ACOUSTIC EVALUATION OF STANDING TREES
- RECENT RESEARCH DEVELOPMENT

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Abstract

This paper presents some research results from recent trial studies on measuring acoustic velocities on standing trees of five softwood species. The relationships between tree velocities measured by time-of-flight method and log velocities measured by resonance method were evaluated. Theoretical and empirical models were developed for adjusting observed tree velocity values to equivalent log velocities.

Introduction

Assessing wood quality in standing trees has been a long-time interest to wood products manufacturers and forest managers worldwide. A significant effort has been devoted to develop robust NDE technologies that are capable of predicting intrinsic wood properties of individual trees and assessing wood quality by stands and forests. The use of such technologies will not only lead to greater profitability to forest industry, but also can help foresters to make wise management decisions and grow good quality wood in the first place. The University of Minnesota Duluth, USDA Forest Products Laboratory, and CHH fibre-gen, Inc. have made significant progress on standing tree quality research in recent years. Several trail studies aimed at proving the acoustic concept for measuring acoustic velocity and wood properties of standing trees have been conducted in the United States and New Zealand. As a result of this collaboration research, a new acoustic wave technology has teen developed and commercialized for tree quality monitoring and assessment. The purpose of this paper is to present the results of some early trial studies on measuring tree acoustic velocities of several softwood species. The paper focuses on establishing reliable relationship between tree velocities measured by a time-of-flight method and log velocities measured by a resonance method, and discuss the causes of the deviation between observed tree velocity and log velocity. Effort was also made to construct analytical models for adjusting apparent tree velocity values in order to eliminate the deviation,

Fundamentals of Wave Propagation in Wood

Wave propagation in wood is, in its nature, a complex dynamic process controlled by the fiber properties, fiber orientation and fiber's microstructure, and perhaps more importantly, by the geometric form of the material. By monitoring and measuring the propagation process of certain waves in raw wood materials or various wood products, useful material information (such as modulus of elasticity, density, moisture content, various defects) can be obtained. This concept has ken explored extensively by many researchers worldwide for characterizing the physical and mechanical properties of various wood products and wood-based composite materials.

When a stress is applied suddenly to the surface of wood, the disturbance that is generated travels through the wood as stress waves. Generally, three types of waves are initiated through such an impact: 1) longitudinal wave (compressional or P-wave); 2) shear wave (S-wave); and 3) surface wave (Rayleigh wave). The longitudinal wave corresponds to the motion of the particles oscillating back and forth along the direction of wave propagation such that the particle velocity is parallel to the wave velocity. Whereas in shear waves, the motion of the particles conveying the wave is perpendicular to the direction of the propagation of the wave itself. The surface wave is usually restricted to the region adjacent to the surface and the particles move both up and down and back and forth, tracing out elliptical paths. Although most of the energy resulting from such an impact is carried by the shear wave and surface wave. the longitudinal wave is the one that travels fastest and easy to detect in field applications [6]. Consequently, it is by far the most commonly used wave type for property characterization.

A basic understanding of the relationship between wood properties and wave velocity (hereafter refer to longitudinal wave velocity) can be acquired from the fundamental wave theory. In a long slender isotropic material, the strain and inertia in transverse direction can be neglected and longitudinal waves propagate in a plane form (wave front). The partial differential equation (PDE) governing the free longitudinal motion of such a wave in a slender rod is as following [6],

$$\frac{\partial^2 u}{\partial t^2} = \frac{E}{\rho}\frac{\partial^2 u}{\partial x^2} \qquad (1)$$

where, *u* is longitudinal displacement variable, *t* is time, *x* is variable along length of a rod, E is longitudinal modulus of elasticity, and mass density of the material. The longitudinal wave velocity is independent of Poisson’s ratio and is given by the following equation (hereafter we refer it as one-dimensional wave equation):

$$C_0 = \sqrt{\frac{E}{\rho}} \qquad (2)$$

where, C_0 is longitudinal wave velocity.

In an infinite or unbounded isotropic elastic medium, a triaxial state of stress is present. The partial differential equation governing the propagation of the longitudinal waves becomes

$$\frac{\partial^2 \Delta}{\partial t^2} = \frac{\lambda + 2\mu}{\rho}\nabla^2 \Delta \qquad (3)$$

where, $\Delta = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33}$,

$\nabla^2 = \frac{\partial^2}{\partial x_1^2} + \frac{\partial^2}{\partial x_2^2} + \frac{\partial^2}{\partial x_3^2}$, and are the Lamé constants.

This second-order PDE is analogous to equation (1) and represents a wave of a general shape traveling at a velocity

$$C = \left(\frac{\lambda + 2\mu}{\rho}\right)^{1/2} \qquad (4)$$

From elasic theory, $\mu = \frac{E}{2(1+\nu)}$,

$\lambda = \frac{\nu E}{(1+\nu)(1-2\nu)}$,

Equation (4) can then be expressed as

$$C = \sqrt{\frac{1-\nu}{(1+\nu)(1-2\nu)}\frac{E}{\rho}} \qquad (5)$$

Equation (5) is the three-dimensional longitudinal wave equation in an unbounded isotropic medium. It implies that the dilatation ( ) is propagated through the medium with velocity C, which is dependent on two elastic parameters (modulus of elasticity and the Poisson’s ratio) and density. To differentiate with the longitudinal wave velocity in a slender rod, we will use the term of "dilatational wave" for unbounded medium hereafter.

The direct application of fundamental wave equations in wood, particularly in standing trees, has been complicated by the fact that wood is neither homogeneous nor isotropic. Wood properties in live trees vary from pith to bark as wood transforms from juvenile wood to mature wood. They also change from butt to top within a tree and differ between trees. Species difference, soil conditions, and environmental factors all affect wood characteristics in both microscopic and macrostructure levels. More importantly, for standing trees with no access to an end surface like in a log, stress waves can only be introduced from the side surface of a tree trunk, which results a non-uniaxial stress state in the stem.

If the dilatational wave is considered in the case of standing trees, the Poisson's ratio of wood is needed for describing the relationship between wave velocity and modulus of elasticity. Figure 1 demonstrates the effect of Poisson's ratio an dilatational wave velocity in theory. It can be seen that dilatational wave velocity is generally highs than C_0. As Poisson's ratio increases, the deviation of dilatational wave velocity from C_0 gets larger. For instance, the ratio of dilatational wave velocity to C_0 is 1.16 for =0.30. The velocity ratio becomes to 1.46 as Poisson's ratio increases to 0.40.

The Poisson's ratio of green wood is not explicitly known. Bodig and Goodman [2] and other investigators obtained Poisson's ratios through plate or compression testing for dry wood. The Poisson's ratio appears to change with species and material sources. However the statistical analysis by Bodig and Goodman indicated that the Poisson's ratios do not seem to vary with density or other anatomical characteristics of wood in any recognizable fashion [2]. Therefore an average value of 0.37 ($_{LR}$) has been suggested for both softwoods and hardwoods [2, 3]. This could translate into a dilatational wave velocity that is 1.33 times of the one-dimensional longitudinal wave velocity, which seems to be in agreement with some previous experimental results [1, 7, 8].

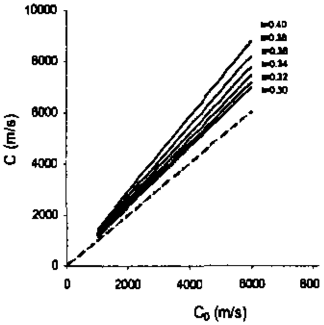


Figure 1. Effect of Poisson's ratio on dilatational wave velocity.

Development of the Acoustic Measurement System

An acoustic flight-of-time (TOF) measurement system was developed and used in field to measure acoustic velocity on standing trees. The system includes two probes, two acoustic sensors (accelerometers), a portable two-channel scopemeter, and a hand-held hammer. During field measurement, two probes are inserted into the tree trunk (pierce the bark and cambium and extend into the sapwood) and aligned within a vertical plane on the same face. The lower probe is put in a position about 400 to 600 mm (1 ½ to 2 ft.) above the ground. The distance between the upper probe and the lower probe is 1.22-m (4-ft), which is kept consistent during field testing. This span length between two probes is used mainly from practical concerns for operators reaching a comfortable height and easing the measurement process.

In inserting the probes into the tree trunk both probes are angled toward each other in a vertical plane to promote longitudinal compression waves. Two acoustic sensors (one start sensor, one stop sensor) are subquently mounted onto the probes, with the sensing directions facing the impact and the wave front of the compression waves respectively. The acoustic energy is then directed into the tree trunk by a mechanical impact on the lower probe. The resulting acoustic waves are detected by start and stop sensors and transmitted to the scopemeter.

The accuracy of this time-of-flight measurement depends on accurate identification of the arrival times of two received waveforms. In this protoype measurement system, the two received acoustic waves can be displayed on the screen so that the quality of the signals is visually evaluated before time measurement is performed. The quality of the signals is defined by the slope of the first rising pulse in the waveforms. A waveform with a sharp-rising pulse (high slope) in the beginning is deemed as a good signal and hence the time-of-flight is determined by measuring the time difference between two rising start points of the received waveforms. In the case of low slope rising pulse detected, a re-hit will be made to improve the quality of the signals. With proper electronic settings and consistent mechanical impacts, good quality acoustic signals can be obtained and the time-of-flight of acoustic waves can be accurately determined through cursory measurements. This slope-detection method is less sensitive to signal amplitude variations than is a simple voltage-threshold-detection method used in traditional TOF devices, and therefore the measurement has a good repeatability and consistence.

After TOF measurement, the acoustic velocities of trees can be computed by the equation:

$$C_T = \frac{S}{\Delta t} \qquad (6)$$

where C_T is tree acoustic velocity (m/s), S is the distance between two probes (or sensors) (m), and t the time-of-flight (s).

Experimental Trials

Several experimental trials aimed at proving the stress wave concept for tree quality evaluation were conducted in the United States and New Zealand in 2003 and 2004. A total of 352 trees were tested in the fist four trials. The species tested included Sitka spruce (*Pica sitchensis*), western hemlock (*Tsuga heterophylla*), jack pine (*Pinus banksiana*), ponderosa pine (*Pinus*

Table 1. Stand age and diameter at breast height of trees tested in five. [a]

Species	Country	Stand age	No. of trees	DBH(mm)				
				Minimum	Maximum	Mean	STD	COV(%)
Sitka spruce	USA	mixed	30	74	406	207	96.2	46.5
Western hemlock	USA	mixed	31	74	325	183	69.2	37.8
Jack pine	USA	40	27	79	348	209	713	41.1
Ponderosa pine	USA	43	114	152	381	236	549	23.3
Radiata pine	New Zealand	8	50	104	236	164	32.4	19.8
	New Zealand	16	50	193	475	363	64.4	17.1
	New Zealand	25	50	265	717	531	87.1	164
Combined			352	74	717	277	136	49.1

[a] DBH - tree diameter at breast height STD - standard deviation; COV - coefficient of variation (%).

ponderosa), and radiata pine (*Pinus radiate*). Table 1 summarizes the stand age and diameter information of the trees tested in these trials.

Acoustic TOF measurement was conducted on each tree sample using the prototype measurement system. Tree measurement was performed on a randomly selected side of the tree trunk and three readings were collected on each tree to derive an average acoustic velosity. in conjunction with acoustic measurement, the diameter at breast height (DBH) of each tree was also measured according to the dommon practice in forestry measurement.

To validate the TOF measurement on standing trees, all tested trees were felled following field tree testing and a 3.66-m-(12-ft-) long butt log of each tested tree was cut. A resonance based acoustic method was then used to measure longitudinal wave velocity in the butt logs. Resonance data was obtained from each butt log using a resonance acoustic tool (Director HM200) and a build-in Fast Fourier Transformation (FFT) program analyzed the acoustic signals following an impact [5]. The log acoustic velocity is determined based on the equation:

$$C_L = 2 f_0 L \qquad (7)$$

Where C_L is acoustic velocity of logs (m/s), f_0 the fundamental natural frequency of an acoustic wave signal (Hz), and L the log length (end-to-end) (m).

Results and Discussion

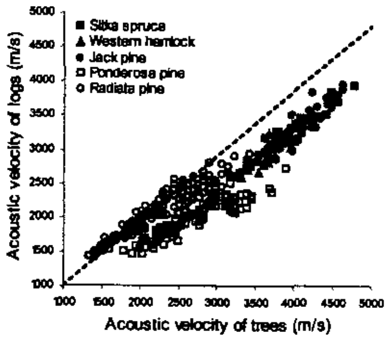
Relationship between tree acoustic velocity and log acoustic velocity

Figure 2 shows the relationship between acoustic velocity measured on the standing trees and acoustic velocity measured on the butt logs. The regression analysis indicates a linear correlation between tree velocity and log velocity for each species tested. The relationship is characterized by the coefficient of determination (R^2) in the range of 0.710 and 0.933 (Table 2). By observing the data plot, we found that Sitka spruce, western hemlock, and jack pine trees are in higher velocity range and have similar relationships. However, in low velocity range, ponderosa pine and radiate pine exhibits a distinct difference in C_T-C_L relationship. This difference could have been caused by the age and diameter differences between two species evaluated in the trials. For the ponderosa pine trees, the stand was even aged and 43 years old at the time of testing. The stems have already contained a significant amount of mature wood. The DBH of the tree samples ranged from 152 to 381 mm. In contrast, radiate pine trees were much younger and included three different ages: 8 years, 16 years, and 25 years. The radiate pine trees contain no

Table 2. Summary of regression equations and their significance (Y = a+bX) [a]

Species	X	Y	a	b	R^2	SEE	Significance @ 95%
Sitka spruce	C_T	C_L	-18.7	0.8265	0.933	92.48	Yes
Western hemlock	C_T	C_L	-152.7	0.8482	0.845	97.8	Yes
Jack pine	C_T	C_L	-191.9	0.8704	0.710	138.91	Yes
Ponderosa pine	C_T	C_L	516.9	0.5426	0.830	109.13	Yes
Radiatapine	C_T	C_L	537.6	0.6951	0.900	115.16	Yes
Combined	C_T	C_L	386.8	0.694	0.854	229.97	Yes

[a] C_T - acoustic velocity measured on trees C_L - acoustic velocity measured on logs, a, b-regression coefficients, R^2 - coefficient of determination, SEE- standard error of estimate.



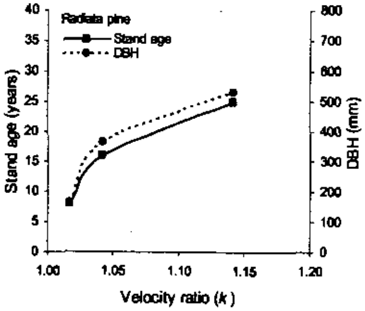


Figure 3. Relationships between stand age, DBH, and velocity ratio of radiata pine.

mature wood or much less mature wood, therefore the acoustic velocity measured on the tree stem are not affected, or much less affected by the mature wood compared with ponderosa pine. In addition, the radiate pine in this group contains some small trees, with DBH as small as 104 mm. The stress waves measured in these small frees would propagate more like one-dimensional longitudinal waves other than dilatational waves in bigger trees. The younger age and smaller diameter of these radiata pine trees would result in tree velocities much closer to log velocities as demonstrated in the data plot of Figure 2.

The fundamental relationship between tree velocity and log velocity seems can be affected by the acoustic velocity range of the trees investigated. For each individual species investigated in these trials, the velocity range is relatively mall due to small sample size and limited age and DBH range of the free samples. To confirm the tree-log correlation in a larger scale, in other words, to cover a larger velocity range, regression analysis was made with all species combined. Despite the distinct difference between ponderosa pine and radiata pine, a strong relationship was found between tree velocity and log velocity as evidenced by the high coefficient of determination ($R^2 = 0.854$). This result indicates a high level of confidence that acoustic velocity of standing trees measured by TOF method may be used to derive equivalent log acoustic velocity.

The trial data shows that acoustic velocity measured on standing trees by TOF method is generally higher than the acoustic velocity measured in the butt logs by resonance method. This result is consistent with previous findings on standing trees and logs [1, 4, 7, 8]. The deviation of tree velocity from log velocity seems be influenced by species, stand age and DBH of the trees. To quantify this velocity difference, we define a velocity ratio k as

$$k = \frac{C_T}{C_L} \qquad (8)$$

where C_T is the acoustic velocity of a tree and C_L is the acoustic velocity of a butt log.

Table 3. Statistic summaries of acoustic velocities measured on trees and logs[a].

	CT (m/s)				CL (m/s)				
Species	Min	Max	Mean	STD	Min	Max	Mean	STD	*k*
Sitka spruce	3175	4763	3892	409.4	2583	3917	3198	350.3	1.22
Western hemlock	3289	4293	3721	2644	2590	3483	3004	244.0	1.24
Jack pine	3751	4618	4218	2447	2980	3940	3480	252.9	1.21
Ponderosa pine	1793	3908	2700	442.7	1460	2730	1982	263.6	1.36
Radiata pine	1327	3771	2277	496.1	1390	2930	2120	363.5	1.07
Combined	1327	4763	2828	801.8	1390	3940	2349	602.0	1.20

[a] C_T -acoustic velocity measured on trees C_L - acoustic velocity measured on logs, STD - standard deviation, *k* · velocity ratio (C_T /C_L).

Table 3 shows the statistic summaries of acoustic velocities measured on trees and logs.
The average velocity ratio is the lowest for radiata pine (1.07) and the highest for ponderosa pine (1.36). For Sitka spruce, western hemlock, and jack pine, the velocity ratios are actually very close, from 1.22 to 1.24. The significant difference in velocity ratios of ponderosa pine and radiata pine could have been caused by the age and DBH differences other than species difference. As indicated in Table 1, two third (2/3) of the radiata pine sample trees are 16 years old and younger, which contains no mature wood. However, all ponderosa pine trees are 43 years old with a significant of amount of mature wood. The younger age, as well as the smaller diameter, of the radiata pine trees would result in tree velocities that are much closer to log velocities than ponderosa pine does.

The age and DBH influence on velocity ratio can be further illustrated by the data from radiate pine trees. Figure 3 shows the inter-relationships between stand age, DBH, and velocity ratio for radiata pine. It is clearly that as stand age increases, velocity ratio increases. Especially when stand age passes 16, velocity ratio increases dramatically as a result of mature wood effect. On the other hand, as stand age increases, DBH of the trees also increases. Therefore, a similar relationship also exists between DBH and velocity ratio, that is, velocity ratio increaser as DBH increases.

Figure 4 shows the relationships between DBH and velocity ratio for all species. Clearly there is a linear relationship between DBH and velocity ratio for ponderosa pine and radiate pine trees. Diameter effect is more prominent in even-aged ponderosa pine stand than in mix-aged radiate pine stands. However, we did not find clear DBH-*k* relationship for Sitka spruce, western hemlock, and jack pine. Some of the contributing factors for this are small sample size, mixed tree ages (Sitka spruce and western hemlock), and mixed species (jack pine group was mixed with some yellow birch).

Tree velocity adjustment - Empirical models

To assess the wood quality directly from acoustic velocity values observed on standing trees is apparently not appropriate because of the skewed relationship between tree velocity and log velocity. Adjustment must be made on observed tree velocity (apparent velocity) to correct the deviation.

One possible way to adjust apparent tree velocities is to use the empirical relationships between tree velocity and log

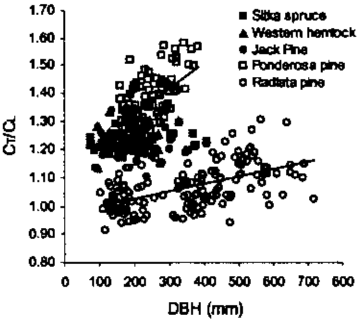


Figure 4. Relationship between DBH and velocity ratio for all species tested.

velocity directly. The drawback for this method is that the adjusted tree velocity will suffer from relatively large variations inherited in the linear regression models. From previous discussion, we know that tree diameter has significant influence on TOF measurement and a positive relationship existed between DBH and tree velocity for some species. Since DBH of trees is a readily available parameter, appropriate multivariate regression models with apparent velocity and DBH as variables can be established to reduce the variation.

The following multiple nonlinear regression model was applied to the experimental data:

$$C_L = a(\frac{DBH}{S})^b C_T^c \qquad (9)$$

where *a, b,* and *c* are coefficients determined by regression analysis, *S* is the span between two probes. In the trial studies discussed in this paper, *S* was kept constant and was 1.2 m (4 ft.). Separate regressions were developed for each species and for all species combined. The regression coefficients and coefficients of determination are listed in Table 4.

Compared with the univariable linear regressions in Table 2, the multiple nonlinear regressions showed better correlation for the ponderosa pine and radiate pine trees. The coefficient of

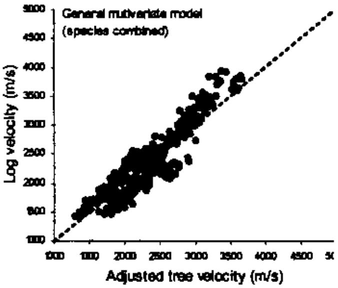


Figure 5. Relationship between adjusted tree velocity (multivariate model) and log velocity for all species combined.

Table 4. Summary of multiple nonlinear regression equations and their significance[a].

	C_L = a $(DBH/S)^b$ C_T^c				
Species	a	b	c	R^2	Significance @95%
Sitka spruce	0.7448	0.0004	1.0119	0.934	Yes
Western hemlock	0.4641	0.0234	1.0616	0.854	Yes
Jack pine	0.7666	0.0025	1.009	0.702	Yes
Ponderosa pine	2.7789	0.0675	0.8175	0853	Yes
Radiata pine	6.7389	0.0075	0.7457	0.920	Yes
Combined	5.5092	0.0295	0.7677	0.825	Yes

[a] C_T - acoustic velocity measured on trees, C_L - acoustic velocity measured on logs.

a, b, c - regression coefficients, R2 - coefficient of determination

determination increased from 0.830 (ponderosa pine) and 0.900 (radiate pine) to 0.853 (ponderosa pine) and 0.920 (radiate pine). However, for Sitka spruce, western hemlock, and jack pine, there is no significant change in the correlation. This is not surprising because no significant diameter effect was observed on DBH-C relationship either for these three species. As mentioned earlier, this was most likely caused by the small sample size and mixed stand ages encountered in the trees we tested. So overall, the multiple nonlinear regression model is probably still a better choice than the univarable linear regression model.

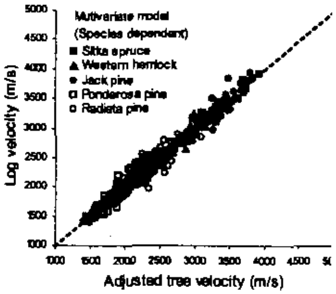


Figure 6. Relationship between adjusted tree velocity (multivariate model) and log velocity for each individual species.

Figure 5 and Figure 6 show the relationships between adjusted tree velocities and log velocities. The tree velocity in Figure 5 was adjusted based on the general multiple regression model (species are combined) and the tree velocity in Figure 6 was adjusted based on species-dependent multiple regression models. In both cases, the average velocity ratio after adjustment is 1, which means the adjusted tree velocity is equivalent to the log velocity. It is apparent that species-dependent regression models product much less variation than the general regression model.

Table 5. Estimated Poisson's ratios of five softwood species.

	Average velocity ratio	Estmated Poisson's ratio
Species	k	v
Sitka spruce	1.22	0.331
Western hemlock	1.24	0.340
Jack pine	1.21	0.321
Ponderosa pine	1.36	0.378
Radiata pine	1.07	0.222
combined	1.20	0.322

Tree velocity adjustment – Theoretical Model

The experimental data indicated that the deviation of tree velocity from log velocity is related to factors such as species, tree diameter, and stand age. But the fundamental cause of this deviation stems from different wave propagation mechanisms for two acoustic measurement methods. For resonance measruement on felled logs, the stress wave is introduced into the log by a direct end impace, which results in a plane wave (or quasi-plane wave) traveling along the longitudinal axis of a log. In the case of TOF measurement on standing trees, stress waves are generated and directed into a tree trunk by indirect impact (through a probe) on the side surface of the trunk. With respect to a small wave-initiating point and a short span length considered, the test object becomes large enough to absorb and dissipate energy in a three-dimensional content. Depending on the diameter of a tree, the wave may travel within the trunk as a quasi-plane wave (if diameter is small enough) or a dilatational wave (if diameter is big enough). The fact that measured tree velocities are significantly higher than the corresponding log velocities is a good indication that time-of-night measurement on trees are dominated by dilatational waves other than one-dimensional plane waves. Through a metal bar experiment, Andrews also confirmed that TOF measurements are indeed influenced by the fast dilatational waves in elastic materials [1].

From dilatational wave equation (5), the theoretical ratio between dilatational wave velocity and one-dimensional wave velocity is given by the Poisson's ration:

$$k = \sqrt{\frac{(1-\nu)}{(1+\nu)(1-2\nu)}} \qquad (10)$$

Based on equation (10), the Poisson's ratio of each species was estimated from average velocity ratio given in Table 3. As shown in Table 5, the calculated Poisson's ratio is in the range of 0.222 to 0.378 with an average value of 0.322. These are very close to the Poisson's ratios given for dry wood and therefore are reasonable values.

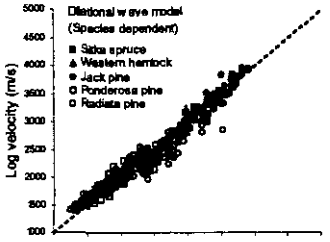


Figure 7. Relationship between adjusted tree velocity (dilatational wave model) and log velocity

With dilatational wave theory, tree velocities measured by TOF method can then be adjusted based on the estimated Poisson's ratio for the species. Figure 7 shows the relationships between the adjusted tree velocity and log velocity. The overall correlation between tree velocity and log velocity has been improved significantly, with a coefficient of determination of 0.950. Analysis indicated that the average velocity ratio after adjustment approached to 1. The average prediction deviation ranged from 2 to 6 percent (in absolute value), which is a very good agreement between adjusted velocity and log velocity.

Summary and Conclusions

Acoustic wave velocities were measured on standing trees of five softwood species by time-of-flight acoustic method. Observed tree velocities were than compared with the acoustic velocities measured on the corresponding butt logs through a resonance acoustic method. The experiment data showed a skewed relationship between tree acoustic measurement and log acoustic measurement. Observed tree velocities are significantly higher than log velocities for most trees tested. The deviation between tree velocity and log velocity seems to link to species, stand age and diameter at breast height of the trees. Positive relationship between tree velocity and DBH has been found in the ponderosa pine and radiata pine trees. We speculate that similar relationship might exist for other species if sufficient data is obtained.

Because of the significant velocity deviation and skewed relationship between tree measurement and log measurement, the tree velocity measured by TOF method can not be directly used for assessing the wood quality of standing trees. To make an appropriate adjustment on observed tree velocities, analytical models were developed for the species evaluated in these trial studies. The multiple variable regression model that relates log velocity to both observed tree velocity and DBH was found effective in reducing the velocity prediction variability. The best tree velocity adjustment can be made through species-dependent individual regression models.

Although the deviation between tree velocity and log velocity seems to link to species, stand age, and DBH of trees, the fundamental cause of this deviation stems from different wave propagation mechanisms of two acoustic approaches. The experiment data from our trial studies indicates that time-of-flight measurement on standing trees is likely dominated by the dilatational waves other than one-dimensional plane waves. Based on dilatational wave theory, the velocity ratios observed for five softwood species corresponds to Poisson's ratio values in the range of 0.222 to 0.378, with the average value of 0.322. The adjustment on tree velocity based on dilatational wave models was also found effective.

The results of these trail studies have proved that the concept of time-of-flight acoustic wave method works for standing trees. As a result of this collaboration research, a commercial tool (Director ST300) has been developed and commercialized for tree quality monitoring and assessment.

Literature

[1] Andrews, M.K. 2003. Which acoustic speed? In: Proceedings of the 13th International Symposium on Nondestructive Testing of Wood; August 19-21, 2002; Berkley, California: 159-165.

[2] Bodig, Jozsef and J.R. Goodman. 1973. Prediction of elastic parameters for wood. Wood Science 5(4): 249-264.

[3] Bodig, Jozsef and B.A. Jayne. 1982. Mechanics of Wood and Wood Composites. Van Nostrand Reinhold Company Inc., New York, NY.

[4] Carter, P., D. Briggs, R.J. Ross, X. Wang. 2004. Acoustic testing to enhance western forest values and meet customer wood quality needs. *Productivity of Western Forests: A Forest Products Focus,* Sponsored by Oregon State University College of forestry, USDA Forest Service PNW Research Station, Western Forestry & Conservation Association, and NW Forest Soils Council, September 20-23, Kamiche, WA.

[5] Harris, P., R. Petherick, and M. Andrews. 2002. Acoustic resonance fools. In: Proceedings, 13th International Symposium on Nondestructive Testing of Wood, August 19-21, 2002; Berkeley, California: 195.201.

[6] Meyers, Marc A. 1994. Dynamic behavior of materials. John Wiley & Sons, Inc., New York, NY.

[7] Wang, X.; R.J. Ross, M. McClellan; R.J. Barbour, J.R Erickson, J.W. Forsman, G.D. McGinnis;. 2001. Nondestructive evaluation of standing trees with stress wave method. *Wood and Fiber Science.* 33(4): 522-533.

[8] Wang, X., R.J. Ross, J. Punches, R.J. Barbour, J.W. Forsman, and J.R. Erickson. 2003. Evaluation of small-diameter timber for value-added manufacturing - A stress wave approach. In: Proceedings, 2nd International Precision Forestry Symposium, 2003 June 15-17; Seattle, WA. Seattle, WA: College of Forest Resources, University of Washington: 91-96.

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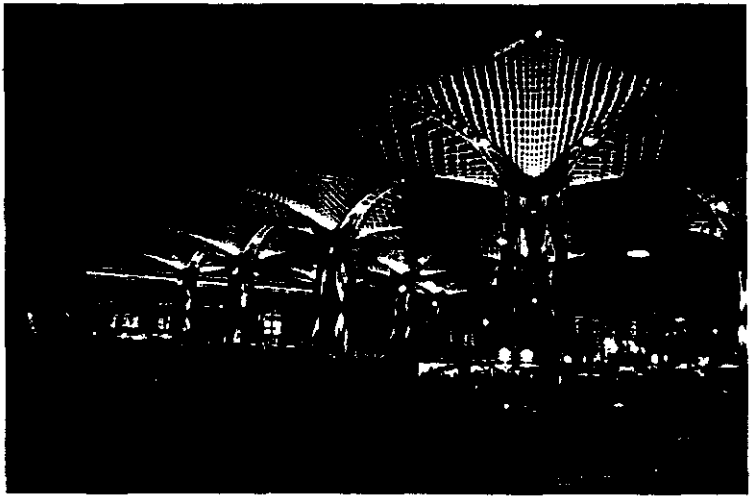

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