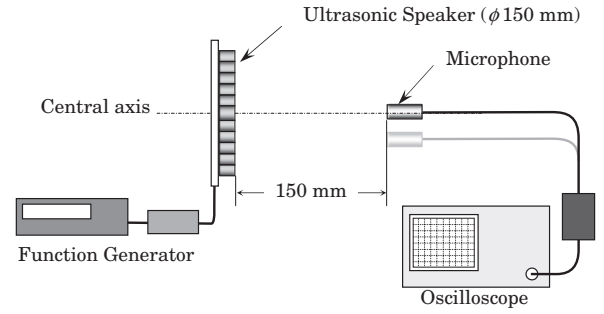


Fig. 1 Experimental setup for measuring acoustic pressure of ultrasonic speaker.

leaf. However, the density ρ of the leaf is the same as that of water (i.e., $\rho = 1.0 \times 10^3$ kg/m³), and the acoustic characteristic impedance Z in the leaf is estimated as

$$Z = \rho c = 1.5 \times 10^6 \text{ Pa·s/m}. \quad (4)$$

Meanwhile, the acoustic characteristic impedance of air at 25°C is $Z_0 = 410$ Pa·s/m. Therefore, $Z/Z_0 = 3.66 \times 10^3 \gg 1$. Thus, using $\sin(2\pi d/\lambda) \simeq 2\pi d/\lambda$ for $d/\lambda \ll 1$, the transmittance T is estimated as

$$T \simeq \frac{1}{1 + 0.25(Z/Z_0)^2 (2\pi d/\lambda)^2} = 1.2 \times 10^{-4} (\ll 1). \quad (5)$$

That is to say, the leaf behaves as a reflector. Thus we may use Eq. (1) to calculate the acoustic radiation force.

Then, we measured the acoustic pressure p in Eq. (1) at a point 150 mm from the speaker face. The experimental setup is as shown in Fig. 1. As the ultrasonic speaker, we used the parametric speaker AS101AW3PF1 (Nippon Ceramic Co., Ltd.). The ultrasonic speaker was driven by a 1 V_{rms} 40 kHz continuous sinusoidal signal from a function generator (Tektronix Inc., AFG3022). The acoustic pressure of the sound was measured with a 1/4-inch electric microphone (ACO Co., Ltd., TYPE4156N).

The measurement was performed every 1 cm to examine the spatial distribution. The result is shown in Fig. 2. The acoustic pressure level was about 145 dB re. 20 μPa (= 345 Pa) within 5 cm area from the center. Incidentally, the sensitivity of this microphone is −56.5 dB re. 1 V/Pa (1.50 mV/Pa), and the average output of rms voltage of the microphone within the range of radius of 5 cm was 0.518 V.

The sound velocity is $c_0 = 346$ m/s and the acoustic characteristic impedance is $Z_0 = \rho_0 c_0 = 410$ Pa·s/m at 25°C. Consequently, the acoustic radiation pressure is theoretically estimated from Eq. (1) as

$$P = 1.67 \text{ Pa}. \quad (6)$$

Here, we assumed $\alpha = 2$ (total reflection), because the round-trip length, or the penetration length, is thought to be very small, so that absorption can be negligible.

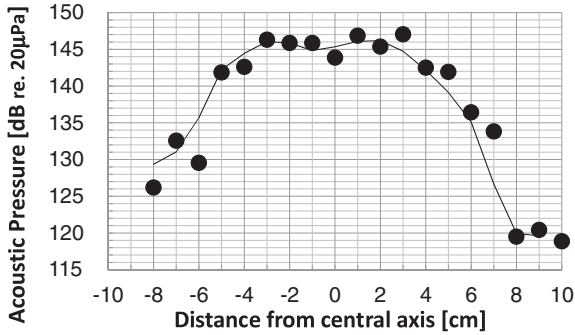


Fig. 2 Distribution of acoustic pressure of ultrasonic speaker.

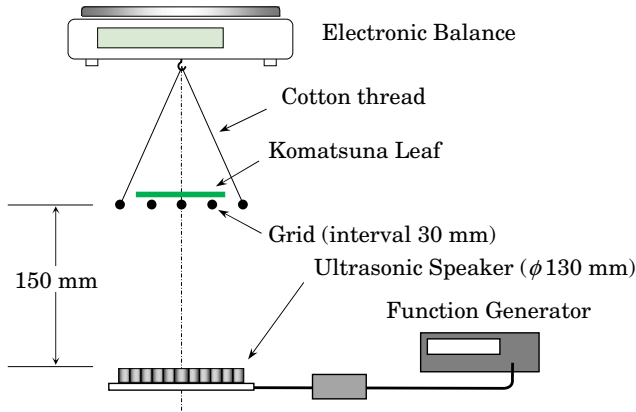


Fig. 3 Experimental setup for measuring the acoustic radiation force.

On the other hand, the force received by a leaf was measured in the setup shown in Fig. 3. A grid with intervals of 30 mm was hung under an electronic balance (A&D Co., Ltd., MC-30K) by four pieces of cotton thread. Then the electric balance was calibrated to indicate 0.00 mg. Next, we irradiated the grid with ultrasound from 150 mm below, using an ultrasonic speaker driven by a 40 kHz, 1 V_{rms} continuous sinusoidal signal from a function generator (Tektronix Inc., AFG3022), and confirmed that the grid does not affect the measurement value. Last, after turning the irradiation off, a piece of leaf was put on the grid, and the same ultrasound was irradiated to the leaf again.

In order to remove the influence of weight loss by transpiration, we measured the weight under irradiation as well as under nonirradiation conditions every time using the electric balance and took the difference.

As a result, when the leaf area was 40 cm², the force received by the leaf was 4.1 mN (0.42 gw). Because the ultrasound was almost uniform within the range of radius of 5 cm as shown in Fig. 2, the leaf was pressed uniformly; then the pressure was calculated as

$$P = 1.0 \text{ Pa (11 mg/cm}^2\text{)}. \quad (7)$$

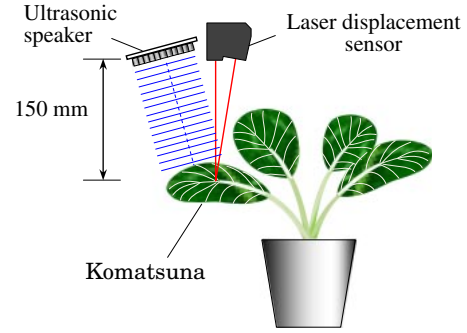


Fig. 4 Experimental setup for measuring the natural frequency of leaf-stalk system using ultrasonic speaker.

This is close to the theoretical value shown in Eq. (6). Therefore, the force received by the leaf is thought to be an acoustic radiation force. Incidentally, if the sound reflection by the leaf is diffuse reflection, the factor α in Eq. (1) is calculated as 1.5. In this case, the theoretical value shown in Eq. (6) becomes $P = 1.25 \text{ Pa}$, and the difference is further reduced.

2.2. Vibration Measurement of Leaf Using an Ultrasonic Speaker

In order to measure the vibration of the plant, we employed a laser displacement sensor (Keyence Corp., LK-G150) which was arranged so as to focus on the central part of a leaf of “komatsuna” (*Brassica rapa* var. *perviridis*), as shown in Fig. 4. On the other hand, an ultrasonic speaker (AS101AW3PF1) was arranged above the plant to irradiate a shot of a 40 kHz burst wave to the leaf for 20 ms. Thus the damping vibration of the leaf-stalk system was observed.

Figure 5(a) shows a typical result of the damping curve observed with the laser displacement sensor, and Fig. 5(b) shows its power spectrum.

From the above results, it is possible to assume that this vibration is a simple damping vibration. In this case, the displacement $x(t)$ is described by the following well-known second-order linear differential equation:

$$\frac{d^2x}{dt^2} + 2\gamma \frac{dx}{dt} + \omega_0^2 x = 0, \quad (8)$$

where γ is the damping coefficient and ω_0 is the natural frequency. When $\gamma > \omega_0$, the solution of Eq. (8) becomes a damping vibration, which is given by

$$x(t) = Ae^{-\gamma t} \cos(\omega_d t + \phi), \quad (9)$$

where A and ϕ are arbitrary constants decided by the initial condition, and ω_d is the frequency of the damping vibration given by

$$\omega_d = \sqrt{\omega_0^2 - \gamma^2}. \quad (10)$$

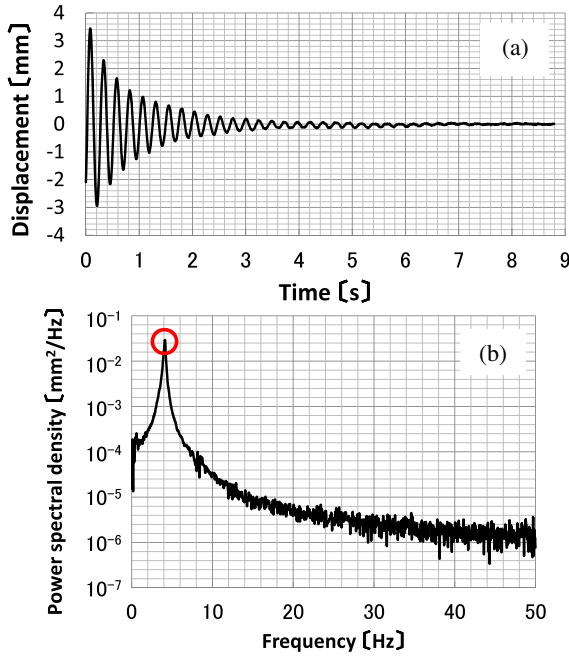


Fig. 5 Typical result of vibration measurement of a leaf-stalk system using a laser displacement sensor. (a) Vibration displacement, (b) power spectral density.

If ϕ is 0 and negative t is replaced by $-t$, the Fourier transformation of $x(t)$ given by Eq. (9) is calculated as

$$\begin{aligned} X(\omega) &= \int_{-\infty}^{\infty} x(t)e^{-i\omega t} dt \\ &= A \left\{ \frac{\gamma}{\gamma^2 + (\omega - \omega_d)^2} + \frac{\gamma}{\gamma^2 + (\omega + \omega_d)^2} \right\} \\ &\approx A \frac{\gamma}{\gamma^2 + (\omega - \omega_d)^2} \quad (\text{for } \omega \sim \omega_d). \end{aligned} \quad (11)$$

Thus the Lorentzian function that takes a maximum at $\omega = \omega_d$ is derived as the Fourier transformation of the damping wave. As γ and ω_d were estimated from the damping curve and its power spectrum respectively, the natural frequency ω_0 was given by

$$\omega_0 = \sqrt{\omega_d^2 + \gamma^2}. \quad (12)$$

In the case of Fig. 5, the frequency f_d corresponding to ω_d was read as 4 Hz from a peak frequency (circle), while γ was estimated to be 0.6 s^{-1} from Fig. 5(a). Therefore, the difference between the natural frequency f_0 and the peak frequency f_d was estimated from Eq. (12) as

$$f_0 - f_d \approx \frac{\gamma^2}{4\pi f_d} = 0.007 \text{ Hz}. \quad (13)$$

Thus, in this study, the natural frequency f_0 can be regarded as the peak frequency f_d of the power spectrum of the damping curve.

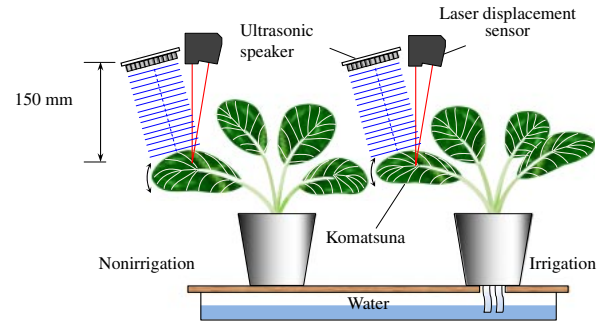


Fig. 6 Experimental setup. Nonirrigated and irrigated plants were prepared in the control experiment.

3. LONG-TIME MEASUREMENT OF NATURAL FREQUENCY

Using our automatic vibrating system, we investigated how the natural frequency of a leaf-stalk system behaves with time after stopping irrigation. The experimental setup is shown in Fig. 6. In the control experiment, we prepared two kinds of komatsuna: nonirrigated and normally irrigated. These were both cultivated in the culture soil, which had been refined with a 2 mm sieve. The environmental conditions were the same for both cases as follows.

- (1) Light was provided from 6:00 am to 6:00 pm with fluorescent tubes (illuminance at the leaf was 3,000 lx).
- (2) Temperature and humidity were kept $22.5 \pm 2.5^\circ\text{C}$ and $50 \pm 5\%$ RH, respectively, using an air conditioner.

The measurement result of natural frequency is shown in Fig. 7. The vertical position of each leaf, which was directly obtained using a laser displacement sensor, is also plotted.

In this experiment, the natural frequency of the nonirrigated plant gradually decreased as the day went on. Meanwhile, that of the irrigated plant did not change greatly. In addition, the daily variations in frequency and position were also observed. These will be discussed later.

It is of interest that the frequency of the nonirrigation plant rapidly decreased in the afternoon of Sept. 21 (arrow (a)). Fortunately, this crisis was avoided because the light was turned off at 6:00 pm. However, the next day, the leaf wilted and the frequency decreased again after turning on the light at 6:00 am (arrow (b)). It is notable that the change in the vertical position was small at the points of (a) and (b). That is, the natural frequency is expected to be more sensitive than the position with regard to the detection of wilting.

Moreover, in order to investigate the influence of the growth of the plant, the length of the leaf-stalks was also simultaneously measured using a CCD camera. The result

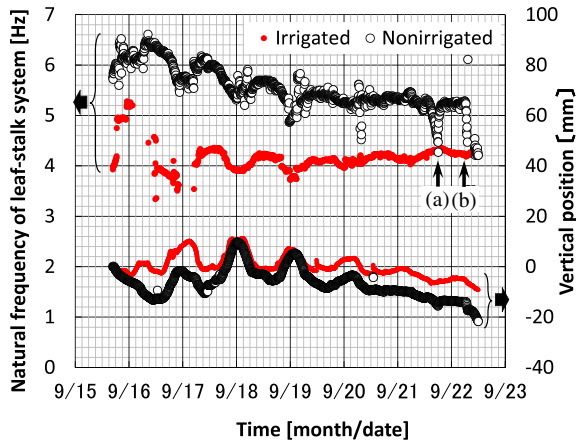


Fig. 7 Measurement results of temporal changes in natural frequency and positions of the leaves. Open and closed circles refer to nonirrigated and irrigated cases, respectively.

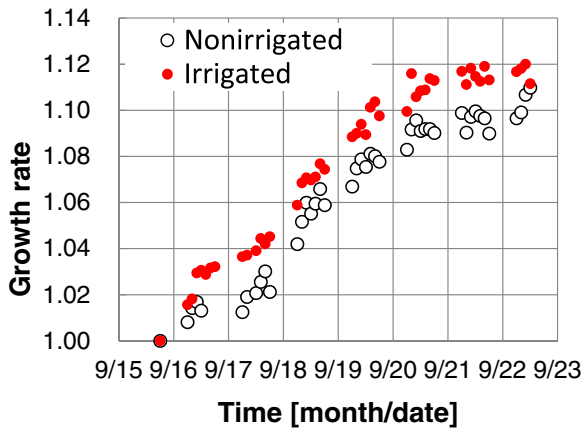


Fig. 8 Temporal change in growth rate of leafstalk.

is shown in Fig. 8, where the growth rate on vertical axis means the ratio of the leafstalk length to the initial length on Sept. 15. The initial length of the nonirrigated plants was 45.7 mm, and that of the irrigated plant was 50.6 mm.

These results show that both plants similarly grew about 10% in one week, although the nonirrigated plant grew slightly slower than the irrigated plant.

4. DISCUSSION

4.1. Behavior of Natural Frequency with Water Content of Leaf

In order to explain the behavior of the natural frequency of the leaf-stalk system, we assumed the cantilever beam model with a mass on the tip shown in Fig. 9. In this model, the natural frequency is calculated as one-dimensional vibration with spring constant k [N/m], which is given by

$$k = \frac{3EI}{L^3}, \quad (14)$$

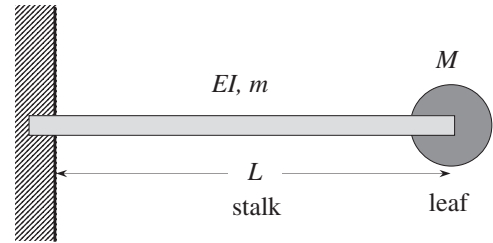


Fig. 9 Cantilever beam with weight on tip.

where E [Pa] is Young's modulus of the stalk, I [m⁴] is the secondary moment of the cross section around the neutral axis (i.e., EI [Nm²] is the bending rigidity), and L [m] is the length of the stalk [26]. Consequently, the natural frequency is given by

$$\omega = \sqrt{\frac{k}{M}} = \sqrt{\frac{3EI}{L^3M}}, \quad (15)$$

where M [kg] is the mass of the leaf. (If the mass m [kg] of the stalk is to be taken into account, mass M in Eq. (15) should be modified to $M + 0.23m$.)

Therefore, the behavior of the natural frequency including daily variation shown in Fig. 7 is thought to be determined by the balance of L^3M and EI of the leaf-stalk system. The reason why the daily variation of the frequency became lower at night is supposed to be that M of the leaf increased more than EI by storing water in leaves at night. Moreover, the reason behind the sudden decrease in natural frequency in the nonirrigated plant is thought to be the decrease in E owing to the water stress.

4.2. Daily Variation

It is known that the plant does not receive water stress at night, because transpiration is halted. In other words, the water stress caused by transpiration in the daytime is absent at night. The daily variation of the natural frequency of the leaf is thought to occur as a result of this healthy transpiration.

However, when the water content of soil is insufficient, the frequency difference between daytime and night time become smaller, because the plant does not recover from water stress sufficiently in spite of the period of rest at night. Therefore, the difference in the natural frequency is expected to be an index of the health of the plant in terms of water stress.

Incidentally, the daily variation becomes smaller as the day progresses, even if the plant is healthy. Namely, the leaf's age is also thought to affect the daily variation.

5. CONCLUSION

Acoustic radiation force was confirmed to be efficient to vibrate the leaf, and long-time measurement of natural

frequency of leaf-stalk system was accomplished. Consequently, it was revealed that the natural frequency is one of the most sensitive indices for the early detection of water stress of the plant. This technique will be effective for developing the most suitable irrigation control system or water-saving systems for advanced precision agriculture.

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