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# Acoustic measurements on trees and logs: a review and analysis

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**Abstract** Acoustic technologies have been well established as material evaluation tools in the past several decades, and their use has become widely accepted in the forest products industry for online quality control and products grading. Recent research developments on acoustic sensing technology offer further opportunities to evaluate standing trees and logs for general wood quality and intrinsic wood properties. Although the concept of using acoustic velocity as an effective measure of stiffness applies to both standing trees and felled logs, the method typically used to measure acoustic velocity in trees is different from that used in logs. Consequently, there is a significant difference in measured velocity values between trees and logs. Other factors affecting tree–log velocity relationships include tree diameter, stand age, operating temperature, and wood moisture content. This paper presents the fundamentals of acoustic wave propagation in trees and logs and discusses two different mechanisms of acoustic velocity measurement, time-of-flight for standing trees and resonance for logs. Experimental data from previous studies are reviewed and analyzed to examine the strength of the tree–log velocity relationships and discuss the factors that influence tree velocity deviation.

## Introduction

Acoustic technologies have been well established as material evaluation tools in the past several decades, and their use has become widely accepted in the forest products industry for online quality control and products grading. Recent research developments on acoustic sensing technology offer further opportunities to evaluate standing trees and logs for general wood quality and intrinsic wood properties (Wang 1999; Carter et al. 2005; Wang et al. 2007). Although the concept of using

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acoustic velocity as an effective measure of stiffness applies to both standing trees and felled logs, the method typically used to measure acoustic velocity in trees is different from that used in logs. Consequently, there could be a significant difference in measured velocity values between trees and the logs cut from the trees. This paper presents the fundamentals of acoustic wave propagation in trees and logs and discusses two different mechanisms of acoustic velocity measurement—time-of-flight (TOF) approach for standing trees and resonance-based approach for logs. Other factors affecting tree–log velocity relationships are also discussed. Experimental data from previous studies are summarized and used to examine the effectiveness of the empirical and theoretical models for converting tree acoustic velocity to resonance-based log velocity.

## Fundamentals of wave propagation in wood

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) 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 material property characterization.

### One-dimensional wave equation

A basic understanding of the relationship between wood properties and longitudinal wave velocity (hereafter referred to as wave velocity) can be acquired from

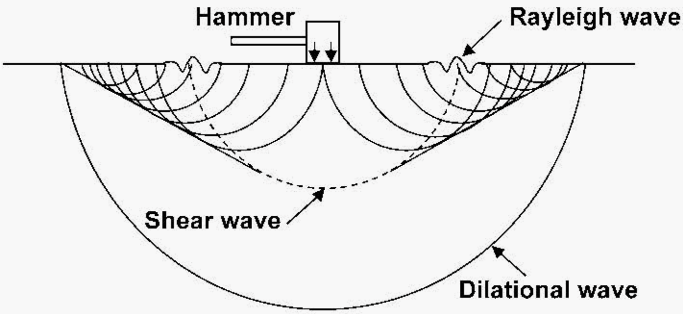


**Fig. 1** Types of stress waves in semi-infinite elastic material

fundamental wave theory. In a long, slender, and isotropic material, strain and inertia in the transverse direction can be neglected and longitudinal waves propagate in a plane waveform (wave front) (Fig. 2). In this case, the wave velocity is independent of Poisson's ratio and is given by the following equation (hereafter referred to as a one-dimensional wave equation):

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

where $C_0$ is longitudinal wave velocity, $E$ is longitudinal modulus of elasticity, and $\rho$ is mass density of material.

## Three-dimensional wave equation

In an infinite or unbounded isotropic elastic medium, a triaxial state of stress is present. The wave front of the longitudinal wave propagating through such a medium is no longer a plane. The wave propagation is governed by the following three-dimensional longitudinal wave equation (Meyers 1994):

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

where C is longitudinal wave velocity in unbounded medium and v is Poisson's ratio of the material. To differentiate from the longitudinal wave velocity in a slender rod, the term "dilatational wave" will be used for unbounded medium. The wave velocity is dependent on density and two elastic parameters, modulus of elasticity ***(E)*** and Poisson's ratio ($v$).

## Wave propagation in logs and standing trees

The direct application of fundamental wave equations in wood, particularly in standing trees and logs, has been complicated by the fact that wood is neither homogeneous nor isotropic. Wood properties in trees/logs 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 in both microscopic and macrostructure levels.

In spite of these natural variations, studies have shown that the one-dimensional wave equation is adequate to characterize the wave propagation behavior in logs that are in a long, slender form (Wang et al. 2004). The modulus of elasticity of the logs predicted by this fundamental equation generally has a high accuracy.


**Fig. 2** Longitudinal waves traveling in a long, slender material as plane waves

Consequently, log grading or sorting using acoustic wave technology has been very effective and widely adopted in the wood industry.

For standing trees, the acoustic measurement approach is completely different from that in logs. Because there is no access to an end surface (in contrast to a log) in a standing tree, acoustic waves have to be introduced from the side surface of the trunk, which results in a non-uniaxial stress state in the stem. One-dimensional wave equation is therefore no longer valid for trees. If the dilatational wave is considered for acoustic measurement in standing trees, Poisson's ratio ($\nu$) of wood is needed to describe the relationship between wave velocity and modulus of elasticity as shown in Eq. (2). Dilatational wave velocity is generally higher than $C_0$ (Eq. 1) (Meyers 1994; Wang et al. 2007). 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 $\nu = 0.30$. The velocity ratio becomes 1.46 as $\nu$ 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 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 ($\nu_{LR}$) 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).

## Acoustic measurements in trees and logs

The use of longitudinal acoustic wave techniques for wood quality assessment is based on the accurate measurement of the propagation velocity of a stress wave generated by a mechanical impact. The success of any field application of this technique is directly related to understanding stress wave behavior in wood materials and the physical and geometrical characteristics of wood itself. Wood, in the form of trees and logs, tends to have variable external and boundary conditions that create technical challenges for measuring acoustic velocities. This is particularly true in trees, where a stress wave has to be initiated from the surface of the trunk, and acoustic sensors need to be attached to the trunk through the spikes.

### Trees—time-of-flight (TOF) approach

A typical approach for measuring acoustic velocity in trees involves inserting two sensor probes (transmit probe and receiver probe) into the sapwood and introducing acoustic energy into the tree through a hammer impact. TOF essentially measures the time for the stress wave to travel from the transmit probe to the receiver probe.

The acoustic velocity is subsequently calculated from the span between two sensor probes and the TOF data using Eq. (3).

$$C_{\mathrm{T}} = \frac{S}{\Delta t} \tag{3}$$

where $C_{\mathrm{T}}$ is tree acoustic velocity (m/s), $S$ is distance between the two probes (sensors) (m), and ***At*** is time-of-flight (s).

During field acoustic 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 40–60 cm above the ground. The span between the probes is determined from a practical standpoint, typically set as 1.22 m; the probes need to be positioned at a comfortable height for the person who takes the measurements.

### Logs—resonance-based approach

Acoustic velocities in logs and long stems are typically measured using a resonance-based approach. In log acoustic measurement, an acoustic sensor is mounted on one end of a log. A stress wave is initiated by a mechanical impact on the end, and the stress waveforms are subsequently recorded by an electronic unit. This acoustic approach is based on the observation of hundreds of acoustic pulses resonating longitudinally in a log and provides a weighted average acoustic velocity. Most resonance-based acoustic tools have a built-in fast Fourier transformation program which can analyze the acoustic signals. Log acoustic velocity is then determined from the following equation:

$$C_L = 2f_0L \tag{4}$$

where $C_{\mathrm{L}}$ 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 nondestructive evaluation (NDE) technique for measuring long, slender wood members such as logs, poles, timber (Harris et al. 2002; Andrews 2003; Wang et al. 2004). 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 approach, the resonance method stimulates many, possibly hundreds, of acoustic pulse reverberation in a log, resulting in a very accurate and repeatable velocity measurement. Because of this accuracy, the acoustic velocity of logs obtained by the resonance-based measurement has served as a standard to validate the TOF measurement in standing trees (Wang et al. 2001; Andrews 2003; Carter et al. 2005).

## Summary of research results

Many field studies have been conducted in different parts of the world to evaluate the effectiveness of TOF acoustic approach in standing trees. Field data from trees of different species and different stand ages were used to examine the relationships between tree acoustic velocities measured by TOF tools and log velocities measured by resonance tools. Table 1 is a summary of the results from these studies showing measured tree velocities, log velocities, their correlation, tree-to-log velocity ratios, as well as the Poisson’s ratio estimated based on acoustic measurements.

In a laboratory experiment, Wang (1999) simulated tree acoustic measurements with ten 2.74 m-long green red pine logs as tree samples using a TOF method with a span distance of 1.2 m, then compared with the log velocities measured using a resonance technique. He found that the tree velocity was strongly correlated with the log velocity ($R^2 = 0.88$), but was on average about 10 % higher than the log velocity. The red pine logs used in the study came from a local sawmill, and the stand age for these logs was not known.

Grabianowski et al. (2006) performed similar measurements on 43 straight-stemmed butt logs that were taken from two young radiata pine stands aged 8 and 11, growing in Canterbury, New Zealand. The TOF readings were taken from two opposite sides (A and B) of each log, and the “tree” velocities were averaged before compared with the resonance value. The TOF “tree” velocities were found greater than those for resonance by 270 m/s, which was 12 % higher. In the same study, Grabianowski et al. also evaluated 150 radiata pine trees in stands aged 8, 16, and 26 years using a TOF tool. They reported an increasing trend of tree velocity with stand age. They did not find statistical or systematic difference in tree velocities between two opposite sides of the stem.

Wang et al. (2007) measured acoustic velocities in trees of five species (Sitka spruce, western hemlock, jack pine, ponderosa pine, radiata pine) using the TOF method. Observed tree velocities were compared with acoustic velocities measured in corresponding butt logs by a resonance acoustic method. They found a skewed relationship between tree and log acoustic measurements. Observed tree velocities were significantly higher than log velocities for most trees tested. They also reported that average ratio of tree-to-log velocity ranged from 1.07 for radiata pine to 1.36 for ponderosa pine. Velocity ratios for Sitka spruce, western hemlock, and jack pine were very close, in the range of 1.22–1.24.

Chauhan and Walker (2006) used TOF acoustic velocity to estimate outerwood stiffness of trees within stands and between stands of different age classes (ages 8, 16, and 25 years). They found a good positive correlation ($R^2 = 0.75$–$0.91$) between acoustic velocity measured on trees using the Fakopp instrument and the Hitman velocity (resonance) measured on butt logs of the corresponding trees after felling. The Fakopp velocity was on an average higher by 9 % in 8- and 16-year-old trees, while 17 % higher in 25-year-old trees. They observed that Fakopp velocity was lower than the Hitman velocity in only three 8-year-old trees. These trees had huge branch-whorls near breast height. They believed that the presence of the excessive branches and distorted grain within the short TOF path (1.5 m) would reduce significantly the measured TOF velocity of the trees.

In a field tree study in the Southeastern United States, Mora et al. (2009) first tested 60 loblolly pine trees of 14–19years old using the TreeSonic tool (Fakopp Enterprise, Agfalva, Hungary). Acoustic velocities were then measured in the butt logs cut from the same trees using the Director HM200 tool (Fibre-gen, Christchurch,

**Table 1** Research summary on acoustic velocity measurement in standing trees

| Reference | Species | Country | Stand age | Number of trees | Average DBH (cm) | Mean tree velocity (m/s) | Mean log velocity (m/s) | Correlation $R^2$ | Velocity ratio $k$ | Estimated Poisson's ratio $\nu^a$ | Acoustic measurement tool | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | Trees | Logs |
| Wang (1999) | Red pine | US | n/a | 10 | 22.2–33.7 | 3,631 | 3,289 | 0.88 | 1.10 | 0.255 | Digital oscilloscope | Digital oscilloscope |
| Chauhan and Walker (2006) | Radiata pine | NZ | 8 | 50 | 16.4 | 1,880 | 1,730 | 0.89 | 1.09 | 0.245 | Fakopp 2D | Hitman HM200 |
| | | | 16 | 50 | 36.3 | 2,380 | 2,190 | 0.91 | 1.09 | 0.245 | | |
| | | | 25 | 50 | 53.1 | 2,880 | 2,450 | 0.75 | 1.18 | 0.312 | | |
| Grabianowski et al. (2006) | Radiata pine | NZ | 8 & 11 | 43 | n/a | 2,466 | 2,202 | 0.92 | 1.12 | 0.272 | Fakopp | WoodSpec |
| | | | 8 | 50 | n/a | 2,020 | n/a | n/a | n/a | n/a | | |
| | | | 16 | 50 | n/a | 2,390 | n/a | n/a | n/a | n/a | | |
| | | | 26 | 50 | n/a | 2,870 | n/a | n/a | n/a | n/a | | |
| Wang et al. (2004, 2007) | Sitka spruce | US | Mixed | 30 | 20.7 | 3,892 | 3,198 | 0.93 | 1.22 | 0.331 | Flukemeter | Director HM200 |
| | Western hemlock | US | Mixed | 31 | 18.3 | 3,721 | 3,004 | 0.85 | 1.24 | 0.340 | | |
| | Jack pine | US | 40 | 27 | 20.9 | 4,218 | 3,480 | 0.71 | 1.21 | 0.327 | | |
| | Ponderosa pine | US | 43 | 114 | 23.6 | 2,700 | 1,982 | 0.83 | 1.36 | 0.378 | | |
| | Radiata pine | NZ | 8 | 50 | 16.4 | | | | | | | |
| | Radiata pine | NZ | 16 | 50 | 36.3 | 2,277 | 2,120 | 0.90 | 1.07 | 0.222 | | |
| | Radiata pine | NZ | 25 | 50 | 53.1 | | | | | | | |
| Lasserre et al. (2007) | Radiata pine | NZ | 11 | 30 | | | | | 1.16–1.31 | 0.300–0.364 | Fakopp | Director HM200 |
| Mora et al. (2009) | Loblolly pine (*Pinus taeda*) | US | 15 | 10 | 18.6 | 2,494–4,484 | 1,910–3,228 | 0.81 | 1.29 | 0.358 | TreeSonic | Director HM200 |
| | | | 16 | 10 | 19.0 | | | | 1.35 | 0.374 | | |

**Table 1** continued

| Reference | Species | Country | Stand age | Number of trees | Average DBH (cm) | Mean tree velocity (m/s) | Mean log velocity (m/s) | Correlation $R^2$ | Velocity ratio $k$ | Estimated Poisson's ratio $\nu$[a] | Acoustic measurement tool | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | Trees | Logs |
| | | | 14 | 10 | 22.7 | | | | 1.30 | 0.360 | | |
| | | | 15 | 10 | 23.9 | | | | 1.33 | 0.369 | | |
| | | | 18 | 10 | 23.9 | | | | 1.29 | 0.358 | | |
| | | | 19 | 10 | 22.2 | | | | 1.35 | 0.376 | | |

[a] The value of estimated Poisson's ratio was calculated from the tree–log velocity ratio based on the following equation (Wang et al. 2007): $k = \sqrt{(1-\nu)/[(1+\nu)(1-2\nu)]}$ where $k = c_{\mathrm{Tree}} / c_{\mathrm{Log}}$

New Zealand). They also observed a strong but biased relationship between tree and log velocities, with tree velocities being 32 % higher (on average) than the corresponding log velocities. They found that the velocity deviation from the line of equivalence increased as tree velocity increased. To explore the tree–log relationship further, Mora et al. added 69 data points obtained from the work of Mahon et al. (2009) to the 60 trees in their study. The combined data set consisted of acoustic velocities on loblolly pine trees ranging from 13 to 22 years old and velocities measured on butt logs cut from the same trees. The relationship between tree and log acoustic velocities for the combined data set ($n = 129$) was similar to that found for the original 60 trees, with an $R^2 = 0.81$ and a mean difference of 32 % between TOF and resonance-based measurements.

## Discussion

There have been different explanations on why tree velocities are so significantly deviated from log velocities. One explanation discussed in many papers is related to the stiffer wood zones in outerwood of the tree stems (Chauhan and Walker 2006 Grabianowski et al. 2006; Mora et al. 2009). For example, Chauhan and Walker (2006) stated that the higher velocity measured by TOF tool is attributed, in part, to the fact that single-pass transit-time velocities are sensitive to the high localized stiffness of the outerwood lying in the “flight path” between the two probes.

Although the deviation between tree velocity and log velocity seems to be linked to the high stiffness of the outerwood layers, the fundamental cause of this deviation stems from the different wave propagation mechanism of the two acoustic approaches. The experimental data indicated that TOF measurement in standing trees is likely dominated by dilatational waves rather than one-dimensional plane waves (Wang et al. 2007). To further explain the fundamental cause of tree velocity deviation, Wang introduced the concept of estimating Poisson’s ratio based on acoustic measurements on trees and logs. Because there is no way to determine the Poisson’s ratio of green wood in the form of tree trunks, Wang et al. derived the $v$ value based on empirical data under the assumption that wave travels within a trunk as a dilatational wave. The velocity ratios observed for five softwood species (Sitka spruce, western hemlock, jack pine, ponderosa pine, and radiata pine) corresponded to Poisson’s ratio values in the range of 0.222–0.378, with an average value of 0.322. Adjustment of tree velocity based on species-dependent Poisson’s ratios was found effective, indicating that the acoustic velocities measured by TOF method are dilatational wave velocity.

Studies indicated that the application of dilatational wave equation for tree evaluation was actually not a straightforward procedure. The use of dilatational wave equation is affected by the diameter of the trees measured. Based on experimental data summarized in Table 1, it is speculated that the acoustic waves may travel in a tree as a quasi-plane wave when tree diameter is small, or as a dilatational wave when tree diameter is large. No diameter threshold has been discussed or proposed to differentiate two types of wave velocity measured in trees.

The tree velocity deviation seems also affected by the stand age of the trees evaluated. Studies showed that tree–log velocity ratio increased as stand age increased. Wang et al. (2007) observed that younger age and smaller diameter of the radiata pine trees resulted in tree velocities that were much closer to log velocities compared with the 43-year-old ponderosa pine. A similar trend was also reported by Chauhan and Walker (2006). This trend is in agreement with the current knowledge on tree growth; that is, as trees age, the outerwood gets stiffer because of the decreasing microfibril angle, and the proportion of mature wood in the cross section of a tree increases. As such, the overall mechanical properties improve with aging.

When comparing velocity ratios or estimated Poisson's ratios from different studies, it is also important to recognize that acoustic instruments used for tree measurements also play a critical role in data analysis. Different acoustic measurement tools may have different algorisms to determine the TOF data from two received signals. Even for the tools that use the same algorism for TOF determination, tree measurements could result in different readings because of different trigger settings. When an acoustic measuring tool functions normally, one expects certain variations on measurement results even from the same type of tool. Repeatability of the TOF reading in trees is typically lower than that of resonance readings in logs. Studies showed that variations of TOF readings exist in terms of the acoustic tool used and how the probes were positioned in the stem (Lasserre et al. 2007; Mahon et al. 2009; Raymond et al. 2008). There are some variations in the recorded TOF, due in part to inconsistency in hammer tapping (Harris and Andrews 1999). This can be minimized by making multiple tapping measurements and using the average value for a tree.

## Conclusion

The experimental data from both laboratory and field studies all indicated a biased relationship between tree and log acoustic measurements. Observed tree velocities were found to be significantly higher than log velocities. Consequently, tree velocity measured by the TOF methods needs to be interpreted differently when assessing the wood properties of standing trees. Although deviation between tree velocity and log velocity seems to be linked to the high stiffness outerwood layers, the fundamental cause of this deviation stems from the different wave propagation mechanism of the two acoustic approaches. Some empirical models have been developed for certain species to convert measured TOF-based tree velocities to equivalent resonance-based log velocities. But the application of these models has been complicated by many factors such as species, stand age, tree DBH, and the instrument used. Comprehensive research is needed to systematically address the inter-effects of these factors on tree acoustic measurement and develop analytical models for converting apparent tree velocity to equivalent log velocity.

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