

Effect of wood properties on within-tree variation in ultrasonic wave velocity in softwood

Hasegawa, Masumi

Department of Agro-Environmental Science, Faculty of Agriculture, Kyushu University

Takata, Masato

Department of Bioresource and Bioenvironment, School of Agriculture, Kyushu University

Matsumura, Junji

Department of Agro-Environmental Science, Faculty of Agriculture, Kyushu University

Oda, Kazuyuki

Department of Agro-Environmental Science, Faculty of Agriculture, Kyushu University

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Corresponding Author: Dr. Masumi Hasegawa,

Corresponding Author's Institution: Kyushu University

First Author: Masumi Hasegawa

Order of Authors: Masumi Hasegawa; Masato Takata; Junji Matsumura; Kazuyuki Oda

Abstract: The radial variations in the velocity of ultrasonic waves propagating through Japanese cedar and Japanese cypress were experimentally investigated. In addition, the tracheid length (TL), microfibril angle (MFA), air-dried density (AD), and moisture content (MC) were measured in order to determine the effect of wood properties on velocity variations within the wood trunk. For both species, the longitudinal wave velocities measured in the longitudinal direction (VL) exhibited minimum values near the pith. For Japanese cedar, VL increased from 3600 m/s toward the bark and soon attained a constant value (= 4500 m/s). On the other hand, for Japanese cypress, VL kept increasing from 4000 m/s near the pith to 4800 m/s at the bark. These radial variations in VL coincided with those in the tracheid length. VL exhibited strong correlations with TL and MFA with a significant level of ($p < 0.01$). These findings suggest that the TL and MFA greatly affect the radial variation in the ultrasonic wave velocity in softwood.

Title

Effect of wood properties on within-tree variation in ultrasonic wave velocity in softwood

Author names and affiliations**Author (Corresponding author)**

Masumi HASEGAWA : Assistant professor, Kyushu Univ., 6-10-1 Hakozaki Higashi-ku Fukuoka

812-8581, Japan, +81-92-642-2982 (TEL/FAX), kmgmtmsm@agr.kyushu-u.ac.jp

Co-authors

Masato TAKATA : Undergraduate student, Kyushu Univ., 6-10-1 Hakozaki Higashi-ku Fukuoka 812-8581,
Japan, +81-92-642-2982,

Junji MATSUMURA : Associate professor, Kyushu Univ., 6-10-1 Hakozaki Higashi-ku Fukuoka
812-8581, Japan, +81-92-642-2980, matumura@agr.kyushu-u.ac.jp

Kazuyuki ODA : Professor, Kyushu Univ., 6-10-1 Hakozaki Higashi-ku Fukuoka 812-8581, Japan,
+81-92-642-2980, odak@agr.kyushu-u.ac.jp

1 1. Introduction

2 A wooden construction can sustain static, dynamic, earthquake, and wind loads over its entire life. However,
3 the stress conditions of its structural components must be determined nondestructively in order to prevent its collapse.
4 In this regard, the ultrasonic technique has been expected to be useful as an important tool for nondestructive testing of
5 a wooden construction. This technique has been researched in order to apply it to the quality control of sawing timber
6 [1,2] and to the maintenance of posts and beams in a wooden construction [3–7]. For the maintenance, Hasegawa et al.
7 suggested that the acoustoelastic technique could be applied to nondestructive stress analysis of structural components
8 comprising a wooden construction [3–5,7]. The ultrasonic velocity is an important parameter for nondestructive testing
9 of wood.

10 The ultrasonic wave velocity in trunk wood is not uniformly distributed because it is an anisotropic material.
11 Bucur et al. reported that the ultrasonic wave velocities in the longitudinal direction (V_L) vary from the pith to the bark
12 in Douglas fir (*Pseudotsuga menziesii*) [8]. Why does V_L exhibit radial variations within the trunk? Such
13 inhomogeneous distributions are disadvantages to apply the ultrasonic technique to a wooden construction as a
14 nondestructive testing method. Therefore, it is needed to know the distributions of velocities and clarify their
15 mechanism.

16 The objective of this study is to elucidate the effect of wood properties on within-tree variation (radial
17 variation) in the ultrasonic velocity in softwood. In the first series of experiments, we focused on the radial variations in
18 tracheid structures i.e., the tracheid length (TL) and the microfibril angle (MFA) of the S_2 layer in order to find the

mechanism of the velocity distributions. Softwood constitutes more than 90% axial cells, i.e., tracheids, which are highly elongated in the grain direction. Tracheid structures determine the physical and mechanical properties of wood. The tracheid cells impart strength and stiffness to the stem and conduct water from the roots to the crown. A tracheid cell comprises a primary layer and three secondary layers, S_1 , S_2 , and S_3 , as shown in Fig. 1. The cellulose microfibrils of three secondary layers are oriented toward the longitudinal axis of tracheid. The angle between the direction of microfibrils and this axis is called the MFA. The S_2 layer occupies about 80% of the secondary cell wall; hence, its MFA is an important factor in determining the physical and mechanical properties of wood [9–11]. Similarly, the MFA of this layer may affect ultrasonic velocity. From this viewpoint, the relations of V_L to TL and MFA were investigated.

In the second series of experiments, we focused on the relations of ultrasonic velocity to density and moisture content (MC). The ultrasonic velocity in solid materials generally depends on the elastic constant and density [12,13]. Hugh and Kelly reported that the ultrasonic wave velocities were determined as a function of the applied stress and were used to calculate the Lamé constants and third-order constants of isotropic materials, e.g., iron and Pyrex glass [12]. In the field of wood science, researchers have reported that physical and mechanical properties, e.g., the density [14–16], elastic constant [17–19], and moisture content [20–22] of wood greatly influence the ultrasonic velocity in the wood. Bucur determined the diagonal and off-diagonal stiffness terms for wood by the ultrasonic method [17]. Sakai et al. reported that the variation in the longitudinal wave velocity decreases with an increase in the MC until the fiber saturation point is reached [20]. In this study, the effects of density and MC on V_L were investigated in addition to those of TL and MFA.

In this experiment, the specimens of Japanese cedar and Japanese cypress, which are major domestic structural lumbars in Japan were used. The velocities of longitudinal ultrasonic waves propagated along three orthotropic (longitudinal, radial, tangential) directions in softwood were measured with the sing-around method. In addition, the radial variations in velocity and in wood properties, namely, TL, MFA, AD, and MC were also measured. From these radial variations in the velocities and wood properties and the correlations among them, the mechanism of velocity distribution was investigated.

2. Materials and method

2.1 Materials

Three 60-year-old Japanese cedar (*Cryptomeria japonica* D.Don) and three 28-year-old Japanese cypress (*Chamaecyparis obtusa* Endl) were used as the test materials. The diameter at the breast height (1.3 m from the ground level) and the height of the sample trees are listed in Table 1.

Logs were cut down from a 1.0-m height from the ground level. Wood disks with a 10-cm thickness were cut from these logs. Strips with a 3-cm thickness were cut from the disks in air-dried conditions for the purpose of measuring the velocities of ultrasonic waves in the longitudinal and tangential directions. Thereafter, the strips were sliced into 1-cm pieces for measuring the velocities in the radial direction.

2.2 Ultrasonic measurement

For measuring velocities in the longitudinal and tangential directions, an ultrasonic sensor was slid from the pith to the outside in 1-cm steps, as shown in Fig. 2, and the ultrasonic wave velocity was measured at every position of the sensor. The velocity in the radial direction was measured at 1-cm intervals on each sliced piece, starting from the pith and sliding the sensor toward the outside. The ultrasonic velocity was measured with the sing-around method [3], using a model UVM-2 unit (Ultrasonic engineering, Tokyo). Piezoelectric transducers with a natural frequency of 0.5 MHz and a diameter of 1 inch (models CR-0016-S for longitudinal waves by Staveley Instruments, USA) were used to detect the ultrasonic waves. Silicone grease (SH111) was used as the coupling medium in order to improve the bonding between the transducers and the wood specimen, and a rubber band was employed to hold the transducers against the specimen [7].

11

2.3 Wood properties

After ultrasonic measurement, the AD of the sliced pieces was measured using the water displacement method. Each sliced piece was cut into two small pieces: one for TL and MFA measurements, and the other for MC measurements. For TL and MFA measurements, latewood was cut from the small pieces. The latewood was macerated by treating it with of a 1:1 mixture solution of glacial acetic acid and 30% hydrogen peroxide for 48 h at 80°C. After staining the macerated tracheids with safranin, they were observed under 50-times magnification with a profile projector (model V-12 by Nikon Instruments, Tokyo), and their lengths were measured. At each point, 30 TLs were averaged. The MFA

is known to follow the orientation of bordered pit apertures [23,24]. In this study, the images of the tangential wall of the stained tracheid were captured with a light microscope (40× objective lens) and a digital camera (DP70, Olympus Co. Ltd, Tokyo), and the angles of bordered pit apertures were measured with an image analysis system (WinROOF, Mitsuya Co. Ltd, Tokyo). At each position, 20 MFAs were measured and their average was regarded as the MFA at that position.

Each sliced specimen was dried overnight in a constant-temperature oven at 105°C. The MC of wood can be calculated as the ratio of the water content weight to oven-dry weight.

3. Results

3.1 Radial variations in longitudinal wave velocities within the wood trunk

Figure 3 shows the radial variations of velocity along three orthotropic directions for Japanese cedar and Japanese cypress. For Japanese cedar, the longitudinal wave velocities in the longitudinal direction (V_L) exhibited a minimum value of about 3600 m/s near the pith. These increased toward the outside, up to a distance of 6 cm from the pith, and reached a constant value of 4500 m/s. For Japanese cypress, V_L exhibited a minimum value of about 4000 m/s near the pith. V_L kept increasing toward the outside and attained a value of 4800 m/s. On the other hand, for both species, the longitudinal wave velocities in the radial and tangential directions (V_R , V_T) exhibited constant values from the pith to the bark. The averaged velocities along the three orthotropic axes for Japanese cedar and Japanese cypress are summarized in Table 2. The values of velocities for other softwood are shown for comparison with those investigated in

this study. For both species, three velocities (V_L , V_R , V_T) were found to have the same values as those in the previous study [15]. These velocities exhibit no significant difference between Japanese cedar and Japanese cypress.

3.2 Radial variations in longitudinal wave velocities and wood properties

Figure 4 shows the radial variations in V_L and TL for Japanese cedar and Japanese cypress. The variations in V_L are the magnified views of a part of Fig. 3. The averaged TLs were minimum near the pith, and their values were 1.5 mm for Japanese cedar and 1.3 mm for Japanese cypress. The TL for Japanese cedar gradually increased toward the outside and attained a constant value (3.0 mm) in regions beyond 6 cm from the pith. The TL for Japanese cypress gradually increased to 3.0 mm toward the outside. The variation patterns of the TL in the radial direction coincided with those of V_L .

Figure 5 shows the radial variations in V_L and the MFA for Japanese cedar and Japanese cypress. The averaged MFA for Japanese cedar and Japanese cypress near the pith exhibited the maximum values of about 37° and 30°, respectively. The MFA for Japanese cedar dropped to 6 cm and thereafter gradually decreased to 12° toward the outside. The MFA for Japanese cypress continuously decreased toward the outside where it attained a value of 10°. The variation patterns of the MFA in the radial direction inversely coincided with those of V_L .

Figure 6 shows the radial variations in V_L and the AD for Japanese cedar and Japanese cypress. The averaged AD was maximum near the pith, and its values were 0.60 g/cm³ for Japanese cedar and 0.52 g/cm³ for Japanese cypress. AD decreased to 0.42 g/cm³ and 0.47 g/cm³ for Japanese cedar and Japanese cypress, respectively.

The decreasing degree of AD was larger for Japanese cedar than that for Japanese cypress. The variation patterns of AD in the radial direction inversely coincided with those of V_L .

3.4 Relationships between longitudinal wave velocities and wood properties

The correlation coefficients between the velocities and wood properties are summarized in Table 3. V_R and V_T had no correlations with wood properties. In this study, the only the correlations between V_L and wood properties were investigated. Figures 7 shows the relations between V_L and the wood properties. Correlations between V_L and TL were positive at a 1% significant level and were $r = 0.91$ for Japanese cedar and $r = 0.85$ for Japanese cypress. It should be noted that until now, there are no reports for relations between V_L and TL. Polge reported a strong correlation ($r = 0.90$) between the fiber length and V_L for a cherry tree [25]. Further, the MFA had negative correlations with V_L at a 1% significant level ($r = -0.90$ for Japanese cedar and $r = -0.82$ for Japanese cypress). These negative correlations agreed with those found in the previous studies [26,27].

AD had negative correlations with V_L at a 1% significant level ($r = -0.83$ for Japanese cedar and $r = -0.74$ for Japanese cypress). Many researchers reported the correlations between the AD and V_L in various wood species since then [14–16]. MC had negative correlations with V_L at a 5% significant level ($r = -0.43$ for both species). Further, it has been reported that V_L decreases with an increase in the MC until the fiber saturation point (FSP) is reached [20–22]. In this study, the MC is less than the FSP by 8% to 15%. The changes in velocity due to MC showed the same tendency as that observed in the previous study.

4. Discussion

V_L exhibited the largest value among the three directions, as shown in Table 2. The values of longitudinal velocities in wood are known to rank in the ascending order of V_L , V_R , V_T . The ratios between V_L , V_R , and V_T were obtained from the data in Table 2. The ratios of V_L to V_R and V_T were 2.3:1 and 3.1:1 for Japanese cedar and 2.4:1 and 3.2:1 for Japanese cypress, respectively (Table 4). Bucur reported that V_L/V_R and V_L/V_T ratios were 2.5 and 3.6 for softwood [8]. The ratios obtained in this study significantly coincided with those in the previous study [8], as indicated by the test of goodness of fit ($p < 0.01$).

As mentioned in the introduction, more than 90% tracheids are oriented parallel to the axial direction in softwood. Their length-to-width ratio is 100:1. As a result of this strong structural anisotropy, the velocity in wood is fastest along the longitudinal direction. For the radial direction, the annual rings constitute earlywood (EW) and latewood (LW), as shown in Fig. 8. The densities of EW and LW are different because of the difference in their lumen diameters and cell wall thicknesses. The density ratios of EW and LW range from 1.3 to 3.1 depending on wood species [28,29]. An ultrasonic wave is refracted at the boundary of solid materials because of the difference of density, and loses its energy. Therefore, V_R is half of V_L . Ray cells extend in the radial direction across the annual ring (Fig.8) and prevent the propagation of ultrasonic waves in the tangential direction. Bucur and Fenrry evaluated the attenuation of ultrasonic waves in relation to the three orthotropic axes [30]. The tangential direction exhibits the highest attenuation of ultrasonic longitudinal waves. For these reasons, V_T was one third as large as V_L .

The distributions of V_L for Japanese cedar and Japanese cypress were different, as shown in Fig. 4. These

1 results were related to the tracheid structures. The TL is minimum near the pith and increases regularly from the pith to
2 the outside. It generally increases at a rapid rate for the first 10 to 15 years and exhibits a constant value after 20 years.
3 The variation in TL is known to be an indicator for distinguishing the line of demarcation between juvenile and mature
4 woods [31]. Wood formed in the region near the pith during the early cambium age is called the juvenile wood. All
5 wood characteristics are quite variable within the juvenile zone and much more constant within the mature zone. From
6 the results presented in Fig. 4, the TL for Japanese cedar shows a constant value (3.0 mm) in a region beyond 6 cm from
7 the pith. The demarcation between both juvenile and mature woods seems to be indicated by the samples cut from a
8 region lying beyond 6 cm from the pith. Test samples constitute the juvenile and mature woods. On the other hand, the
9 TL for Japanese cypress did not attain a constant value, as shown in Fig. 4. The test specimens obtained from Japanese
10 cypress constitute only the juvenile wood. The difference in V_L variations is not due to that in the characteristics of the
11 wood species, but due to the difference in the cambium ages of the wood species.

12 V_L exhibited strong positive correlations with TL at a 1% significant level. So far, there have been no
13 reports for the correlations between V_L and TL. We could experimentally confirm the correlations among them for the
14 first time. Bucur et al. compared the velocities in the longitudinal direction for Douglas fir between the compression
15 wood (CW) and the normal wood (NW) [8]. In general, CW is formed on the under (compression) side of branches and
16 on the lower side of leaning trunks of softwood. Its TL is generally 10% to 40% shorter than that of NW. In the
17 abovementioned study, Bucur et al. reported that the velocities in the CW were smaller than those in the NW. The
18 tracheid length seems to affect V_L .

V_L had strong negative correlations with MFA at a 1% significant level. Geoffrey M.D. et al. reported that the velocities in green timber for *Pinus radiata* were strongly related with the MFA ($r = -0.65$, $p < 0.05$) [26]. B. Lachenbruch et al. reported that the velocity was correlated more strongly with the MFA ($r = -0.69$) than with density ($r = 0.33$) [27]. In addition, the path coefficient for the MFA was statistically significant ($\beta = -0.667$, $p < 0.001$), but that for the density was not ($\beta = -0.067$, $p = 0.255$), as indicated by the path analysis [27]. The arrangement of the microfibril may affect V_L in a manner similar to the TL. Further, there is room for investigating which wood properties have a significant impact on V_L in softwood.

V_L had strong negative correlations with AD at a 1% level, as shown in Fig. 7. Bucur reported that the longitudinal wave velocities for Australian hardwoods have negative correlation with their AD [14]. Mishiro reported that the velocities for seven softwoods and twelve hardwoods were independent of the AD [15]. Fabiana reported a positive correlation between the velocities and the AD for the Brazilian tropical wood species [16]. They investigated the correlations among wood species, while we did the correlations within the same wood species. We could not compare the results between this study and the previous studies [14–16]. The changes in the TL and MFA affected those in V_L . The TL and MFA were found to change in the area of juvenile wood and exhibited constant values in the mature wood, as shown in Figs. 5 and 6. For estimating the effect of only AD on V_L , it is required to classify the measuring positions as pertaining to the juvenile and mature woods in order to remove the effect of changes in the TL and MFA.

V_R and V_T had almost no correlations with the TL, MFA, and AD, as shown in Table 3. V_R and V_T exhibited constant values independent of the changes in the wood properties. Further research is required to find out why V_R and

V_T show no variations from the pith to the bark. It is interesting to investigate the relations between V_R , V_T , and other factors, e.g., the annual ring width, latewood percentage (ratio of the latewood width to the annual ring width), and the cell wall thickness.

5. Conclusion

The effect of wood properties on within-tree variation in longitudinal wave velocities in softwood was experimentally investigated. The velocities in the longitudinal direction (V_L) changed from the pith toward the bark, while those in the radial and tangential directions exhibited constant values. The radial variation in V_L showed the same patterns as those in the tracheid length (TL) and opposite to those in the microfibril angle (MFA) and the air-dried density (AD). V_L exhibited strong correlations with the TL, MFA, and AD at a 1% significant level. These findings revealed that the wood properties, i.e., the TL, MFA, and AD greatly influence the velocities in the longitudinal direction. In the future, we will investigate the following three topics, and clarify the mechanism of radial variations in ultrasonic wave velocity in wood.

(1) Velocity distributions in hardwood: Hardwoods have more complex wood structures than do softwoods. The effect of wood anatomy and structure on the radial variations of velocity in wood will be investigated by comparing the results between softwood and hardwood.

(2) Difference between juvenile and mature woods: V_L and the wood properties in the radial direction change within the areas of juvenile woods. Hence, it is necessary to classify the wood specimens into juvenile and mature woods.

(3) Multivariate statistics: The wood properties are not solely but mutually related to the velocities. Therefore, by multivariate statistics it is essential to analyze which wood properties have a significant impact on V_L .

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References

- 1 [1] J.L. Sandoz., Grading of construction timber by ultrasound, Wood Sci. Technol. 23 (1989) 95–108.
- 2 [2] S.Y. Wang, C.J. Lin, C.M. Chiu, Evaluation of wood quality of Taiwan trees grown with different
- 3 thinning and pruning treatments using ultrasonic-wave testing, Wood Fiber Sci. 37 (2005) 192–200.
- 4 [3] M. Hasegawa, Y. Sasaki, Acoustoelastic birefringence effect in wood I: Effect of applied stresses on the
- 5 velocities of ultrasonic shear waves propagating transversely to the stress direction, J. Wood
- 6 Sci. 50 (2004) 47–52.
- 7 [4] M. Hasegawa, Y. Sasaki, Acoustoelastic birefringence effect in wood II: Influence of texture anisotropy on
- 8 the polarization direction of shear wave in wood, J. Wood Sci. 50 (2004) 101–107.
- 9 [5] M. Hasegawa, Y. Sasaki, Acoustoelastic birefringence effect in wood III: Ultrasonic stress determination of
- 10 wood by acoustoelastic birefringence method, J. Wood Sci. 50 (2004) 108–114.
- 11 [6] M. Yamasaki, Y. Sasaki, Determining Young's modulus of timber on the basis of a strength database and
- 12 stress wave propagation velocity I: an estimation method for Young's modulus employing Monte Carlo
- 13 simulation, J. Wood Sci. (2010) 1–7.
- 14 [7] M. Hasegawa, J. Matsumura, R. Kusano, S. Tsushima, Y. Sasaki, K. Oda, Acoustoelastic effect in *Melia*
- 15 *azedarach* for nondestructive stress measurement, Constr. Build. Mater. 24 (2010) 1713–1717.
- 16 [8] V. Bucur., Acoustics of wood 2nd edition, Springer-Verlag, Berlin, 2006.
- 17 [9] D.J. Cown, J. Hebert, R. Ball, Modelling Pinus radiata lumber characteristics. Part 1: Mechanical
- 18 properties of small clears, N. Z. J. For. Sci. 29 (1999) 203–213.
- 19 [10] K. Yamashita, Y. Hirakawa, Y. Fujisawa, R. Nakada, Effects of microfibril angle and density on variation
- 20 of modulus of elasticity of sugi (*Cryptomeria japonica*) logs among eighteen cultivars (in Japanese),
- 21 Mokuzai Gakkaishi 46 (2000) 510–522.

- 1 [11] T. Deresse, R.K. Shepard, S.M. Shaler, Microfibril angle variation in red pine (*Pinus resinosa* Ait.) and
2 its relation to the strength and stiffness of early juvenile wood, *For. Prod. J.* 53 (2003) 34–40.
- 3 [12] D.S. Hughes, J.L. Kelly, Second-Order elastic deformation of solids, *Phys. Rev.* 92 (1953)
4 1145–1149.
- 5 [13] R.H. Bergman, R.A. Shahbender, Effect of statically applied stresses on the velocity of propagation of
6 ultrasonic waves, *J. Appl. Phys.* 29 (1958) 1736–1738.
- 7 [14] V. Bucur, R.C. Chivers, Acoustic properties and anisotropy of some Australian wood species, *Acustica*
8 75 (1991) 69–74.
- 9 [15] A. Mishiro, Effect of density on ultrasonic velocity in wood, *Mokuzai Gakkaishi* 42 (1996) 887–894.
- 10 [16] F.G.R. de Oliveira, A. Sales, Relationship between density and ultrasonic velocity in Brazilian tropical
11 woods, *Bioresour. Technol.* 97 (2006) 2443–2446.
- 12 [17] V. Bucur, R.R. Archer, Elastic constants for wood by an ultrasonic method, *Wood Sci. Technol.*
13 18 (1984) 255–265.
- 14 [18] D. Keunecke, W. Sonderegger, K. Pereteanu, T. Lüthi, P. Niemz, Determination of Young's and shear
15 moduli of common yew and Norway spruce by means of ultrasonic waves, *Wood Sci. Technol.* 41 (2007)
16 309–327.
- 17 [19] M. Ivković, W.J. Gapare, A. Abarquez, J. Ilic, M.B. Powell, H.X. Wu, Prediction of wood stiffness,
18 strength, and shrinkage in juvenile wood of radiata pine, *Wood Sci. Technol.* 43 (2009) 237–257.
- 19 [20] H. Sakai, A. Minamisawa, K. Takagi, Effect of moisture content on ultrasonic velocity and attenuation in
20 woods, *Ultrasonics* 28 (1990) 382–385.
- 21 [21] A. Mishiro, Ultrasonic velocity in wood and its moisture content I: Effect of moisture gradients on

- 1 ultrasonic velocity in, *Mokuzai Gakkaishi* 41 (1995) 1086–1092.
- 2 [22] F.G.R. de Oliveira, M. Candian, F.F. Lucchette, J. Luis Salgon, A. Sales, A technical note on the
3 relationship between ultrasonic velocity and moisture content of Brazilian hardwood (*Goupia glabra*),
4 *Build. Environ.* 40 (2005) 297–300.
- 5 [23] Y. Hirakawa, Y. Fujisawa, The relationships between microfibril angles of S2 layer and latewood tracheid
6 lengths in elite sugi tree (*Cryptomeria japonica*) clones (in Japanese), *Mokuzai Gakkaishi* 41 (1995)
7 123–131.
- 8 [24] M. Nishimura, K. Oda, J. Matsumura, H. Matsunaga, Pit aperture angle of sugi (*Cryptomeria japonica*)
9 tracheid as an index of wood quality for forest tree breeding (in Japanese). *Bull. Kyushu. Univ.* 81 (2003)
10 51–58.
- 11 [25] H. Polge, Essai de caractérisation de la veine verte du merisier, *Ann. Sci. For.* 41 (1984) 45–58.
- 12 [26] G.M. Downes, J.G. Nyakuengama, R. Evans, et al., Relationship between wood density, microfibril angle
13 and stiffness in thinned and fertilized *Pinus radiata*, *IAWA J.* 23 (2002) 253–265.
- 14 [27] B. Lachenbruch, G.R. Johnson, G.M. Downes, R. Evans, Relationships of density, microfibril angle, and
15 sound velocity with stiffness and strength in mature wood of Douglas-fir, *Can. J. For.*
16 *Res.* 40 (2010) 55–64.
- 17 [28] F.F.P. Kollmann, W.A. Côté Jr., *Principles of Wood Science and Technology I: Solid Wood*,
18 Springer- Verlag, Berlin, 1968.
- 19 [29] S. Cramer, D. Kretschmann, R. Lakes, T. Schmidt, Earlywood and latewood elastic properties in loblolly
20 pine, *Holzforschung* 59 (2005) 531–538.
- 21 [30] V. Bucur, F. Feeney, Attenuation of ultrasound in solid wood, *Ultrasonics* 30 (1992) 76–81.

1 [31] T. Shiokura, Extent and differentiation of the juvenile wood zone in coniferous tree trunks (in Japanese),
2 Mokuzai Gakkaishi 28 (1982) 85–90.

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21 **Figure captions**

- 1 Fig. 1 Cell wall structure of tracheid.
- 2 Fig. 2 Setup for ultrasonic velocity measurement in three orthotropic directions: (a) Ultrasonic propagation direction
3 and (b) Sliding direction of ultrasonic sensor.
- 4 Fig. 3 Radial variations in the longitudinal wave velocities in three orthotropic directions. *Filled marks*: Japanese
5 cypress, *Open marks*: Japanese cedar.
- 6 Fig. 4 Radial variations in longitudinal wave velocities and tracheid length: (A) Japanese cedar and (B) Japanese
7 cypress. *Solid lines*: tracheid length, *Dotted lines*: longitudinal wave velocity.
- 8 Fig. 5 Radial variations in longitudinal wave velocities and microfibril angle: (A) Japanese cedar and (B) Japanese
9 cypress. *Solid lines*: microfibril angle, *Dotted lines*: longitudinal wave velocity.
- 10 Fig. 6 Radial variations in longitudinal wave velocities and air-dried density: (A) Japanese cedar and (B) Japanese
11 cypress. *Solid lines*: air-dried density, *Dotted lines*: longitudinal wave velocity.
- 12 Fig. 7 Relationships between longitudinal wave velocities and wood properties: (A) tracheid, (B) microfibril angle, (C)
13 air-dried density, and (D) moisture content. *Filled marks*: Japanese cedar, *Open marks*: Japanese cypress.
- 14 Fig. 8 Wood structure of softwood: L, Longitudinal direction; R, Radial direction; T, Tangential direction.
- 15 Table 1 Diameter at the breast height and tree height of Japanese cedar and Japanese cypress.
- 16 Table 2 Ultrasonic wave velocities along three orthotropic axes for Japanese cedar and Japanese cypress.
- 17 Table 3 Correlation coefficients between ultrasonic velocities in and wood properties of Japanese cedar and Japanese
18 cypress.
- 19 Table 4 Ratios of longitudinal wave velocities along three orthotropic axes.

Table 1 Diameter at the breast height and tree height of Japanese cedar and Japanese cypress.

Species	DBH [cm]	Height [m]
Japanese cedar	27.5 (2.1)	20.9 (3.4)
Japanese cypress	25.4 (1.6)	13.9 (0.5)

Numbers in parentheses denote standard deviations

Table 2 Ultrasonic wave velocities along the three orthotropic axes for Japanese cedar and Japanese cypress.

Species	V_L [m/s]	V_R [m/s]	V_T [m/s]
Japanese cedar	4310 (339)	1863 (9.0)	1388 (15.1)
Japanese cypress	4492 (285)	1865 (8.1)	1389 (14.6)
Japanese cedar ¹⁵	4950	2150	1610
Japanese cypress ¹⁵	5010	2050	1220
Spruce ³⁰	5600	2000	1600
Douglas fir ³⁰	5500	2330	1990

Numbers in parentheses denote standard deviations

Table 3 Correlation coefficients between ultrasonic wave velocities and wood properties of Japanese cedar and Japanese cypress.

Japanese cedar	V_L	V_R	V_T	TL	MFA	AD	MC
V_L							
V_R	- 0.40 *						
V_T	0.06	0.03					
TL	0.91 **	- 0.30	- 0.02				
MFA	- 0.90 **	0.41 *	0.04	- 0.93 **			
AD	- 0.83 **	0.26	0.09	- 0.81 **	0.83 **		
MC	- 0.43 *	0.54 **	- 0.03	- 0.24	0.28	0.23	
Japanese cypress	V_L	V_R	V_T	TL	MFA	AD	MC
V_L							
V_R	0.16						
V_T	0.17	0.07					
TL	0.85 **	- 0.04	0.24				
MFA	- 0.82 **	- 0.06	- 0.20	- 0.90 **			
AD	- 0.74 **	- 0.13	- 0.14	- 0.61 **	0.61 **		
MC	- 0.43 **	- 0.37	- 0.18	- 0.09	0.28	0.55 **	

** and * statistically denote 1% and 5% significant level, respectively.

Table 4 The ratios of longitudinal wave velocites along three orthotropic axis.

Species	V_L/V_R	V_L/V_T	V_R/V_T
Japanese cedar	2.31	3.12	1.34
Japanese cypress	2.41	3.23	1.34
Japanese cedar ¹⁵	2.30	3.07	1.34
Japanese cypress ¹⁵	2.44	4.11	1.68
Spruce ³⁰	2.80	3.50	1.25
Douglas fir ³⁰	2.36	2.76	1.17

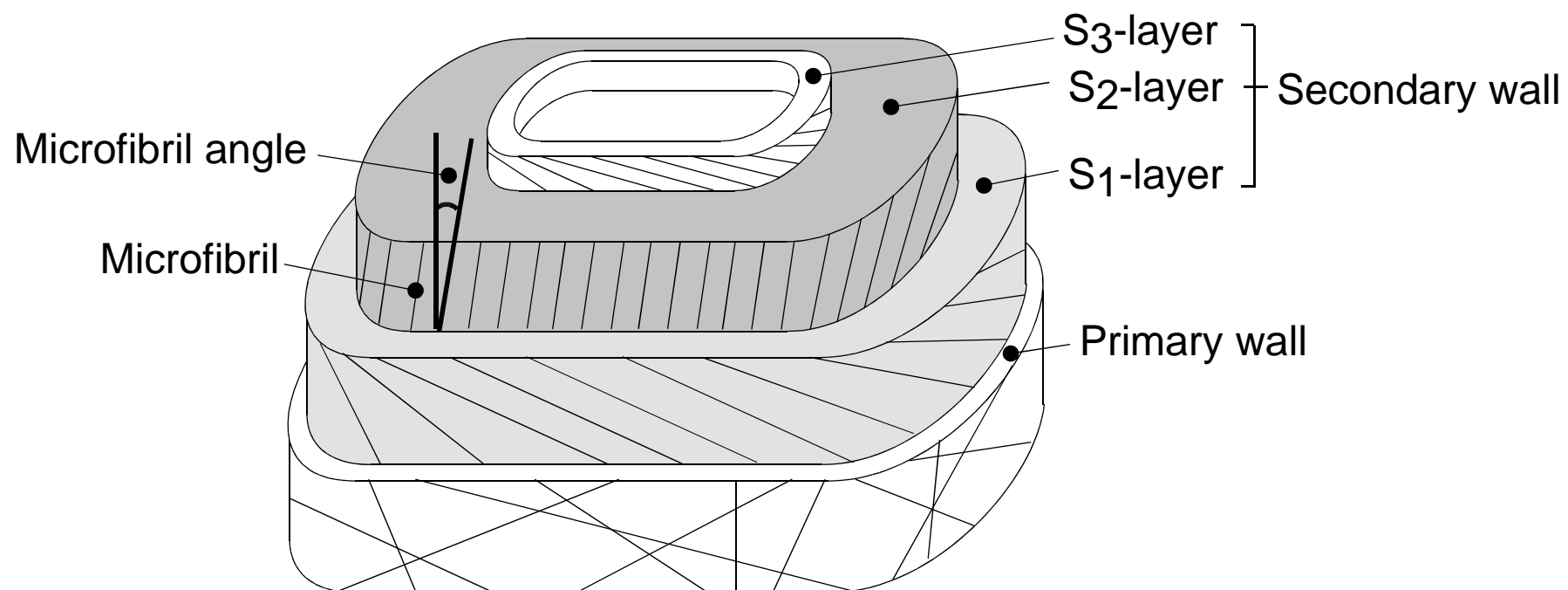
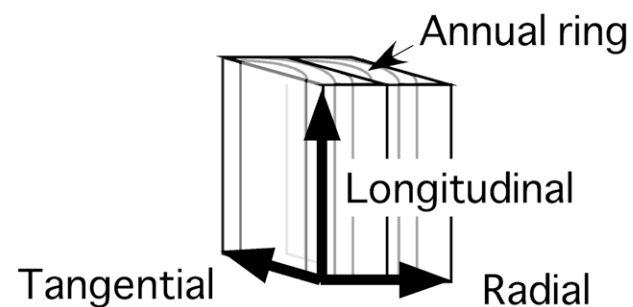
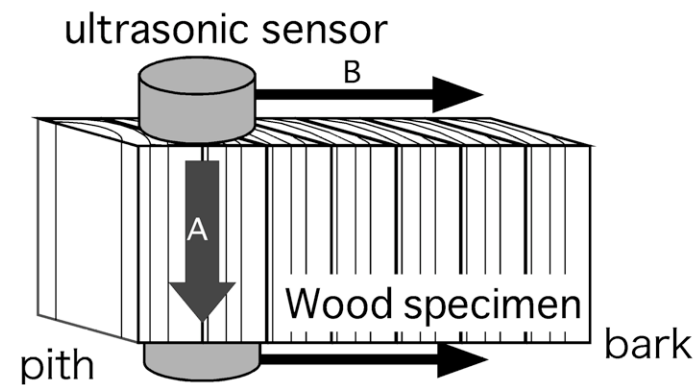


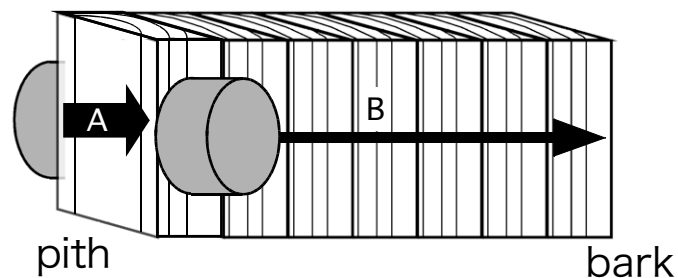
Fig. 1 Cell wall structure of tracheid.



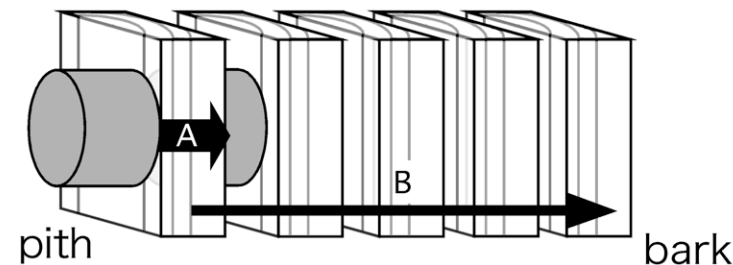
(a) Three orthotropic axis



(b) Longitudinal direction



(c) Tangential direction



(d) Radial direction

Fig. 2 Setup for ultrasonic velocities measurement in three orthotropic directions: (a) Ultrasonic propagation direction and (b) Sliding direction of ultrasonic sensor.

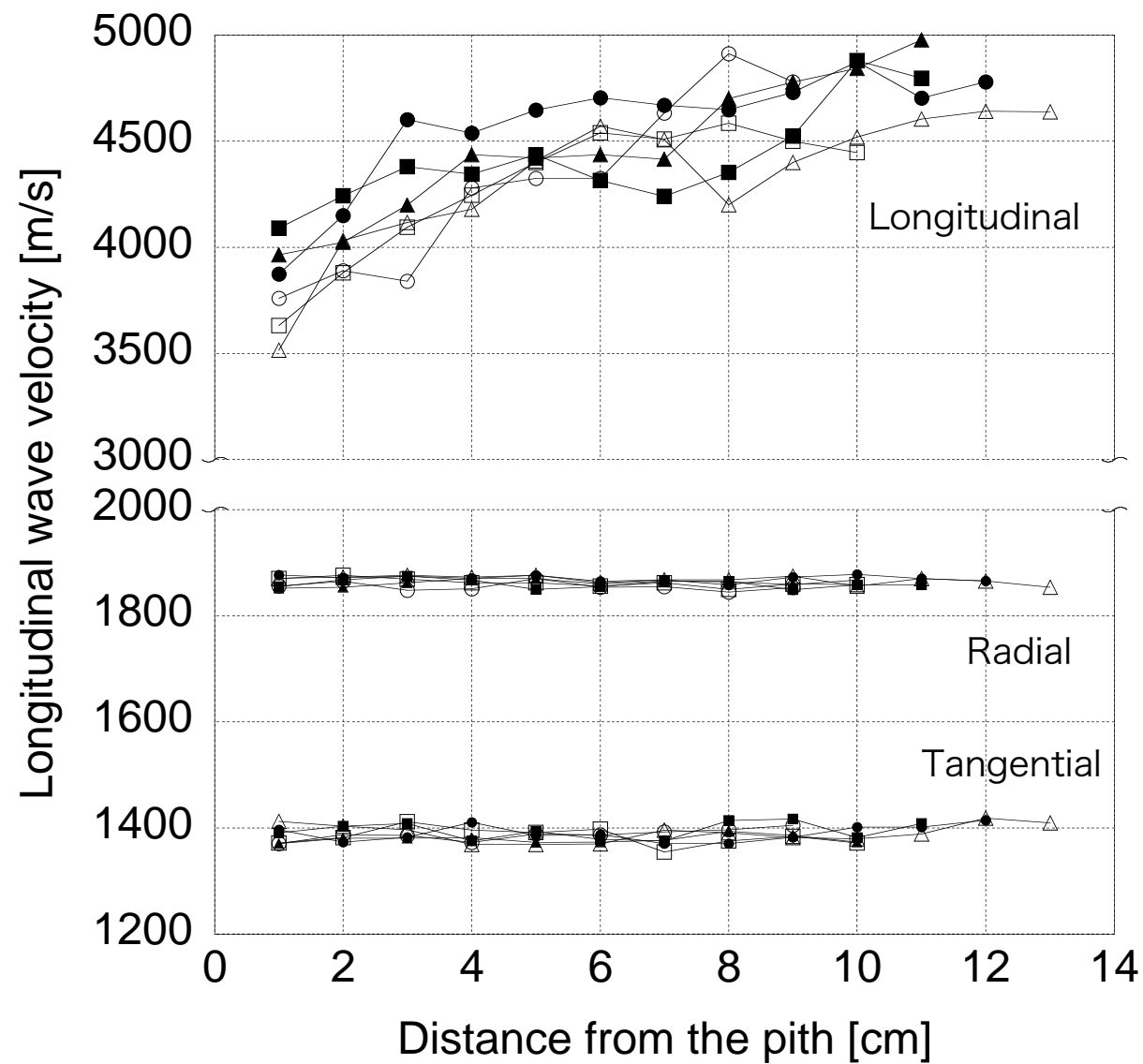


Fig. 3 Radial variations in the longitudinal wave velocities in three orthotropic directions. *Filled marks*: Japanese cypress, *Open marks*: Japanese cedar.

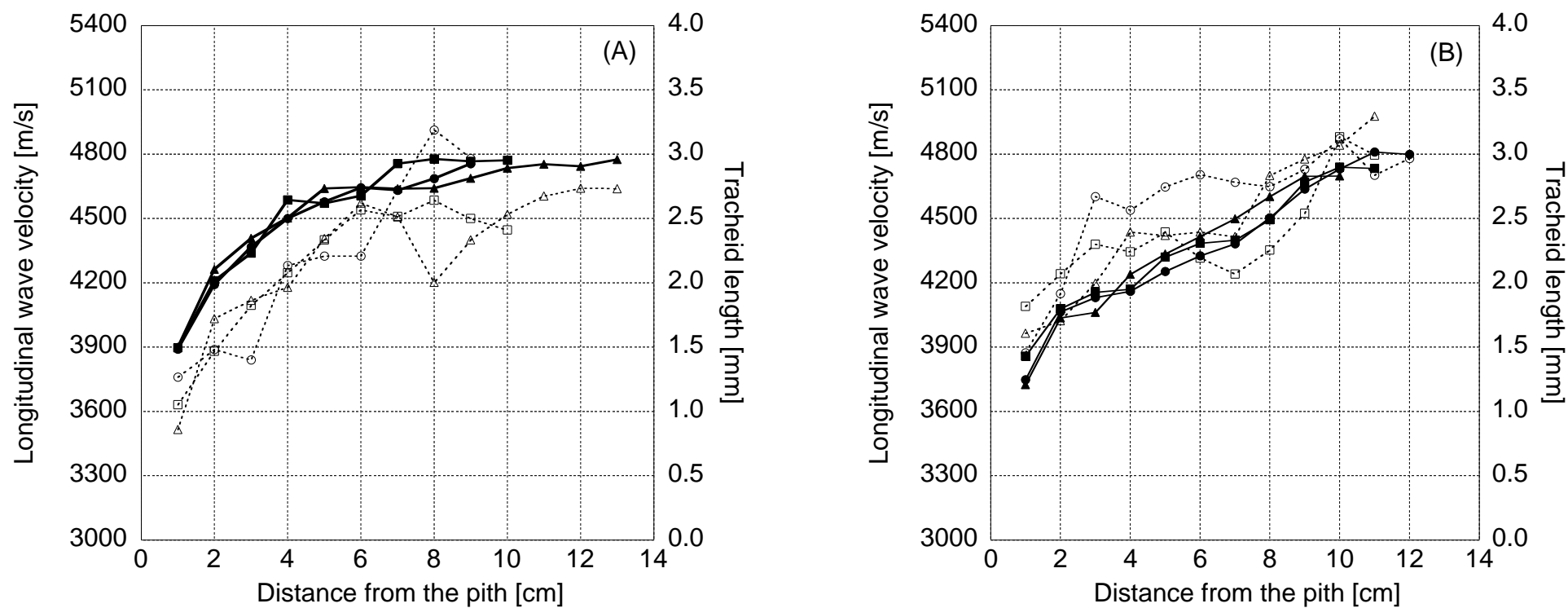


Fig. 4 Radial variations in longitudinal wave velocity and tracheid length: (A) Japanese cedar and (B) Japanese cypress. *Solid line* : tracheid length, *Dotted line* : longitudinal wave velocity.

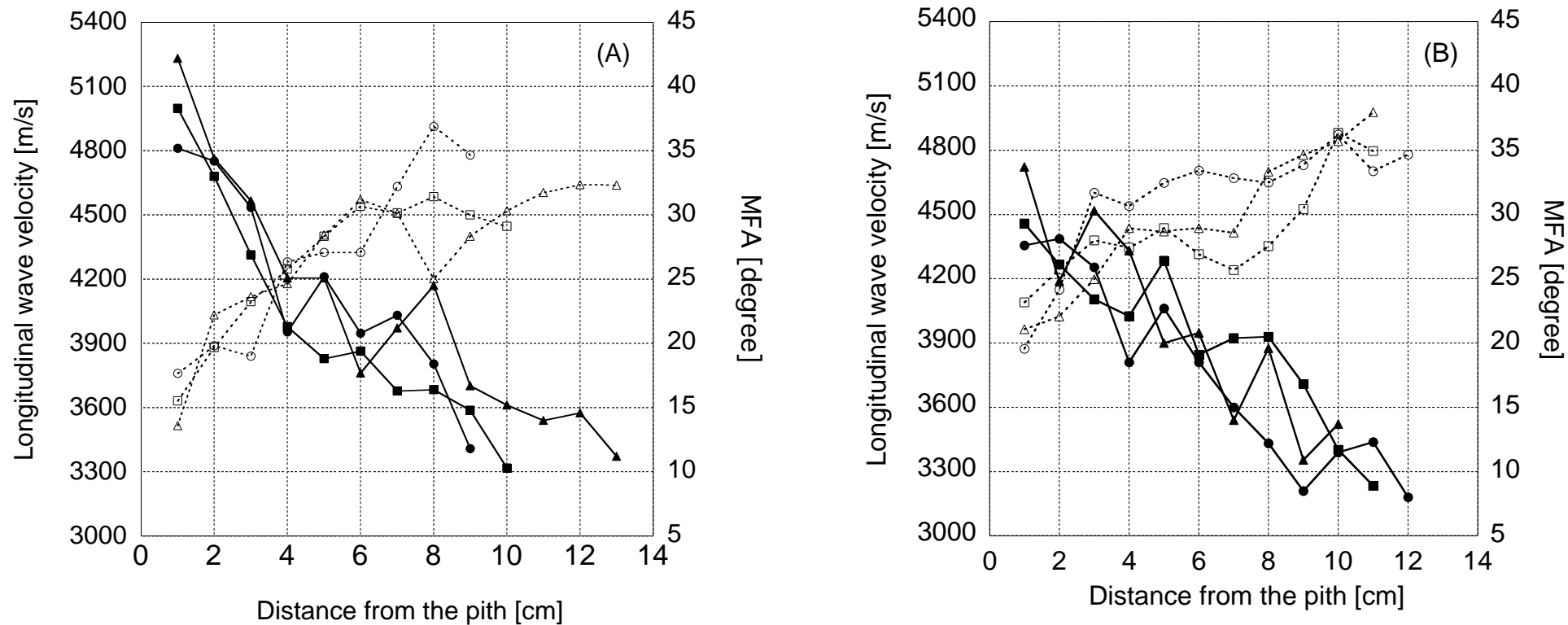


Fig. 5 Radial variations in longitudinal wave velocity and microfibril angle: (A) Japanese cedar and (B) Japanese cypress. *Solid line* : microfibril angle, *Dotted line* : longitudinal wave velocity.

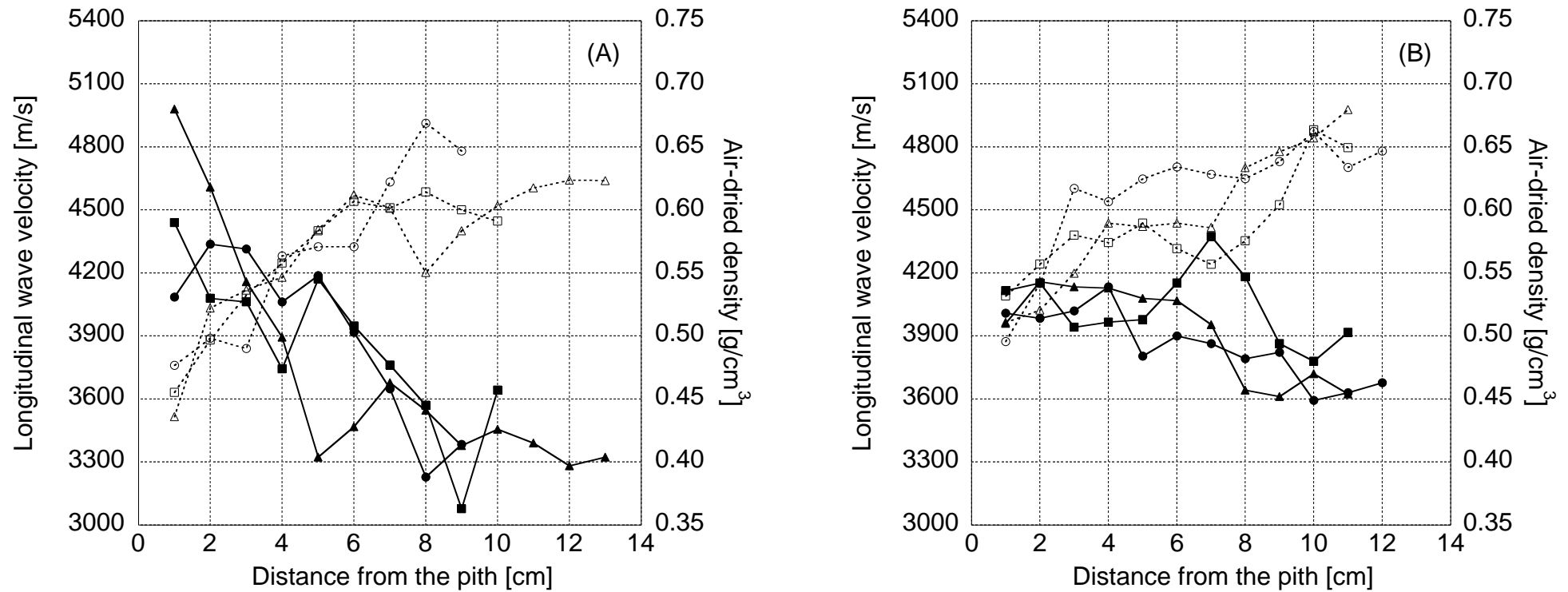


Fig. 6 Radial variations in longitudinal wave velocity and air-dried density: (A) Japanese cedar and (B) Japanese cypress. *Solid line* : air-dried density, *Dotted line* : longitudinal wave velocity.

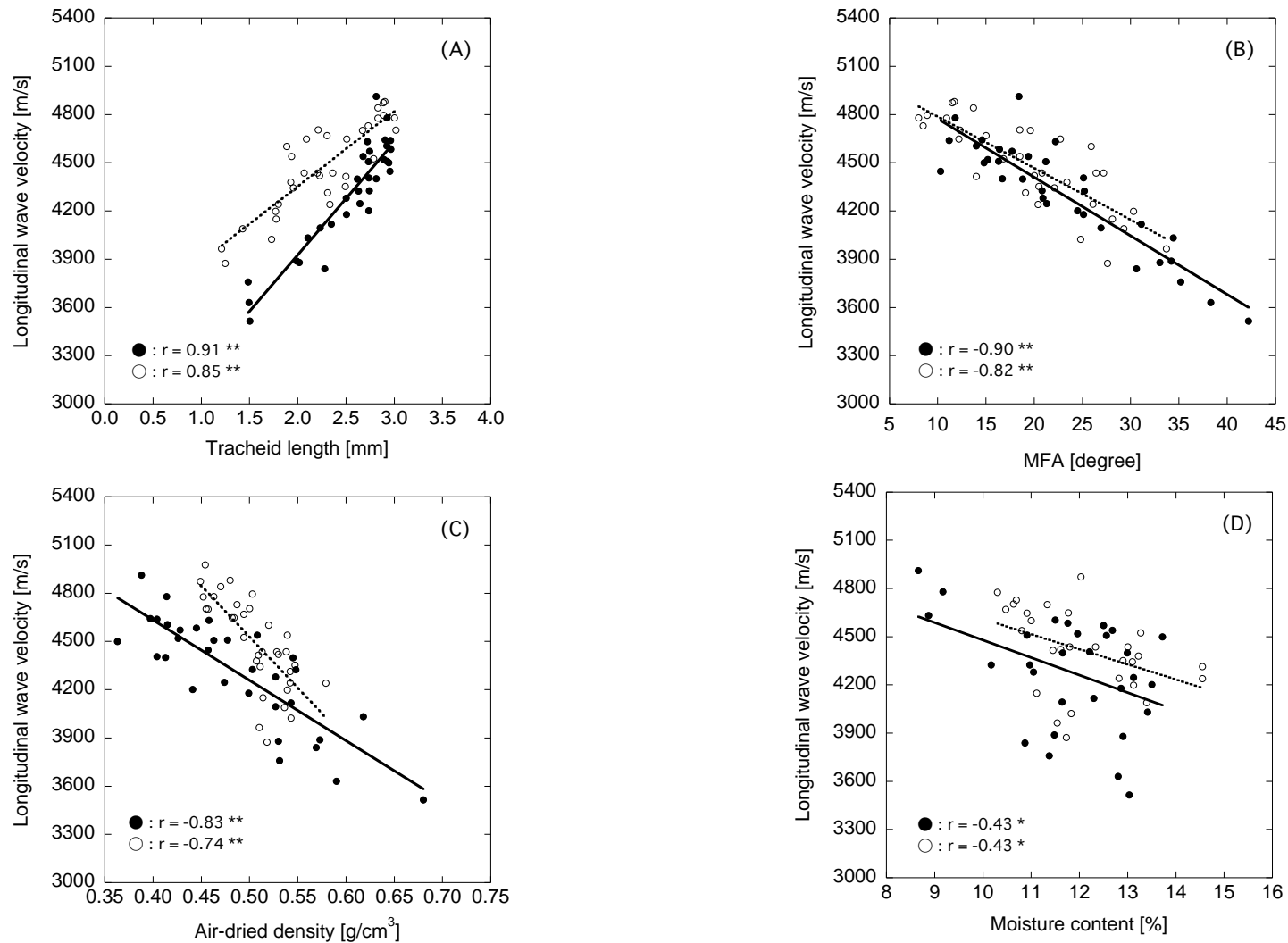


Fig. 7 Relationships between longitudinal wave velocities and wood properties: (A) tracheid length, (B) microfibril angle, (C) air-dried density, and (D) moisture content. *Filled marks* : Japanese cedar, *Open marks* : Japanese cypress.

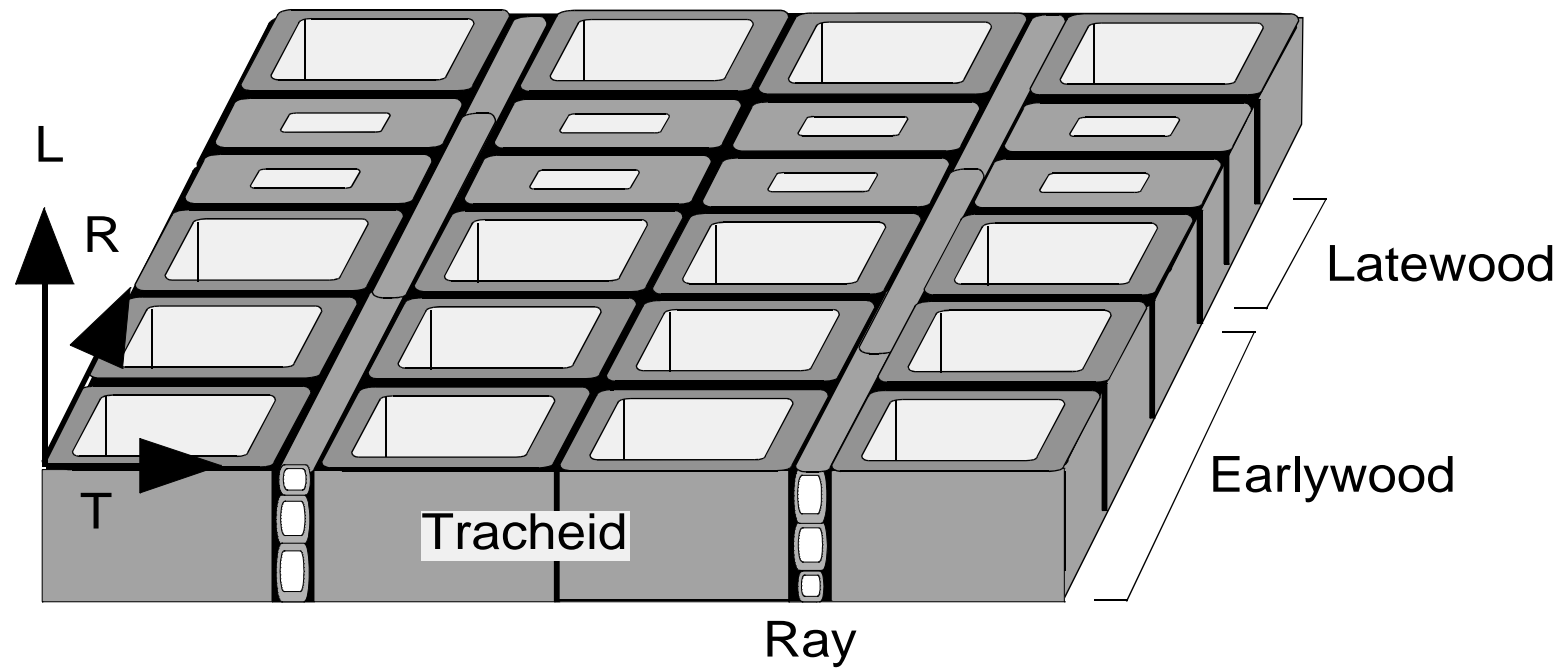


Fig. 8 Wood structure of softwood: L, Longitudinal direction; R, Radial direction; T, Tangential direction.