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Acoustic characteristics of botanical leaves using ultrasonic transmission waves

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Abstract

The acoustic characteristics of 111 kinds of leaves were determined using longitudinal ultrasonic waves (LUW) passing through the leaves suspended in water. The phase velocity of LUW in the leaves correlated with their thickness ($r = 0.776$). In leaves LUW wavelengths were almost equal to leaf thickness ($r = 0.720$). On the other hand, the group velocity did not correlate well ($r = 0.210$). The more delayed the phase of the transmitted wave, the greater the phase velocity, i.e. phase delay correlates with higher viscosity. The velocity increased as the frequency increased between 1.2 and 1.9 MHz, suggesting development of rigid reticular tissues. The propagation velocities of all the leaves were smaller than that (1497 m/s) of pure water. We therefore believe that the negative thickness and velocity dependencies of the attenuation coefficients are intrinsic characters of leaves, associated with the tissue's morphology. © 2002 Elsevier Science Ireland Ltd. All rights reserved.

Keywords: Acoustic characteristics; Ultrasound transmission waves; Phase velocity; Viscosity; Attenuation coefficient; Tissue's morphology; Tea leaves

1. Introduction

Ultrasonic techniques are useful for analyzing and evaluating the physical characteristics of industrial materials; e.g. velocity, damping and elasticity [1–4]. They also have many medical applications. However, few applications of these techniques have been made in biological fields such as agricultural and plant science. In this paper, we shall discuss the application of ultrasonic techniques to the bio-physical evaluation of plant leaves.

Leaves are the principal organs in which photosynthesis, transpiration and food-manufacturing occur [5]. Leaves also provide important and useful information about a plant's maturation. They vary greatly in size, shape, venation, surface nature and internal texture during maturation. Their textures have many characteristics; e.g. succulent, hyaline, chartaceous, scarious and coriaceous.

In general, it is very difficult to measure the acoustic characteristics of thin biological specimens. Thus, for all their importance, as far as we know, until now there has been no effective method for examining the acoustic characteristics of living leaves nondestructively. Here, we shall show a nondestructive method of evaluating the acoustic characteristics of leaves in terms of their viscoelasticity as associated with the imaginary parts of complex waves.

In Fukuhara et al. (1999), we reported a relation between ultrasonic propagation time and hardness for some kinds of plant leaves, using longitudinal ultrasonic waves (LUW) passing through the leaves suspended in water [6]. The idea is to use a particular broadband spectroscopy to effectively penetrate even soft and acoustically absorbent materials such as leaves. It is called 'Broadband Spectroscopy Technique (BST)' method. Acoustic energy is transmitted from the transmitter to the receiver through the medium of water. Using this technique, the phase shift caused by moving leaves into and out of the acoustic pathway between the transmitting and receiving transducers can be measured accurately. The BST method is capable of providing a bio-physical evaluation of the fundamental character-

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Table 1
Thickness, d/λ and logarithmic damping ratio δ for 111 kinds of leaves used in this study and amplifier gain adjusted for measurement

Plant Name	d (mm)	δ/λ	δ	Gain (dB)
Japanese bush clover	0.165	0.639	0.76	51.1
Violet	0.166	0.618	0.69	35.2
Beefsteak plant	0.184	1.497	0.97	26.6
Adlay	0.185	0.49	0.83	23.9
Spathiphyllum	0.185	0.497	0.40	61.8
Pomegranate	0.199	0.541	0.76	20.5
Honewort	0.201	0.842	0.67	36.4
Willow	0.202	0.497	0.80	22.7
Dandelion	0.203	0.489	0.75	56.3
Mulberry	0.209	0.529	0.61	16.8
Chinquapin	0.21	0.467	0.80	25.1
Arrowroot	0.214	0.594	0.61	54.5
Tomato	0.216	0.58	0.94	62.7
Pachira	0.216	0.746	1.20	8.9
Lily of the valley	0.217	0.599	0.71	41.6
Bamboo	0.218	0.84	0.89	13.2
Cherry	0.219	0.547	0.82	30
Campanumaea javanica	0.22	0.524	0.88	58.5
Plantain	0.222	0.571	0.69	50.8
Bletilla	0.223	0.557	0.53	51.7
Japanese ivy	0.224	0.77	0.90	39.8
Japanese privent	0.225	0.575	0.63	26.9
Camphor	0.227	0.595	0.65	29.1
Japanese persimmon	0.228	0.479	0.65	47.1
Rose	0.228	0.577	0.62	30
Dogwood	0.228	0.782	1.07	27.5
Maple	0.229	0.991	0.97	13.2
Yam	0.231	0.588	0.59	50.8
Ginger	0.232	0.597	0.65	44.7
Strawberry	0.235	0.869	0.62	55.4
Japanese pepper	0.242	0.539	0.77	38.3
Aspidistra	0.243	0.586	0.52	37.3
Prunus tomentosa	0.243	0.607	0.72	19.6
Crocosmia	0.244	0.538	0.69	61.6
Poplar	0.246	0.59	0.72	32.1
Marvel-of-Peru	0.246	0.595	0.48	62.7
Jasmine	0.25	0.628	0.57	15.6
Plane	0.251	0.569	0.67	37.6
Chinese matrimony vine	0.252	0.656	0.55	52.6
Pappermint	0.252	0.889	0.89	25.2
Japanese kerria	0.254	0.899	0.91	18.1
Nandin	0.262	0.594	0.80	27.5
Gourd	0.263	0.653	0.83	18.7
Scarlet sage	0.264	0.541	0.61	44.7
Zelkova	0.264	1.151	0.82	42.2
Aethiopica	0.266	0.559	0.70	53.6
Tea	0.267	0.682	0.80	39.2
Saururaceae	0.275	0.744	0.70	61.8
Eggplant	0.276	0.584	0.33	56.9
Laurel	0.279	0.686	0.29	37.3
Japanese laurel	0.287	0.703	0.42	52.9
Hemp palm	0.288	0.66	1.29	2.5
Vine	0.298	0.489	0.92	34
Bindweed	0.299	0.721	0.78	54.2
Potato	0.303	0.784	0.45	54.8
Japanese bladder Cherry	0.304	0.669	0.78	48.4
Datura	0.305	0.494	0.71	58.5
Akebi	0.305	0.635	0.65	52.6
Raspberry	0.305	0.682	0.78	15
Chloranthus glaber	0.305	0.732	0.70	63.3

Table 1 (*Continued*)

Plant Name	d (mm)	δ/λ	δ	Gain (dB)
Ginkgo	0.308	0.705	0.89	56
Ilex	0.311	0.884	0.69	38
Pothos	0.312	0.538	0.33	58.8
Althea	0.315	0.683	0.69	35.8
Rose campion	0.319	0.627	0.44	62.4
Cape jasmine	0.325	0.716	0.76	35.2
Oleaster	0.326	0.724	0.99	56.9
Orange	0.331	0.648	0.72	42.2
Fragrant olive	0.335	0.984	0.73	24.5
Blue berry	0.338	0.795	0.89	37.6
Azalea	0.34	0.672	0.54	37.6
Taro	0.342	0.758	0.70	64
Canna	0.344	0.659	0.87	61.8
Mahonia japonica	0.345	0.724	0.81	42.8
Red robin	0.347	0.71	0.85	38
Ioqual	0.355	0.524	0.74	26.3
Japanese chestnut	0.355	0.679	0.65	27.5
Sunflower	0.363	0.492	0.41	38
Hydrangea	0.383	0.741	0.69	36.4
Japanese apricot	0.389	0.725	0.95	26.9
Lily	0.393	0.833	0.91	46.8
Japanese andromeda	0.399	0.747	0.77	29.4
Begonia	0.401	0.775	0.78	66.4
Chrysanthemum	0.402	0.617	0.71	67
Magnolia hypoleuca	0.403	0.78	0.59	43.5
Everygreen shrub of the family	0.418	0.589	0.69	48
Pumpkin	0.421	0.598	0.51	56.9
Butterbur	0.422	0.755	1.13	61.8
Camellia	0.429	0.498	0.93	30.9
Schefflera arbolicala	0.435	0.497	0.71	39.5
Rhodea japonica	0.462	1.001	0.32	61.8
Skevish	0.466	0.817	0.41	55.7
Daphne	0.486	0.596	0.56	59.7
Calanthe	0.495	0.811	0.77	36.4
Morning glory	0.502	0.865	0.75	56
Combflower	0.521	0.845	0.66	39.8
Spinach	0.531	0.585	0.70	60
Dayflower	0.543	0.87	0.85	48
Spiderwort	0.543	0.857	0.92	43.8
Everygreen oak	0.556	0.933	0.65	35.8
Spearflower	0.558	0.649	0.71	40.4
Peony	0.587	0.696	0.53	58.8
Geranium	0.595	0.498	0.74	56.9
Sakaki	0.598	1.018	0.69	44.1
Kiwi tree	0.623	1.056	0.77	50.2
Holly tree	0.65	0.98	0.98	39.2
Gum tree	0.683	1.039	0.76	45.9
Thistle	0.733	0.595	0.78	62.7
Kaffir lily	0.741	1.258	0.78	59.4
Perple heart	0.845	1.248	0.45	60.3
Cyclamen	0.923	1.352	0.89	60.9

istics of living leaves, which are a dispersive media. However, as far as we know, we are the first to carry out research on this subject.

For the ultrasonic nondestructive measurement of rigid thin specimens, the frequency domain [7], time domain [8] and variable trigger and strobe (VTS) [9] methods have been developed. However, these measurements are limited to the evaluation of the real parts of the complex acoustic properties of transmitted waves. We have focused on the imaginary parts of complex waves for the acoustic evaluation of acoustically absorbent materials such as leaves. For materials that are more acoustically absorbent and softer than polymers, the phase velocity method must be generally used in place of the group velocity method.

2. Materials and experimental methods

The specimens used in this study were 111 kinds of leaves from plants which grow in the Tokyo area of Japan. Since all the leaves were picked on July 1 (midsummer), they were fully developed. The thickness of their lamina ranged from 0.17 to 0.93 mm. All these leaves were over 4 mm wide.

After the leaves were picked, micro bubbles of air were removed from the surface of the leaves by ultrasonic vibration (20 s). Wave transmission measurements were performed between 20 and 60 s after the leaves were picked, since the acoustic characteristics of leaves gradually change due to stomata respiration during immersion in water. Leaf thickness was measured five times by micrometer before picking. The variance of thickness values was ± 5 and $\pm 18\%$ for hard and soft leaves, respectively. These margins of error are much greater than those for industrial materials. The thickness d, d/λ (where λ is wavelength) and logarithmic damping ratio coefficient δ of these leaf blades are presented in Table 1, along with amplifier gains adjusted for measurement. The smaller gain means good ultrasonic transmissibility for leaves.

Phase velocity, frequency and attenuation coefficient were determined from through-sample and reference (waterpath-only) signals; this was done by comparing the magnitudes and phases of their Fourier coefficients using a diagnosis and analysis apparatus (USH-B, Toshiba Tungaloy) equipped with a transmitter/receiver set. The apparatus and block diagram for measurement are presented schematically in Fig. 1. The electric power of 200 V applied to the pulser. Time clock fluctuation error in the circuit signal between the pulser and the receiver was reduced by using synchronized ISA boards. Flight time accuracy reading was ± 50 ps (pico seconds). We adjusted the amplifier gain from -5.5 to $+65$ dB, to compensate for impedance differences between the specimens and the water medium. Facing broad-bandwidth longitudinal wave transducers of 3.3 MHz frequency and 4 mm in diameter were used as the transmitter and the receiver. Planar PZT transducers were used to suppress the phase modulation which occurred at the boundary between the leaf surface and the water. The leaf was suspended between the two facing transducers, which were separated by 9 mm of water. The wave transmission was measured from the front surface of the leaf to the back at the right side of leaf blade half way between the midrib and the outer edge of the leaf. Although the central frequencies of the received waves for leaves were between 1 and 2 MHz, other waves with high frequencies propagated from the transducer holders into the water as noisy wavelength signals. Thus, software control was used to limit the receiving waves to between 1 and 2 MHz.

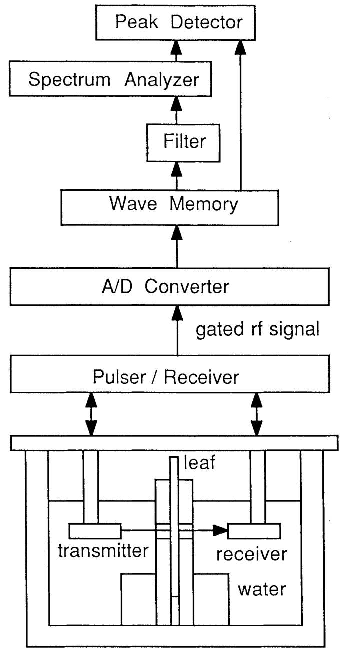

Fig. 1. The apparatus and block diagram for measurement.

To accurately measure the acoustic velocity of uneven leaves with soft tissue, group [9] and phase [10,11] velocities, V_g and V_p, respectively, were calculated using the following formulae,

$$V_g = \frac{V_w}{1 - V_w \Delta t/d} \quad (1)$$

$$V_p = \frac{V_w}{1 - V_w \Delta\phi(\omega)/d\omega} \quad (2)$$

where time shift $\Delta t = t_w - t$ and phase shift $\Delta\phi = \phi_w - \phi$ were the differences of the starting point and of the phase angle in power spectra of the transmitted waves caused by including the specimen in the acoustic pathway, respectively. The V_w is the sound velocity (1497.0 m/s at 298 K) of water [12]. Angular frequency is ω ($\omega = 2\pi f$). The time shift Δt can be either positive or negative depending on whether V_g is faster or slower than V_w. To confirm measurement reliability, the group velocity of a thin aluminum foil with a thickness of 0.016 mm ($d/\lambda = 0.0086$) was measured three times using the BST method. The average velocity (6189 m/s) was fairly consistent with an average value (6223 m/s) of an aluminum column obtained by direct contact using transducers of 10 MHz and reported data (6240 m/s) by the BST method [13].

Fourier transformation of the digitized receiving waveform from the dispersive media was carried out to determine the main frequencies f and phases ϕ at f. To match the frequency of the test and the reference signals, we used the frequency (f_w) of 1.6 MHz for water and phase (ϕ_w) of 0.0019 rad at f_w. The phase shift $\Delta\phi$ is defined as

$$\Delta\phi = \arctan\left[\frac{\mathrm{Im}(\omega_w)}{\mathrm{Re}(\omega_w)}\right] - \arctan\left[\frac{\mathrm{Im}(\omega)}{\mathrm{Re}(\omega)}\right], \quad \left(0 < \phi < \frac{\pi}{2}\right) \tag{3}$$

where $\mathrm{Re}(\omega)$ and $\mathrm{Re}(\omega_w)$, $\mathrm{Im}(\omega)$ and $\mathrm{Im}(\omega_w)$ are, respectively, the real and imaginary parts of complex waves passing through the sample and water. Since all the phases were observed at f lay in between 0 and $\pi/2$, the unfolding problem was avoided.

The attenuation coefficient α and the damping ratio δ of the samples were determined by the form:

$$\alpha = \frac{\delta}{\mathrm{d}} = \frac{\ln(A_1/A_2)}{d}, \tag{4}$$

where A_1 and A_2 are amplitudes of the first and the second wavelets for receiving wave patterns, respectively.

The correlation coefficients between two random parameters were calculated by the standard method of least squares.

3. Results and discussions

3.1. Transmission wave patterns of leaves

The leaves used in this study are divided into five categories [5]: (1) thick-juicy-succulent (gum tree, cyclamen, purple heart, geranium, spinach, peony, dayflower, daphne, spearflower, morning glory, etc.); (2) thin-transparent-hyaline (vine, dandelion, mulberry tree, cherry tree, marvel-of-Peru, bletilla, peppermint, jasmin, ginger, hydrangea, etc.); (3) thin-opaque-chartaceous (violet, honewort, arrowroot, Japanese privet, Japanese ivy, pomegranate, nandin, camphor tree, rose, Japanese bush clover, etc.); (4) thin-dry-scarious (plantain, beafsteak plant, bamboo, dogwood, strawberry, Japanese kerria, Prunus japonica, raspberry, lily of the valley, aspidistra, etc.); (5) tough-thickish coriaceous (holly tree, Kaffir lily, thistle, everygreen shrub of the family, hemp palm, ilex, sakaki, Rhodea japonica, loquat, etc.).

As can be seen from Table 1, since the acoustic transmissibility of each category are similar, the receiving wave patterns of representative leaves of five categories ((a) gum tree, (b) vine, (c) violet, (d) plantain and (e) holly tree) are presented in Fig. 2 along with the pattern (f) of medium water in the same time scale. Since frequency range of the receiving waves passing through water lies in between 0.8 and 6.2 MHz and the component of the low frequency is low, excess gain (~66.4 dB) over water alone was required for transmission of the soft and thick leaves. All patterns of leaves are characterized by higher damping and lower frequency, compared with that of water; the number of wavelets is fewer than those of water and artificial solids obtained by direct contact with transducer [14,15]. These results suggest that the leaves absorb waves with high frequencies during waves passage, even more than in

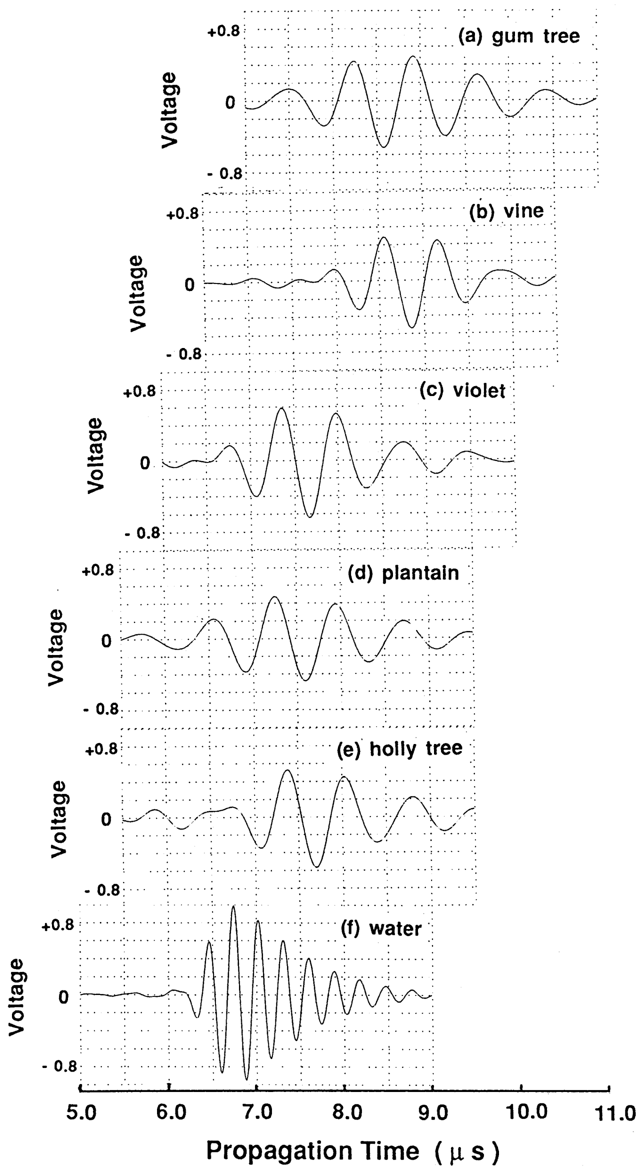

Fig. 2. Receiving wave patterns of representative five classes of leaves, (a) gum tree (d = 0.683 mm, V_g = 234 m/s, V_p = 1224 m/s); (b) vine (d = 0298 mm, V_g = 130 m/s, V_p = 907 m/s); (c) violet (d = 0.166 mm, V_g = 164 m/s, V_p = 689 m/s); (d) plantain (d = 0.222 mm, V_g = 236 m/s, V_p = 790 m/s); (e) holly tree (d = 0.650 mm, V_g = 484 m/s, V_p = 1218 m/s); and (f) water.

case of polymers [14,16,17]. In other words, the leaves can transmit waves with relatively low frequency only, because of their filtering effect. Furthermore, the more thickness increases, the longer the propagation time becomes.

Since acoustic waves which are passed through leaves with the aid of vibrating resonance, reflect leaves' characteristics, what is measured by the BST method are acoustic properties (velocity, wavelength, damping ratio and filtering) of the leaves. Thus dependencies of thickness, frequency and phase angle for the acoustic properties are described in the following sections.

3.2. Thickness dependence of wave velocities

As can be seen from Eqs. (2) and (3), both the group and phase velocities are functions of thickness. The thickness dependences of group and phase velocities are shown in Figs. 3 and 4, respectively. The former does not correlate well ($r = 0.210$), but the latter varies smoothly with increasing thickness ($r = 0.776$). We can posit two causes for the irregularity of the former. One is that the mechanical contact required in making the thickness measurement causes sample deformation, making it difficult to determine the sound speed in leaves with high accuracy. The other possibility is that the micro bubbles inside of leaves hinder the accurate measurement. Thus the group velocity is remarkably affected by measurement errors of thickness, as compared with the phase velocity which is a function of thickness and angular frequency. The angular frequency has no relationship to the contact problem. Indeed, a usage of the phase velocity has been recommended for dispersive media such as soft materials [11]. However, when we note the error margin of the velocity data in Fig. 4, the velocity deviation at a representative thickness (0.25 mm) for soft leaves is $\pm 20.7\%$, being near deviation ($\pm 18\%$) of the thickness for soft leaves. This suggests that the scattering of velocity is a reflection of measurement error of thickness. Since this needs further study, we use the phase velocity hereafter in this study.

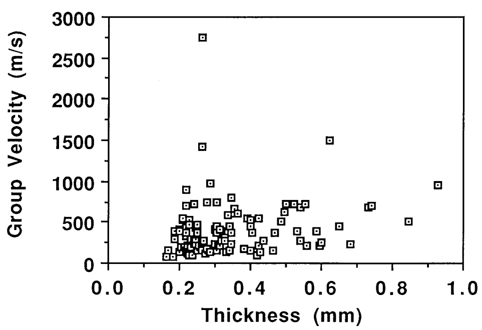

Fig. 3. The thickness dependence of group velocity for 111 kind of leaves. The correlation coefficient is 0.210.

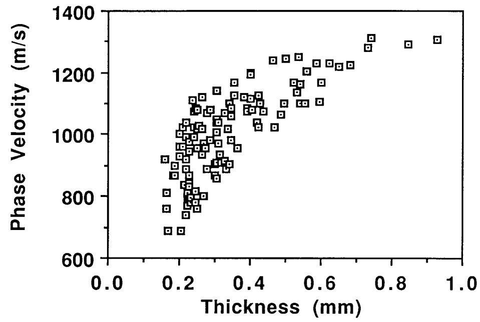

Fig. 4. The thickness dependence of phase velocity for 111 kinds of leaves. The correlation coefficient is 0.776.

The higher velocity in Fig. 4 is characterized by the leaves with rigid reticular tissues, such as sakaki, kiwi fruit tree, holly tree, thistle, etc. Furthermore, the velocities of all the leaves were smaller than that (1497 m/s) [12] of pure water. This would be explained by leaves' internal structures which have loosely packed parenchyma cells separated by intercellular air spaces [5].

The thickness dependence of wavelength for all the leaves is presented in Fig. 5. The wavelengths were almost equivalent to their thickness ($r = 0.720$). As can be seen from internal structure of a dicotyiedon [5], the standing wave with the second harmonic mode occurs in leaves of thickness d fixed at three points on front and back surfaces and on the midrib (xylem and phyloem), situated midpoint between both surfaces.

3.3. Phase angle and frequency dependences for phase velocity

Since the phase velocity is also a function of two parameters; phase and frequency, phase angle and frequency dependences for phase velocity are shown in Figs. 6 and 7, respectively. Both figures show a linear relation with wide dispersion. The wide dispersion would be due to combined effects of two parameters. In Fig. 6, the more delayed the phase is, the greater the velocity becomes ($r = 0.546$).

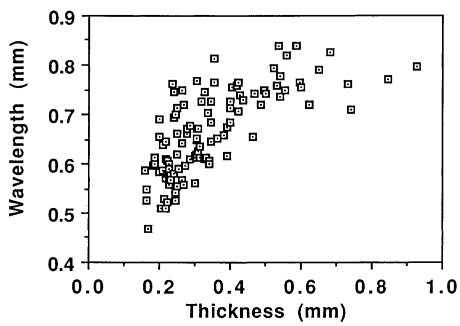

Fig. 5. Relation between wave length and thickness of 111 kind of leaves. The correlation coefficient is 0.720.

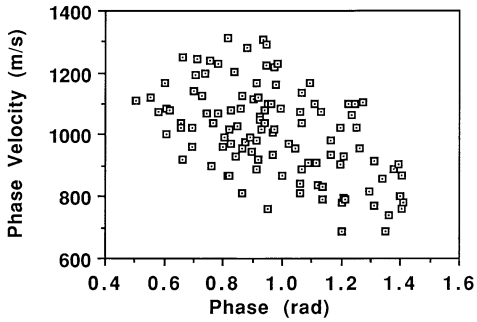

Fig. 6. Relation between phase velocity and phase angle of 111 kind of leaves. The correlation coefficient is 0.546.

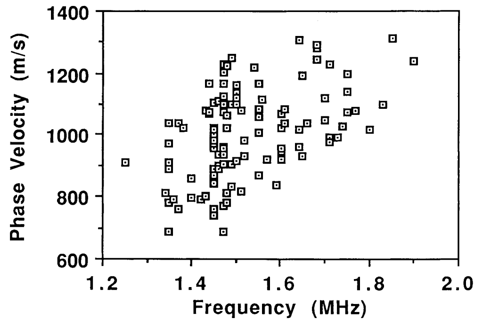

Fig. 7. Relation between phase velocity and frequency of 111 kind of leaves. The correlation coefficient is 0.476.

Since viscoelastic properties of polymers are evaluated from phase modulation in complex waves [14,16–18], the phase modulation of the leaves, like that of soft polymers (e.g. rubber), must involve a Newtonian viscous component to the elastic response: such a situation is denoted as viscoelasticity, associated with the imaginary part of complex waves. To study an effect of the phase modulation, we consider the reflection and transmission from medium 1 to medium 2 of time harmonic longitudinal waves at the interface between two isotropic linearly viscoelastic media. When the ratio of the amplitudes of transmitted to reflected waves and the phase shift between the transmitted and reflected waves are described by $\exp(-2\alpha)$ and $\exp(-2\beta)$, respectively, the ratio of the acoustic complex impedances between two linearly viscoelastic media can be expressed by [19],

$$\frac{\rho_2 c_2^*}{\rho_1 c_1^*} = \tanh(\alpha + i\beta) \tag{5}$$

$$c^* = \frac{W}{\kappa^*} \tag{6}$$

where ρ is density of the medium, c^* complex wave velocity, κ^* complex transmission coefficient, and α and β the attenuation and phase shift coefficients, respectively.

According to Eq. (5), when medium 1 is water and medium 2 is leaf, the phase variation in Fig. 6 indicates change in tissue's morphology of the living leaves. Here we note a similarity between leaf and polymer properties. We have observed this phase delay of polymers that have been thermally degraded by thermal chain scission (e.g. polyvinyl chloride [PVC] [14] and polypropylene [PP] [16]), and by thermal cross-linking of acrylonitrile-butadiene and chloroprene rubbers (NBR and CR, respectively) [17], accompanied by regression in viscoelasticity. Hence, by analogy we infer that delay in phase corresponds to development of the dermal and vascular tissues. These tissues have complicated structures arranged in a flat plane perpendicular to the propagation direction of the waves. Thus we can regard the leaves as an assembly of natural polymers with high viscoelasticity.

The effective transmitted frequency of all the leaves lies in between 1.2 and 1.9 MHz. This frequency range is morphologically consistent with that of polymers with net structures [14,16,17]. The positive straight band ($r = 0.476$) in Fig. 7 also shows increase in frequency by development of the rigid reticular tissue. Although many artificial viscoelastic materials show a slightly positive dependency of phase velocity for frequency, the leaves exhibit a considerable enhancement in velocity with increasing frequency. The frequency increment in the artificial materials comes from atomic lattice shrinkage [20], whereas the leaves (e.g. holly tree, Kaffir lily and thistle) with high frequency make the wavelength shorter by developed veins. Thus, the frequency shift can serve conveniently as a measure of plant' vegetation.

3.4. Acoustic damping and viscosity of leaves

The attenuation coefficients are presented in Figs. 8 and 9, as a function of thickness and phase velocity, respectively. The attenuation coefficients ($r = 0.844$, 0.596) decrease parabolically with increase of thickness and phase velocity, respectively. We, therefore, believe that the negative relation shows an intrinsic character of leaves, associated with the tissue's morphology such as

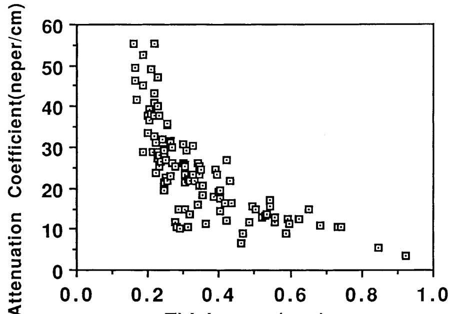

Fig. 8. Relation between attenuation coefficient and thickness of 111 kind of leaves. The correlation coefficient is 0.844.

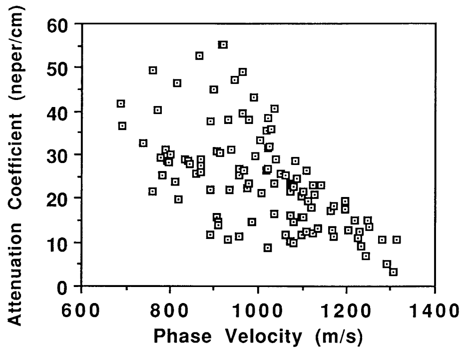

Fig. 9. Relation between attenuation coefficient and phase velocity of 111 kind of leaves. The correlation coefficient is 0.596.

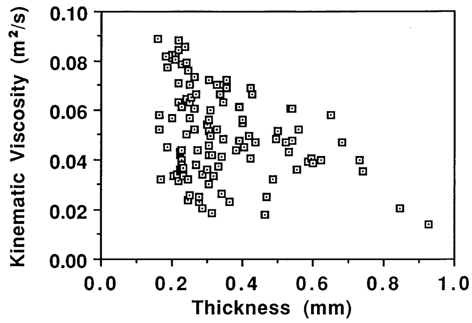

Fig. 10. Relation between kinematic viscosity and thickness of 111 kind of leaves. The correlation coefficient is 0.379.

epidermis, palisade and spongy mesophylls and phloem. The violet ($d = 0.166$ mm, $V_p = 689$ m/s, $\alpha = 41.8$ neper/cm) with a soft leaf and cyclamen ($d = 0.925$ mm, $V_p = 1305$ m/s, $\alpha = 3.4$ neper/cm) with a hard leaf are poles apart in morphology. Indeed, the degree of maturity of tea leaves could be estimated by the attenuation coefficient [21]. As a result, this technique will be applied for remote sensing and spectroscopic laboratory method.

Since the damping behaviors in Figs. 8 and 9 suggest an increase in viscosity, we next consider dynamic viscosity η of the leaves. Here we note a complex elasticity M^* of polymers [22].

$$M^* = M_1 + i\omega\eta, \tag{7}$$

where M_1 is a dynamic elasticity. In case of general glass polymer, we can regard $\delta V_p/\omega$ as 1. Thus we can use the following formula for dynamic viscosity.

$$\eta = \frac{2\rho\delta V_p^3}{\omega^2}, \tag{8}$$

where ρ is density. Since it is very difficult to measure accurately the density of the leaves, we use conveniently a kinematic viscosity η' as a measure of viscosity in place of dynamic viscosity.

$$\eta' = \frac{2\delta V_p^3}{\omega^2} \tag{9}$$

The thickness dependency of the kinematic viscosity is presented in Fig. 10. This figure is divided into two groups: thickness dependent band line ($r = 0.379$) and thickness independent region below 0.5 mm. The former shows lower viscosity for thick leaves. The latter suggests that the viscosity depends on the leaves' internal structures. Furthermore, a typical value ($\eta' = 0.09$ m^2/s) for thin leaves is consistent with that [23] of glycerin at 289 K.

In this interesting area, further study is needed; attention will be given to acoustic interactions of chloroplast tissue associated with phase modulation and damping variation. The nondestructive BST method may also prove useful in sap physiology, fluid pathology and the study of many other kinds of leaves.

4. Conclusion

In this study, the acoustic characteristics for 111 kinds of botanical leaves having leaf blades between 0.17 and 0.93 mm were measured using LUW passing through the leaves suspended in water. The phase velocity of the leaves correlated with their thickness ($r = 0.776$). The leaves' wavelengths were almost equal to their thickness ($r = 0.720$), producing the second harmonic wave fixed at three points on both surfaces of the leaves, and on the midrib. On the other hand, the group velocity did not correlate well ($r = 0.210$). The more delayed the phase of the transmitted wave, the greater the phase velocity ($r = 0.546$), associated with increments in viscosity ($r = 0.379$). The positive frequency dependence for phase velocity correlates to the development of the rigid reticular tissues of the leaves ($r = 0.476$). The attenuation coefficients ($r = 0.844$, 0.596) decreases parabolically as thickness and phase velocity increase, respectively, showing intrinsic characters of leaves, which are associated with their tissue morphology. The phase velocities of the leaves were smaller than that of pure water (1497 m/s), because of their loosely packed parenchyma cells. The thickness dependency of the kinetic viscosity shows a linear decrease band and a thickness independent region associated with leaves' internal structures.

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