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ORIGINAL ARTICLE

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Acoustoelastic birefringence effect in wood II: influence of texture anisotropy on the polarization direction of shear wave in wood

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Abstract Ultrasonic shear waves were propagated through the breadth direction of a wood beam which was subjected to a bending load such that it was in a plane-stress state. The oscillation direction of the shear waves with respect to the wood beam axis was varied by rotating an ultrasonic sensor, and the relationship between the shear wave velocity and the oscillation direction was examined. The results indicate that when the oscillation direction of the shear wave corresponds to the tangential direction of the wood beam, the shear wave velocity decreases sharply and the relationship between shear wave velocity and rotation angle tends to become discontinuous. When the oscillation of the shear waves occurs in the anisotropic direction of the wood beam instead of in the direction of principal stress, the shear wave velocity exhibits a peak value. In addition, the polarization direction was found to correspond to the direction of anisotropy of the wood beam according to the theory of acoustoelastic birefringence with respect to plane stress. This indicates that when the acoustoelastic birefringence method is applied to stress measurement of wood, it is appropriate to align the oscillation direction of the shear wave with the principal axial direction of anisotropy in order to carry out ultrasonic measurement.

Key words Acoustoelasticity · Acoustoelastic birefringence · Texture anisotropy · Polarization direction · Ultrasonic wave velocity

Introduction

When two ultrasonic shear waves propagate transversely to the stress direction in an elastic body that is in a stressed state, a difference in the velocities of the two shear waves polarized in the direction of principal stress is induced. This phenomenon is called the acoustoelastic birefringence effect.[1–3]

An isotropic material under stress is considered to be an orthotropic body in which the direction of principal stress is along the axis of symmetry, and its acoustoelastic effect is explained in terms of stress-induced anisotropy.[4] However, in general, slight anisotropy resulting from the aggregate texture, i.e., texture anisotropy, produced during manufacturing processes such as plastic working and thermal processes, is present in metal materials. Therefore, in most cases, the acoustoelastic effect has been explained as a composite effect of stress-induced anisotropy and texture anisotropy. In the acoustoelastic method, in which high-precision ultrasonic measurement is carried out, the influence of texture anisotropy cannot be ignored, even in materials regarded to be isotropic.[5–7]

The acoustoelastic birefringence effect has been utilized in the measurement of the residual stress in metallic materials, and much research has been carried out on this effect thus far.[8–13] However, in order to measure residual stress, it is necessary to precisely evaluate texture anisotropy and separate the component of the acoustoelastic effect caused by texture anisotropy. Fukuoka et al.[12] measured residual stress at the rim of a train wheel, and concluded that when the distribution of texture anisotropy is uniform in the train wheel, the measurement of residual stress in another train wheel of the same type is possible using the mean value of texture anisotropy. As explained, when stress measurement is carried out by the acoustoelastic birefringence method, the texture anisotropy of the material should be known or the distribution of the texture anisotropy of the material should be uniform.

The ultimate goal of this study is to apply the acoustoelastic birefringence phenomenon to stress measurement in wood. In the previous report,[14] we confirmed the following regarding the acoustoelastic birefringence phenomenon of wood: the ultrasonic velocity of a shear wave propagating in wood in a stressed state decreases with increasing compressive stress but increases with increasing tensile stress within

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the elastic range, regardless of the oscillation direction of the ultrasonic shear wave; and, the relative difference of ultrasonic velocities (difference in ultrasonic velocities divided by the mean ultrasonic velocity) of the wood in an unstressed state, i.e., an indicator of texture anisotropy, is larger than those of metals and ceramics, indicating that wood is more orthotropic. The shear wave propagating in a material in a stressed state is polarized in the direction of principal stress due to the stress-induced anisotropy generated in the material.[15–18] Inoue et al.[16] measured the polarization direction of the shear wave and the difference in ultrasonic velocities of aluminum alloy with weak orthotropy, using the phase spectrum of shear waves. However, for a material having pronounced strong anisotropy, such as wood,[14] it is considered that the polarization direction of the shear wave does not always correspond to the direction of principal stress when the acoustoelastic birefringence effect, induced as a composite effect of stress-induced anisotropy and texture anisotropy, is taken into consideration.

Under such circumstances, the purpose of this study is to examine the influence of texture anisotropy on the polarization direction of the shear wave, within the acoustoelastic birefringence effect of wood, by propagating ultrasonic shear waves in the transverse direction with respect to the stress plane of a wood beam under unstressed or stressed states. The oscillation direction of the ultrasonic shear waves was changed by rotating an ultrasonic sensor with respect to the direction of anisotropy of the wood beam, and the relationship between the rotation angle (oscillation direction) and the shear wave velocity was examined. In addition, using the acoustoelastic birefringence law regarding plane stress, the polarization angle of the shear wave was calculated. Based on these results, the influence of the texture anisotropy on the polarization direction of the shear wave is discussed.

Experimental

Air-dried sapwood of Japanese magnolia (*Magnolia obovata* Thunb.) was used to prepare the specimen. The density and moisture content of the specimen were 0.51 g/cm^3 and 6.92%, respectively. The specimens were plate shaped with dimensions of 1300 (L) × 105 (H) × 15 (W) mm. In order to induce stress in the specimen, bending load was applied using an Instron testing machine, as shown in Fig. 1. Approximately 2 kN of bending load was applied to the specimen using a four-point loading method with a span of 1100 mm and distance of 350 mm between loading points. Consequently, the plate specimen was under plane stress composed of bending stress and shearing stress.

For the measurement of shear wave velocity, an ultrasonic velocity measurement apparatus (UVM-2, Ultrasonic Engineering, Tokyo) employing the sing-around method was used. The characteristic frequency of the ultrasonic sensor was 0.5 MHz and the sensor incorporated a piezoelectric element a diameter of 25.4 mm (CR-0016-SA, Harisonic Laboratories, CT, USA). The ultrasonic shear wave was propagated in the breadth (radial) direction of the wood beam (Fig. 1). Between the ultrasonic sensor and the specimen, a thin layer of epoxy resin (the main agent of the Araldite adhesive agent, AR-R30) was applied to increase adhesion between the sensor and the specimen.[19,20] The number of repetitions of sing-around was adjusted to 10 000 in this experiment. Ultrasonic velocity was measured at seven positions along the height direction of the beam 250 mm from the supporting point, as shown in Fig. 2. The seven points were at −37.5, −22.5, −7.5, 0, +7.5, +22.5, and +37.5 mm from the neutral axis in the height direction of the beam. At each measurement position, the ultrasonic sensor was rotated 360° in 15° steps assuming that the reference oscillation direction of the shear wave, i.e., 0°, corresponds to the longitudinal direction. Therefore, when the sensor rotates 90° (270°), the oscillation direction of the shear wave corresponds to the tangential direction. The sensors were rotated as explained above, and the shear wave velocity at each point was measured every 15°. To obtain the same degree of adhesion between the ultrasonic sensor and the specimen at the seven measurement positions, ultrasonic sensors were fastened using rubber bands, as shown in Fig. 3.

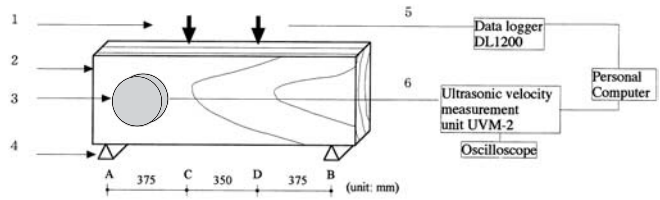

Fig. 1. Geometry of wood beam specimen, and setup for four-point loading and ultrasonic velocity measurement. *1*, Loading points (*C* and *D*); *2*, wood beam specimen; *3*, ultrasonic sensor; *4*, supporting points (*A* and *B*); *5*, load; *6*, sing-around periodic time

The measurement of the ultrasonic velocity was carried out for wood beam specimens under unstressed (without load) and stressed states (with load) (Fig. 2). The ultrasonic velocity was calculated by dividing the sing-around periodic time by the distance between transducers (i.e., the breadth of wood beam). During loading, the breadth of wood beam was changed by Poisson's effect, although the change in breadth was very small and had little effect on the ultrasonic velocity calculation. In this report, the wave velocity was calculated without consideration of the change in breadth. Measurement was carried out in a laboratory in which the temperature and relative humidity were held constant at 24°C and 55%, respectively.

For comparison with the results for anisotropic materials, i.e., wood, the ultrasonic shear wave velocity was measured using acrylic resin, which is isotropic. The acrylic resin specimen was a rectangular parallelepiped with dimensions of 30 × 30 × 60 mm, and Young's modulus and density of 3.33 GPa and 1.20 g/cm^3, respectively.

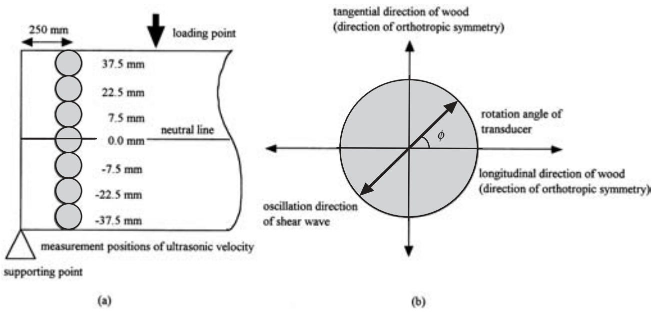

Fig. 2a,b. Illustrations of ultrasonic velocity measurement. **a** Measurement positions of shear wave velocity. **b** Directions of orthotropy and oscillation

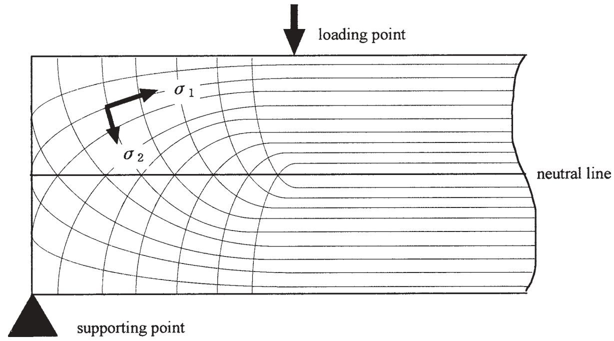

Fig. 4. Schema of lines of principal stress

Fig. 3. Setup for fastening ultrasonic transducers to wood beam specimen. *1*, Wood beam specimen; *2*, rubber band; *3*, ultrasonic sensor; *4*, holder

Principal stresses in bending beams

Each point at which shearing stress is applied is under plane stress. Assuming the plane-stress component at an arbitrary point (x, y) is expressed by σ_x, σ_y, and τ_{xy}, the principal stress (σ_1, σ_2) and the direction of the principal stress (θ) are given by Eqs. 1–3.[21,22]

$$\sigma_1 = \frac{1}{2}\left(\sigma_x + \sigma_y\right) + \frac{1}{2}\sqrt{\left(\sigma_x - \sigma_y\right)^2 + 4\tau_{xy}^2} \tag{1}$$

$$\sigma_2 = \frac{1}{2}\left(\sigma_x + \sigma_y\right) - \frac{1}{2}\sqrt{\left(\sigma_x - \sigma_y\right)^2 + 4\tau_{xy}^2} \tag{2}$$

$$\tan 2\theta = \frac{2\tau_{xy}}{\sigma_x - \sigma_y} \tag{3}$$

At each point in an elastic body, a curve that is tangential to the two directions of principal stress, which are orthogonal to each other, can be drawn and is called the line of principal stress (or trajectory of stresses). Equation 4 or 5 is obtained as the differential equation of the line of principal stress based on Eq. 3.[22]

$$\frac{dy}{dx} = \frac{\left(\sigma_x - \sigma_y\right) \pm \sqrt{\left(\sigma_x - \sigma_y\right)^2 + 4\tau_{xy}^2}}{2\tau_{xy}} \tag{4}$$

$$\frac{dy}{dx} = -\frac{2\tau_{xy}}{\left(\sigma_x - \sigma_y\right) \pm \sqrt{\left(\sigma_x - \sigma_y\right)^2 + 4\tau_{xy}^2}} \tag{5}$$

The arbitrary point (x, y) on the simply supported beam shown in Fig. 1 is under plane stress, which consists of bending stress σ_x due to the bending moment and shearing stress τ_{xy} due to the shearing force, and the condition $\sigma_y = 0$ holds. The lines of principal stress of the beam in such a state are shown in Fig. 4. The direction of principal stress at an arbitrary point is the tangential direction at the intersection of the two lines of principal stress. For example, when a 2-kN bending load is applied to the simply supported beam shown in Fig. 1, the principal stress and the direction of principal stress are calculated using Eqs. 1–3, and are shown in Table 1. The values in Table 1 were calculated for the positions 250 mm from the supporting point as shown in Fig. 2.

Assuming the longitudinal, tangential, and radial directions of the wood beam are along the X_1, X_2, and X_3 axes, respectively, ultrasonic shear waves propagating in the direction of the X_3 axis (radial direction), as shown in Fig. 1, are considered. As shown in Fig. 5, angles between the polarization directions of the shear wave and the X_1 axis are ϕ and $\phi + \pi/2$; angles between the directions of principal stresses, σ_1 and σ_2, and the X_1 axis are θ and $\theta + \pi/2$; and the direction in which σ_3 (principal stress) = 0 corresponds to the X_3 axis. According to the theory of acoustoelastic birefringence, the ultrasonic shear waves propagating in the direction of the X_3 axis are polarized in two mutually orthogonal directions due to the influence of texture anisotropy and stress-induced anisotropy. If the specimen material is isotropic, the polarization direction of the shear wave generally corresponds to the direction of principal stress due to the influence of only stress-induced anisotropy, and a difference in the velocities of the two shear waves which are polarized in the direction of principal stress (θ direction in Table 1) is observed; one velocity is maximal and the other is minimal.[15–18] However, in the case of a material with strong anisotropy, such as wood, it is not

Table 1. Principal stresses and direction of principal stress in this experiment

Position[a] (mm)	Principal stress (MPa)		Direction of principal stress (degrees)
	σ_1	σ_2	θ
37.5	0.033	−6.262	4.180
22.5	0.150	−3.887	11.103
7.5	0.484	−1.730	27.890
0	0.934	−0.934	45.000
−7.5	1.730	−0.484	62.110
−22.5	3.887	−0.150	78.897
−37.5	6.262	−0.033	85.820

[a] At the position 250 mm from the supporting position

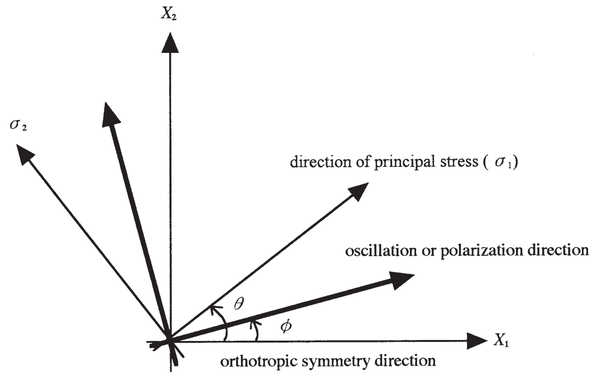

Fig. 5. Orientations of the axes of orthotropic symmetry, principal stress, and oscillation direction. ϕ, Oscillation or polarization angle (rotation angle); θ, direction of principal stress

known whether the polarization directions of the shear waves propagating in the material correspond to the direction of principal stress because texture anisotropy influences this phenomenon.

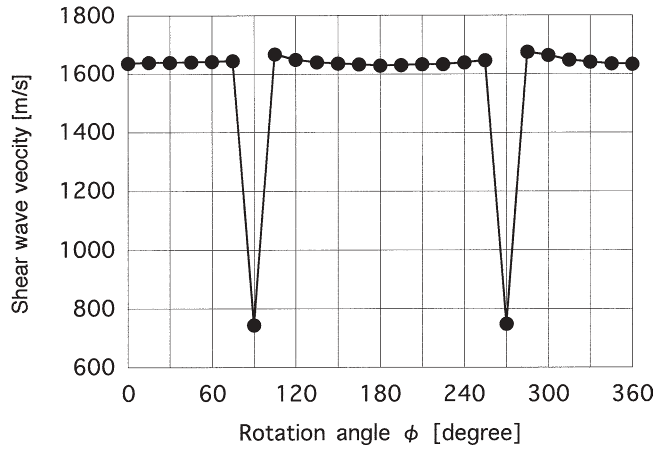

Fig. 6. Relationship between shear wave velocity and rotation angle of sensor for Japanese magnolia in unstressed condition

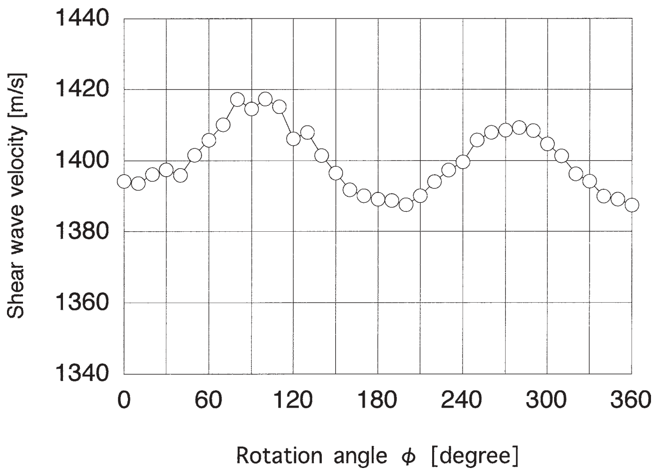

Fig. 7. Relationship between shear wave velocity and rotation angle of sensor for acrylic in an unstressed condition

Results and discussion

Relationships among anisotropic principal axis, oscillation direction of shear wave, and its velocity in the unstressed state

Figure 6 shows an example of the relationship between the rotation angle of the ultrasonic sensor and shear wave velocity in the unstressed state. The oscillation direction of the shear wave corresponds to the longitudinal and tangential directions when the rotation angle of the sensor is 0° (180°) and 90° (270°), respectively. The measurement position is +7.5 mm from the neutral axis. According to Fig. 6, shear wave velocity shows an almost constant value in general, although it changes slightly with changing rotation angle except at rotation angles of 90° and 270° and shows the minimum value at rotation angles of 0°, 180°, and 360°. At rotation angles of 90° and 270°, shear wave velocity decreases markedly and the relationship between shear wave velocity and rotation angle becomes discontinuous. Assuming the change of rotation angle from 0° to 180° to constitute one cycle, the trend of the change in shear wave velocity is similar for the next cycle. As explained above, shear wave velocity shows a peak value and discontinuous tendency when the oscillation direction corresponds to the anisotropic direction of the wood. This tendency was also observed at other measurement positions.

Figure 7 shows the relationship between shear wave velocity and rotation angle of the sensor for acrylic in the unstressed state. Unlike the case of wood (Fig. 6), the shear wave velocity changes continuously with increasing rotation angle of the sensor; it is a maximum at rotation angles of 90° and 270° and a minimum at 0° (360°) and 180°. The shear wave velocity is in the range of approximately 1390–1420 m/s. The change of shear wave velocity is much smaller than in the case of wood.

It is known that even in materials such as acrylic and metal, which are generally considered to be isotropic, anisotropy, i.e., texture anisotropy due to processing during manufacturing and thermal treatment, is included, and therefore the material exhibits a slight acoustoelastic bire-

Table 2. Shear wave velocities and texture anisotropy for Japanese magnolia and acrylic

Measurement position (mm)	Shear wave velocity (m/s)		Texture anisotropy
	V_1	V_2	α
Japanese magnolia			
37.5	1623.292	677.422	0.822
22.5	1637.969	713.832	0.786
7.5	1632.704	745.994	0.746
0	1625.858	759.852	0.726
−7.5	1624.607	813.723	0.665
−22.5	1630.345	815.460	0.666
−37.5	1592.249	830.599	0.629
Acrylic	1392.575	1400.645	0.006

V_1, Shear wave velocity polarized parallel to the longitudinal axis; V_2, shear wave velocity polarized normally to the longitudinal axis

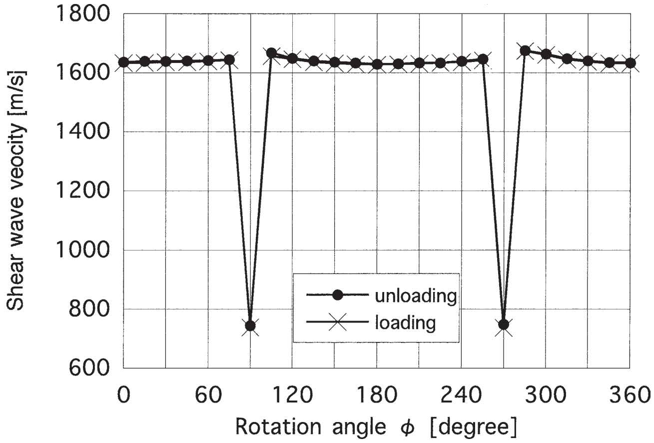

Fig. 8. Relationships between shear wave velocity and rotation angle of sensor for Japanese magnolia under stress

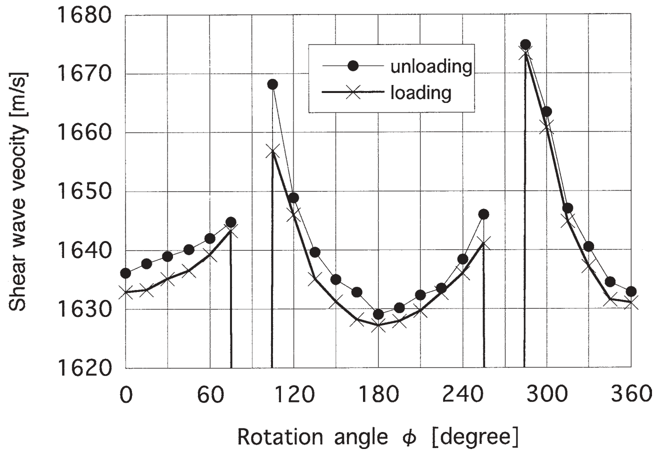

Fig. 9. Relationships between shear wave velocity and rotation angle of sensor for Japanese magnolia under stress. (Magnification of part of Fig. 8)

fringence effect.[5–7] The results shown in Fig. 7 support this finding.

In this study, we define the shear wave velocity at the rotation angles of 0° (180°) and 90° (Figs. 6, 7) to be V_1 and V_2, respectively. Using V_1 and V_2, texture anisotropy ($\alpha = (V_1 - V_2) / V_T$; V_T is the mean value of V_1 and V_2) was determined.[14] Table 2 summarizes the results. As shown in Table 2, the texture anisotropy of Japanese magnolia is two orders of magnitude higher than that of acrylic, confirming that the anisotropy of the wood is strong.

Relationship between oscillation direction and shear wave velocity in the stressed state

Figure 8 shows an example of the relationship between shear wave velocity and rotation angle of the ultrasonic sensor for Japanese magnolia under stress. Similar to the case shown in Fig. 6, the result was obtained at the measurement position +7.5 mm from the neutral axis. For reference, results obtained in an unstressed state, shown in Fig. 6, are also included in Fig. 8. When the rotation angle is either 90° or 270°, i.e., the oscillation direction of the shear wave corresponds to the tangential direction of the wood, the shear wave velocity decreases markedly, and the relationship between shear wave velocity and rotation angle becomes discontinuous and is similar to the case of the unstressed state. This change of shear wave velocity was also observed at other measurement positions.

Figure 9 shows a detailed view of part of Fig. 8. As shown in Fig. 9, the shear wave velocity in a stressed state is lower than that in an unstressed state. At measurement positions above the neutral axis (+37.5, +22.5, +7.5 mm), the shear wave velocities in the stressed state are lower than those in the unstressed state. In contrast, at measurement positions below the neutral axis (−37.5, −22.5, −7.5 mm), the shear wave velocities in the stressed state are higher than those in the unstressed state. Regarding the stress in a wood beam to which load is applied as shown in Fig. 1, it is considered that compressive bending stress is distributed on the upper (concave) side of the neutral axis, while tensile bending stress is distributed on the lower (convex) side of the neutral axis. In Part I of this study,[14] we reported that the shear wave velocity propagating across a stress axis decreases with increasing compressive stress, and increases with increasing tensile stress. Based on these findings, the difference in shear wave velocity in stressed and unstressed states, as shown in Fig. 9, is judged to be reasonable.

Figure 10 is obtained by adding the direction of principal stress to the relationship between shear wave velocity and rotation angle of the sensor shown in Fig. 9. In Fig. 10, the numbers outside the circle indicate the oscillation direction of the shear wave (rotation angle of sensor) and the distance from the circle center indicates the shear wave velocity. The solid bold orthogonal lines are the directions (θ = 27.89°, 117.89°) of the two principal stresses, σ_1 and σ_2, at the velocity measurement position, as shown in Table 1. According to Fig. 10, the oscillation direction of the shear wave at which the shear wave velocity shows the peak value does not correspond to the direction of principal stress.

In general, it is known that the ultrasonic wave propagating in the isotropic material under a stressed state shows the maximum and minimum velocities when the wave oscillates along the two directions of principal stress, and a difference between the two velocities in the two directions is observed (acoustoelastic birefringence effect). However, in the case of a material with strong anisotropy, such as wood, the peak of the shear wave velocity is observed in what is approximately the direction of anisotropy, instead of the direction of principal stress, as shown in Fig. 10. This tendency was also observed at other measurement positions. This finding indicates that the shear wave velocity propagating in a material with strong anisotropy is more strongly influenced by texture anisotropy than stress-induced anisotropy.

Polarization angle of shear wave

When the direction of the principal axes of texture anisotropy and stress-induced anisotropy do not correspond in the plate surface in the plane-stress state (θ π 0, $\pi/2$), as in this study, the polarization direction of the shear wave is governed by the composite effect of stress-induced anisotropy and texture anisotropy.[6,23] Therefore, the angle between the polarization direction of the shear wave and direction of anisotropy X_1 becomes ϕ, as shown in Fig. 5. According to the theory of acoustoelastic birefringence proposed by Iwashimizu,[6] the polarization angle ϕ can be expressed as

$$\tan 2\phi = \frac{Ca(\sigma_1 - \sigma_2)\sin 2\theta}{\alpha + Ca(\sigma_1 - \sigma_2)\cos 2\theta} \tag{6}$$

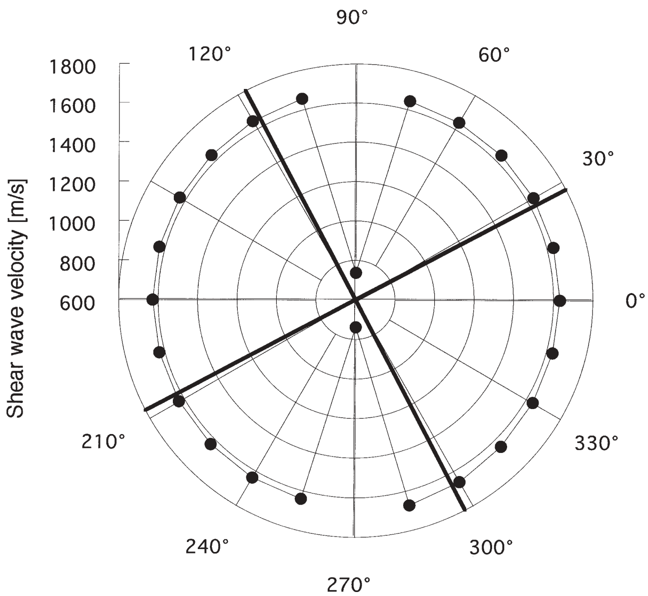

Fig. 10. Relationships between shear wave velocity and rotation angle of sensor, and between direction of principal stress and rotation angle. *Filled circles*, shear wave velocity; *solid bold lines*, direction of principal stress

Using Eq. 6, the polarization angle of the shear wave at each measurement position was calculated (Table 3). Here, Ca is the acoustoelastic birefringence coefficient; as the value of Ca, we used the mean of the values obtained in the previous report (6.68×10^{-4}/MPa).[14] For texture anisotropy (α), principal stress (σ_1, σ_2) and direction of principal stress (θ), values given in Tables 1 and 2 were used. Table 3 shows that the polarization angle (ϕ) is much less than the direction of principal stress, and is almost zero regardless of the measurement position. This indicates that the polarization direction of the shear wave almost corresponds to the direction of anisotropy, regardless of the direction of principal stress. In addition, the results in Figs. 8 and 10 support the calculation results.

In the case of an isotropic material, the polarization direction of the shear wave corresponds to the direction of principal stress. However, in the case of a material with strong anisotropy, such as wood, the polarization direction of the shear wave preferentially follows the direction of anisotropy because it is influenced more by texture anisotropy than by stress-induced anisotropy.

Based on the discussions above, we confirmed that the ultrasonic shear wave propagating in wood under stress is polarized in the direction of anisotropy of the wood. This indicates that when the acoustoelastic birefringence method is applied to stress measurement of wood, it is appropriate to align the oscillation direction of the shear wave with the direction of anisotropy of the wood, instead of the direction of principal stress, in order to measure the ultrasonic shear wave velocity in the wood. When the stress in an isotropic material is measured by means of the acoustoelastic birefringence method, it is necessary to confirm the direction of

Table 3. Direction of principal stress and polarization angle of shear wave

Position[a] (mm)	Difference of the principal stresses $\sigma_1 - \sigma_2$ (MPa)	Direction of principal stress θ (degrees)	Polarization angle ϕ (degrees)
37.5	6.296	4.180	0.021
22.5	4.036	11.103	0.037
7.5	2.214	27.890	0.047
0	1.868	45.000	0.049
−7.5	2.214	62.110	0.053
−22.5	4.036	78.897	0.044
−37.5	6.296	85.820	0.028

[a] At the position 250 mm from the supporting position

principal stress using the direction in which the shear wave velocity shows a peak value, by rotating the ultrasonic sensor, because, in general, the direction of principal stress is not known. On the other hand, in the case of wood, the direction of anisotropy is determined from the grain of the wood, and the shear wave velocity polarized in the two orthogonal directions can be measured. This is extremely advantageous for applying the acoustoelastic birefringence method to stress measurement of wood.

Conclusions

Ultrasonic shear waves were propagated transversely to the stress plane of wood in unstressed and stressed states; the relationship between shear wave velocity and oscillation direction was determined by changing the oscillation direction of the ultrasonic shear wave by rotating the ultrasonic sensor. The results indicated that when the oscillation direction of the ultrasonic shear wave corresponds to the tangential direction of the wood beam, the ultrasonic shear wave velocity decreases sharply and the relationship between shear wave velocity and rotation angle tends to become discontinuous. This change of ultrasonic velocity was observed for wood in both unstressed and stressed states. Also, the peak value of the shear wave velocity was observed when the oscillation direction of the shear wave corresponds to the direction of anisotropy of wood, regardless of the direction of principal stress. In addition, the polarization angle of the shear wave was calculated based on the theory of acoustoelastic birefringence; the polarization angle of the shear wave was almost zero regardless of the direction of principal stress, and the polarization direction corresponds to the direction of anisotropy of wood.

The polarization direction of the shear wave corresponds to the direction of anisotropy, regardless of the direction of principal stress for materials with strong anisotropy, such as wood. This indicates that when the acoustoelastic birefringence method is applied to stress measurement of wood, the oscillation directions of the ultrasonic shear wave should correspond to the two directions of texture anisotropy, which are orthogonal to each other. This is advantageous in applying the acoustoelastic birefringence method to stress measurement of wood. Based on the results reported in Part I[14] and Part II, we will measure the stress state of wood by the acoustoelastic birefringence method and report the results in Part III.

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