RELATIONS OF FIBER LENGTH TO WITHIN-TREE VARIATION OF ULTRASONIC WAVE VELOCITY IN FAST-GROWING TREES

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Abstract. The within-tree variation of longitudinal wave velocities in *Acacia auriculiformis* (AA), *Eucalyptus dunnii* (ED), and *Melia azedarach* (MA) was experimentally investigated. The velocities in the longitudinal direction (V_L) exhibited a minimum value near the pith. The minimum values in AA, ED, and MA were measured to be 4000, 4600 and 3600 m/s, respectively. V_L increased from the pith to the bark. On the other hand, the velocities in the radial and tangential directions exhibited constant values. The radial variation patterns of the V_L coincided with those of fiber length (FL). V_L exhibited a strong correlation with the FL at a 1% significant level. These findings revealed that wood properties such as FL greatly influence the velocity in the longitudinal direction.

Keywords: Fast-growing tree, ultrasonic wave, velocity, hardwood, fiber length.

INTRODUCTION

Fast-growing trees could contribute to lowering the impact of global warming because of their high carbon-stocking capacity. Generally, fast-growing trees are used as pulping materials due to their high productivity. Fast-growing trees grow rapidly for a short period and have a large trunk diameter. Using fast-growing trees as a building material (eg as posts and beams in timber construction) increases their value. Experimental research has described physical and mechanical properties of some fast-growing trees such as the *Eucalyptus* species (Yang and Waugh 1996a,b; Llic 2001; Yang and Evans 2003; Thomas et al 2009), the *Acacia* species (Shukla et al 1990, 2007; Hai et al 2010), and *Melia azedarach* (MA) (Shukla et al 1990; Venson et al 2008). Venson et al (2008) experimented with the physical, mechanical, and biological properties of MA in Mexico. They demonstrated that MA could be used as structural lumber if the appropriate genotypes and clones were selected. For Japanese fast-growing trees, Matsumura et al (2007, 2006) reported compression strength variations in the stems of MA and modulus of elasticity and modulus of rupture variations in the stems of *Choerospondias axillaris*. Hasegawa et al (2010) demonstrated the potential of applying the acoustoelastic

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effects experimentally to determine the stress condition of MA.

An ultrasonic technique has been researched to be applied to the quality control of timber materials (Sandoz 1989) and to the maintenance of posts and beams in wooden construction (Hasegawa et al 2012, 2010). The ultrasonic velocity is an important parameter in the nondestructive testing of wood. The ultrasonic wave velocity in trunk wood is not uniformly distributed because the trunk is an anisotropic material. Such inhomogeneous distributions make it difficult to apply ultrasonic techniques to a wooden construction as a nondestructive testing method; therefore, we must know the distributions of velocities and clarify the mechanism of distributions. For softwood, the ultrasonic wave velocities in the longitudinal direction (V_L) vary from the pith to the bark. Bucur (2006) reported this behavior for Douglas fir (*Pseudotsuga menziesii*). Hasegawa et al (2011) also reported this behavior for Japanese cedar (*Cryptomeria japonica*) and Japanese cypress (*Chamaecyparis obtusa*). They demonstrated that the tracheid structures (ie tracheid length and microfibril angle) greatly influence V_L. However, until now, there were few reports for within-tree variation of V_L for fast-growing trees.

The objective of this study is to elucidate the effect of wood properties on within-tree variation in the ultrasonic velocity in fast-growing trees. In this experiment, *Acacia* species, *Eucalyptus* species, and MA were used as the test specimens. Velocities propagated through the longitudinal, radial, and tangential directions were measured with the sing-around method (Hasegawa and Sasaki 2004). In addition, the radial variation in velocities and fiber length (FL) were measured. From these radial variations and the correlations among them, the mechanism of velocity distribution in fast-growing trees was investigated.

MATERIALS AND METHODS

Materials

Two 10-yr-old *Acacia auricuilformis* (AA) in Indonesia, two 8-yr-old *Eucalyptus dunnii* (ED) in Australia, and 22-yr-old MA in Japan were used as the test materials. Strips with 3 cm thickness were cut from wood disks in air-dried conditions to measure the velocities of ultrasonic waves in the longitudinal and tangential directions. Thereafter, the strips were sliced into 1 cm pieces to measure velocities in the radial direction. The air-dried density and MC of test specimens are shown in Table 1.

Table 1. Air-dried density and MC of test specimens.

Species	Air-dried density (kg/m^3)	MC (%)
Acacia auriculiformis	679	9.43
Eucalyptus dunnii	686	9.51
Melia azedarach	563	9.87

Ultrasonic Measurement

For measuring velocities in the longitudinal and tangential directions, an ultrasonic sensor was slid from the pith toward the outside in 1 cm steps, 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, using a model UVM-2 unit (Ultrasonic engineering, Tokyo, Japan). Piezoelectric transducers with a natural frequency of 0.5 MHz and a diameter of 2.5 cm (models CR-0016-S for longitudinal waves by Staveley Instruments, Washington, USA) were used to detect the ultrasonic waves. Silicone grease (SH111 by Dow Corning Toray, Tokyo, Japan) was used as the coupling medium to improve the bonding between the transducers and the wood specimen, and a rubber band held the transducers against the specimen as shown in Fig 1.

Fiber Length

After ultrasonic measurement, a small piece was removed from the outermost side of each sliced piece. The small piece was macerated by treating it with of a 1:1 mixture solution of glacial

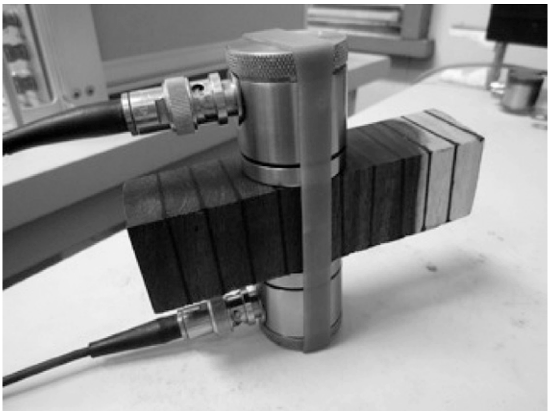

Figure 1. Setup for ultrasonic velocity measurement.

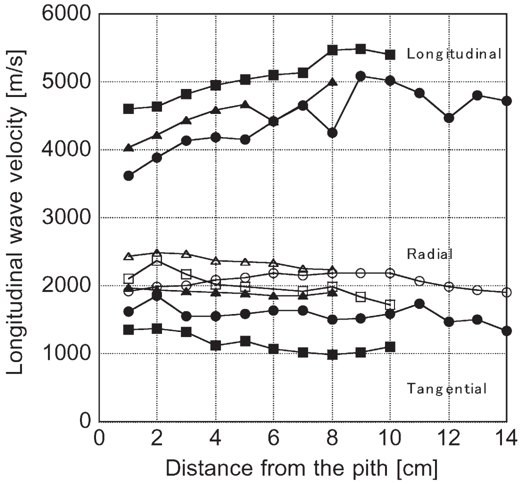

Figure 2. Radial variations in the longitudinal wave velocities in three orthotropic directions, triangle: AA, square: ED, circle: MA.

acetic acid and 30% hydrogen peroxide for 48 h at 80°C. After staining the macerated fibers with safranin, they were observed at 50-times magnification with a profile projector (model V-12 by Nikon Instruments, Tokyo, Japan), and their FLs were measured. At each point, 30 FLs were averaged.

RESULTS AND DISCUSSION

Radial Variation in Longitudinal Wave Velocities within the Wood Trunk

Figure 2 shows the radial variation of velocity in three orthotropic directions for the three wood species. The longitudinal wave velocities (V_L) exhibited a minimum value near the pith. The minimum longitudinal wave velocity for AA, ED, and MA were 4000, 4600, and 3600 m/s, respectively. V_L kept increasing toward the outside and attained values of 5000, 5400, and 4600 m/s at the furthest points of measurement, respectively. V_L in this study varied from pith toward the outside similar to the behavior of V_L in softwood (Bucur 2006; Hasegawa et al 2011). The velocities in the radial and tangential direction (V_R, V_T) remained constant as shown in Fig 2. The three fast-growing trees used in this study are hardwoods. Until now, there have been no reports of radial variations of V_L, V_R, and V_T in hardwood. For the first time, we have experimentally confirmed the radial variations of velocity. As mentioned in the introduction, V_L for softwood is influenced by the tracheid structures. For hardwood, the wood fibers are oriented parallel to the axial direction. In the next section, we focus on FL to examine the effect of wood properties on V_L.

The average velocities along all three directions are summarized in Table 2. As there have been no data for V_L, V_R, and V_T in AA, ED, and MM until now, it is difficult to compare the values of V_L in this study with those of previous works; however, we can examine the values of velocities in similar wood species. As shown in Table 3, the results for AA and ED in this study are consistent with these previous studies. V_L exhibited the largest wave velocities of the three directions. The values of longitudinal velocities in wood are known to increase in the following order: V_L, V_R, V_T. For hardwood, wood fibers and vessels are oriented longitudinally. As a result of this structural anisotropy,

Table 2. Ultrasonic wave velocities in the three orthotropic directions.

Species	V_L (m/s)	V_R (m/s)	V_T (m/s)
Acacia auriculiformis	4500 ± 296	2368 ± 94	1902 ± 39
Eucalyptus dunnii	5060 ± 322	2012 ± 188	1151 ± 143
Melia azedarch	4500 ± 410	2035 ± 121	1566 ± 117

Table 3. Velocities in the longitudinal direction in this study and previous studies.

Species	V_L (m/s)	Air-dried density (kg/m^3)
Acacia auriculiformis	4500	679
Eucalyptus dunnii	5060	686
Acacia mangium (Sharma and Shukla 2012)	4100	470
Acacia mangium (Hamdan et al 2011)	5144	520
Eucalyptus grandis (Fabiana and Almir 2006)	5100	660

Table 4. Ratio of longitudinal wave velocity in three directions.

Species	V_L/V_R	V_L/V_T	V_R/V_T
Acacia auriculiformis	1.9	2.4	1.2
Eucalyptus dunnii	2.5	4.4	1.7
Melia azedarach	2.2	2.9	1.3

the velocity is fastest in the longitudinal direction. The ratios between V_L, V_R, and V_T were obtained from the data in Table 2. These ratios are shown in Table 4. The ratios obtained in this study are consistent with the findings of Bucur (2006), who reported that V_L/V_R and V_L/V_T ratios for hardwood ranged from 1.7 to 2.8 and 2.3 to 4.2, respectively.

Relationships between Longitudinal Wave Velocities and Fiber Length

Figure 3 shows the radial variations in V_L and FL for AA, ED, and MA. The variations in V_L from Fig 2 are included in Fig 3 for comparison. FL values were at a minimum near the pith, and their values were 0.7 mm for AA, 0.7 mm for ED and MA. These FL gradually increased to 1.0 mm for AA, 0.9 mm for ED and MA toward the outside. Chowdhury et al (2009) reported that the FL in 11-yr-old AA in Bangladesh ranged from 0.89 to 1.06 mm. Matsumura et al (2006) reported that the averaged FL over the 10th ring in 17-yr-old MA in Japan ranged from 0.86 to 1.02 mm. FL measurements obtained in this study were consistent with the FL measurements from those studies. As shown in Fig 3, the variation patterns of the FL in the radial direction coincided with those of V_L.

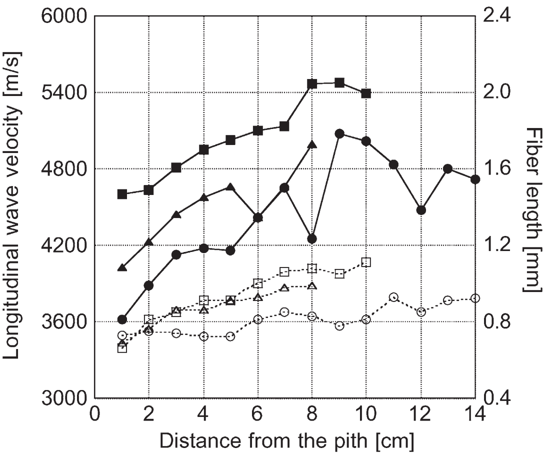

Figure 3. Radial variations in longitudinal wave velocities and FL, solid lines: longitudinal wave velocity, dotted lines: FL, triangle: AA, square: ED, circle: MA.

Figure 4 shows the relationships between V_L and FL. V_L was related positively with FL at 1% significant level. Correlation coefficients between V_L and FL were 0.90 for AA, 0.92 for ED, and 0.68 for MA. Polge (1984) reported a strong correlation ($r = 0.90$) between the FL and V_L for a cherry tree. Baar et al (2013) reported that V_L in the tropical hardwoods (*Afzelia bipindensis*, *Intsia bijuga*, and *Astronium graveolens*) was strongly related to FL. Their correlation coefficients were

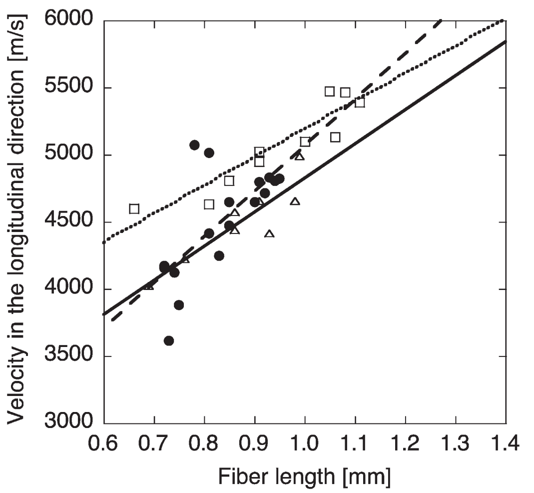

Figure 4. Relationships between longitudinal wave velocities and FL, open triangle: AA, open square: ED, filled circle: MA, solid line: AA, dotted line: ED, broken line: MA.

0.92, 0.82, and 0.81, respectively. In addition, Bucur (2006) made the point that an ultrasonic wave dissipates the acoustical energy when it takes place at the end of fiber. The FL contributes, in part, to the radial variations in V_L. On the other hand, Baar et al (2013) demonstrated that the ray ratio, which is the ratio of ray height to ray width, was strongly related to V_L, suggesting the ray dimensions is one of the most important anatomical characteristics determining V_L. Further experiments will be needed to determine the relationships between V_L and ray dimensions in fast-growing trees. However, until our study, there has been no measurement of the relationship between V_L and FL. On the other hand, V_R and V_T remained constant as shown in Fig 2. Further research is required to determine why V_R and V_T show no variation from the pith to the bark. The structure of hardwood is more complex than that of softwood. Hardwood mainly consists of wood fiber, vessel element, and parenchyma. It would, therefore, be interesting to investigate the relationship between V_R and V_T and cell dimensions for hardwoods other than those examined in this study.

CONCLUSIONS

The within-tree variation in longitudinal wave velocities in AA, ED, and MA 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. As above, the radial variations of ultrasonic wave velocity in fast-growing trees were measured for the first time. V_L exhibited a strong correlation with the FL at a 1% significance level. These findings revealed that FL greatly influences the velocities in the longitudinal direction; however, FL is not the sole determinant of the velocities. Microfibril angle, density, and MC are also important factors. Therefore, a multivariate statistical analysis is required to determine which wood properties have a significant impact on V_L. We will clarify the mechanism of radial variations in ultrasonic wave velocity in fast-growing trees.

In addition, it is essential to elucidate the mechanical properties and growth characteristics to produce the sustainable and stable fast-growing trees. The radial variation in ultrasonic velocity is a useful indicator for elucidation of mechanical properties within the wood trunk. We will clarify the relations between ultrasonic velocity, mechanical properties, and growth characteristics in the future.

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