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Acoustoelastic effect of wood II: Effect of compressive stress on the velocity of ultrasonic longitudinal waves parallel to the transverse direction of the wood*

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Abstract The changes in the velocity of ultrasonic waves propagating in wood parallel to the direction of applied stress are discussed. The ultrasonic mode was longitudinal waves traveling along the direction of applied stress with the compressive load applied parallel to the transverse direction of the wood. The ultrasonic velocities were measured by the sing-around method. The experimental results indicated the existence of an acoustoelastic phenomenon in the transverse direction of the wood. The percent change in the ultrasonic velocity was given as a function of the applied stress. The change in the velocity depended on the species and structural direction of the wood. That is, in the radial direction of hardwood, the ultrasonic velocity increased with increases in compressive stress at the initial stress level of less than 2MPa; it then gradually decreased with increases in stress. A change in velocity from an increase to a decrease was considered a unique phenomenon for wood. In contrast, in the radial direction of softwood and the tangential direction of hardwood, the ultrasonic velocity decreased with increases in stress from the beginning of loading. This phenomenon is also generally observed in metallic materials. The relations between velocity and stress at the initial stress level and between velocity and strain in the range of large deformation are represented by essentially straight lines. The acoustoelastic constants of wood were obtained from these relations at the initial stress level. The absolute values of the constants in the transverse direction of wood were larger than those for metals and were larger than those for the longitudinal direction of wood reported in our previous paper.

Key words Acoustoelasticity · Acoustoelastic effect · Ultrasonic velocity

Introduction

Ultrasonic waves propagating through an elastic material under stressed conditions change speed somewhat due to the stress.[1–6] This change is called an acoustoelastic effect, and the acoustoelastic technique can be applied to the stress analyses of materials.[7–15]

In our previous report,[16] we reported the results of an experimental investigation of changes in the velocity of ultrasonic waves propagating in wood parallel to the direction of the applied stress. The ultrasonic mode was longitudinal waves traveling along the direction of the applied stress, and the compressive load was applied parallel to the longitudinal direction of the wood. The ultrasonic velocities were measured by the sing-around method, and stress-induced velocity changes were confirmed. The findings indicated the existence of an acoustoelastic phenomenon in wood, and the percent changes in the ultrasonic velocities were given as functions of applied stress.

The purpose of the present study was to investigate the acoustoelastic phenomena of wood in the transverse direction. The effect of compressive stress on the ultrasonic velocity of longitudinal waves propagating through the transverse direction of wood was discussed following the previous report.[16] Compressive stress was applied in the radial or tangential direction of wood, and an ultrasonic longitudinal wave was propagated parallel to the compressive stress axis. Stress-induced velocity changes in longitudinal waves for some wood species in the transverse direction were measured by the same method used in the previous study. Acoustoelastic constants for longitudinal waves for wood under radial and tangential compression were also obtained.

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Table 1. Wood species and their basic properties

Species	Average moisture content (%)		Average air-dried density (g/cm^3)		Average Young's moduli during compression (GPa)	
	Radial	Tangential	Radial	Tangential	Radial	Tangential
Alaska-cedar [*Chamaecyparis nootkatensis* (D. Don) Spach.]	9.6 (0.1)	–	0.47 (0.02)	–	1.06 (0.08)	–
Japanese cypress [*Chamaecyparis obtusa* (S. and Z.) Endl.]	8.3 (0.1)	–	0.41 (0.00)	–	0.96 (0.03)	–
Japanese beech [*Fagus crenata* Blume]	9.4 (0.4)	9.4 (0.2)	0.66 (0.01)	0.66 (0.01)	1.86 (0.06)	0.80 (0.04)
Ash [*Fraxinus excelsissima* Koidz.]	9.3 (0.3)	9.5 (0.2)	0.54 (0.01)	0.53 (0.01)	1.42 (0.16)	0.74 (0.02)
Japanese magnolia [*Magnolia obovata* Thunb.]	9.2 (0.3)	9.6 (0.1)	0.45 (0.01)	0.48 (0.01)	1.37 (0.06)	0.66 (0.02)
White spruce [*Picea glauca* (Moench) Voss]	9.5 (0.1)	–	0.42 (0.01)	–	1.11 (0.30)	–

Numbers in parentheses are standard deviations.

Materials and methods

Materials used in this experiment were the six species shown in Table 1, i.e., three softwood and three hardwood species. Small, clear specimens of solid wood were processed from air-dried lumber. At least 10 specimens of each species were prepared for the tests. Their dimensions were 6cm (radial or tangential) ×3cm (tangential or radial) × 3cm (longitudinal). The longitudinal axis of the specimen coincided with the radial or tangential direction. They were kept in an air-dried condition. The properties of the specimens are shown in Table 1.

The compressive load was applied parallel to the longitudinal axis (radial or tangential direction) of a wood specimen by an Instron-type testing machine. The ultrasonic wave was propagated through a wood specimen in the same direction of the loading. The ultrasonic velocity under compressive loading of the wood was measured by the sing-around method,[17–20] and a model UVM-2[19] was used for the velocity measurements.

Figure 1 shows the experimental arrangement for acoustoelastic measurements of wood. The transducers used were a commercially available piezoelectric type for a longitudinal wave, 0.5MHz center frequency, and 1-inch diameter (model CR-0016-S, Harisonic Laboratories, CT, USA). Special holders made from duralumin were used to protect the transducers from compressive loading (Fig. 1). The compressive loading against a wood specimen was exerted through these holders. The ultrasonic velocity traveling through these duralumin holders is influenced by the loading. To prevent this influence on the ultrasonic velocity measurements, the propagation time of the ultrasonic pulse through the duralumin holders was measured as a function of loading in advance, without the wood specimen. The propagation time through the specimen and the holders was then measured by subtracting the time without the specimen as a function of loading.

Coupling medium (silicone grease SH-111) was used to ensure bonding of the transducers to the holders and the wood specimen. Load-cell and strain gauges were used for the stress–strain measurements. Strain gauges 10mm long were attached to the center of the symmetrical surfaces of the radial or tangential section of the specimen around the radially or tangentially loading axis, respectively. Dimensional changes of the specimen during the test were measured by a highly sensitive electric displacement meter. The distance between the ultrasonic transducers was corrected by this measurement to calculate the ultrasonic velocity. The equipment for the stress, strain, displacement, and velocity measurements was connected to a personal computer, and the data were recorded. The above procedures were done in an air-conditioned chamber at 24°C and 55% relative humidity.

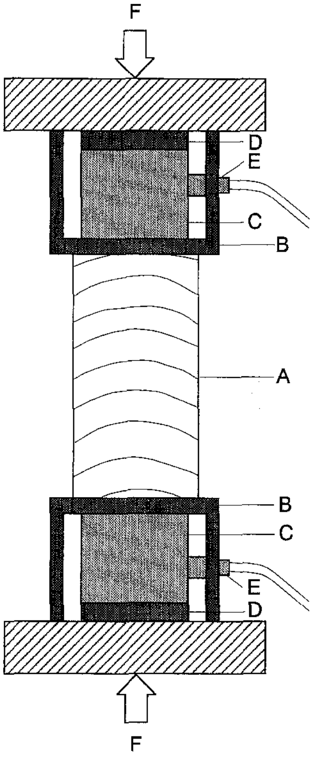

Fig. 1. Experimental arrangement for measuring ultrasonic velocity under compressive loading of wood. *A*, Wood specimen under investigation; *B*, Duralumin holder; *C*, ultrasonic transducer of piezoelectric type; *D*, Silicone rubber; *E*, connecting cable; *F*, force exerted by testing machine

Results and discussion

Changes in velocities under uniaxial stress for wood in transverse directions

There were some differences in the experimental results for the hardwood and the softwood species in terms of radially compressive loading and ultrasonic propagation. Figure 2 is an example of the experimental results with hardwood: the relations between the stress, strain, and the changes in velocity of a longitudinal wave under compressive stress for the Japanese beech in the radial direction. The mean ±SD of the initial velocity (V_0) for the natural state (zero stress, zero strain) was 2198 ± 28.1 m/s. At an initial stress level of less than 1–2 MPa, the strain and ultrasonic velocity increased with increases in compressive stress. The velocity then gradually decreased with increases in stress and strain from a stress level of more than 2 MPa. Similar results were obtained with other hardwood species in this experiment. This phenomenon was also common in the case of compression of longitudinal wood samples.[16]

On the other hand, the experimental results with softwood species were different from those of hardwood described above and in the case of compression of longitudinal wood samples. Figure 3 shows the curves of the compressive stress–strain relations and changes in the ultrasonic velocities for Japanese cypress in the radial direction. The stress–strain relations are represented by essentially straight lines. The ultrasonic velocity decreased with increases in compressive stress and strain. The initial average ±SD velocity (V_0) was 2079 ± 4.51 m/s. The ultrasonic velocity decreased from the beginning of compressive loading and deformation. This phenomenon differed from that seen with compression of longitudinal wood samples in terms of the velocity variation at the initial stage of the compressive loading and deformation, as reported previously.[16] This phenomenon was common and characteristic for the softwood species in this experiment.

Ultrasonic measurements could not be performed well in the tangential direction for softwood species in this experiment. The ultrasonic transducer could not receive the ultrasonic pulse traveling in the tangential direction of softwood species despite shortening the specimen length from 6 cm to 3 cm. The highest attenuation is expected in this direction in which no continuous structural elements exist.[21]

The results from hardwood species are as follows. Figure 4 is an example of these experimental results. Note the relations between the stress, strain, and changes in the velocity of the longitudinal wave under compressive stress in the tangential direction in the Japanese magnolia. The

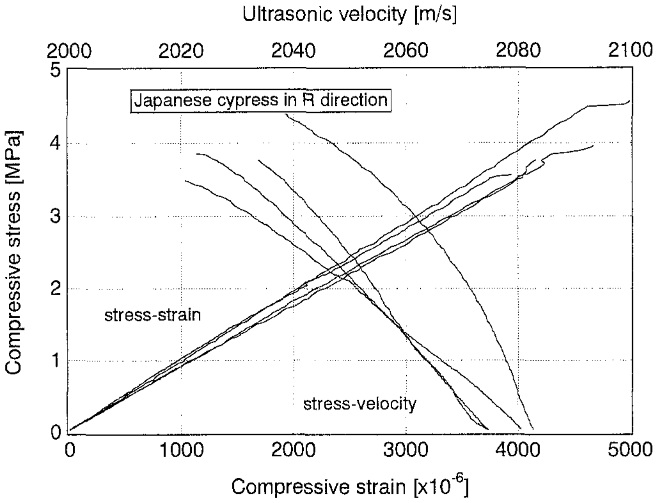

Fig. 3. Relations between stress, strain, and velocity of Japanese cypress in the radial direction

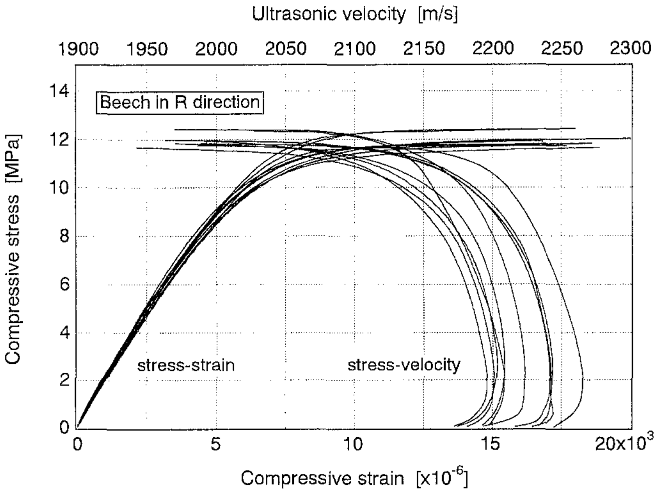

Fig. 2. Relations between stress, strain, and velocity of Japanese beech in the radial (*R*) direction

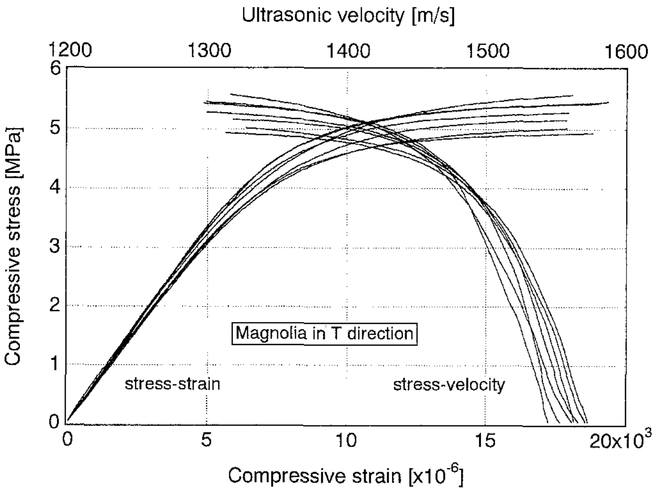

Fig. 4. Relations between stress, strain, and velocity of Japanese magnolia in the tangential (*T*) direction

stress-strain relations are represented by generally recognized curves for transverse compression of hardwood species. The average ±SD ultrasonic velocity in the natural state (V_0) was 1558 ± 13.2 m/s. It decreased with increases in stress and strain immediately after the natural state, similar to that in the radial direction in softwood species. With severe deformation of more than 0.8% strain, the ultrasonic velocity decreased more steeply. Similar results were observed in other hardwood species.

The phenomena observed in Figs. 3 and 4 are also generally observed in metallic materials. For chrome steel SCr440, for example, the longitudinal ultrasonic wave propagated parallel to the stress axis decreases its speed slowly and linearly beginning with the initial stress state.[19,20] As described above and in our previous report,[16] the ultrasonic velocity changes depend on the species and the structural direction of the wood, suggesting that there is a relation between the acoustoelastic phenomenon and the anatomic structure of wood.

Changes in velocity as a function of transverse strain

Figure 5 shows examples of ultrasonic velocity changes as a function of radial strain induced in the Japanese beech. (Figure 5 was obtained from Fig. 2.) At the beginning of loading and deformation the ultrasonic velocity increased with increased strain and soon reached a maximum at about 0.1% strain. At a strain of more than 0.2%, the velocity gradually decreased with increases in strain. The relations between them gave essentially straight lines in this range of severe deformation. Similar phenomena were observed in that range for other hardwood species (not discussed here), and the results were qualitatively similar to those obtained with longitudinal compression.[16] For steel the relations between the velocity and strain produced straight lines from the beginning of deformation, as mentioned previously.[16] That the ultrasonic wave changed its speed gradually from an increase to a decrease near 0.1% strain is considered a unique phenomenon of wood.

In contrast, a different phenomenon was observed for softwood with radial compression. Examples of ultrasonic velocity changes for softwood are shown in Fig. 6 as functions of the radial strains induced in Japanese cypress. (Figure 6 was obtained from Fig. 3.) From the beginning of loading and deformation the ultrasonic velocity decreased with increased strain. The relations between them showed parabolic or nearly straight lines. Similar phenomena were observed for other softwood species in the radial direction.

Figure 7 shows examples of the ultrasonic velocity changes as functions of the tangential strains induced in the Japanese magnolia. (Figure 7 was obtained from Fig. 4.) From the beginning of loading and deformation, the ultrasonic velocity decreased with increased strain, as in Fig. 6. The relations between them gave essentially straight lines for the entire process, and the linearity of the lines was much clearer than those in Fig. 6. Similar phenomena were observed in this direction for other hardwood species. This phenomenon is characteristic and much different from the results for radial compression of hardwoods and longitudinal compression.[16] It can be explained by the acoustoelastic theory.[22] The linear relations between velocity and strain are similar for steel materials.

Relative changes of longitudinal-wave speeds and acoustoelastic constants in the transverse direction of wood

From the results of Figs. 2–4, the relations between the relative changes of ultrasonic velocities and stresses were obtained at a low stress level of less than 1–2 MPa. Following our previous report,[16] the percent changes in velocity were calculated by $(V - V_0) \times 100/V_0$ (%), where V is the velocity for an arbitrary stress, and V_0 is the initial velocity for the natural state.

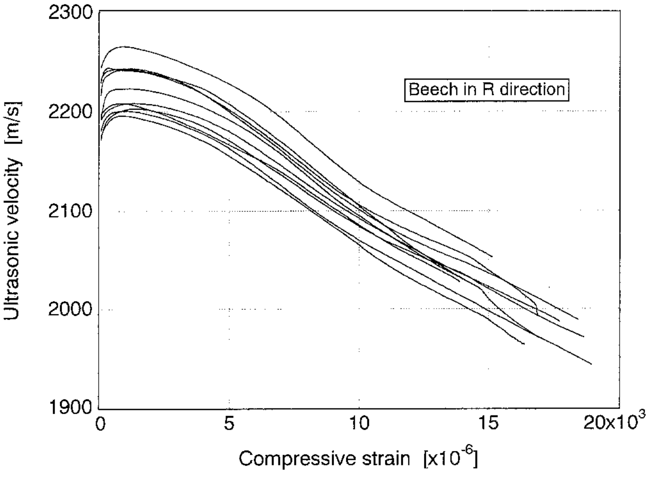

Fig. 5. Relations between velocity and strain of Japanese beech in the radial direction

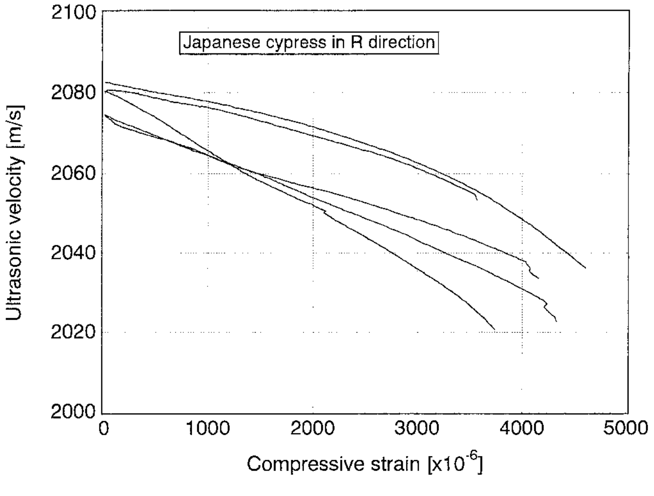

Fig. 6. Relations between velocity and strain of Japanese cypress in the radial direction

Figure 8 shows the percent changes in velocity due to radially applied compressive stress for Japanese beech, a hardwood. The velocity changes increased with increased application of compressive stress, and they revealed clearly proportional relations. The proportional constants of the lines in Fig. 8 indicate $-16.4 \times 10^{-3}\,\mathrm{MPa}^{-1}$, on average, but with large variation. This finding was the same as the results with longitudinal compression.[16]

Figure 9 shows examples of the percent changes in velocity due to radially applied compressive stress for Japanese cypress, a softwood. The relations between the velocity change and applied compressive stress indicated essentially straight lines, but in contrast to the changes seen in Fig. 8 they showed inverse proportion. In Fig. 9 the proportional constants of these lines were $4.77 \times 10^{-3}\,\mathrm{MPa}^{-1}$ on average and showed large variation.

Figure 10 shows the changes in velocity due to tangentially applied compressive stress on Japanese magnolia. The velocity changes decreased with increased compressive stress. The relations between them resulted in essentially straight lines, as in Fig. 9. The average proportional constant of these lines was $9.05 \times 10^{-3}\,\mathrm{MPa}^{-1}$.

The acoustoelastic constants were obtained from the proportional constants of the relations in Figs. 8–10. The relations between the velocity changes and applied stresses were expressed as follows: $(V - V_0)/V_0 = K \cdot \sigma$, where K is the acoustoelastic constant and σ the applied stress. The average values of K for each species are shown in Table 2. The values for the longitudinal direction obtained in the previous study[16] are shown for comparison.

The constants for hardwood species in the radial direction had negative signs; the others were positive. A negative

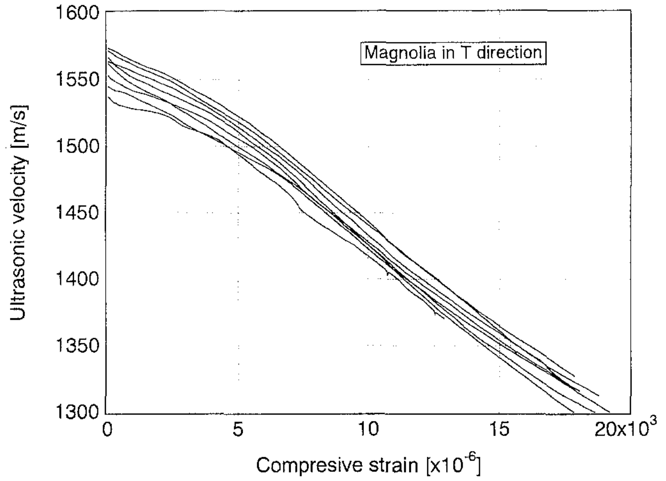

Fig. 7. Relations between velocity and strain of Japanese magnolia in the tangential direction

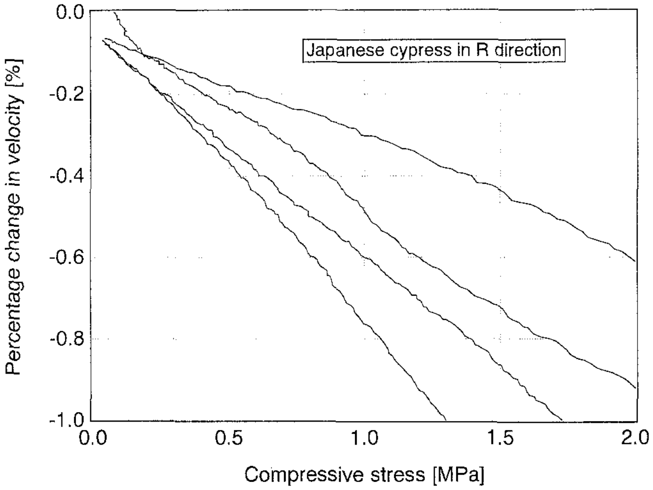

Fig. 9. Relations between percent changes in velocity and stress of Japanese cypress in the radial direction

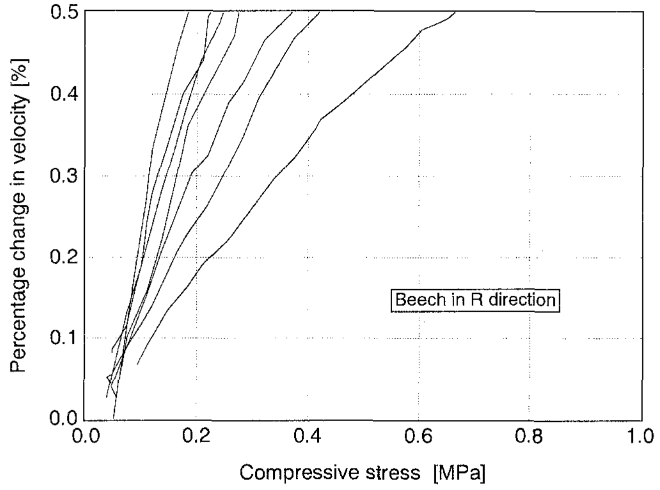

Fig. 8. Relations between percent changes in velocity and stress of Japanese beech in the radial direction

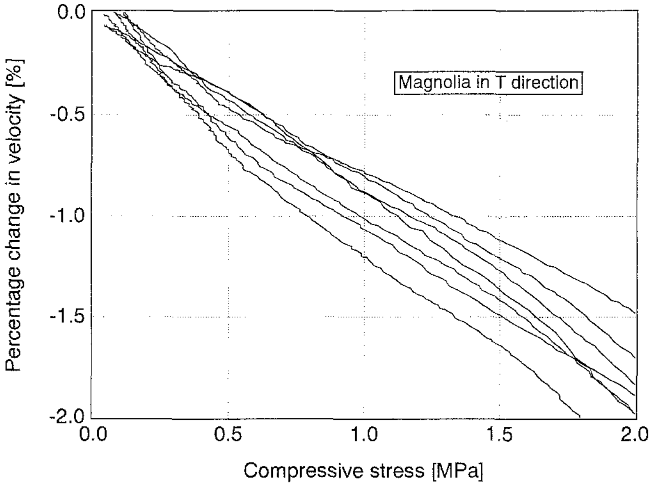

Fig. 10. Relations between percent changes in velocity and stress of Japanese magnolia in the tangential direction

Table 2. Acoustoelastic constants of wood

Specimen	Averaged acoustoelastic constants (MPa^{-1})		
	In radial direction (K_R)	In tangential direction (K_T)	In longitudinal direction (K_L)[16]
Alaska cedar	3.06×10^{-3} (1.60×10^{-3})	–	-3.28×10^{-3} (2.78×10^{-3})
Japanese cypress	4.77×10^{-3} (1.84×10^{-3})	–	-2.31×10^{-3} (1.38×10^{-3})
Japanese beech	-16.4×10^{-3} (3.47×10^{-3})	4.16×10^{-3} (1.84×10^{-3})	-4.44×10^{-3} (2.65×10^{-3})
Ash	-1.69×10^{-3} (0.76×10^{-3})	4.08×10^{-3} (0.52×10^{-3})	-1.12×10^{-3} (1.38×10^{-3})
Japanese magnolia	-10.0×10^{-3} (5.79×10^{-3})	9.05×10^{-3} (1.69×10^{-3})	-1.62×10^{-3} (0.81×10^{-3})
White spruce	3.67×10^{-3} (0.71×10^{-3})	–	-2.24×10^{-3} (1.04×10^{-3})

Numbers in parentheses are standard deviations.

sign means an increase in velocity with compressive stress, and a positive sign means a decrease. The magnitudes and signs of velocity changes were much different depending on the materials, ultrasonic wave mode, direction of propagation, and so on. The signs of the constants obtained in this study seemed to depend on the species and the structural directions of the wood, suggesting a relation between the acoustoelastic phenomena and the anatomical structure of wood.

The absolute values in the transverse direction were somewhat larger than those in the longitudinal direction. As mentioned previously,[16] the acoustoelastic constants for wood were extraordinarily higher than those for metallic materials, suggesting that the ultrasonic velocity propagating through a material whose Young's modulus is relatively small changes with a higher sensitivity to the applied stress.

As shown in Table 2, the acoustoelastic constants obtained in this experiment showed large variations. Large variations in the constants were also obtained for longitudinal compression, as reported previously.[16] The reason the constants were so variable is not clear. The origins of the large variations may be considered to be an unexpected problem of acoustoelastic experiments, or a natural property of wood.

Conclusions

The effect of compressive stress on the ultrasonic velocity of the longitudinal wave propagating through the transverse direction of wood was investigated experimentally. The results obtained can be summarized as follows.

1. An acoustoelastic phenomenon exists in the transverse direction of wood. The changes in the velocities of propagation of longitudinal waves in relation to applied stress are functions of the applied stress.
2. The changes in ultrasonic velocity depended on the species and the structural direction of the wood. There were two types: (1) The ultrasonic velocity increased with increases in compressive stress and then gradually decreased with further increases in stress. (2) The ultrasonic velocity decreased with increased stress from the beginning of loading. Changing the velocity gradually from an increase to a decrease at a low stress level was considered a unique phenomenon for wood.
3. The relations between velocity and stress at the initial stress level and those between velocity and strain with severe deformation gave essentially straight lines.
4. The acoustoelastic constants of wood were obtained from the relations between the changes in velocity and the applied stress at a low stress level. The absolute values of the constants in the transverse direction of wood were larger than those in the longitudinal direction of wood.

The ultrasonic velocity propagating through wood changed with great sensitivity to the applied stress. This finding suggests that the acoustoelastic technique can be used to determine the stress conditions of wood. On the other hand, the origins and the mechanism of the changes in ultrasonic velocities are not yet explained for wood. The results, inclusive of the previous ones,[16] suggest that there is a relations between the acoustoelastic phenomenon and the anatomical structure of wood. It also suggests a difference in the mechanism of the acoustoelastic phenomena for wood and metallic materials. Further experimental and theoretical investigations should be undertaken to determine the mechanism and to better apply the technique.

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