Correlation of Stress Wave Velocity Transmitted Through Stem with Stem Structure of Miniature Tomato

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Abstract
The stress waves at frequency of 5 kHz through the stem of the miniature tomato were transmitted and received to investigate the potential to evaluate the development of vascular tissue of tomato stem by vibration measurement. Two waves were detected and extracted using AE sensor. The wave velocities and the influence of holding a stem on the wave propagation indicated that the detected waves might be the longitudinal and flexural modes. The velocity of detected waves showed strong correlation with the thickness of a vascular tissue rather than a stem diameter. Furthermore, the velocity of the slow wave showed good correlation (correlation coefficient was 0.82) with the parameter calculated from the thickness of a vascular tissue and the stem diameter.

Key words
Stress Wave Velocity, Tomato, Stem, Vascular Tissue, Herbaceous Plant

1. Introduction
Measurement of stress waves including guided waves is widely used for the nondestructive evaluation of engineering materials [1,2]. A stress wave also transmits through a trunk of tree and the nondestructive evaluation of wood quality using vibration and ultrasound has been studied for long time [3,4]. Such a technique should be available for herbaceous plants including vegetables and the nondestructive evaluation of the stem could be quite effective tool for high quality cultivation of the vegetables. Most of herbaceous plants have vascular system, filled with pipe-like vascular tissue. The two main structures in the vascular tissue are the xylem and phloem. The phloem carries nutrients from the leaves down to the rest of the plant. The xylem carries water and nutrients up from the roots to the rest of the plant. The excessive irrigation (free drought stress) causes poor development of the vascular tissue followed by poor nutrients supply to the fruits. On the other hand, the poor irrigation (severe drought stress) causes the xylem wall collapse followed by growth inhibition of the plant. If the development of vascular tissue can be evaluated nondestructively, it would contribute on the irrigation control for achievement of good balance between the development of vascular tissue and the low risk of xylem water collapse. Such a irrigation control has been required for vegetable cultivation [5]. Specially, Tomatoes are sensitive to water application [6].

Fig. 1 shows a typical cross section of a stem of a miniature tomato. The vascular tissue shows the circular structure and its elastic modulus is much higher than other tissues. Authors have tried to detect the ultrasonic waves wave propagating along a vascular tissue when a transmitter and a receiver were fixed to a miniature tomato face to face [7]. The velocity of detected waves was related to the thickness of the vascular tissue but this relation showed large scatter. Furthermore, the any modes of ultrasonic waves could not be extracted from the detected waves because multiple waves were overlapped. Extending the traveling distance of the stress waves is effective for separating multiple modes of waves from detected waves by difference of wave velocity [8]. For a miniature tomato, it can be expected that the multiple modes of the waves can be separated by the long distance measurement along a stem axis. The frequency of the vibration wave, however, prefers to be low because living plants have high attenuation [9].

The purpose of this study is to investigate the potential to evaluate the development of vascular tissue of tomato stem by vibration measurement. In this study, the stress waves of 5 kHz generated by vibration were transmitted and received on the stem of a miniature tomato. The separation of the multiple modes of the detected waves was tried. The correlation between the wave velocities, the stem diameter and the thickness of vascular tissue was investigated.

2. Experimental Procedures
2.1 Materials
Potted miniature tomato (Lycopersicon esculentum Mill. ‘Chika’, Takii Seed) plants were used for experiments. Pots with 27 cm height and 33 cm diameter were filled with a soil mixture of peat moss, perlite, ash, and fertilizer. Seedlings were transplanted in the soil. The plants had been grown with an artificial light irradiance from a high-pressure sodium lamp (FEC Sunlux Ace NHR220LS, Iwasaki Electric). The lighting intensity was set to 120 µmol·m⁻²·s⁻¹ at the base of the shoot; the lighting cycle ran 12 h light per day. The temperature was set at 24 and 20 °C for day and night, respectively. The pots were irrigated...
once a day. The well-grown fourteen plants from 1 to 3 months after seedling transplanting were examined for the measurement of stress waves. The all measurements were done at daytime and all samples were well irrigated with 2 1 of water 2 hr before the measurements. to restrain the influence of the water stress on the stress properties of the stem.

2.2 Measurements
The stress waves were transmitted and received on a primary stem of a miniature tomato. Fig. 2 shows the experimental set up for the measurement of the stress waves. A pair of piezoelectric vibration plates of 12.5-mm-diameter (EFBS12D43; Panasonic Inc.) was used for a transmitter. The each vibration plate was sandwiched between a 12.7-mm-diameter acrylic semicircular column and a 5-mm-thickness acrylic plate. A pair of sandwiched vibration plates were clamped to the stem face to face using threaded rods, nuts and springs as shown in Fig.2 (clamping force was 10 N). The single-cycle-sine-wave with 20 V (peak to peak) and 5 kHz was applied to the transmitter to generate vibration. The resonance vibration can be negligeable because the resonant frequency of the piezoelectric plate was much higher than 5 kHz (12 kHz according to the manufacture’s catalog). The stress waves in the stem was generated by the vibration of the transmitter and detected by the receiver. A piezoelectric AE sensor with 300 kHz of resonance frequency (M304A; Fuji Ceramics Corp.) and an acceleration sensor (BW21SG; Fuji Ceramics Corp.) with 5.5 kHz of resonance frequency were used for the receiver. For AE sensor, the receiver was clamped to the stem using threaded rods, nuts and springs (clamping force was 8 N) as shown in Fig.2. For acceleration sensor, the receiver was bonded on the stem with its sensitive axis in a radial direction of the stem. The transmitter and the receiver were clamped at the middle of the nodes and the distance between them was set to 40-400 mm. The transmitter was attached 100-200 mm above the base of the shoot and the receiver was attached on 9-23 points above the transmitter for each sample (fifteen samples were examined). The detected signals by the receiver was amplified using pre-amplifier and recorded to a personal computer by averaging 256 signals. The gain of the amplifier of the AE sensor was much higher than that of the acceleration sensor because of lack of sensitivity at 5 kHz (55 dB for the AE sensor and 20 dB for the acceleration sensor).

The tested stem was sliced into 200 µm sections with a microtome for observation of the cross section by a stereomicroscope as shown in Fig.3. The stem was sliced at the interval of 5-30 mm without nodes. The stem diameter and the thickness of vascular tissue were measured randomly 10 times for each section from the observed images. Using these measurements, the average stem diameter, $D$ and the average thickness of the vascular tissues, $t_v$ were calculated.

3. Results and Discussions
3.1 Detection of stress waves propagating through a stem of miniature tomato
Fig.4 shows the typical waveforms of the detected waves propagating through the stem of miniature tomato using an acceleration sensor and an AE sensor. The acceleration sensor could clearly detect the stress waves of 5 kHz because the resonance frequency is 5.5 kHz although the gain of the amplifier was much lower than that for the AE sensor. The waveform in Fig.4 indicated the existence of at least two modes of wave (black arrows in Fig.4). The waves detected by the acceleration sensor, however, overlapped because the waveforms gradually attenuated. On the other hand, the AE sensor also could detect the waves of 5 kHz because of high gain of the amplifier although its resonance frequency (300 kHz) was much higher than 5 kHz. Furthermore, the waveform of each mode of stress wave rapidly attenuated. Eventually, the AE sensor is better for extracting the modes of the stress waves than the acceleration sensor if the waves are detectable. Hence, the AE sensor was used for the following results.
Fig. 4 Typical waveforms of the detected acoustic waves when the traveling distance was 291 mm; (a) acceleration sensor, (b) AE sensor.

Fig. 5 shows the waveforms of the waves with several traveling distances. Fig. 5 indicated that two modes (A and B) were observed and the velocity of mode A was higher than that of mode B. Fig. 5 also showed the wavelet spectrum of these waveforms at the frequency of 5 kHz. The location of 1st peak and maximum peak roughly corresponded to the center of the waveforms of mode A and B, respectively when the traveling distance was longer than 50 mm. The peaks of mode A and B at the traveling distance of 50 mm, however, overlapped and could not be separated. The wavelet spectrum of the waves with traveling distance from 200 to 400 mm, therefore, were used for the measurement of the velocity of mode A and B ($v_A$ and $v_B$, respectively).

The velocity was calculated dividing the traveling distance by the traveling time. The traveling distance was set to the center to center distance between a transmitter and a receiver. The traveling time was set to the time from the signal input at a transmitter to the peak time of the wavelet spectrum. As a result, the velocity of A and B has widely changed (247-502 and 93-240 m/s, respectively).

Fig. 5 Change of the waveform and wavelet spectrum of the detected stress waves; (a) signal waveform, (b) wavelet spectrum at frequency of 5 kHz; solid circle: mode A, solid triangle: mode B, traveling distance; i: 50 mm, ii: 154 mm, iii: 249 and iv: 384 mm.
The wavelength of a stress wave is defined by the phase velocity and the frequency. In this study, it can be considered that the phase velocity nearly equals to the group velocity \( (v_g, v_p) \) because the frequency dispersion effect was not observed as will be mentioned in 3.2. Hence, the wavelength of the mode \( A \) and \( B \) was at least 1.8 times longer than \( \bar{D} \). The mode \( A \) and \( B \), therefore, are similar with the stress waves propagating through a rod because the wave with such a long wavelength should propagate not only the vascular tissue but also the whole stem. Typical modes of the stress waves propagating through a rod are longitudinal, flexural and torsional modes [10]. Torsional stress was not applied to the stem in this study and the velocity of longitudinal mode is higher than flexural mode [8,10]. Hence, mode \( A \) and \( B \) are supposed to be longitudinal and flexural mode, respectively. Then, the influence of clamping stem on the propagation path of the waves. To restrain the vibration in a radial direction, the stem was hold by a natural rubber sheet, a clamp and a stand at propagation path of the waves. The waveform of the mode \( B \) greatly attenuated by holding stem as shown in Fig.6. Fig.6 is another evidence that the mode \( A \) is longitudinal and the mode \( B \) is flexural because the flexural wave generates the vibration of the stem in a radial direction. The further study (a numerical analysis and/or a multiple frequency measurement), however, is needed for the identification of the mode for the detected waves in this study.

3.2 Correlation between the wave velocity, the stem diameter and the thickness of vascular tissue

Fig.7 shows the relationship between \( \bar{D} \) and \( \bar{t} \). Both of \( \bar{D} \) and \( \bar{t} \) are generally increased with the growth of the plants. Fig.7, however, showed poor correlation between \( \bar{D} \) and \( \bar{t} \) because there is large difference between the shoots in the growing period and the irrigation condition.

Fig. 8 and 9 show the influence of \( \bar{D} \) and \( \bar{t} \) on the velocity of mode \( A \) and \( B \). The wave velocities showed stronger correlation with \( \bar{t} \) than \( \bar{D} \). The correlation coefficients of \( v_g, v_p \) with \( \bar{t} \) were 0.66 and 0.76, respectively. The mode \( B \), therefore, is more useful for the nondestructive evaluation of \( \bar{t} \) by the measurement of the velocity than the mode \( A \) (longitudinal mode).

It is known that the stress wave shows the frequency dispersion effect [10]. The wave velocity depends on the frequency and the diameter of the rod when the stress wave propagates through a rod. The mode \( A \) and \( B \) should be similar with stress waves propagating through a rod as mentioned in previous section. The velocity of the mode \( A \) and \( B \), however, depended on the thickness of the vascular tissue rather than the stem diameter as shown in Fig.9. The frequency dispersion effect, therefore, did not influence on the velocity of the mode \( A \) and \( B \) so much.

The wave velocity \( v \) propagating in solids depends on the elastic modulus, \( E \) and the density, \( \rho \) of the solid.

\[
v = \frac{E}{\sqrt{\rho}} \tag{1}
\]

The difference of the density between the tissues in the stem can be neglected because the water content in a stem is more than 80 % for the well-irrigated plants [11]. On the other hand, the elastic modulus of vascular tissues is much higher than the other tissues in a stem [12]. Assuming that a stem of a miniature tomato is a hollow cylinder, the flexural stiffness, \( S_f \) can be expressed as following,

\[
S_f = \frac{\pi}{64} \left( \frac{d_2^4 - d_1^4}{d_2^4} \right) E
= \frac{\pi}{64} \frac{d_2^4 - d_1^4}{d_2^4} E_c
\tag{2}
\]

The \( d_1 \) and \( d_2 \) are inner and outer diameter of the circular vascular tissue, respectively. The \( E_c \) is apparent elastic modulus of a stem when a stem is considered to be a rod. The flexural waves through a hollow cylinder could be approximated to be the waves through a solid cylinder using \( E_c \) if the wavelength is longer than a diameter of a hollow cylinder. Assuming \( d_1 = \bar{D} \) and \( d_2 = \bar{D} - 2\bar{t} \), because the thickness of the cortex was thin as shown in Fig.1, \( E_c \) can be calculated using \( \bar{D} \) and \( \bar{t} \).

\[
E_c = sE
\tag{3}
\]

The \( v_p \), therefore, should be proportional to \( \sqrt{s} \) according to Eq. (1) and (3) if the mode \( B \) is a flexural wave. Fig. 10 shows a good correlation of \( v_p \) with \( \sqrt{s} \) and the correlation coefficient was 0.82. Hence, \( v_p \) had more correlation with \( \sqrt{s} \) than \( \bar{t} \). From these results, it can be concluded that there is strong possibility to evaluate thickness of a vascular tissue using a velocity of flexural waves and a stem diameter for a miniature tomato. It is useful to measure thickness of vascular tissues nondestructively in cultivation of miniature tomato.

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because vascular tissues greatly influence on the growth of shoots and amount of crop.

4. Conclusions
The stress waves at frequency of 5 kHz through the stem of the miniature tomato were transmitted and received to investigate the correlation of the wave velocities with the structure of the stem.

(1) Two waves were detected by long distance measurement (200-400 mm). The propagation velocity and the influence of holding a stem on the wave propagation indicated that the detected waves might be the longitudinal and flexural modes.

(2) The detected waves showed strong correlation with the thickness of the vascular tissue rather than the stem diameter. The velocity of the stress wave showed good correlation (correlation coefficient was 0.82) with the parameter calculated from the thickness of the vascular tissue and the stem diameter when the stem was considered to be a rod. This relationship indicates the potential to evaluate the development of vascular tissue in tomato stem by vibration measurement.

Nomenclature

\[ D \] average diameter of stem where wave propagates, m
\[ d_1 \] inner diameter of hollow cylinder, m
\[ d_2 \] outer diameter of hollow cylinder, m
\[ E \] elastic modulus of solid, Pa
\[ E_v \] elastic modulus of vascular tissue, Pa
\[ E_a \] apparent elastic modulus of hollow cylinder, Pa
\[ \rho \] density of solid, Pa
\[ S_f \] flexural stiffness of hollow cylinder, Pa
\[ \bar{t}_v \] average thickness of vascular tissue where wave propagates, m
\[ v_A \] velocity of mode A (longitudinal wave), m/s
\[ v_B \] velocity of mode B (flexural wave), m/s

Fig. 7 Relationship between stem diameter and thickness of vascular tissue of miniature tomato

Fig. 8 Relationship between stem diameter and the velocity of mode A and B; open circle: mode A, open triangle: mode B

Fig. 9 Relationship between thickness of vascular tissue and the velocity of mode A and B; open circle: mode A, open triangle: mode B

Fig. 10 Correlation of the velocity of mode B with the parameter calculated from the thickness of the vascular tissue and the stem diameter when the stem was considered to be a rod.
$v$ wave velocity, m/s

References