Acoustoelastic Effect in Fast Growing Tree for Ultrasonic Stress Analysis

Masumi HASEGAWA, Junji MATSUMURA, Kazuyuki ODA, Kyushu Univ., Fukuoka, Japan
Yasutoshi SASAKI, Nagoya Univ., Nagoya, Japan

Abstract. Ultrasonic longitudinal wave was propagated through the orthotropic axes of the fast growing tree for natural state. The wave velocity in the longitudinal direction of wood was larger than that in radial or in tangential direction. In addition, the longitudinal waves were propagated through transversely to the applied stress direction of wood. The velocities decreased as the compressive or tensile load increased. Velocity changes in the longitudinal waves were proportional to the stress within the elastic stress range. The acoustoelastic constants obtained in this report were the same as the other wood species, but larger than those in metals. These investigations suggested that the acoustoelastic method could be applied to stress analysis in fast growing tree.

1.Introduction

Wood is mostly used as the building materials. It is necessary to estimate the stress conditions produced in timber construction due to maintain the safeness. We have investigated that the acoustoelastic technique [1,2] could be applied to nondestructive stress analysis of structural components in timber construction [3-6]. In previous report, we indicated the existence of acoustoelastic phenomenon in wood [3,4]. Moreover, the stress states of wood under bending were estimated using this acoustolastic phenomenon [5,6].

Wood is a natural living material absorbing and assimilating carbon dioxide in growing process. After felling, wood can keep on stocking carbon dioxide in the timber components in a long period. Especially, the fast growing tree is well known as wood species with the characteristic of fast initial growth. It can contribute to prevention of global warming due to it's high ability of carbon stock. It grows into the large stems on the short rotation because of fast growth rate. The application of the fast growing tree as a new building material (e.g., posts and beams in timber construction) is expected.

The goal objective of our study is to develop a new method for the stress analysis of fast growing tree by the ultrasonic technique. Firstly, the ultrasonic wave propagation properties of wood were investigated. Ultrasonic waves were propagated in three orthotropic axes (longitudinal, radial, tangential direction of wood) under the unstressed state. Secondly, the acoustoelastic phenomenon in fast growing tree was investigated experimentally. Changes in the velocity of ultrasonic waves propagating in wood normal to the direction of applied stresses were discussed. Stress-induced velocity changes of the ultrasonic waves were measured, and acoustoelastic constants are obtained from experimentally observed relations between velocity changes and stress.

2. Materials and Method

Sendan (*Melia azedarach* L.), which is one of Japanese fast growing tree species, was used as material for this study. It is a broad-leaved deciduous species of warm temperature zone (Distributed in the southwest of the Japan, the south of Korean Peninsula, and China). It is used as material for furnishing lumber and furniture production. Wood properties and their variations of Sendan trees were investigated by Matsumura et al. [7] with suggestion of the possibility of useful Japanese fast growing tree as new timber materials.

The specimens were processed from air-dried lumbers. At least ten specimens were prepared for the test. The dimensions of the test specimens were 6 cm (longitudinal) × 3 cm (tangential) × 2 cm (radial) for compressive loading test and 25 cm (longitudinal) × 3 cm (tangential) × 1.5 cm (radial) for tensile loading test. The specimens were kept under air-dried condition prior to the tests. The means± standard deviations (SD) of the moisture content, Young's modulus, and density were 12.8±0.36 %, 10.5±1.36 GPa, and 0.57±0.03 g/cm^3, respectively.

The longitudinal wave velocities were measured with the sing-around method, using a model UVM-2 unit (a commercially available sing-around unit made by Ultrasonic Engineering Co., Ltd., Tokyo). The sing-around repeating time was adjusted to 10000. Piezoelectric transducers with a natural frequency of 0.5 MHz and a diameter of 1 inch (models CR-0016-S made by Harisonic Laboratories, CT, USA) were used to detect the ultrasonic waves. Silicone grease was used as coupling media to improve the bonding between the transducers and a specimen, and a rubber band was employed to hold the transducers against the specimen.

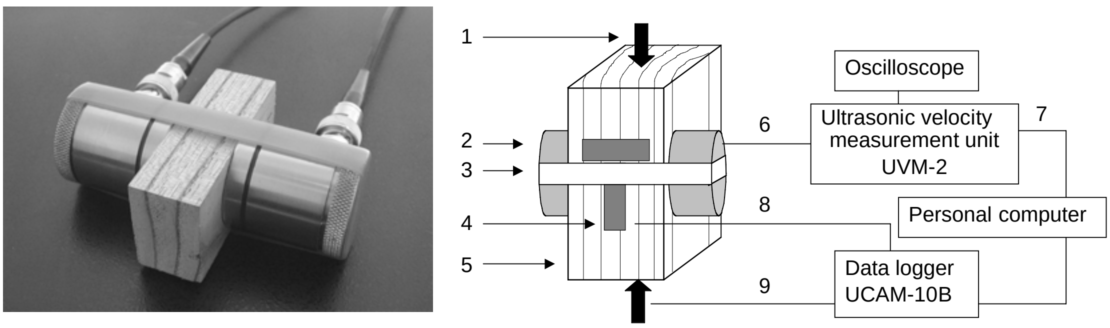

Fig. 1 (a) Wood specimen with ultrasonic transducers. (b) Setup for ultrasonic velocity measurement. 1. Load; 2. ultrasonic transducers; 3. rubber band; 4. strain gauge; 5. wood specimen; 6. electric signal; 7. sing-around periodic time; 8. strain; 9. load

For the first investigation of the longitudinal velocities in three orthotropic axes, longitudinal wave was propagated through the orthotropic axes of unstressed wood, those are, longitudinal, radial, and tangential directions of wood, respectively. Figure 1(a) shows an example of wave velocity measurement. The propagation direction here was coincided with the radial direction of wood.

For the second investigation of the effect of applied stresses on the ultrasonic velocity, both compressive and tensile loads were applied parallel to the longitudinal axis of wood specimens using an Instron-type testing machine. Crosshead speeds of 1.0 mm/min and 2.0 mm/min were applied to the specimen in the compressive and tensile loading tests, respectively. An ultrasonic longitudinal wave was propagated transversely to the loading direction, it means the radial direction of the wood.

The ultrasonic velocity was calculated by dividing the sing-around periodic time by the distance between transducers. The distance, however, was changed by Poisson's effect during loading. Strains in the radial direction of the specimen were measured with strain gauges during loading to correct the distance between the transducers. Strain gauges (5 or 10 mm long) were attached to the center of the symmetrical surfaces of the radial section of the specimen to measure the strains along the directions of loading and wave propagation. Figure 1(b) shows the setup for acoustoelastic measurement in wood specimen. Data from stress, strain, and velocity transducers were digitally recorded on a personal computer.

3. Results and discussion

3.1 Longitudinal wave velocities in three orthotropic axes

The longitudinal wave velocities in three orthotropic axes are shown in Table 1. Values of velocities for other wood species are also shown in the table for comparison. The longitudinal velocity in longitudinal direction (V_L) was twice larger than that in radial or tangential direction. The reason for this result is that wood consists mostly of axial elements (e.g., fibers in hardwood, tracheids in softwood). V_L in Sendan is smaller than that in other softwoods (Douglas fir, Sitka spruce) or in other hardwoods (Oak, Beech) as shown in Table 1. The dissipation of acoustic energy takes place at the end of trachieds or fibers [8]. The dissipation of acoustic energy in hardwood takes place frequently than that of softwood, because the fiber is shorter than the tracheid. In generally, V_L in hardwood is smaller than that in softwood. The reason why V_L in Sendan is smaller is still not clear clarified, but Polge reported that the relation between fiber length and V_L was strong correlation (r=0.90) [9].

Table 1. Longitudinal wave velocities in three orthotropic axes

Species	V_L [m/s]	V_R [m/s]	V_T [m/s]	Density [g/cm^3]
Sendan	3849	1760	1492	0.57
Oak [8]	5071	2148	1538	0.60
Beech [8]	5074	2200	1560	0.67
Douglas fir [8]	5500	2330	1990	0.44
Sitka spruce [8]	5550	2300	1500	0.43

V_L, Velocity in the longitudinal direction; V_R,Velocity in the radial direction; V_T,Velocity in the tangential direction

3.2 Changes in longitudinal wave velocities

Figure 2 shows typical experimental results indicating the relationships between the compressive stress and the strain, and between compressive stress and longitudinal wave velocity. The mean±SD of the initial velocities, which are the wave velocities without any stress, was 1822.5±49.4 m/s. The wave velocities decreased with increasing compressive stress. It decreased by 0.14% within the elastic range. As the deformation became more severe, the decline in longitudinal velocities was even steeper. The result obtained in this experiment was different from that in the previous report [3]. The longitudinal wave velocities in four wood species increased with increases in compressive stress up to arbitrary stress level, beyond that the velocities gradually decreased with increases in compressive stress.

Figure 3 shows typical experimental result under the tensile stress in the elastic region and the relationships between the tensile stress and the strain, and between the tensile stress and the longitudinal wave velocity. The mean±SD of initial velocities was 1707.6±78.9 m/s. The wave velocities decreased continuously as the tensile stress increased. It decreased by

0.12% within the elastic range. The range of the change in velocity shown in Fig. 3 was smaller than that shown in Fig. 2. The resulut from experiment under tensile stress was the same as the previous report [3].

Changes in velocity with stress were due to differences in material, ultrasonic wave mode, wave propagation direction, and so on. The changes in ultrasonic velocities in wood due to the combinations of various modes were summarized in Table 2. For example, when longitudinal wave was propagated parallel to the applied compressive stress direction, the velocities in longitudinal direction increased with increase in compressive stress [10], but those in radial or tangential direction decreased with increase in tensile stress [11]. In metals,

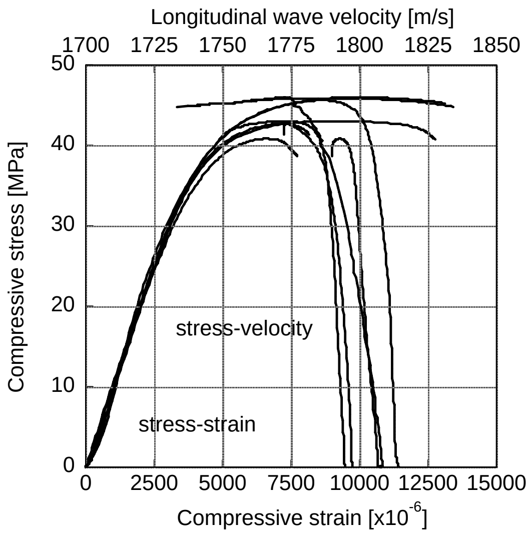

Fig.2. Relationships between compressive stress and strain, and compressive stress and longitudinal wave velocity.

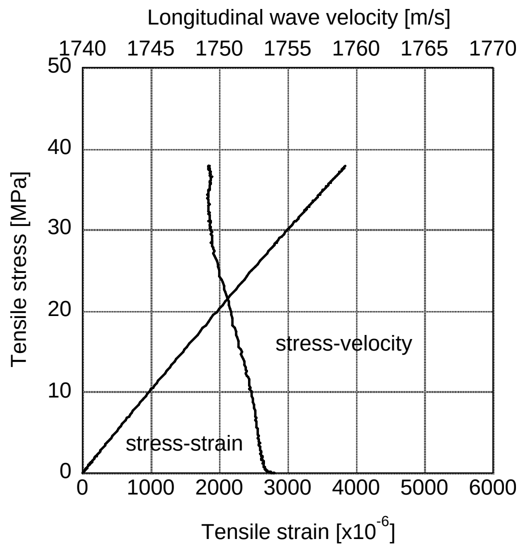

Fig.3. Relationships between tensile stress and strain, and tensile stress and longitudinal wave velocity.

for example, 99.9 % pure copper (Cu), and 0.01% carbon iron (Fe), velocities of the longitudinal wave under uniaxial stresses change slightly with increasing stress. There exist obviously linear relationships between velocities and stresses and the magnitude of changes in the velocities in these metals was smaller than those in wood [12].

3.3 Relative changes of longitudinal wave velocities and acoustoelastic constants

From relationships between wave velocities and stresses, the relative changes of ultrasonic velocities and stresses were obtained at the stress level less than 10 MPa. According to our previous reports [3,10,11] the percentage change in velocity was calculated as follows:

$$(V - V_0) \times 100 / V_0 \ (\%) \qquad (1)$$

Table 2. The changes in ultrasonic velocities for wood in the combinations of various modes

Wave	Stress	Loading direction	Propagation direction	Experimental mode	Change in velocity
Longitudinal	Compressive [10]	L	L	parallel [a]	increase [c]
	Compressive [11]	R, T	R, T	parallel [a]	decrease [d]
	Compressive [3]	L	R	perpendicular [b]	increase [c]
	Tensile [3]	L	R	perpendicular [b]	decrease [d]
Shear	Compressive [3]	L	R	perpendicular [b]	decrease [d]
	Tensile [3]	L	R	perpendicular [b]	increase [c]

L, Longitudinal direction of wood; R, Radial direction of wood; T, Tangential direction of wood; [a], Ultrasonic wave was propagated parallel to the loading direction.; [b], Ultrasonic wave was propagated transversely to the loading direction; [c], Velocity increases with increase in stress.; [d], Velocity decreases with increase in stress

where V is the velocity for a given stress and V_0 is the initial velocity without any stress.

Figure 4 shows the percentage change in longitudinal wave velocity due to compressive stress. The percentage changes in velocity decreased with increase in compressive stress, and relations between velocity changes and compressive stress are represented by essentially straight-lines. Similar straight-line relations between velocity changes and stress were exhibited under tensile stress (Figure 5). As shown in Figs. 4-5, the slopes of relations of

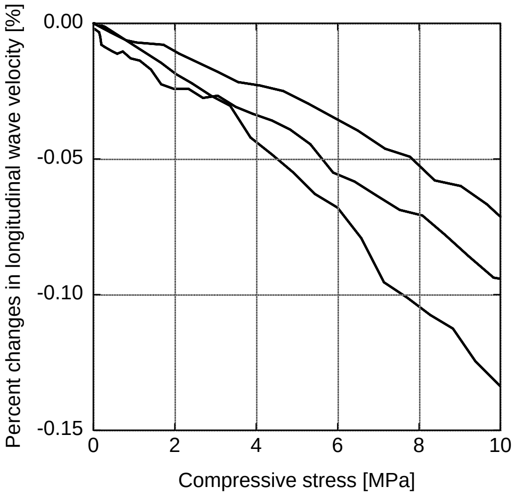

Fig.4. Relationship between percentage change in longitudinal wave velocity and compressive stress.

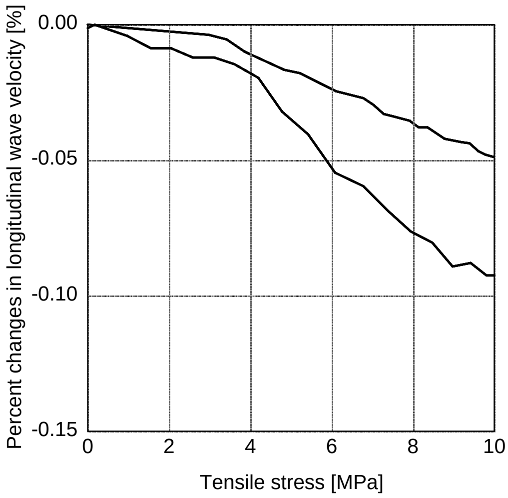

Fig.5. Relationship between percentage change in longitudinal wave velocity and tensile stress

tensile were smaller than that of compressive.

The proportional constants in the relationship between the changes of wave velocity and stresses were used to obtain the acoustoelastic constants. The relation between velocity change and applied stress is expressed as follows:

$$(V - V_0) / V_0 = K\sigma \qquad (2)$$

where V, K and$\sigma$are the longitudinal wave velocity, the acoustoelastic constant and the applied stress, respectively. The acoustoelastic constants are used for stress determination by acoustoelastic method. If the values of K are known beforehand, the stress state in the materials can be estimated from Eq 2. The averaged values of K are shown in Table 3. Values of acoustoelastic constants for other wood species and materials are also shown in the table for comparison. As observed in Table 3, the constants of Sendan for compressive stress were positive in sign, and those for tensile stress were negative. This means that the same phenomena are observed for longitudinal waves under both applied stresses. In this case, the longitudinal velocities decreased with increases in applied stresses. This is important for Sendan and it seems difficult to apply longitudinal waves to measure stress conditions of Sendan. The absolute values of constant are the same as those of other wood in the previous, larger than those of metals. It means that the wave velocity in Sendan is more sensitive to the applied stress than in metals.

Table 3. Acoustoelastic constants of wood obtained experimentally and literature values for metals

Materials	Stress	Mean values [MPa^{-1}]
Sendan	Compressive	1.08 x 10^{-4} (0.63 x 10^{-4})
	Tensile	-0.78 x 10^{-4} (0.19 x 10^{-4})
Japanese cypress [3]	Compressive	-0.60 x 10^{-4} (0.37 x 10^{-4})
	Tensile	-2.12 x 10^{-4} (1.59 x 10^{-4})
Aluminum [13]	Tensile	1.56 x 10^{-6}
Iron [13]	Tensile	1.96 x 10^{-7}

4. Conclusion

Propagation properties of ultrasonic longitudinal waves along the three orthotropic axes of unstressed wood were investigated experimentally. The ultrasonic longitudinal wave velocity in longitudinal direction was twice larger than that in radial or tangential direction. In addition, the effect of applied stress on the wave propagating through the stress aplication direction in wood was clarified. The experimental results are summarized as follows. The longitudinal wave velocities decreased with increases in both compressive and tensile stress. These behaviors were different from the previous reports. This result should be considered when applying the acoustoelastic technique by using longitudinal waves for stress determination of fast growing tree. The values of the acoustoelastic constants in this study were the same as those in the previous studies but larger than those of other materials. The wave velocity in Sendan was more sensitive to the applied stress than that in metals.

These investigations suggest that the acoustoleastic technique could potentially be applied to determination of the stress conditions of wood of fast growing tree. However, the constants for Sendan were the different sign regardless of the applied stress (compression or tension). Further experimental researches, e.g., the acoustoelastic effect for Sendan in the mode of ultrasonic shear wave, should be done to clarify the possibility of using the acoustoelastic technique for wood stress analysis of fast growing tree.

5. References

[1] Bergman R.M., Shahbender R.A., Effect of statically applied stresses on the velocity of propagation of ultrasonic waves. J Appl Phys 29, 1958, pp.1736-1738

[2] Crecraft D.I., The measurement of applied and residual stresses in metals using ultrasonic waves. J Sound and Vibration 5, 1967, pp.173-192

[3] Hasegawa M., Sasaki Y., Iwata T., Acoustoelastic effect of wood III. Effect of applied stresses on the velocity of ultrasonic waves propagating normal to the direction of the applied stress. J Wood Sci 46, 2000, pp.102-108

[4] Hasegawa M., Sasaki Y., Acoustoelastic birefringence effect in wood I: Effects of applied stresses on the velocities of ultrasonic shear waves propagating transversely to the stress direction, J Wood Sci 50, 2004, pp.47-52

[5] Sasaki Y., Hasegawa M., Iwata T., Acoustoelastic stress measurement of wood in bending, Holz als Roh-und Werkstoff 59, 2001, pp.237-243

[6] Hasegawa M., Sasaki Y., Acoustoelastic Birefringence effect in wood for ultrasonic stress determination, Proceedings of the 8th World Conference on Timber Engineering, Vol. II, 2004, pp.173-178

[7] Matsumura J., Inoue M., Yokoo K., Oda K., Cultivation and Utilization of Japanese Fast Growing Trees with High Capability for Carbon Stock I: Potential of *Melia azedarach* (in Japanese), *Mokuzai Gakkaishi* 52, 2006, pp.77-82

[8] Bucur V., *Acoustics of wood*, CRC Press, Boca Raton, 1995, pp. 119-121.

[9] Polge H., Essai de caractèrisation de la veine verte du merisier, Ann. Sci. For. 41, 1984, pp.45-58

[10] Sasaki Y., Iwata T., Kuraya K., Ando K., Acoustoelastic effect of wood I. Effect of compressive stress on the velocity of ultrasonic longitudinal waves parallel to the longitudinal direction of the wood. J Jpn Wood Res Soc 43,1997, pp.227-234

[11] Sasaki Y., Iwata T., Ando K., Acoustoelastic effect of wood II. Effect of compressive stress on the velocity of ultrasonic longitudinal waves parallel to the transverse direction of the wood. J Wood Sci 44, 1998, pp.21-27

[12] Fukuoka H., Toda H., Preliminary experiment on acoustoelastic for stress analysis. Arch Mechanics 29, 1977, pp.671-686

[13] Iwashimizu Y., An introduction to acoustoelasticity (in Japanese), Ultrasonic Technol, 1994, pp.19-22