Measuring fluttering frequency of a leaf under water stress

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Abstract

Water is one of the most important substances for plants. Limited water supplies directly influence crop yield, which eventually leads to food scarcity to humans. In this present study, we quantify the dynamics of a fluttering leaf as a function of the days without water. The deformation and vibration of a plant leaf can be induced by dropping an object or tapping with a finger. Using multiple cameras, the 3D motion of a leaf can be measured. We found that the frequency of a leaf increases with water stress. In terms of natural frequency, it tends to increase when moisture stress is applied to leaves. These results suggest that the stiffness of leaves according to moisture stress is related, so it can be used as an indicator of the overall performance of plants. This would lead to a nondestructive way to measure water stress through leaf stiffness.

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ABSTRACT

Water is one of the most important substances for plants. Limited water supplies directly influence crop yield, which eventually leads to food scarcity to humans. In this present study, we quantify the dynamics of a fluttering leaf as a function of the days without water. The deformation and vibration of a plant leaf can be induced by dropping an object or tapping with a finger. Using multiple cameras, the 3D motion of a leaf can be measured. We found that the frequency of a leaf increases with water stress. In terms of natural frequency, it tends to increase when moisture stress is applied to leaves. These results suggest that the stiffness of leaves according to moisture stress is related, so it can be used as an indicator of the overall performance of plants. This would lead to a nondestructive way to measure water stress through leaf stiffness.

Keywords: Fluttering leaf, water stress, high-speed imaging

1. INTRODUCTION

Water plays an important role throughout the life cycle of plant growth and has a significant effect on the crop yield.[1] Therefore, drought is a deadly disaster to plants and it can lead to a severe food crisis. A water potential/stress is widely used to measure the water condition in plants, which is affected by various environmental factors. To measure the water potential/stress in the plant leaf, a Scholander type pressure chamber is used.[2] In this method, leaf samples from the plant should be excised and placed in the chamber. Then, as the chamber is pressurized with a compressed gas canister, the critical pressure can be measured for the water to sip out of the open ends of the xylem conduit. Other invasive methods are commonly used.

There is another way to check the water stress by taking the temperature of the canopy. In general, plants that are under water stress are known to have lower transpiration and higher leaf temperatures than nonstressed crops. This approach is noninvasive but has limitations in relying on stomata closure as an initial indicator of water shortages. It is also too sensitive to small stress.

There were some investigations to understand the biomechanics of a fluttering leaf using physics analysis. Some studies focused on how leaves are deformed by external forces caused by wind or rain. Gart et al.[3] investigated the dynamical response of leaves upon raindrop impact, which shows the effect of surface wettability on the vibration. Bhosale et al.[4] demonstrated and characterized the bending, fluttering, and flapping motions of a leaf using a 3D tracking system with two high-speed cameras. De Lange et al. showed the fluttering frequency upon blowing air, which showed the lowered frequency in water-stressed plant leaves. In "plant biomechanics" book by Karl Niklas, the frequency of a fluttering leaf depends on leaf shape and material properties. Especially, the material properties change depending on turgor pressure and cell composition/arrangement.

In this study, we characterize the frequency of a leaf upon an external perturbation as a function of its droughtness. Experiments are designed to estimate the rigidity of the leaf by analyzing the frequency and the leaf shape of two different groups: the dry pot with water stress and the healthy pot without water stress. These experimental results suggest a remote sensing of water stress and have a potential to be applied in various plants for smart agriculture with an automatic tracking system.

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2. MATERIALS AND METHODS

2.1 Preparation of leaf samples

We planted soybean seeds in a plant nursery pot. After two weeks, we replanted these seedlings in individual pots. Then, after another three weeks, four pots of soybean plants were divided into two groups: one group was continuously watered and the other group was not watered. Soybean cultivation temperature was kept in the range of 21-23°C. Figure 1 (a) shows the seedlings of a soybean plant, and figure 1 (b) shows one of the individual pots.

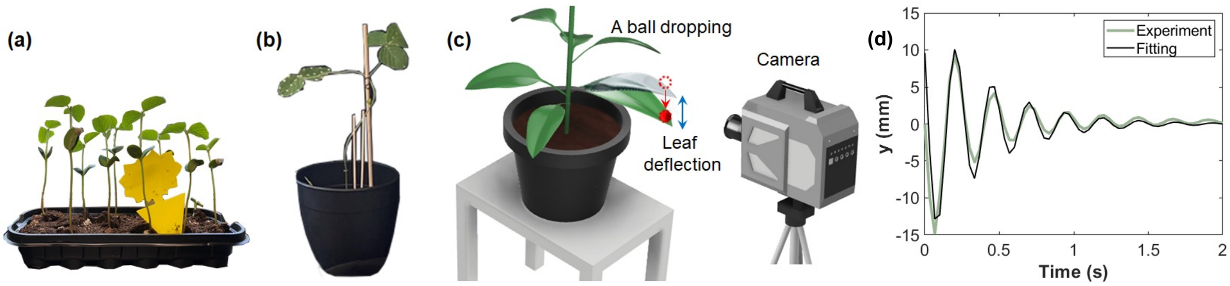

Figure 1. (a) two-week-old seedlings of soybean. (b) individual soybean plant pots after replanting. (c) schematic drawing for the fluttering leaf test by dropping a ball. (d) Deflection of the leaf tip vs time.

2.2 Vibration test

The frequency of leaves was measured in quiescent environments over 25 days after the initial 5 weeks of nurturing period. Figure 1(c) shows an experimental setup for the vibration recording. To generate oscillations in the leaves, we dropped an 81 ± 2 mg delrin ball to the tip of leaves. These dropping processes were recorded using a DSLR camera (D7000, NIKON) at 30 fps. Displacement of the tip was analyzed by Tracker software to get the natural frequency. The resulting displacement shows a damped oscillation as shown in Figure **??**. The natural frequency is a measure of the dynamic property of a leaf since it is directly related to flexural rigidity (EI) and length of the leaf as

$$f \propto \sqrt{\frac{EI}{ML^3}}\,. \tag{1}$$

where E is the elastic modulus and M is the leaf mass, and L is the leaf length. I is the second moment of area defined as $I = bt^3/12$ (t is the leaf thickness and b is the leaf width).

3. RESULTS

3.1 Vibration test

Figure 1(d) shows the tip displacement of a healthy leaf versus time from one of experiments. We clearly observe that the leaves exhibit damped oscillations when a force is applied near the tip. The displacement was fitted with a function of damped oscillation as $\delta(t) = \exp(-\zeta t)\sin(2\pi f t + \phi)$, which is a solution of $\delta''(t) - \zeta\delta'(t) + (2\pi f)^2\delta(t) = 0$. Here, ζ is the damping ratio, and f is the frequency of motion.

3.2 Frequency change

The dynamics of the response of the leaf are monitored over 25 days after the initial 5 weeks of germination/nurturing period. Figure 2 (a) shows the image sequence of leaves over time. Leaves from a healthy pot maintain their shape throughout the experimental period. However, leaves from a water-stressed pot slowly change their shape from the leaf perimeter after 13 days and completely fold approximately after 3 weeks.

Using Fast Fourier Transform (FFT), we can calculate the dominant mode of the natural frequencies of leaves. Figure 2 (b-d) indicates the oscillations on the 1st, 13th, and 25th days of the test. On the first day, the frequency is similar since plants still are absorbing water from soil. On the 13th day, the water-stressed pot shows higher

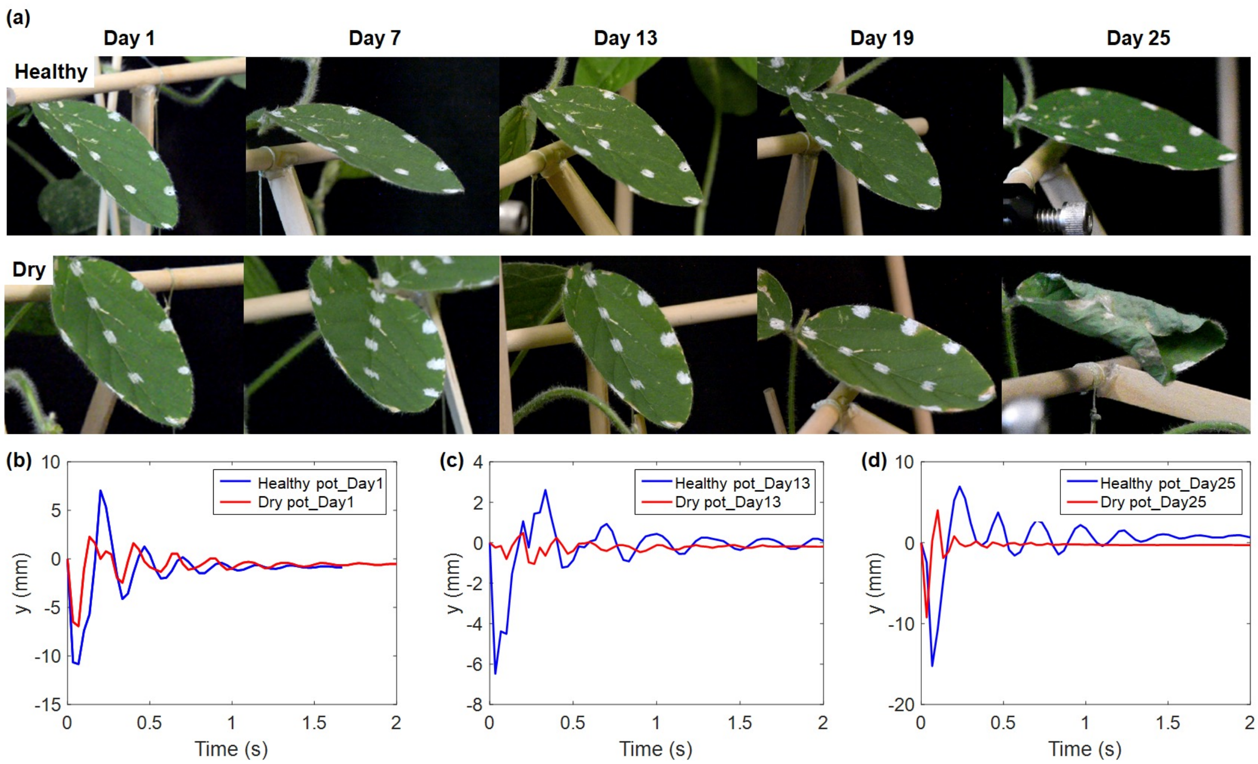

Figure 2. (a) images of leaves over the number of drought days. The upper panel shows a healthy leaf, and the lower panel shows a water-stressed leaf. For the water-stressed leaf, the perimeter of the leaf noticeably began to curve up after 13 days, and on the 25th of droughtness, the leaf dried completely and displayed a folded form. (b), (c), and (d) show tip deflections versus the 1st, 13th, and 25th days of droughtness, respectively.

vibration frequencies. Similarly, on the 25th day, leaves in the water-stressed pot show higher frequencies and sharp peaks.

Additionally, an Analysis of Variance (ANOVA) test (Figure 3 (d)-(f)) was used to evaluate a statistically significant difference between the two groups. The results confirm that water-stressed plants and watered plants have significant changes in frequency. Even though the two groups have a similar range of frequencies until the 10th day (p-value =0.1312), after 13 days, the two groups' frequencies diverged. At this time, the p-value decreases down to 3×10^{-4} which means that these two groups are statistically different. Even when comparing all data, the p-value stays at the level of 10^{-4} or less. Therefore, it concludes that water stress significantly lowers the bending rigidity, thereby decreasing the leaf bending frequency.

3.3 Damping ratio

Damping ratio is another factor determining the dynamics of a fluttering leaf. The damping ratio was calculated based on the amplitude difference between the first and third peaks that were clearly visible. We found that there was no significant difference in the damping ratio over the drought period. The ANOVA test resulted in a p-value of 0.9954, indicating that there was no statistical difference between water-stressed and healthy pots. This result indicates that the water stress affects the frequency itself, not the damping ratio.

4. DISCUSSION

We performed a series of experiments to quantify the fluttering frequency as a function of the number of drought days. Our results show that the vibration frequency is significantly different under water stress, which indicates the bending rigidity change due to the droughtness. This indicates that leaf rigidity is a good candidate to easily

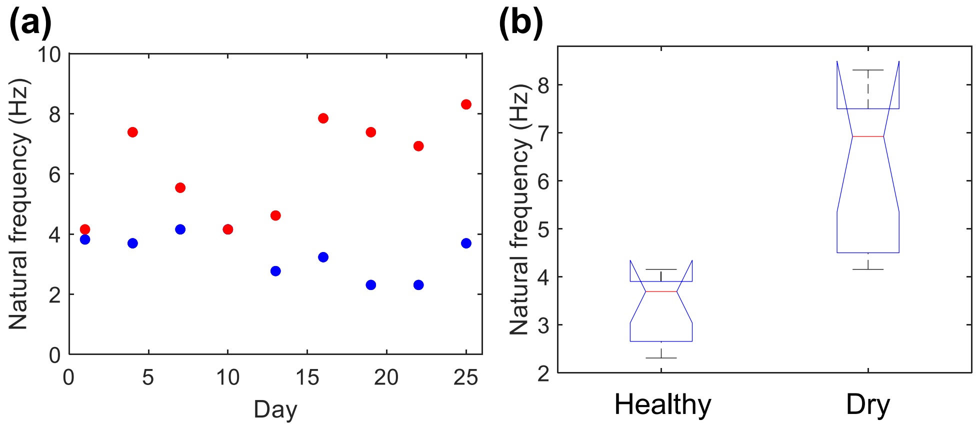

Figure 3. (a) natural frequency versus the number of drought days . (b) Overall statistics of healthy vs. dry leaves. The corresponding p-value is 1.8×10^{-4}.

determine the internal water content to some extent. Also, it sheds light on the possibility of a nondestructive way to diagnose the water stress of plants.

Our experiments can be improved in several points. First, it is necessary to quantify the complex fluttering motion as combined bending, twisting, and flapping motions. Since the leaves are not perfectly symmetric and the impact point can be off-center, there is always a slight chance of inducing other twisting and flapping motions. Therefore, future research is needed to investigate the correlation of twisting and/or flapping motions with water stress.

Second, the tendency of a higher vibration frequency with water stress is arguable.[6] showed the similar trend of increasing frequency like ours. However, other research showed that with water stress, a fluttering frequency decreases.[7,8] Even in our previous experiments with peace lily leaves, the natural frequency decreased remarkably over time within five days.[9] There are several potential hypotheses for showing different trends in the vibration test. The first would be the effect of the petiole and stem, which were not taken into account. The petiole and stem also dry out over time. The drying rate of the petiole and stem is different from that of the laminar. Then, the effective length of the bending could be shortened depending on the drying rate of different parts of the plant. The second may be due to an out-of-plane (transerve) curvature of the laminar. We observed that some leaves are curbed up and form a ladle-like shape. By having such a transverse curvature, the leaf can have more second moment of area.

Third, it requires more optimization processes to transition to smart sensing systems. Modern agriculture is operating more systematically and automatically with the combination of digital technologies such as artificial intelligence, machine learning, and drones. In order to apply our technology to sustainable agriculture that actually saves water, it is necessary to automatically calculate natural frequencies from the recognition and tracking of individual leaves and perform irrigation accordingly.

Furthermore, since we only tested soybean, supplemental investigations are necessary to determine how frequency information can be applied if the leaf shape and properties are different. Although there are a number of things that need to be improved, this method still has advantages in that it can be utilized as a new water stress indicator.

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