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ORIGINAL ARTICLE

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Acoustoelastic birefringence effect in wood I: effect of applied stresses on the velocities of ultrasonic shear waves propagating transversely to the stress direction

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Abstract The velocity changes of ultrasonic shear waves propagating transversely to the applied stress direction in wood were investigated. The wave oscillation directions were parallel and normal to the uniaxially applied stress direction. The velocities of the shear waves for both oscillations decreased as the compressive load increased, and increased as the tensile load increased. The velocity of the normally oscillated shear wave showed smaller change against the stress applied than that of the parallel oscillated wave. The initial birefringence due to the orthotropy of wood was observed without any stress. Velocity changes in the two principally oscillated shear waves were proportional to the stress within the stress range tested. The acoustoelastic birefringence effect was obtained from the velocity difference between the two shear waves. The relative difference between the two velocities (called acoustic anisotropy) was given as a function of the applied stress. The acoustoelastic birefringence constants were obtained from the relationships between the acoustic anisotropy and the applied stress.

Key words Acoustoelasticity · Acoustoelastic birefringence · Ultrasonic wave velocity

Introduction

Acoustoelasticity was proposed by Benson and Raelson as a method for stress measurement using the acoustoelastic birefringence effect of ultrasonic shear waves.[1] As a result of their discovery, the possibility of developing a new method for stress analysis was reported.[2–5]

Ultrasonic shear waves propagating transversely to the stress direction through an elastic body are polarized to the two principal stress directions due to stress-induced anisotropy. The two shear waves show a difference in their velocities. This phenomenon is called the acoustoelastic birefringence effect. Theoretical laws for the acoustoelastic birefringence effect and many experimental results have been reported thus far. [6–17] Tokuoka and Iwashimizu[6] indicated that acoustic anisotropy, which is the relative difference between the two shear wave velocities, was proportional to the difference between the principal stresses. They derived the acoustoelastic birefringence law for isotropic elastic materials.[6] Iwashimizu and Kubomura[8] showed in their acoustoelastic birefringence law for slightly anisotropic materials that stress-induced anisotropy had an effect on the polarization direction of the two shear waves. The acoustoelastic birefringence method is expected to be a new method for nondestructive stress measurement of elastic materials.[10–17]

In previous studies,[18–22] we experimentally investigated the velocity changes of ultrasonic waves propagating in wood parallel and transversely to the applied stress direction. The ultrasonic modes were longitudinal wave and shear wave oscillated parallel to the stress direction. We indicated the existence of acoustoelastic phenomenon in wood, and the relative change in ultrasonic velocity was given as a function of the applied stress. Moreover, the stress states of wood under bending were estimated using this acoustoelastic phenomenon.[22] However, the stress states (compression or tension) in wood could not be determined, and only the stress values could be estimated. This was a disadvantage of applying the ultrasonic technique to determine stress states in wood. The acoustoelastic birefringence method was adopted to overcome this disadvantage.

The acoustoelastic birefringence effect of wood was investigated in this study to determine the stress states using the acoustoelastic birefringence method. As the first step of this study, two ultrasonic shear waves whose oscillation directions perpendicularly intersected each other were propagated transversely to the loading direction, and changes in shear wave velocity due to the applied stress were

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measured. In addition, the acoustoelastic birefringence constants, which are important for acoustoelastic stress analysis, were determined.

Experimental

Acoustoelastic birefringence experiment

Sapwood of Japanese magnolia (*Magnolia obovata* Thunb.) was used as material for the test specimens. The specimens were processed from air-dried lumbers. At least ten specimens were prepared for the test. The dimensions of the test specimens were 6cm (longitudinal) × 3cm (tangential) × 2cm (radial) for compressive loading tests and 25cm (longitudinal) × 3cm (tangential) × 1.5cm (radial) for tensile loading tests. The test specimens were kept in an air-dried condition prior to the tests. The means ± standard deviations (SD) of the moisture content, Young's modulus, and density were 6.81% ± 0.28%, 9.85 ± 0.73GPa, and 0.51 ± 0.01g/cm^3, respectively.

Both compressive and tensile loads were applied parallel to the longitudinal axis of wood specimens using an Instron-type testing machine. Crosshead speeds of 0.3mm/min and 1.0mm/min were applied to the specimen in the compressive and tensile loading tests, respectively. An ultrasonic shear wave was propagated transversely to the loading direction, that is, in the radial direction of the wood. The oscillation directions of the shear waves were parallel and normal to the loading direction. These directions corresponded to the longitudinal and tangential directions of the wood specimens. We obtained the velocities of the two shear waves oscillated in the longitudinal and tangential directions, V_1 and V_2, respectively. Figure 1 shows the spacial relationship between loading direction, and propagation and oscillation directions of the shear waves. The velocities of the shear waves were measured with the sing-around method, using a model UVM-2 unit (Ultrasonic Engineering, Tokyo).

The sing-around method is a method for measuring the transit time of ultrasonic waves propagating through material with very high accuracy and the principle of the method is explained as follows. An electric signal is transmitted from a generator to an emitter and is transformed to an ultrasonic pulse. The pulse travels through the specimen and is received by a transducer that transforms the mechanical vibration to an electric signal. The signal can be visualized on an oscilloscope. Because of triggering by this received pulse, the next pulse transmission waits for a fixed delay time until the ultrasonic reverberation vanishes. After waiting for a fixed delay time, the next pulse is transmitted. This operation is repeated many times, and this repeated operation is the so-called sing-around. The sing-around periodic time is counted by a counter, and the elapsed time between emission and reception is measured. The UVM-2 sing-around unit conducts these procedures automatically. In this experiment, the sing-around repeating time was adjusted to 10000.

Piezoelectric transducers with a natural frequency of 0.5MHz and a diameter of 2.54cm (model CR-0016-SA, Harisonic Laboratories, CT, USA) were used to detect the ultrasonic waves.[23] Epoxy resin (AR-R30) was used as coupling media to improve the bonding between the transducers and the wood specimen, and a rubber band was employed to hold the transducers against the specimen.[24,25]

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 10mm 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 2 shows the setup for acoustoelastic measurement. Data from stress, strain, and velocity transducers were digitally recorded on a personal computer. The measurement was conducted in an air-conditioned chamber at 24°C and 55% relative humidity.

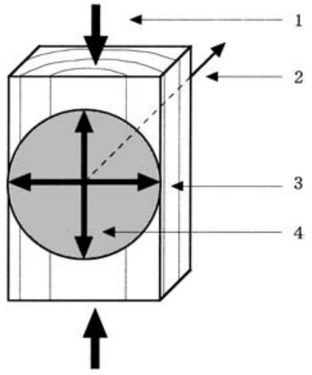

Fig. 1. Relationship between loading direction, and propagation and oscillation directions of shear wave. *1*, Loading direction; *2*, propagation direction; *3*, oscillation direction of shear wave (oscillation normal to the loading direction, wave velocity given by V_2); *4*, oscillation direction of shear wave (oscillation parallel to the loading direction, wave velocity given by V_1)

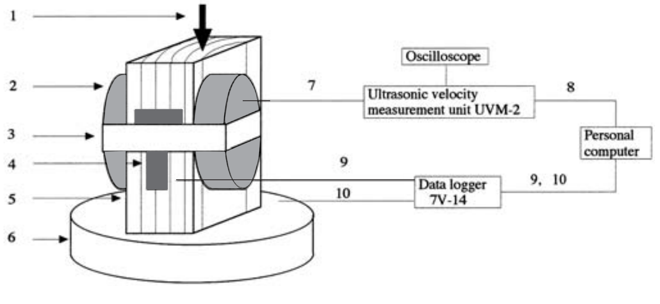

Fig. 2. Setup for ultrasonic velocity measurement under compression load. *1*, Compressive load; *2*, ultrasonic transducers; *3*, rubber band; *4*, strain gauge; *5*, wood specimen; *6*, load cell; *7*, electric signal; *8*, sing-around periodic time; *9*, strain; *10*, load

Results and discussion

Changes in shear wave velocities under uniaxial stress

Figures 3 and 4 show typical experimental results indicating the relationships between the compressive stress and the strain, and between the shear wave velocity and the compressive stress in the elastic region less than 10 MPa. The oscillation directions of shear waves in Figs. 3 and 4 were parallel and normal to the stress direction, respectively. The means ± SD of the initial velocities, which are the wave velocities without any stress, were 1524.5 ± 13.6 m/s and 743.1 ± 13.8 m/s for V_1 and V_2, respectively. The former value was much larger than the latter one owing to the anisotropy in wood. As shown in these figures, the wave velocities decreased with increasing compressive stress. They decreased by 0.13% for V_1 and 0.05% for V_2 within the stress range tested. The change in the velocity in Fig. 3 was larger than that in Fig. 4. The changes in the polarized wave velocities due to compressive stress may depend on the relation with the loading direction.

Figures 5 and 6 show typical experimental results under the tensile stress in the elastic region. They show the relationships between the tensile stress and the strain, and between the shear wave velocity and the tensile stress. The oscillation directions of the shear waves in Figs. 5 and 6 were parallel and normal to the direction of the applied stress, respectively. The means ± SD of initial velocities obtained were 1564.6 ± 11.5 m/s and 671.8 ± 11.5 m/s for V_1 and V_2, respectively. The shear wave velocities increased as the tensile stress increased. They increased by 0.06% and 0.04% within the stress range tested for V_1 and V_2, respectively. The range of the change in velocity shown in Fig. 5, in which the oscillation of the wave was parallel to the loading direction, was larger than that shown in Fig. 6.

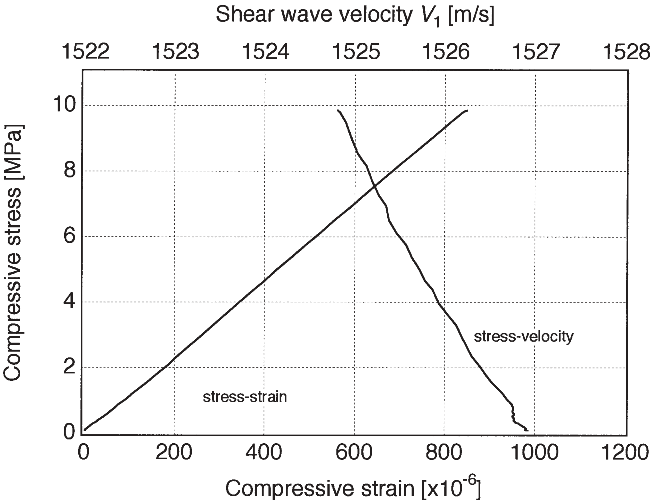

Fig. 3. Relationships between compressive stress and strain, and between compressive stress and ultrasonic velocity of shear wave oscillating parallel to the loading direction

Relative changes of shear wave velocities and acoustoelastic constants

From the results depicted in Figs. 3–6, relationships between the relative changes of ultrasonic velocities and stresses were obtained at the stress level less than 10 MPa. Following our previous reports,[18–20] the percentage change in velocity was calculated as follows:

$$\left(V - V_0\right) \times 100/V_0(\%) \tag{1}$$

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

Figure 7 shows the percentage change in shear wave velocity due to applied stress for the parallel and normal oscillations to the loading direction. As observed in Fig. 7,

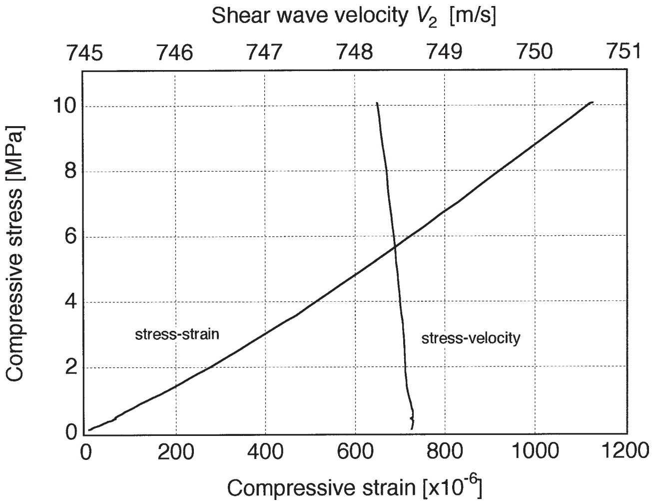

Fig. 4. Relationships between compressive stress and strain, and between compressive stress and ultrasonic velocity of shear wave oscillating normal to the loading direction

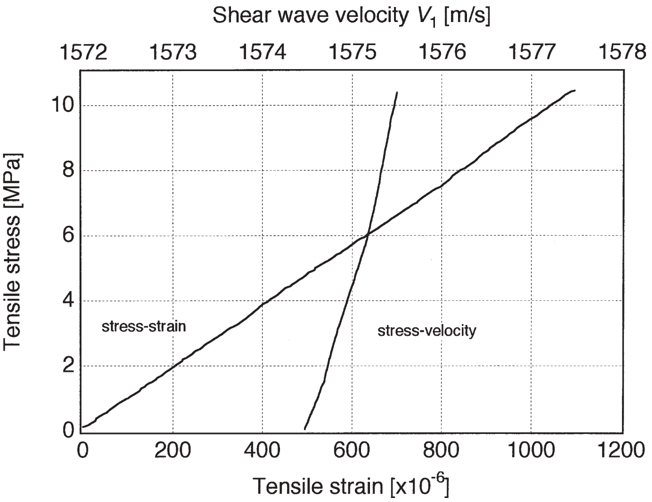

Fig. 5. Relationships between tensile stress and strain, and between tensile stress and ultrasonic velocity of shear wave oscillating parallel to the loading direction

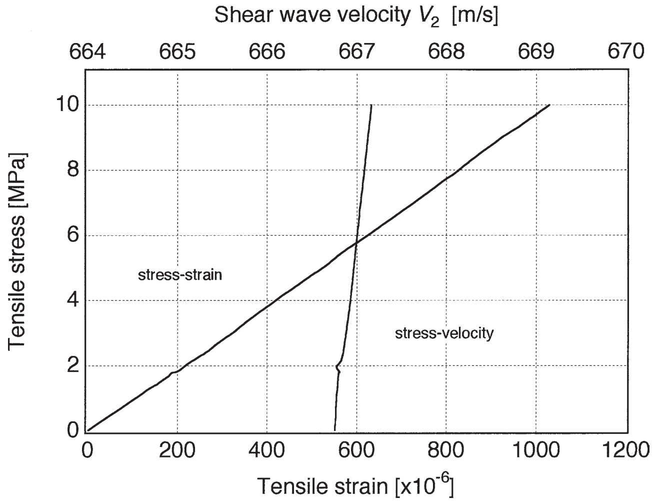

Fig. 6. Relationships between tensile stress and strain, and between tensile stress and ultrasonic velocity of shear wave oscillating normal to the loading direction

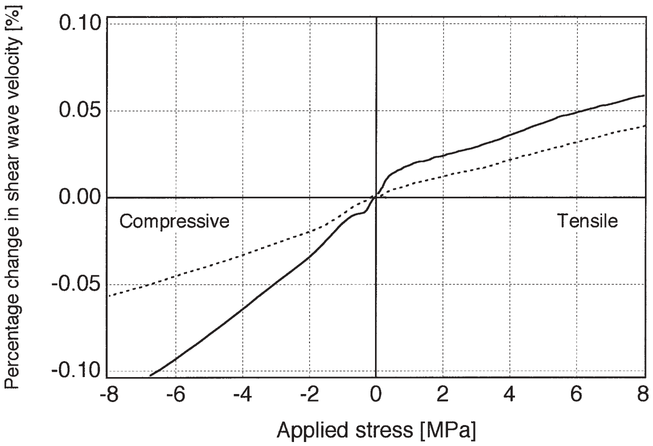

Fig. 7. Relationships between percentage change in velocity of shear wave and applied stress. *Solid line*, shear wave oscillating parallel to the loading direction; *dotted line*, shear wave oscillating normal to the loading direction

Table 1. Acoustoelastic constants of wood obtained experimentally and literature values for metals

Material	Stress	K_1 (MPa^{-1})	K_2 (MPa^{-1})
Japanese magnolia	Compressive	1.81×10^{-4} (0.68×10^{-4})	0.52×10^{-4} (0.20×10^{-4})
	Tensile	0.69×10^{-4} (0.24×10^{-4})	0.47×10^{-4} (0.23×10^{-4})
Aluminum[26]	Compressive	-3.28×10^{-5}	-1.34×10^{-5}
Iron[27]	Compressive	-0.95×10^{-5}	-0.13×10^{-5}
Copper[27]	Tensile	-4.52×10^{-5}	-1.74×10^{-5}

Numbers in parentheses denote standard deviations

K_1, Acoustoelastic constant for shear wave oscillating parallel to the loading direction; K_2, acoustoelastic constant for shear wave oscillating normal to the loading direction

positive correlations were found between the shear wave velocity change and the applied stress. These correlations may be regarded as proportional relationships.

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

$$\left(V_i - V_{i0}\right)/V_{i0} = K_i \cdot \sigma \quad \left(i = 1,2\right) \tag{2}$$

where V, K, and σ are the shear wave velocity, the acoustoelastic constant, and the applied stress, respectively. Numbers 1 and 2 denote the directions of shear wave oscillating parallel and normal to the loading direction, respectively; and the number 0 following i denotes the natural state (zero stress and zero strain). The averaged values of K_1 and K_2 are shown in Table 1. Values of acoustoelastic constants for metals are also shown in the table for comparison.[26,27] As observed in Table 1, the constants for the wood in these experiments were all positive regardless of the applied stress (compression or tension). Similar results were also obtained in our previous study.[21] This means that the acoustoelastic behaviors were different depending on the applied stress.

The values of K_1 are larger than those of K_2 and their values under compression were larger than those under tension. The constants are smaller than those in the previous reports by about two orders of magnitude.[18–20] The absolute values are larger than those of metals. This means that the velocity in wood is more sensitive to the applied stress than in metals.

Changes in velocity with stress were due to differences in material, ultrasonic wave mode, wave propagation direction, and others. The phenomena observed in Figs. 3–7 are also generally observed in metals, for example 99.9% pure copper (Cu), and 0.01% carbon iron (Fe). For these metals, velocities of the shear wave under uniaxial stresses change slightly with increasing stress. There are obvious linear relationships between stress and velocity and changes in the velocities in these metals are smaller than those in wood.[27]

Relative differences in shear wave velocities and acoustoelastic birefringence constants

From the results of acoustoelastic birefringence experiments, the relationships between the relative difference in shear wave velocities and the applied stress were derived. The relative difference in wave velocities is given by (V_1 −

V_2) / V_T, where V_T is the average of V_1 and V_2. This is also called acoustic anisotropy.

Figure 8 shows examples of the relative differences in shear wave velocities due to the applied compressive stress. One of the lines in Fig. 8 was obtained from Figs. 3 and 4. The relative differences in shear wave velocities decreased with increasing compressive stress, and negative correlations were observed. The average proportional constant of the lines in Fig. 8 was 6.68×10^{-4} MPa^{-1}. Figure 9 also shows examples of the relative differences in velocities due to the applied tensile stress. One of the lines was obtained from Figs. 5 and 6. The relationships between them were also expressed by straight lines, but in contrast to the changes observed in Fig. 8, they clearly showed positive linear correlation. The average proportional constant of these lines in Fig. 9 was 1.80×10^{-4} MPa^{-1}. The proportional constants of the relations in Figs. 8 and 9 are called the acoustoelastic birefringence coefficient (*Ca*). The intercepts of the asymptotes shown in Figs. 8 and 9 represent the texture anisotropy (α).

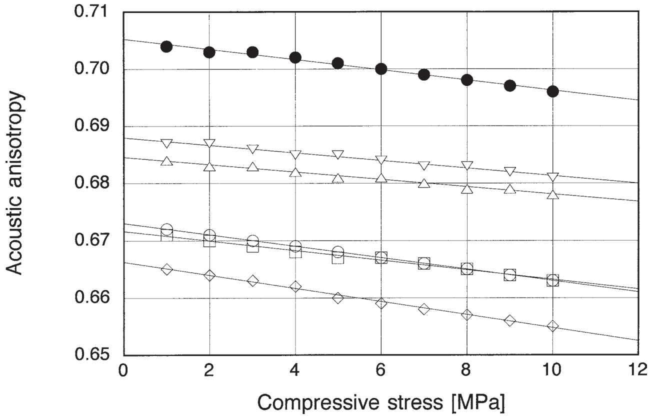

Fig. 8. Changes in acoustic anisotropy as a function of applied compressive stress

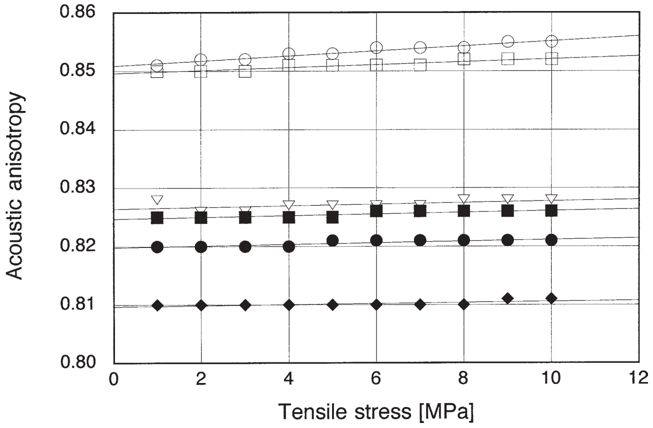

Fig. 9. Changes in acoustic anisotropy as a function of applied tensile stress

Generally, a material possesses orthotropy in its natural state. There are several possible causes of this initial anisotropy. Because metallic materials are crystalline, and because manufacturing processes such as casting, rolling, and heat treatment are used in producing these crystalline materials, preferred grain orientation exists, causing an anisotropic behavior. In addition, if some residual stress were present in these materials due to heat treatment, it would manifest itself as acoustical birefringence. Wood is an orthotropic material that possesses anisotropy due to its anatomical structure. In the analysis of the stress state of wood using the acoustoelastic birefringence method, it is necessary to consider the existence of the texture anisotropy. Texture anisotropy (α) is also called acoustic anisotropy for the natural state. According to the acoustoelastic birefringence formula, Eq. 3 can be written as[13,16]

$$\left(V_1 - V_2\right)/V_T = \alpha + Ca\left(\sigma_1 - \sigma_2\right) \tag{3}$$

where σ_1 and σ_2 are the principal stresses. As shown in Eq. 3, the acoustoelastic birefringence effect is the sum of α and stress-induced anisotropy [Ca ($\sigma_1 - \sigma_2$)]. These acoustoelastic birefringence constants (α and Ca) were used for stress determination by the acoustoelastic birefringence method. If the values of α and Ca are known beforehand, the stress state in the material can be estimated from Eq. 3.

The average values of constants α and Ca, for each set of experimental conditions, are shown in Table 2. The larger the value of α, the more severe the anisotropy. It is found that the magnitudes and signs of the velocity changes strongly depend on materials and directions of propagation, among other factors. The sign of *Ca* was the same regardless of the applied stress (compression or tension), as shown in Table 2. This means that different phenomena were observed due to the applied stress (compression or tension), as shown in Figs. 8 and 9. This is important for the

Table 2. Texure anisotropy and acoustoelastic birefringence coefficients of Japanese magnolia and metals

Material	Stress	Texture anisotropy α	Acoustoelastic birefringence coefficient Ca (MPa^{-1})
Japanese magnolia	Compressive	0.686 (0.014)	6.68×10^{-4} (3.94×10^{-4})
	Tensile	0.807 (0.031)	1.80×10^{-4} (1.80×10^{-4})
Aluminum[26]	Compressive	0.770×10^{-2}	-3.97×10^{-5}
	Tensile	0.750×10^{-2}	-4.14×10^{-5}
Soft steel[28]	Tensile	2.470×10^{-2}	-1.39×10^{-5}

Numbers in parentheses denote standard deviations determination of the stress; namely, compression or tension. If the difference between acoustic anisotropy and texture anisotropy $[(V_1 - V_2) / V_T - \alpha]$ shows a positive sign, the stress is tensile. If it shows a negative sign, the stress is compressive. Knowing the stress state (compression or tension) is considered an advantage of applying the acoustoelastic birefringence phenomenon to stress measurement in wood.

Conclusions

The effect of applied stress on the ultrasonic velocity of shear waves propagating transversely to the stress application direction in wood was investigated experimentally. The ultrasonic modes considered were shear waves that oscillated parallel and normal to the applied stress direction. The experimental results are summarized as follows.

The shear wave velocities decreased as the compressive stress increased. On the other hand, the ultrasonic velocities under the tensile stress increased as the stress increased. The relative difference in the shear wave velocities, called acoustic anisotropy, was obtained as a function of the applied stress. The acoustelastic birefringence constants were obtained from the relationships between the relative differences in shear wave velocities and the applied stress. The absolute values of the constants for wood were larger than those for metals.

These results indicate the existence of acoustoelastic birefringence phenomena in wood. This finding makes it possible to determine the stress state (compression or tension). It is expected that this will allow the disadvantage described in the previous report to be overcome.[22]

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