ACOUSTIC EVALUATION OF WOOD QUALITY IN STANDING TREES. PART I. ACOUSTIC WAVE BEHAVIOR

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ABSTRACT

Acoustic wave velocities in standing trees of five softwood species were measured by the time-of-flight (TOF) method. Tree velocities were compared with acoustic velocities measured in corresponding butt logs through a resonance acoustic method. The experimental data showed a skewed relationship between tree and log acoustic measurements. For most trees tested, observed tree velocities were significantly higher than log velocities. The results indicate that time-of-flight measurement in standing trees is likely dominated by dilatational or quasi-dilatational waves rather than one-dimensional plane waves. To make appropriate adjustments of observed tree velocities, two analytical models were developed for the species evaluated. Both the multivariate regression model and dilatational wave model were effective in eliminating deviation between tree and log velocity and reducing variability in velocity prediction.

Keywords: Acoustic velocity, time-of-flight, dilatational wave, Poisson's ratio, standing trees, logs.

INTRODUCTION

Assessment of the quality of wood in standing trees has long been of interest to wood products manufacturers and forest managers worldwide. A significant effort has been devoted toward developing robust nondestructive evaluation (NDE) technologies capable of predicting the intrinsic wood properties of individual trees and assessing wood quality by stand and forest. The use of such technologies not only leads to greater profitability for the forest industry, but can also help foresters make wise management decisions and grow high quality wood in the first place.

Acoustic technologies have been well established as material evaluation tools in the past several decades, and their use has become widely accepted by the wood industry for quality control and product grading, such as veneer and

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lumber grading and log segregation. Consequently, the focus of research has turned to applying acoustic technology to the assessment of tree quality. Key issues for applying this technology to standing trees include (1) the accurate measurement of acoustic wave velocity in standing trees and (2) the implications of acoustic measures for wood and fiber quality. The results of research will determine how effectively acoustic based NDE technologies can be implemented in the field.

The objectives of this paper were to evaluate the use of a time-of-flight (TOF) acoustic method in measuring acoustic velocity of standing trees and to better understand the differences of acoustic wave behavior in standing trees and that in felled logs. Analysis was based on the results of trial studies conducted in the United States and New Zealand on measuring tree acoustic velocity of several softwood species. The paper focused on examining the relationship between tree velocity measured by a TOF method and log velocity measured by a resonance method. Effort was also made to construct analytical models for adjusting apparent tree velocity values to eliminate deviation between observed tree and log velocities.

This Paper is Part I of a series of papers on the acoustic evaluation of wood quality in standing trees. Part 2 will address relationships between tree acoustic velocity and wood fiber properties. Part 3 will focus on relationships between tree acoustic velocity and the mechanical properties and grade yield of structural lumber.

FUNDAMENTALS OF WAVE PROPAGATION IN WOOD

Wave propagation in wood is a complex dynamic process controlled by the properties, orientation, and microstructure of wood fiber and, perhaps more importantly, by the geometric form of the material. Information about wood properties, such as modulus of elasticity, density, and moisture content, as well as wood defects can be obtained by monitoring and measuring the propagation of certain waves in raw wood materials and wood products. This concept has been explored extensively for characterizing the physical and mechanical properties of various wood products and wood-based composite materials.

When stress is applied suddenly to the surface of wood, the disturbance that is generated travels through the wood as stress waves. In general, three types of waves are initiated by such an impact: (1) a longitudinal wave (compressive or P-wave), (2) shear wave (S-wave), and (3) surface wave (Rayleigh wave) (Fig. 1). A longitudinal wave corresponds to the oscillation of particles along the direction of wave propagation such that particle velocity is parallel to wave velocity. In a shear wave, the motion of the particles conveying the wave is perpendicular to the direction of the propagation of the wave itself. A Rayleigh (surface) wave is usually restricted to the region adjacent to the surface; particles move both up and down and back and forth, tracing elliptical paths. Although most energy resulting from an impact is carried by shear and surface waves, the longitudinal wave travels the fastest and is the easiest to detect in field applications (Meyers 1994). Consequently, the longitudinal wave is by far the most commonly used wave for property characterization.

A basic understanding of the relationship between wood properties and wave velocity (hereafter referred to as longitudinal wave velocity) can be acquired from fundamental wave theory. In a long, slender, isotropic material, strain and inertia in the transverse direction can be ne-

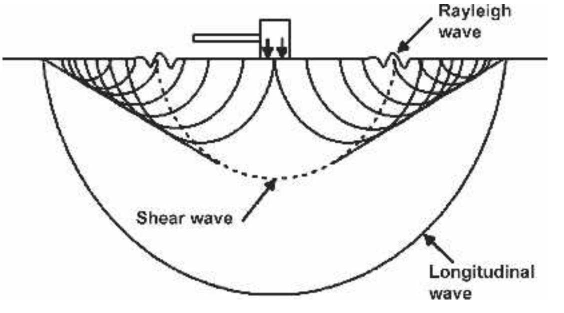

FIG. 1. Types of stress waves in semi-infinite elastic material.

glected and longitudinal waves propagate in a plane form (wave front). The partial differential equation (PDE) that governs the free motion of a longitudinal wave in a slender rod is as follows (Meyers 1994):

$$\frac{\partial^2 u}{\partial t^2} = \frac{E}{\rho}\frac{\partial^2 u}{\partial x^2} \tag{1}$$

where u is a longitudinal displacement variable, t is time, x is a variable along the length of a rod, E is longitudinal modulus of elasticity, and ρ is mass density of material. Longitudinal wave velocity is independent of Poisson's ratio and is given by the following equation (hereafter referred to as a one-dimensional wave equation):

$$C_0 = \sqrt{\frac{E}{\rho}} \tag{2}$$

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 longitudinal waves becomes

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

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 λ and μ are Lamé constants.

This second-order PDE (Eq. (3)) is analogous to Eq. (1) and represents a wave of a general shape traveling at a velocity

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

From elastic theory,

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

Equation (4) can then be expressed as

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

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

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. Properties also change from butt to top within a tree and differ between trees. Species, soil conditions, and environmental factors all affect wood characteristics on both microscopic and macrostructure levels. More importantly, for standing trees with no access to an end surface (in contrast to a log), stress waves can be introduced only from the side surface of the trunk, which results in a non-uniaxial stress state in the stem.

If the dilatational wave is considered in the case of standing trees, Poisson's ratio of wood is needed to describe the relationship between wave velocity and modulus of elasticity. Figure 2 demonstrates the effect of Poisson's ratio on dilatational wave velocity in theory. As the figure illustrates, dilatational wave velocity is generally higher than C_0 (Eq. (2)). As Poisson's ratio (ν) 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 $\nu = 0.30$. The velocity ratio becomes 1.46 as ν increases to 0.40.

The Poisson's ratio of green wood is not explicitly known. Bodig and Goodman (1973) and other investigators obtained Poisson's ratios through plate or compression testing for dry wood. Poisson's ratio appears to change with

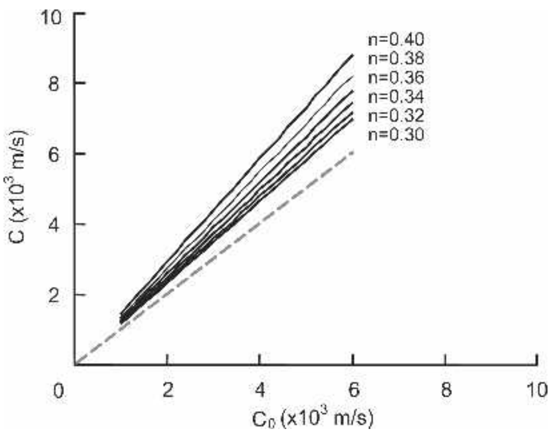

FIG. 2. Effect of Poisson's ratio on dilatational wave velocity.

species and material sources. However, statistical analysis by Bodig and Goodman (1973) indicated that Poisson's ratios do not seem to vary with density or other anatomical characteristics of wood in any recognizable fashion. Therefore, an average value of 0.37 (ν_{LR}) has been suggested for both softwoods and hardwoods (Bodig and Goodman 1973; Bodig and Jayne 1982). This could translate into a dilatational wave velocity that is 1.33 times that of the one-dimensional longitudinal wave velocity, which is apparently in agreement with previous experimental results (Andrews 2003; Wang et al. 2001, 2003).

TIME-OF-FLIGHT ACOUSTIC MEASUREMENT IN STANDING TREES

A time-of-flight (TOF) acoustic measurement system was developed by the research team for measuring acoustic velocity in standing trees (Wang et al. 2004a). The prototype system includes two probes (input probe and receive prove), two acoustic sensors (start sensor and stop sensor), a portable two-channel scopemeter, and a hand-held hammer (Fig. 3a). During field measurement, the probes are inserted into the tree trunk (probes pierce bark and cambium and extend into sapwood) and aligned within a vertical plane on the same face. The lower probe is placed about 400 to 600 mm above the ground.

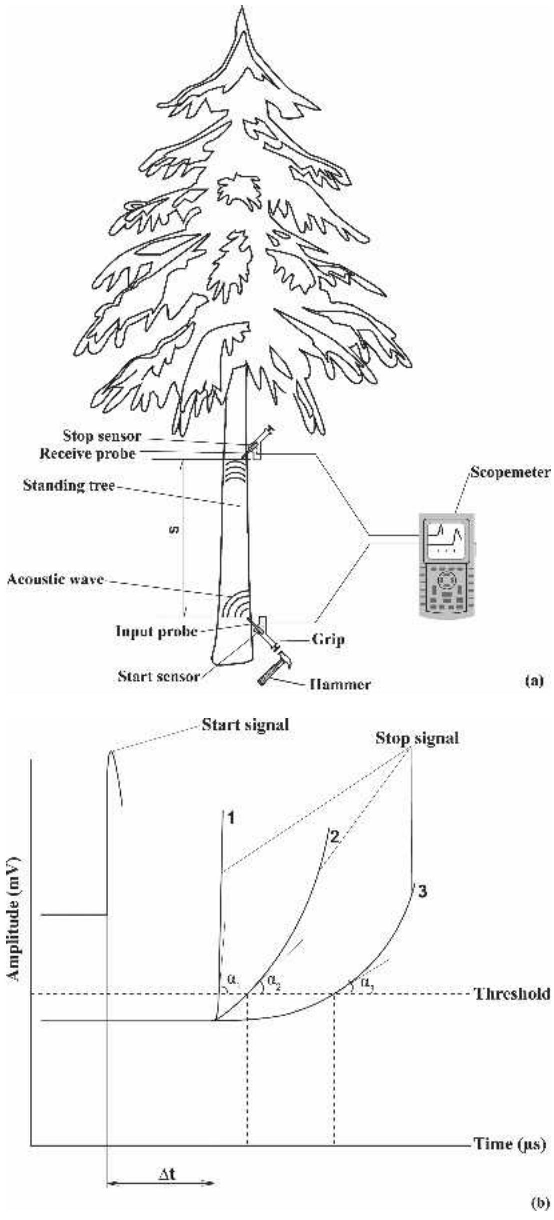

FIG. 3. Time-of-flight (TOF) acoustic measurement in standing trees: (a) Prototype system; (b) TOF determination.

The distance between the upper and lower probes is 1.22 m; this distance is kept constant during field testing. The length of the span between the probes is determined from a practical standpoint; the probes need to be positioned at a comfortable height for the person who takes the measurements.

When the probes are inserted into the tree trunk, they are angled toward each other in a vertical plane to promote the propagation of longitudinal compression waves. Two acoustic sensors (start and stop sensors) are subsequently mounted onto the probes, with the sensing directions facing the impact and the wave front of the compression waves. The acoustic energy is then directed into the tree trunk by a mechanical impact on the input probe. The resulting acoustic waves are detected by the sensors and transmitted to the scopemeter.

The accuracy of TOF measurement depends on accurate identification of the arrival times of the acoustic wave signals, each from a start sensor and a stop sensor. In this prototype measurement system, both acoustic waves can be displayed on the screen so that the quality of the signals is visually evaluated before time of flight is measured. The quality of the signals is defined by the slope of the first rising pulse in the waveforms. A waveform (such as the stop signal 1 in Fig. 3b) with a sharp-rising pulse (high slope) in the beginning is deemed as a good signal. Hence, time-of-flight is determined by measuring the time difference between the two rising start points of the received waveforms (Fig. 3b). If a low-rising pulse (low slope) (such as the stop signals 2 and 3 in Fig. 3b) is detected, another impact is generated 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 the simple voltage threshold detection method used in traditional TOF devices, and therefore the measurement has good repeatability and consistence (Wang et al. 2004a).

After TOF measurement, acoustic velocities can be computed by

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

where C_T is tree acoustic velocity (m/s), S is distance between the two probes (sensors) (m), and Δt is time of flights.

HYPOTHESIS

For acoustic measurement in standing trees, with respect to a small wave-initiating point and a short span length (1.2 m), the object (tree section under testing) is large enough to absorb and dissipate energy in a three-dimensional content. In other words, TOF measurement in standing trees is dominated by dilatational waves or quasi-dilatational waves other than one dimensional plane waves.

EXPERIMENTAL

Tree Measurement

Several experimental trials aimed at proving the stress wave concept for evaluating tree quality were conducted in the United States and New Zealand in 2003 and 2004. A total of 352 trees were tested in the first four trials. Species included Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*), jack pine (*Pinus banksiana*), ponderosa pine (*P. ponderosa*), and radiata pine (*P. radiate*). Table 1 provides information on the age and diameter of the test trees.

Acoustic TOF measurement was conducted in each tree using the prototype measurement system. Tree measurements were taken from a randomly selected side of the tree trunk. Three readings were collected from each tree to derive average acoustic velocity. Diameter at breast height (DBH) of each tree was also measured.

Log Measurement

To validate TOF measurement in standing trees, all tested trees were felled after testing and a 3.66-m-long butt log was cut from each tree. A resonance based acoustic method was then used to measure longitudinal wave velocity in the butt logs. Resonance data were obtained using a resonance acoustic tool (Director HM200, CHH fibre-gen, New Zealand). Acoustic signals were

TABLE 1. *Stand age and tree diameter for test trees.*[a]

Species	Country	Stand age (years)	No. of trees	DBH (mm) Min	Max	Mean	SD	COV (%)
Sitka spruce	USA	Mixed	30	74	406	207	96.2	46.5
W. hemlock	USA	Mixed	31	74	325	183	69.2	37.8
Jack pine	USA	40	27	79	348	209	71.3	34.1
Ponderosa pine	USA	43	114	152	381	236	54.9	23.3
Radiata pine	New Zealand	8	50	104	236	164	32.4	19.8
	New Zealand	16	50	193	475	363	64.4	17.7
	New Zealand	25	50	265	717	531	87.1	16.4
Combined			352	74	717	277	136.0	49.1

[a] W. hemlock is western hemlock; DBH, diameter at breast height; SD, standard deviation; COV, coefficient of variation.

analyzed by a built-in fast Fourier transformation (FFT) program following impact (Harris et al. 2002). Log acoustic velocity was determined on the basis of the following equation:

$$C_L = 2f_0L \tag{7}$$

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

The resonance-based acoustic method is a well-established NDE technique for measuring long, slender wood members (Harris and Andrews 2002; Andrews 2003; Wang et al. 2004b). The inherent accuracy and robustness of this method provide a significant advantage over TOF measurement in applications such as log measurement. In contrast to TOF measurement, the resonance approach stimulates many, possibly hundreds, of acoustic pulse reverberations in a log, resulting in a very accurate and repeatable velocity measurement. Because of this accuracy, the acoustic velocity of the logs obtained by the resonance-based acoustic method was used as a standard to validate the TOF measurement in standing trees.

RESULTS AND DISCUSSION

Relationship between tree and log acoustic velocity

Figure 4 shows the relationship between acoustic velocity measured in standing trees and butt logs. Regression analysis indicated a linear correlation between tree and log velocity for each species tested. The relationship was characterized by a coefficient of determination (R^2) in the range of 0.710 to 0.933 (Table 2). The relationship between tree velocity (C_T) and log velocity (C_L) was similar for Sitka spruce, western hemlock, and jack pine; velocity of these species was at the higher end of the range. Ponderosa pine and radiata pine were found to be at the low end of the velocity range and differed in their C_T-C_L relationship. This difference could have been caused by the different ages and diameters of these trees. The even-aged ponderosa pine stand was 43 years old at the time of testing, and the stems contained a significant amount of mature wood, which affected the measurement of acoustic velocity. Diameter of the tree samples ranged from 152 to 381 mm in

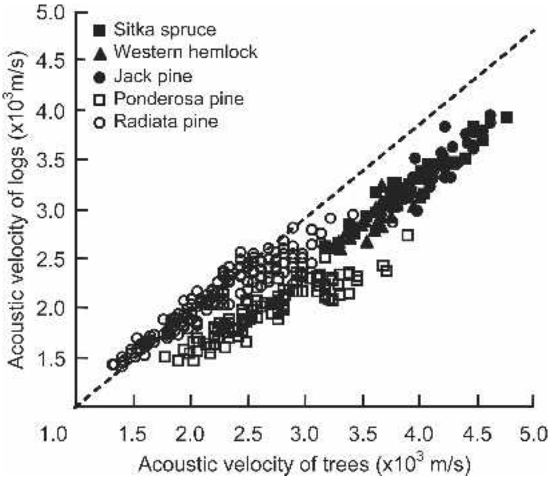

FIG. 4. Relationship between acoustic velocity measured in standing trees and butt logs.

TABLE 2. *Data for regression equations (*y = a + bx*).*[a]

Species	x	y	a	b	R^2	SEE
Sitka spruce	C_T	C_L	−18.7	0.8265	0.933	92.48
W. hemlock	C_T	C_L	−152.7	0.8482	0.845	97.80
Jack pine	C_T	C_L	−191.9	0.8704	0.710	138.91
Ponderosa pine	C_T	C_L	516.9	0.5426	0.830	109.13
Radiata pine	C_T	C_L	537.6	0.6951	0.900	115.16
Combined	C_T	C_L	386.8	0.6940	0.854	229.97

[a] All data were significant at a 95% level of confidence. C_T and C_L are acoustic velocity measured on trees and logs, respectively; a and b are regression coefficients; R^2 is coefficient of determination; SEE is standard error of estimate.

DBH. In contrast, the different-aged radiata pine stands were much younger (8, 16, and 25 years old). In addition, the radiata pine in this group contained some small trees, with DBH as small as 104 mm. Stress waves measured in these trees would propagate more like one-dimensional longitudinal waves rather than the dilatational waves measured in larger trees. The younger age and smaller diameter of the radiata pine trees resulted in a closer relationship between tree and log velocity (Fig. 4).

The fundamental relationship between tree velocity and log velocity seemed to be affected by the acoustic velocity range of the trees investigated. For each species investigated, the range in velocity was relatively small as a result of the small sample size, limited age, and narrow DBH range. To confirm the correlation between tree and log velocity on a larger scale, i.e., to cover a larger velocity range, a regression analysis was made of 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 the acoustic velocity of standing trees measured by the TOF method may be used to derive equivalent log acoustic velocity.

The trial data showed that acoustic velocity measured in standing trees by the TOF method is generally higher than acoustic velocity measured in butt logs by the resonance method. This result is consistent with previous findings from tests in standing trees and logs (Wang et al. 2001, 2003; Andrews 2003; Carter et al. 2004). The deviation of tree velocity from log velocity seems be influenced by species, stand age, and tree diameter. To quantify this velocity difference, we define a velocity ratio k as

$$k = \frac{C_T}{C_L} \tag{8}$$

where C_T is tree acoustic velocity and C_L is butt log acoustic velocity.

Acoustic velocity values are shown in Table 3. The average ratio of tree to log velocity was lowest for radiata pine (1.07) and highest for ponderosa pine (1.36). Velocity ratios for Sitka spruce, western hemlock, and jack pine were very close (1.22 to 1.24). The significant differ-

TABLE 3. *Statistical summary of acoustic velocities measured on trees and logs.*

	C_T (m/s)				C_L (m/s)				
Species	Min	Max	Mean	SD	Min	Max	Mean	SD	k[a]
Sitka spruce	3,175	4,763	3,892	409.4	2,583	3,917	3,198	350.3	1.22
W. hemlock	3,289	4,293	3,721	264.4	2,590	3,483	3,004	244.0	1.24
Jack pine	3,751	4,618	4,218	244.7	2,980	3,940	3,480	252.9	1.21
Ponderosa pine	1,793	3,908	2,700	442.7	1,460	2,730	1,982	363.6	1.36
Radiata pine	1,327	3,771	2,277	496.1	1,390	2,930	2,120	363.5	1.07
Combined	1,327	4,763	2,828	801.8	1,390	3,940	2,349	602.0	1.20

[a] k = velocity ratio (C_T/C_L).

ence in the velocity ratio for ponderosa pine and radiata pine could have been caused by age and DBH differences rather than species. As indicated in Table 1, two-thirds of the radiata pine trees sampled were ≤16 years old and so did not contain mature wood. However, all ponderosa pine trees were 43 years old and had a significant amount of mature wood. The younger age and the smaller diameter of the radiata pine trees resulted in tree velocities that were much closer to log velocities compared with the tree and log velocities of ponderosa pine.

The influence of age and tree diameter on the velocity ratio can be further illustrated by the data from the radiata pine trees. Figure 5 shows the interrelationship of stand age, tree DBH, and tree/log velocity ratio for radiata pine. As stand age increased, the velocity ratio increased. Especially for stands over 16 years of age, the velocity ratio increased dramatically as a result of the presence of mature wood. On the other hand, as stand age increased, tree DBH also increased. Therefore, a similar relationship also exists between tree diameter and the tree/log velocity ratio; i.e., the velocity ratio increased as DBH increased.

Figure 6 shows the relationship between DBH and the tree/log velocity ratio for all species. As the figure shows, there is a linear relationship between DBH and velocity ratio for ponderosa pine and radiata pine. The diameter effect was more prominent in the even-aged ponderosa pine stand than in the mix-aged radiata pine stand. However, we did not find a clear DBH–velocity relationship for Sitka spruce, western hemlock, and jack pine. The factors contributing to this result were small sample size, mixed tree ages (Sitka spruce and western hemlock), and mixed species (jack pine group mixed with some yellow birch).

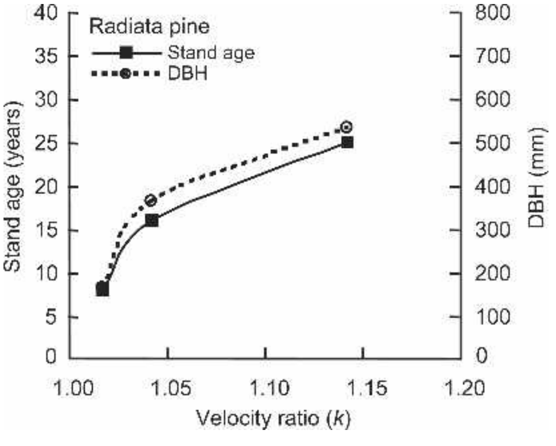

FIG. 5. Relationship between stand age, tree diameter at breast height (DBH), and acoustic velocity ratio for radiata pine.

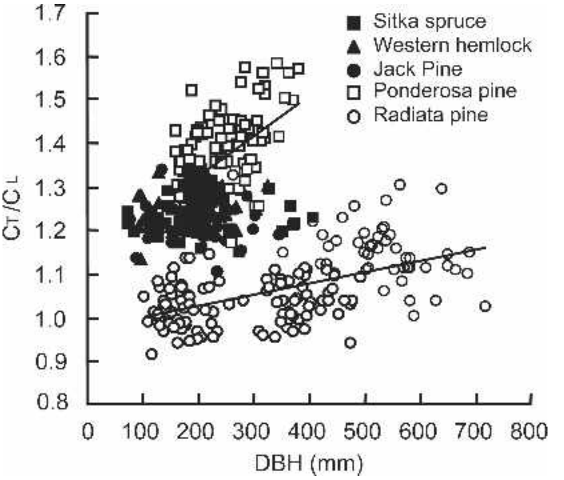

FIG. 6. Relationship between tree diameter and acoustic velocity ratio for test species.

Tree velocity adjustment—empirical models

Assessing wood quality directly from acoustic velocity values observed in standing trees is not appropriate because of the skewed relationship between tree velocity and log velocity. The observed tree velocity (apparent velocity) needed to be adjusted to correct the deviation.

One possible way to adjust apparent tree velocities is to use the empirical relationship between tree velocity and log velocity directly. The drawback to this method is that the adjusted tree velocity will suffer from the relatively large variation inherent in linear regression models. As the previous discussion indicates, tree diameter has a significant influence on TOF measurement, and a positive relationship exists between tree diameter and tree velocity for some species.

TABLE 4. *Data for multiple nonlinear regression equations.*[a]

	$C_L = a(\text{DBH}/S)^b C_T^{\ c}$			
Species	*a*	*b*	*c*	R^2
Sitka spruce	0.7448	0.0004	1.0119	0.934
W. hemlock	0.4641	0.0234	1.0616	0.854
Jack pine	0.7666	0.0025	1.0090	0.702
Ponderosa pine	2.7789	0.0675	0.8175	0.853
Radiata pine	6.7389	0.0075	0.7457	0.920
Combined	5.5092	0.0295	0.7677	0.825

[a] All data were significant at a 95% level of confidence.

Since tree diameter is a readily available parameter, appropriate multivariate regression models can be established, with apparent velocity and DBH as variables to reduce variation.

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

$$C_L = a\left(\frac{\text{DBH}}{S}\right)^b C_T^c \quad (9)$$

where *a*, *b*, and *c* are coefficients determined by regression analysis. In the trial studies discussed in this paper, *S* was kept constant at 1.2 m. 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 a better correlation between tree velocity and log velocity for ponderosa pine and radiata pine compared with the other species. The coefficient of determination increased from 0.830 to 0.853 for ponderosa pine and from 0.900 to 0.920 for radiata pine. However, there was no significant change in correlation for Sitka spruce, western hemlock, and jack pine. This is not surprising because no significant diameter effect was observed on the diameter–velocity relationship for these three species. As previously mentioned, the lack of correlation between velocity and tree diameter was most likely caused by the small sample size and mixed stand ages. Overall, the multiple nonlinear regression model is still a better choice than the univariable linear regression model in reducing variation.

Figures 7 and 8 show the relationship between adjusted tree and log velocities. In Fig. 7, tree velocity was adjusted based on the general multiple regression model (species combined); in Fig. 8, tree velocity was adjusted based on a species-dependent multiple regression model. In both cases, the average velocity ratio after adjustment was 1, which means the adjusted tree velocity was equivalent to the log velocity. It is apparent that a species-dependent regression model produces much less variation than does a general regression model.

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 the different wave propa-

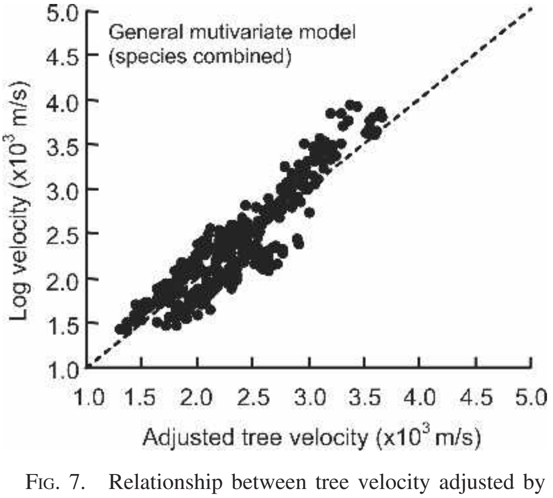

FIG. 7. Relationship between tree velocity adjusted by multivariate regression model and log velocity for all species combined.

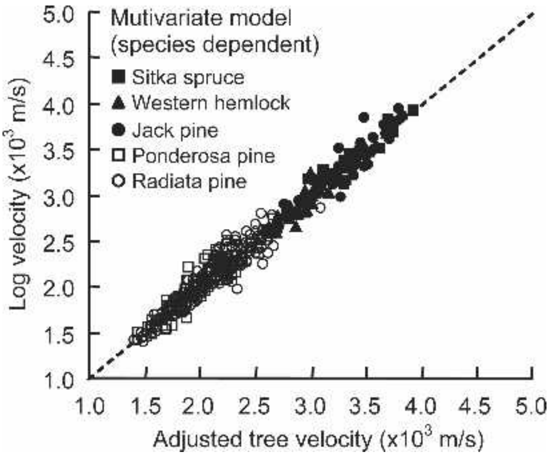

FIG. 8. Relationship between tree velocity adjusted by multivariate regression model and log velocity for individual species.

gation mechanisms in the two acoustic measurement methods. For resonance measurement in felled logs, the stress wave is introduced into the log by a direct end impact, which results in a plane wave (or quasi-plane wave) traveling along the longitudinal axis of a log. In the case of TOF measurement in 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 short span length, the test object becomes large enough to absorb and dissipate energy in a three-dimensional content. Depending on the tree diameter, the wave may travel within the trunk as a quasi-plane wave (if diameter is small enough) or as a dilatational wave (if diameter is large enough). The fact that measured tree velocities were significantly higher than the corresponding log velocities is a good indication that TOF measurement in trees is dominated by dilatational waves rather than one-dimensional plane waves. Through a metal bar experiment, Andrews (2003) also confirmed that TOF measurements are indeed influenced by the fast dilatational waves in elastic materials.

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

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

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

With dilatational wave theory, tree velocities measured by the TOF method can then be adjusted based on the estimated Poisson's ratio for the species. Figure 9 shows the relationship between adjusted tree velocity and log velocity. The overall correlation between tree velocity and log velocity was improved significantly ($R^2 = 0.950$). Analysis indicated that the average velocity ratio after adjustment approached 1. Deviation in average prediction ranged from 2% to 6% (in absolute value), which indicates very good agreement between adjusted velocity and log velocity.

CONCLUSIONS

Acoustic wave velocities were measured in standing trees of five softwood species using the time-of-flight (TOF) acoustic method. Observed tree velocities were compared with acoustic velocities measured in corresponding butt logs by a resonance acoustic method. The experimental data showed a skewed relationship between tree and log acoustic measurements. Observed tree velocities were significantly higher than log velocities for most trees tested. The deviation between tree and log velocity seems to be linked to

TABLE 5. *Estimated Poisson's ratios.*

Species	Average velocity ratio k	Estimated Poisson's ratio ν
Sitka spruce	1.22	0.331
W. hemlock	1.24	0.340
Jack pine	1.21	0.327
Ponderosa pine	1.36	0.378
Radiata pine	1.07	0.222
Combined	1.20	0.322

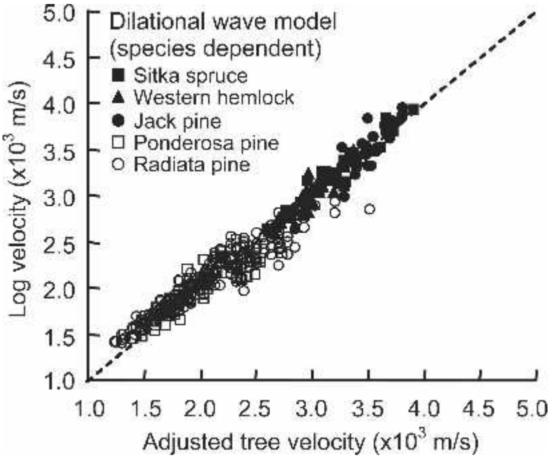

FIG. 9. Relationship between tree velocity adjusted by dilatational wave model and log velocity for individual species.

species, stand age, and tree diameter. A positive relationship was found between tree velocity and diameter for ponderosa pine and radiata pine trees. We speculate that a similar relationship might be found for other species if sufficient data were obtained.

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

Although the deviation between tree velocity and log velocity seems to be linked to species, stand age, and tree diameter, the fundamental cause of this deviation stems from the different wave propagation mechanisms of the two acoustic approaches. The experimental data indicate that TOF measurement in standing trees is likely dominated by dilatational waves rather than one-dimensional plane waves. Based on dilatational wave theory, the velocity ratios observed for five softwood species corresponded to Poisson's ratio values in the range of 0.222 to 0.378, with an average value of 0.322. Adjustment of tree velocity based on dilatational wave models was also found effective.

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