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Non-Contact Velocity Measurement of Japanese Cedar Columns Using Air-Coupled Ultrasonics

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Abstract

The ultrasonic wave velocities of Japanese cedar columns were measured using a non-contact method. An air-coupled ultrasonic wave was propagated through the axial and lateral directions of wood. The velocities in the axial direction (V_L) showed the minimum values around the pith. The averaged V_L increased from 3600 m/s towards the outside of measurement area and attained the maximum values (=4010 m/s). The velocities in the lateral direction (V_{RT}) showed no tendency among measurement points. The averaged V_{RT} was 1450 m/s. The velocities obtained using the non-contact method showed a significant positive relationship with those obtained using the contact method. The averaged ratio of V_L to V_{RT} was measured to be approximately 2.2 to 2.8. These ratios were in agreement with those from a contact method. These findings suggest that it is possible to measure the velocity in Japanese cedar columns with the non-contact method by using air-coupled ultrasonics.

Keywords

Air-Coupled Ultrasonics, Velocity, Non-Contact Method, Nodestructive Evaluation, Japanese Cedar

1. Introduction

Japanese cedar is a popular tree cultivated in Japan. The distribution area of Japanese cedar is the largest among planted forestry species, accounting for 26% of the country's total. In addition, 64% of roundwood production of Japanese cedar is used for sawnwood. The Plan to Create Dynamism through Agriculture, Forestry, and Fishe-

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ries and Local Communities was enacted in 2013. Forestry will become a growth industry through the creation of new wood demand and the building of a stable and efficient supply scheme [1]. As a result, demand for Japanese cedar as an engineering wood is expected to increase significantly in the future. Therefore, it is important to understand the usage of ultrasonic techniques to perform nondestructive evaluation of Japanese cedar. Hasegawa *et al*. demonstrated that the ultrasonic wave velocities along the longitudinal direction of Japanese cedar exhibited strong correlations with the tracheid length and microfibril angle with a significant level of $p < 0.01$ [2]. In addition, Mori *et al*. evaluated the surviving strength of bending of Japanese cedar damaged by termite [3]. It was possible to evaluate the surviving strength using the ultrasonic velocity in the longitudinal direction. Hasegawa *et al*. investigated the within-tree variation of the acoustoelastic behaviors in Japanese cedar to clarify the possibility of nondestructive stress measurement [4].

Recently, air-coupled ultrasonic waves have been studied for use in the quality control of sawing timber and the maintenance of posts and beams in a wooden construction [5]-[9]. This technique makes it possible to evaluate the current state of the wood without contacting the wood. Vun *et al*. evaluated the relationships between moisture content and ultrasonic wave velocity in red pine [5], while Dahmena *et al*. measured the elastic constants of an olive wood plate [6]. To the best of our knowledge, there is no report for evaluating Japanese cedar by using air-coupled ultrasonics.

In this study, we tried to measure the ultrasonic wave velocity in Japanese cedar columns with a non-contact method. The air-coupled ultrasonic wave was propagated through the axial and lateral directions in wood. The validity of the ultrasonic wave velocities using the non-contact method was experimentally investigated. In addition, the velocities obtained using the non-contact method were compared with those obtained using the contact method.

2. Materials and Methods

2.1. Materials

Japanese cedar (*Cryptomeria japonica* D. Don) was used as the test material. Test specimen dimensions were 100 mm (longitudinal) × 100 mm (radial) × 100 mm (tangential). Numbers of test specimens were 3 pieces (S1, S2, S3). The air-dried density and moisture content show in **Table 1**.

2.2. Ultrasonic Measurement

An air-coupled ultrasonic wave was propagated through air and specimens of wood, as shown in **Figure 1**. Ultrasonic wave velocities were measured by using a pulser-receiver (JPN-10CKN, Japan probe Co. Ltd., Japan), a preamplifier, and monolithic composite transducers of type 14 × 20 mm with a natural frequency of 200 kHz (Japan probe Co. Ltd., Japan). The propagation directions of the ultrasonic wave corresponded to the axial (longitudinal) and lateral (radial or tangential) directions in wood. Ultrasonic velocity was measured at nine points on the surface of cross and tangential sections, respectively (**Figure 2**). The room temperature (t) and velocity measurement were recorded at the same time. The ultrasonic velocity (V) was calculated using Equations (1) and (2).

$$V = L \big/ \left(T - \left(T_a - L/V_a \right) \right) \tag{1}$$

$$V_a = 331.5 + 0.61t \tag{2}$$

where L is the propagation distance of wood, T is the propagation time with a wood sample, T_a is the propagation time without a wood sample, and V_a is the velocity in air.

Table 1. Density and moisture content of test specimens.

Specimens	Density (kg/m^3)	Moisture content (%)
S1	333	9.2
S2	323	9.2
S3	336	9.1

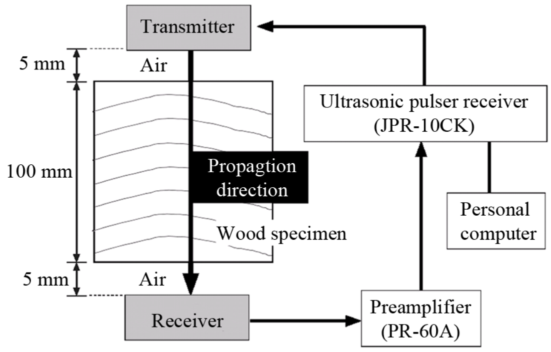

Figure 1. Diagram of ultrasonic wave measurement.

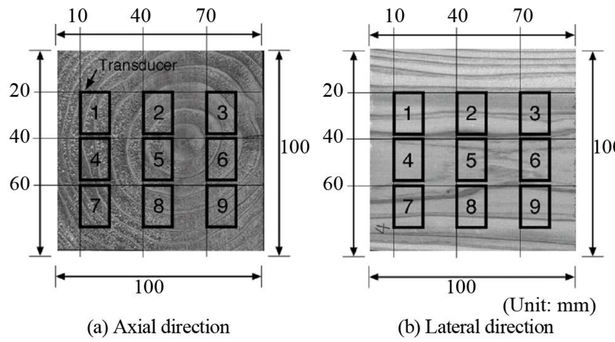

Figure 2. Measurement positions of ultrasonic wave velocities.

In addition, the ultrasonic wave velocities were measured using the contact method. The measurement equipments were the same as those used in the non-contact method. The ultrasonic velocity (V_c) was calculated using Equation (3).

$$V_c = L/(T_c - T_0) \tag{3}$$

where L is the propagation distance of wood, T_c is the propagation time with a wood sample, and T_0 is the propagation time without a wood sample.

3. Results and Discussion

3.1. Receiving Waveform for Air-Coupled Ultrasonics

Figure 3 shows the receiving waveform in air at 110 mm distance between transducers. The propagation time was determined using a zero-crossing method. The propagation time showed about 330 µs. **Figure 4** shows the examples of receiving waveforms in axial and lateral directions of wood. The propagation time in wood is smaller than that in air, because an ultrasonic velocity in wood is faster than that in air. The averaged propagation time in axial and lateral directions was about 60 µs and 100 µs, respectively. The propagation time was ranked in the ascending order of lateral and axial directions. These propagation times were substituted for Equation (1) in order to calculate the velocities. As shown in **Figure 3**, some small signals that were observed before the receiving waveform are used to determine the propagation time. The small signals may have some important information for ultrasonic propagation characteristics. Further research is required to study these small signals.

3.2. Ultrasonic Wave Velocities in the Axial and Lateral Directions

Table 2 shows the ultrasonic wave velocities in the axial and lateral directions for three test specimens (S1, S2, S3). The average values of velocity in the axial direction (V_L) were 3964 m/s, 3515 m/s, and 3468 m/s, respectively. **Figure 5** shows the values of ultrasonic wave velocity each position in the axial and lateral directions. The minimum values for V_L show 3597 m/s, 3234 m/s, and 2733 m/s, respectively. Their values existed around

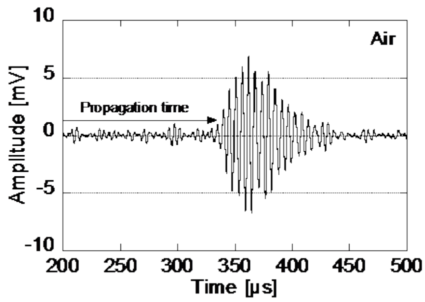

Figure 3. Waveform of ultrasonic wave in the air at 110 mm distance.

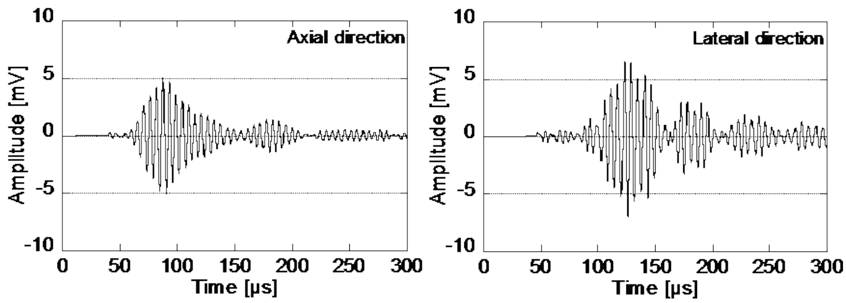

Figure 4. Waveforms of ultrasonic wave in the axial and lateral directions of wood specimens.

Table 2. Ultrasonic wave velocities in axial and lateral directions.

Specimens	V_L	V_{RT}	V_L/V_{RT}	Frequency	Method
	(m/s)			(kHz)	
S1	3964 ± 283	1412 ± 155	2.8		
S2	3515 ± 180	1606 ± 92	2.2	200	Non-contact
S3	3468 ± 335	1331 ± 235	2.6		
S1	4118 ± 240	1664 ± 147	2.5		
S2	4164 ± 253	1677 ± 84	2.5	200	Contact
S3	4096 ± 410	1700 ± 130	2.4		
Japanese cedar[a]	4310 ± 339	1863 ± 9.0[c]	2.3	500	Contact
		1388 ± 15.1[d]	3.1		
Japanese cedar[b]	4950	2150 [c]	2.3	2500	Contact
		1610 [d]	3.1		

[a]Measurement by Hasegawa *et al*. [2], [b]Measurement by Mishiro [14], [c]Velocity in the radial direction, [d]Velocity in the tangential direction.

the pith. On the other hands, the maximum values show 4414 m/s, 3816 m/s, and 3796 m/s, respectively. Their values existed in the outside point of measurement area. In general, the tracheid length gradually increases toward the outside and attains a constant value. An ultrasonic wave dissipates acoustical energy when it occurs at the end of a fiber [10]. Hasegawa *et al.* demonstrated that V_L for Japanese cedar and Japanese cypress were significantly related to the tracheid length [2]. Tracheid length seems to affect V_L. On the other hand, the average values of velocity in the lateral direction (V_{RT}) were 1412 m/s, 1606 m/s, 1331 m/s, respectively. The ratios of V_L to V_{RT} ranged from 2.2 to 2.8. Distinct relationship among measurement points such as the axial directions was not observed. As shown in **Figure 2**, the growth ring structure significantly influences the wave propagation. In the center of the test specimens, the propagation path coincides with the radial direction. However, at the edge of

1	2	3
4	5	6
7	8	9

(a) Measurement postions

S1

4239	3654	4016
4197	3597	3798
4414	4006	3754

S2

3715	3436	3551
3816	3234	3381
3629	3439	3436

S3

3754	2733	3520
3796	3173	3409
3632	3686	3510

(Unit: m/s)

(b) Axial direction

S1

1510	1496	1597
1397	1498	1512
1364	1156	1176

S2

1550	1529	1558
1605	1534	1685
1552	1809	1636

S3

1568	1134	806
1524	1409	1282
1450	1359	1444

(Unit: m/s)

(c) Lateral direction

Figure 5. Distributions of ultrasonic wave velocity in the axial and lateral directions of wood specimens.

the test specimens, the propagation path coincides with the radial and tangential directions. As a result, the ultrasonic beam is deflected and shifted laterally with respect to the incident angle [11]. In addition, for the measurement of V_{RT}, the distance between the test specimen and sensor was within the near field distance. As a result, there is a large variation of V_{RT} in wood. In the future, we will determine the optimal measurement condition such as near-field distance for Japanese cedar column.

As shown in **Table 2**, the velocities obtained using the contact method (V_c) were larger than those obtained using the non-contact method (V) at a significant level of 5%. The correlation coefficients in the axial and lateral directions were 0.48 and 0.40, respectively. The ratios of V_L to V_{RT} ranged from 2.4 to 2.5. The ratios of velocity obtained using the contact method were similar to those obtained using the non-contact method. Vun *et al*. demonstrated that the velocities measured using the non-contact method showed higher values than those measured using the contact method for an oriented strand board [12]. Raffaella *et al*. reported that the non-contact ultrasonic velocity of food items was significantly higher than the velocity measured using the contact method ($P < 0.05$) [13]. Results in this study were not in agreement with those in the previous study [12] [13]. Further research is needed to clarify the reason V_c shows larger values than V.

The values of velocity in this study were smaller than those in the previous study, which used a contact method, as shown in **Table 2**. An ultrasonic wave velocity changes with the specimen dimensions and natural frequency [10]. Bucur demonstrated that the ratios of V_L to V_R in European wood species ranged from 2.4 to 3.4 for softwood [10]. For Japanese cedar, Hasegawa *et al*. [2] and Mishiro [14] reported that the ratios of velocity in the longitudinal direction to that in the radial direction were 2.3; the ratios of velocity in the longitudinal direction to that in the tangential direction were 3.1. The ratios for a non-contact method were almost the same as those for a contact method. The findings in this study suggest that the ultrasonic wave velocities in Japanese cedar could be measured with a non-contact method by using air-coupled ultrasonics.

4. Conclusion

Ultrasonic wave velocities in the axial and lateral directions on Japanese cedar columns can be measured with a non-contact method by using air-coupled ultrasonics. As compared, the velocities were also measured by using the contact method. The velocities in the non-contact method were smaller than those measured using the contact method. The ratios of velocity were the same as those in a contact method. These results in the present study have suggested that the air-coupled ultrasonic wave is a useful tool for non-contact and nondestructive evaluation in Japanese cedar. Most importantly, this study could be considered as the first step toward the application of air-coupled ultrasonics to the nondestructive evaluation in Japanese cedar columns. In the future, the need is envisaged to measure an ultrasonic velocity in a full-sized lumber and to explore the possibility of non-contact and nondestructive evaluation in existing wood constructions using air-coupled ultrasonics.

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References

[1] Forestry Agency (2013) Annual Report on Trends in Forests and Forestry. Forestry Agency, Tokyo (in Japanese).

[2] Hasegawa, M., Takata, M., Matsumura, J. amd Oda, K. (2011) Effect of Wood Properties on Within-Tree Variation in Ultrasonic Wave Velocity in Softwood. *Ultrasonics*, **51**, 296-302. http://dx.doi.org/10.1016/j.ultras.2010.10.001

[3] Mori, T., Yanase, Y., Tanaka, K., Kawano, K., Noda, Y., Mori, M., Kurisaki, H. and Komatsu, K. (2013) Evaluation of Compressive and Bending Strength Properties of Wood Damaged from Bio-Deterioration. *Zairyo*, **62**, 280-285 (in Japanese with English Abstract). http://dx.doi.org/10.2472/jsms.62.280

[4] Hasegawa, M., Yano, Y., Matsumura, J. and Oda, K. (2012) Prospects for Within-Tree Variation of the Acoustoelastic Behaviors in Japanese Cedar. *NDT and E International*, **49**, 57-63. http://dx.doi.org/10.1016/j.ndteint.2012.03.010

[5] Vun, R.Y., Hoover, K., Janowiak, J. and Bhardwaj, M. (2008) Calibration of Non-Contact Ultrasound as an On-Line Sensor for Wood Characterization: Effects of Temperature, Moisture and Scanning Direction. *Applied Physics A*: *Materials Science & Processing*, **90**, 191-196. http://dx.doi.org/10.1007/s00339-007-4256-6

[6] Dahmena, S., Ketatab, H.M., Hédi, B.G. and Hosten, B. (2010) Elastic Constants Measurement of Anisotropic Olivier Wood Plates Using Air-Coupled Transducers Generated Lamb Wave and Ultrasonic Bulk Wave. *Ultrasonics*, **50**, 502-507. http://dx.doi.org/10.1016/j.ultras.2009.10.014

[7] Hsu, D.K., Utrata, D. and Kuo, M. (2010) NDE of Lumber and Natural Fiber Based Products with Air-Coupled Ultrasound. *Review of Progress in Quantitative Nondestructive Evaluation*, **29**, 1533-1540.

[8] Sanabria, S.J., Furrer, R., Neuenschwander, J., Niemz, P. and Sennhauser, U. (2011) Air-Coupled Ultrasound Inspection of Glued Laminated Timber. *Holzforschung*, **65**, 377-387. http://dx.doi.org/10.1515/hf.2011.050

[9] Sanabria, S.J., Furrer, R., Neuenschwander, J., Niemz, P. and Sennhauser, U. (2013) Novel Slanted Incidence Air-Coupled Ultrasound Method for Delamination Assessment in Individual Bonding Planes of Structural Multi-Layered Glued Timber Laminates. *Ultrasonics*, **53**, 1309-1324. http://dx.doi.org/10.1016/j.ultras.2013.03.017

[10] Bucur, V. (2006) Acoustics of Wood. 2nd Edition, Springer-Verlag, Berlin.

[11] Sanabria, S.J., Furrer, R., Neuenschwande, J., Niemz, P. and Schütz, P. (2015) Analytical Modeling, Finite-Difference Simulation and Experimental Validation of Air-Coupled Ultrasound Beam Refraction and Damping through Timber Laminates, with Application to Non-Destructive Testing. *Ultrasonics*, **63**, 65-85. http://dx.doi.org/10.1016/j.ultras.2015.06.013

[12] Vun, R.Y., Wu, Q., Bhardwaj, M.C. and Sted, G. (2003) Ultrasonic Characterization of Structural Properties of Oriented Strandboard: A Comparison of Direct-Contact and Non-Contact Methods. *Wood and Fiber Science*, **35**, 381-396.

[13] Raffaella, S. and John, N.C. (2001) Non-Contact Ultrasonic Measurements in Food Materials. *Food Research International*, **34**, 865-870. http://dx.doi.org/10.1016/S0963-9969(01)00110-7

[14] Mishiro, A. (1996) Effect of Density on Ultrasonic Velocity in Wood. *Mokuzai Gakkaishi*, **42**, 887-894.