

Acoustic Assessment of Wood Quality in Trees and Logs

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Assessing the quality of raw wood materials has become a crucial issue in the operational value chain as forestry and the wood processing industry are increasingly under economic pressure to maximize extracted value. A significant effort has been devoted toward developing robust nondestructive evaluation (NDE) technologies capable of predicting the intrinsic wood properties of individual trees, stems, and logs and assessing the value of stands and forests. Such technologies can help foresters make wise management decisions and grow higher quality wood and can lead to greater profitability for the forest industry.

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 on-line quality control and products grading (Schad et al. 1995; Pellerin and Ross 2002; Ross et al. 2004). Recent research developments on acoustic sensing technology offer further opportunities for wood manufacturers and forest owners to evaluate raw wood materials (standing trees, stems, and logs) for general wood quality and intrinsic wood properties. This provides strategic information that can help make economic and environmental management decisions on treatments for individual trees and forest stands, improve thinning and harvesting operations, and efficiently allocate timber resources for optimal utilization. For example, the information could be used to sort and grade trees and logs according to their suitability for structural applications and for a range of fiber properties of interest to paper makers. Another example is to determine the relationships between environmental conditions, silvicultural treatments, and wood fiber properties so that the most effective treatment can be selected for desired fiber quality in future plantations.

Today, the precision of acoustic technology has been improved to the point where tree quality and intrinsic wood properties can be predicted and correlated to the performance of final products. With continuous advancements and refinements, this technology could assist in managing wood quality, assessing forest value, and improving timber quality of future plantations.

Background

Traditionally, the quality of trees, stems, and logs has been assessed through simple physical measurements (height/length, diameter, taper, and sweep) and human visual observation of surface characteristics (size and distribution of knots, wounds, and other defects). Assignment to one of several possible grades is based on simple, broad, allowable ranges for physical features. Although these grades may be sufficient where appearance is the primary consideration, the adequacy of visual grades for applications involving stiffness and strength is questionable because no measure of these properties is actually obtained. A concern over reliability and the broad conservative design values associated with visual grades for structural applications led to the development of machine strength rating (MSR) technology for lumber, which uses a pre-established relationship between stiffness and bending strength to define a set of strength-based lumber grades (FPS 1997; Galligan 2002). This provides a more refined and flexible approach than visual grading for identifying and sorting lumber into stress grades used in products such as structural framing, glued-laminated timber (glulam), and engineered trusses.

With the development and rapid growth of new engineered wood products such as laminated veneer lumber (LVL), I-beams, and I-joists, there has been a parallel growth in nondestructive testing for stiffness and strength of lumber and veneer used as components of these products. In addition, concerns with design values of structural lumber graded with visual methods are creating demand for stiffness verification of visually graded lumber. These trends have renewed interest of mills in nondestructive testing and evaluation methods. Mills seeking to capture a price premium by producing nondestructively tested lumber and veneer find that it is very expensive to process logs or purchase timber stands that have low yields of product with the stiffness and strength levels desired by their customers. Consequently, researchers have developed technology for applying acoustic methods to measure stiffness of logs and trees and improve sorting and matching with desired levels of lumber or

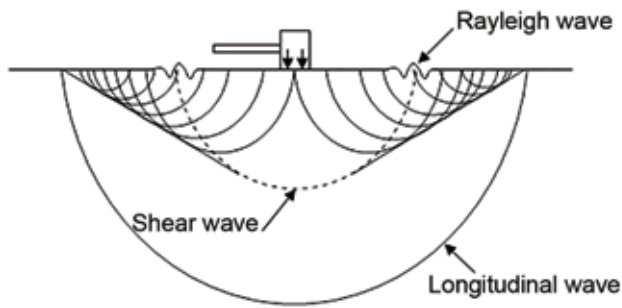


Figure 8.1—Types of stress waves in semi-infinite elastic material.



Figure 8.2—Longitudinal waves traveling in a long, slender material as compression and tension waves.

veneer stiffness (Aratake et al. 1992; Aratake and Arima 1994; Wang 1999; Harris and Andrews 1999; Huang 2000; Addis et al. 2000a,b; Wang et al. 2001, 2002; Harris et al. 2003; Andrews 2003). The research has led to the development and introduction of a series of acoustic tools that allow rapid assessment of wood resource quality at early stages of the operational value chain.

Fundamentals of Acoustic 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. 8.1). 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 fundamental

wave theory. In a long, slender, isotropic material, strain and inertia in the transverse direction can be neglected and longitudinal waves propagate in a plane waveform (wave front) (Fig. 8.2). In this case, the wave velocity is assumed to be independent of Poisson's ratio and is given by the following equation (hereafter referred to as a one-dimensional wave equation):

$$C_0 = \sqrt{\frac{E}{\rho}} \quad (8.1)$$

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

Three-Dimensional Wave Equation

In an infinite or unbounded isotropic elastic medium, a tri-axial 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):

$$C = \sqrt{\frac{1-\nu}{(1+\nu)(1-2\nu)}} \frac{E}{\rho} \quad (8.2)$$

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

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 and 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. Genetics, 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; Wang 2013). The modulus of elasticity of the logs predicted by this fundamental equation generally has a high accuracy. Consequently, log grading or sorting using acoustic wave technology has been very effective and widely adopted in the forest and wood processing industries.

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 nonuniaxial stress state in the stem. The 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 (ν) of wood is needed to describe the relationship between wave velocity and modulus of elasticity, as shown in Eq. (8.2). Dilatational wave velocity is generally higher than C_0 (Eq. (8.1)) (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 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 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).

Acoustic Measurements in Trees and Logs

The use of longitudinal acoustic wave techniques for wood quality assessment is based on accurate measurement of 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 spikes (probes).

Trees—Time-of-Flight-Based 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 on the transmit probe. The time-of-flight (TOF) is the time taken for the stress wave to travel from the transmit probe to the receiver probe. Acoustic velocity is subsequently calculated from the

span between the two sensor probes and the TOF measure using

$$C_T = \frac{S}{\Delta t} \quad (8.3)$$

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

During field acoustic measurement, the probes are inserted into the tree trunk (probes are inserted through bark and cambium to extend into the sapwood) and aligned within a vertical plane on the same face (Fig. 8.3). The lower probe is placed about 40 to 60 cm above the ground. The span between the probes is determined from a practical standpoint, typically in the range 1.0–1.2 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 of known length are typically measured using a resonance-based approach. In log acoustic measurement, an acoustic sensor is mounted or held on one end of a log (Fig. 8.4). A stress wave is initiated by a mechanical impact on the same 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 (FFT) program that can analyze and output the natural frequencies of the acoustic signals. Log acoustic velocity is then determined from

$$C_L = 2f_0L \quad (8.4)$$

where C_L is acoustic velocity of logs (m/s), f_0 is fundamental natural frequency of an acoustic wave signal (Hz), and L is 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, and timber (Harris et al. 2003; 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 the TOF approach, the resonance method 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 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).

Assessing Wood Quality of Logs

It is well recognized that the variation in wood and fiber properties is enormous within any pile of logs that has been

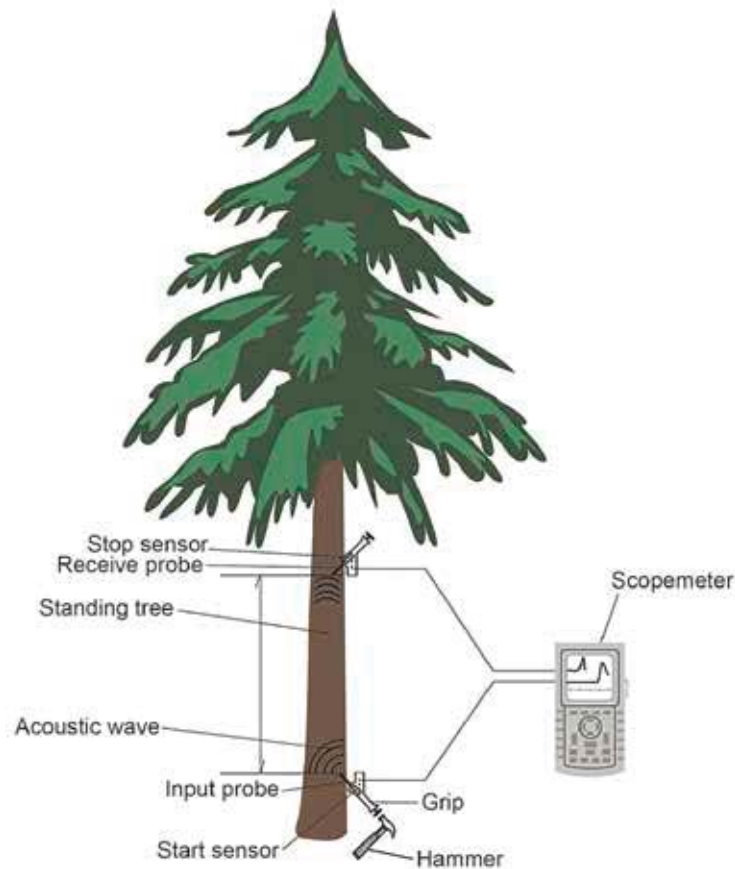


Figure 8.3—Acoustic measurement on standing trees.



Figure 8.4—Resonance acoustic measurement on a log.

visually sorted for similar grade. The same is true for logs from trees of the same age and from the same forest stand (Huang et al. 2003). Dyck (2002) reinforced this view by stating “All logs are different even if they are clonal and even if they come from the same tree.” As an example, Figure 8.5 shows the acoustic velocity of a large sample of similar logs from two geographically distinct radiata pine forests in New Zealand, demonstrating the large variability in intrinsic wood properties of the logs (Andrews 2000). Clearly, there are major commercial benefits to be gained by assessing wood properties at the log level and optimizing the use of resource through appropriate log sorting and processing.

The ability to improve log sorting with resonance-based acoustic methods has been well recognized in the forest

products industry (Walker and Nakada 1999; Harris et al. 2003; Huang et al. 2003; Carter and Lausberg 2003; Wang et al. 2002, 2004). This technology is based on the observation of hundreds of acoustic pulses resonating longitudinally in a log and provides an acoustic velocity dependent on the weighted average wood properties and moisture status of the log. Because the MOE of the log is simply equal to the density times the acoustic velocity squared, the technology is basically measuring fiber properties that influence macro properties such as stiffness, strength, and stability. The challenge is to interpret what the log is “saying” and translate this information into meaningful values (Dyck 2002).

Sorting Logs for Lumber Quality

Research has shown that log acoustic measures can be used to predict the strength and stiffness of structural lumber that would be produced from a log (Aratake et al. 1992; Aratake and Arima 1994; Ross et al. 1997; Iijima et al. 1997; Wang 1999; Wang and Ross 2000). In the early 1990s, scientists in Japan did some pioneering research exploring the possibility of using the natural frequency of longitudinal compression waves in a log to predict the strength and stiffness of the structural timbers (Aratake et al. 1992; Aratake and Arima 1994). They succeeded in identifying close relationships

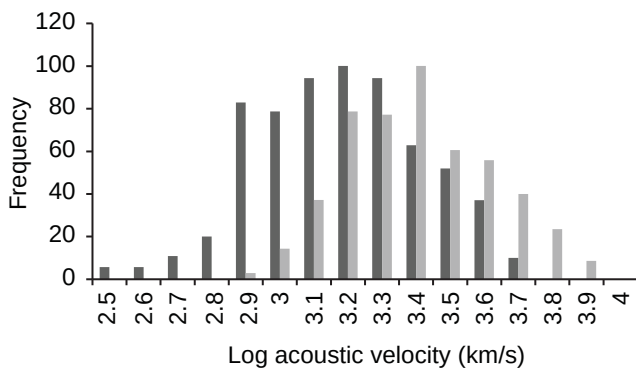


Figure 8.5—The acoustic velocity (km/s) of a large sample of similar logs from two geographically distinct radiata pine forests in New Zealand, demonstrating the large variability in the intrinsic wood properties of the logs (Andrews 2000).

between the fourth resonant frequency of the logs and MOE and modulus of rupture (MOR) of the scaffolding boards and square timbers cut from the log. Years later, a trial study in the United States also revealed a good correlation between acoustic-wave-predicted MOE and mean lumber MOE (Ross et al. 1997). This research opened the way for acoustic technology to be applied in mills for sorting logs and stems for structural quality.

To validate the usefulness of the resonance acoustic method for a practical log sorting process, Wang and Ross (2000) conducted a mill study and examined the effect of log acoustic sorting on lumber stiffness and lumber E-grades. After acoustically testing 107 red maple logs, they sorted the logs into four classes according to acoustic velocity. Figure 8.6 illustrates the average lumber MOE for each log class, with a significant differentiation and clear trend between the log acoustic classes. They further compared log acoustic classes to lumber E-grades and found a good relationship between them. Logs that have a high acoustic velocity contain higher proportions of high-grade lumber. A study in New Zealand revealed similar results when presorting untested logs of radiata pine into three acoustic classes (Addis et al. 1997). The logs with the highest acoustic velocity (the top 30%) produced timber that was 90% stiffer than that from the group with the lowest velocity (the bottom 30%).

In a practical log-sorting process, the industry can achieve benefits by developing a sorting strategy based on the log sources and desired end products. Currently, companies implementing acoustic sorting strategies measure only the velocity of acoustic waves and segregate logs into velocity groups using predetermined cut-off velocity values. Appropriate cut-off acoustic velocity values can be determined for either selecting the highest quality logs for superior structural applications or isolating the low grade logs for nonstructural uses.

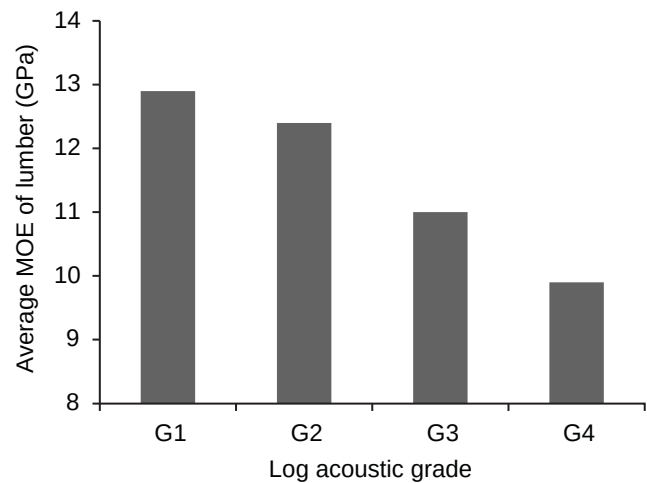


Figure 8.6—Relationship between log acoustic grade and average MOE of lumber (Wang and Ross 2000).

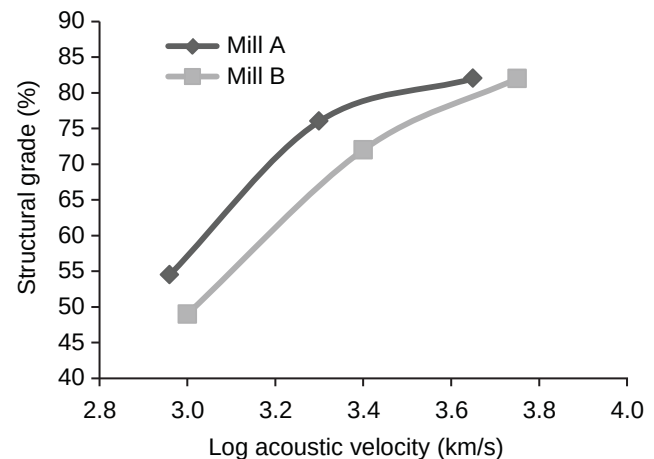


Figure 8.7—Relationship between log acoustic velocity and yield of structural grades of lumber for two New Zealand radiata pine sawmills (Carter et al. 2005).

Figure 8.7 demonstrates the increasing yield of structural grades of lumber with increasing acoustic velocity of logs processed, as measured at two New Zealand radiata pine sawmills. Assuming a price differential of NZ\$200/m³ (value estimated in 2004) between structural and nonstructural lumber, an increase in average log acoustic velocity of 0.1 km/s produces an increase in structural lumber yield of about 5%. This translates into a gain of about NZ\$6/m³ on log volume or about NZ\$1.8 million for a mill processing 300,000 m³ of logs per year.

Sorting Logs for Veneer Quality

Log acoustic measurement has also been successfully used to assess the quality of veneer obtained from logs. Figure 8.8 illustrates the relationship between acoustic velocity for Southern Pine log batches (10 percentile groups from log sample) and the average ultrasound propagation time (UPT)

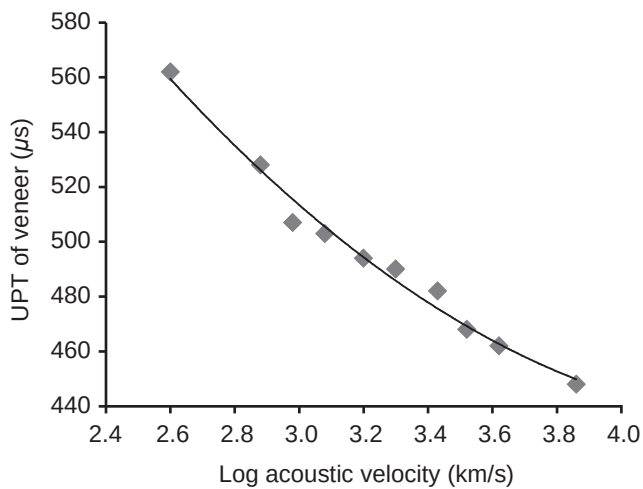


Figure 8.8—Relationship between acoustic velocity of Southern Pine log batches and the average ultrasound propagation time (UPT) of veneer from the logs (Carter et al. 2005).

of veneer peeled from the logs. UPT is the elapsed time for ultrasound to travel longitudinally within the veneer sheet between fixed roller wheel points on the Metriguard veneer tester.

Several trials have been run in New Zealand to quantify the effectiveness of acoustic sorting strategy and potential value gains from segregation of logs for veneer production (Carter and Lausberg 2003). Typical results show that for Central North Island logs segregated into three classes, the high stiffness logs resulted in production of 52% premium high stiffness veneer product, compared with unsegregated logs at 24%. These results clearly show that segregation using acoustics results in substantially higher proportions of higher stiffness veneer being produced. Equally, if a higher grade out turn is required for plywood veneer production, log segregation with acoustics will result in a value gain. An economic analysis of sorting veneer logs for LVL production in the United States resulted in a gain of about US\$16/m³ on log volume (about \$80–\$100 per thousand board feet Scribner log scale) (Carter et al. 2005).

Sorting Logs for Pulp and Paper Quality

One challenge that paper mills face is to quantify the quality of pulp logs going into the mill. Unlike saw logs that are used to produce structural lumber and veneer, quality specification for pulp logs deals with fiber characteristics, especially fiber length. Without appropriate sorting technologies to help “see through” individual logs for internal fiber quality, buyers or producers of pulp logs will not be able to know if logs meet the quality specifications for the product out turn. If unsorted, the below-specification logs must be processed along with the in-specification logs. This results in pulp and paper products of variable quality, depending on the proportion of below-specification logs entering the mill

process at any time and the extent to which they depart from the specified quality (Albert et al. 2002).

Similar to sorting saw logs for improving structural uses, acoustic technology could be used in pulp and paper mills to segregate pulp wood for pulp and paper manufacture. Albert et al. (2002) tested the hypothesis that acoustic measures of pulp logs are linked to fiber characteristics and paper properties. In a trial with 250 radiata pine peeler cores, they sorted the cores into 18 classes using acoustic velocity. Subsequent chemical pulping and testing demonstrated that fiber length, wet strength, and various handsheet properties varied systematically. The acoustic velocity of the peeler cores was found to be strongly related to the length-weighted fiber length and the wet zero-span tensile strength of the fibers from the peeler cores. Two follow-up studies carried out in New Zealand were summarized by Clark et al (2003). In the first study, the velocity of sound was measured in each of 250 small-diameter radiata pine logs (120–420 mm large-end diameter), the logs were segregated into one of four groups based on velocity, the logs in each group were chipped, each chip sample was then chemically pulped, and the resultant pulps were evaluated. This study confirmed the relationship between a range of fiber properties and whole log acoustic velocity. The second study involved 5,000 radiata pine logs segregated into three acoustic velocity based groups and pulped through a commercial continuous digester. Resulting pulp characteristics are shown in Figures 8.9 to 8.11, and the conclusion was that acoustics offers a means of sorting pulp logs and this study demonstrates that commercially useful separations can be obtained.

Mechanical pulp properties were evaluated in another mill study with 2,247 radiata pine logs. Bradley et al. (2005) confirmed that acoustics could be used to segregate logs into groups that perform very differently in terms of pulp properties when refined to a given freeness or at a certain energy input. At a given target freeness, there was a 20% difference in energy requirement between the lowest and highest velocity logs for a given specific energy. They conclude that acoustic sorting and subsequent reblending has great potential to reduce fluctuations in pulp quality of the mill output.

Monitoring Moisture Changes in Log Stocks

A further application of acoustic methods has been identified for monitoring changes in moisture content of freshly harvested logs from as high as 150% down to an air-dry state of 30% to 40%. Moisture content (MC) is important for fuel wood supplies to determine at what stage a log should be chipped and burned, as well as for certain mechanical and semi-chemical pulping processes where MC is critical for effective processing. Traditional sampling methods are cumbersome and time consuming, and there is no convenient portable tool capable of measuring MC at these levels because standard electrical conductivity or impedance methods become inaccurate at MCs above fiber saturation

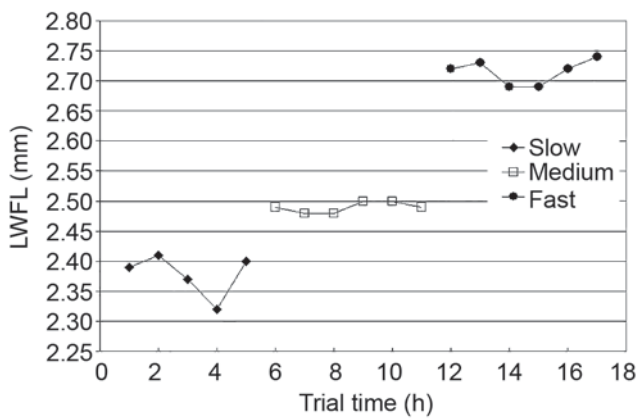


Figure 8.9—Chronological plot of pulp fiber length as each log group was processed (Clark et al. 2003).

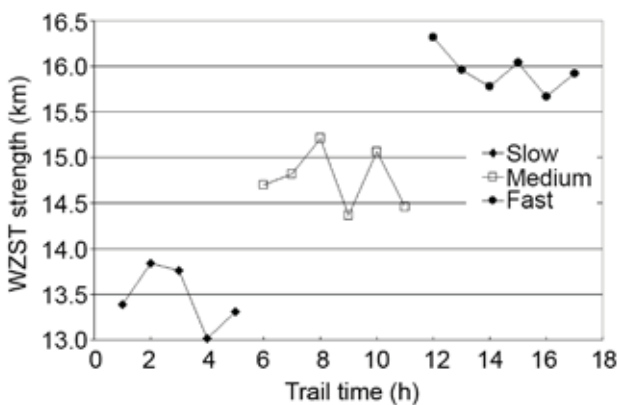


Figure 8.10—Chronological plot of pulp WZST strength as each log group was processed (Clark et al. 2003).

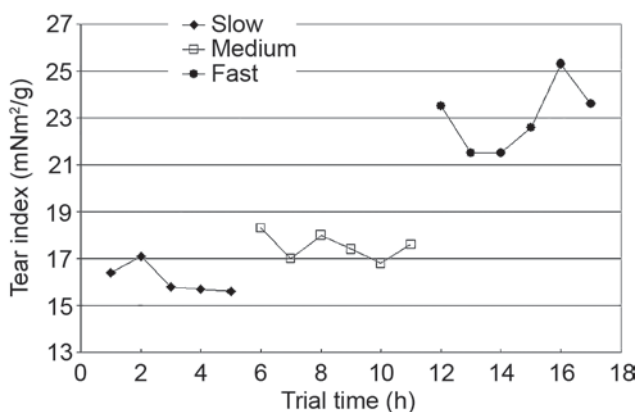


Figure 8.11—Chronological plot of pulp tear strength as each log group was processed (Clark et al. 2003).

point. Yet the defined relationship between acoustic velocity and green density enables the evaluation of changes in density caused by loss of moisture simply by monitoring the average increase in acoustic velocity that is observed as MC and associated green density decline with time.

Results are currently being evaluated (Foulon 2006) but look very encouraging for the emerging fuel wood sector in the United Kingdom where they need to measure and manage moisture content of log stockpiles because generating companies do not want to chip and burn wood above 40% to 55% MC (dry basis). The acoustic-based procedure has the following steps for monitoring the increase in velocity as green density declines:

- Establish a definitive MC start point using the traditional lab-based sampling method
- Mark a sample of logs within the log stack
- Measure acoustic velocities using a portable acoustic tool
- Remeasure acoustic velocities at any later date
- Compare average velocity increase, which defines loss of water such that reduction in green density is proportional to increase in velocity squared

Acoustic Verification of Log Supply for Visually Graded Lumber

The introduction of Verified Visual Grading (VVG) in New Zealand has been the response to variability in the design strength of visually graded lumber, typical of younger plantation-grown softwood resources around the world. Following an extensive consultation process, new standards and building regulations were introduced in New Zealand in 2006 with full compliance required by early 2007. According to the new standards, all visually graded lumber became subject to a sample proof test (1 in 1,000 pieces of lumber). A 30-sample rolling average must exceed the requirements for MOE and MOR, meeting both average and minimum standards. An implication of these new VVG standards is that the stiffness of log supply becomes even more critical to ensure that suitable logs are processed to meet end-of-line proof testing standards. Otherwise, structural lumber is cut and processed at significant cost, only to find that it does not meet end-of-line stiffness standards. Acoustic tools provide valuable guidance and decision support for the forest and wood processing sector to meet these new standards.

Assessing Wood Quality of Standing Trees

A logical and desirable extension from log acoustic assessment is to apply the technology to measure wood properties in standing trees, thereby providing timber sellers and purchasers with a means for improved harvest scheduling and timber marketing based on the potential yield of stress-graded products that can be obtained from trees within a stand.

The applicability of using acoustic waves to assess intrinsic wood properties of standing trees has been validated by many researchers around the world (Nanami et al. 1992a,b, 1993; Wang 1999; Ikeda and Kino 2000; Huang 2000; Wang

et al. 2001, 2005; Lindstrom et al. 2002). A typical approach for measuring acoustic velocity in standing 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. Unlike the resonance method, which obtains the weighted average velocity by analyzing whole wave signals transmitted between the ends of a log, the standing tree acoustic tool measures TOF for a single pulse wave passing through the tree trunk from transmit probe to receiver probe.

Measuring Wood Properties of Standing Trees

Several trial 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 (Wang et al. 2005). A total of 352 trees were tested in 2003 and 2004. The species tested included Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*), jack pine (*Pinus banksiana*), ponderosa pine (*Pinus ponderosa*), and radiata pine (*Pinus radiata*). The trial data showed a good 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 0.71 and 0.93. However, further analysis revealed a skewed relationship between tree acoustic measurement and log acoustic measurement. Observed tree velocities were found significantly higher than log velocities. The results support the hypothesis that TOF measurement in standing trees is likely dominated by dilatational or quasi-dilatational waves rather than one-dimensional plane waves, as in the case of logs.

Because of the significant deviation in velocity and the skewed relationship between tree and log measurements, tree velocity measured by the TOF method needs to be interpreted differently when assessing wood properties of standing trees. To make appropriate adjustments on observed tree velocities, Wang et al. (2005) developed two models (multivariate regression model and dilatational wave model) for the species evaluated in those trials. As an example, Figure 8.12 shows the relationship between tree velocities adjusted through a multivariate regression model and log velocities. Their results indicated that both the multivariate regression model and dilatational wave model were effective in eliminating the deviation between tree and log velocity and reducing the variability in velocity prediction.

With simple velocity measurements, individual trees and stands can be evaluated and sorted for their structural quality and stumpage value. In a series of studies evaluating tree quality in terms of structural performance, Ikeda and Kino (2000) found highly significant correlations between tree velocity and MOE of logs and square sawn timbers. Through several mill trials, Huang (2000) demonstrated that trees with the potential to produce high and low stiffness lumber

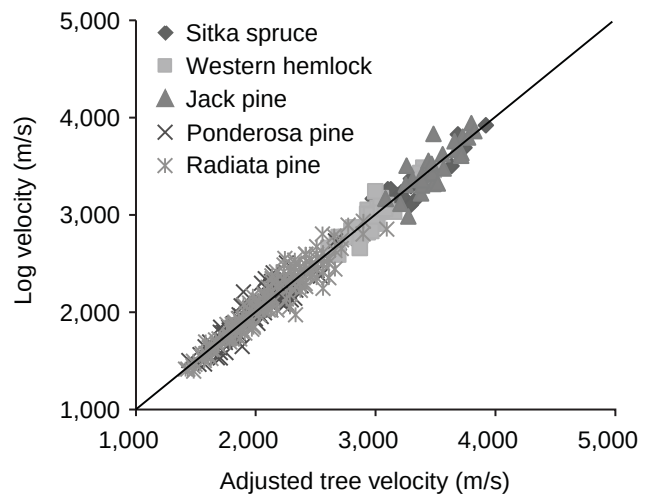


Figure 8.12—Tree acoustic velocity (adjusted) versus log acoustic velocity (Wang et al. 2007).

can be identified by tree acoustic velocity alone. The upper 15% and lower quartile of the population can be sorted by high and low velocity, respectively.

For standing trees, going from velocity measurement to wood property prediction is also a necessary step for many applications. Until recently, post-harvest NDE methods such as lumber E-rating, machine stress rating, and ultrasound veneer grading have been the standard procedures for evaluating wood stiffness and strength. The timber owner does not have a reliable way to assess the value of the final product prior to harvest. Recent wood quality research has shown that a range of wood and fiber properties can be predicted through a simple acoustic measurement in standing trees. Figures 8.13 and 8.14 show the relationships between tree acoustic velocity and MOE and microfibril angle (MFA) of core samples from trees measured by x-ray densitometry, diffractometry, and image analysis.

Assessing Silvicultural Treatment Effects

Quality and intrinsic wood properties of trees are generally affected by silvicultural practices, especially by stand density. Some silvicultural practices not only increase the biomass production of trees but also might improve the quality of the wood in trees. Nakamura (1996) used ultrasonically induced waves to assess Todo-fir and larch trees and observed significant differences in acoustic velocities and acoustic-determined MOE for trees in forest stands at different locations and trees of different ages.

Wang (1999) examined the effect of thinning treatments on both acoustic and static bending properties of young growth western hemlock and Sitka spruce trees obtained from seven sites in southeast Alaska. He found that trees with higher acoustic velocity and stiffness were mostly found in unthinned control stands and stands that received light thinning, whereas the lowest values were found in stands that received heavy and medium thinning. A typical trend of

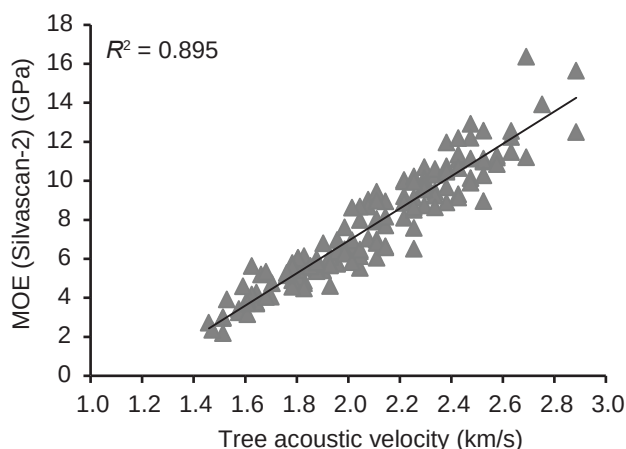


Figure 8.13—Relationship between tree acoustic velocity and modulus of elasticity (MOE) of the core samples measured by Silvascan-2 for radiata pine (Wang et al. 2007).

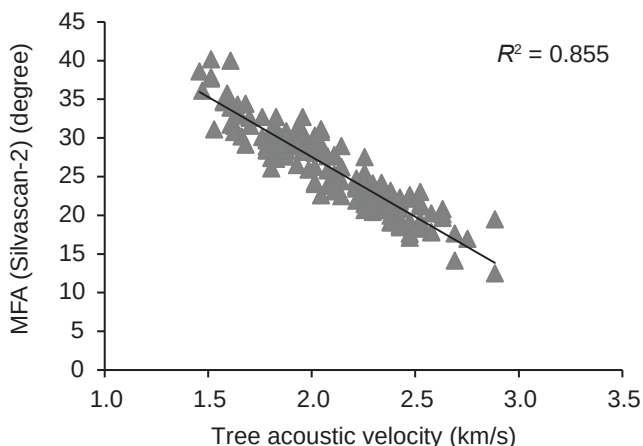


Figure 8.14—Relationship between tree acoustic velocity and microfibril angle (MFA) of the core samples measured by Silvascan-2 for radiata pine (Wang et al. 2007).

acoustic and static MOE as a function of thinning regimes is illustrated in Figure 8.15. These results were encouraging and indicated that TOF acoustic technology may be used in the future to monitor wood property changes in trees and stands and to determine how environmental conditions and silvicultural innovations affect wood and fiber properties so that the most effective treatment can be selected for future plantations for desired fiber quality.

Assessing Young Trees for Genetic Improvement

The future of the forest industry lies in fast-grown plantations. The economic imperative continuously seeks shorter rotations to meet the needs of a growing market. Young plantations will contain a higher percentage of juvenile wood, thus creating a lower quality and more variable wood resource for industry to process (Kennedy 1995).

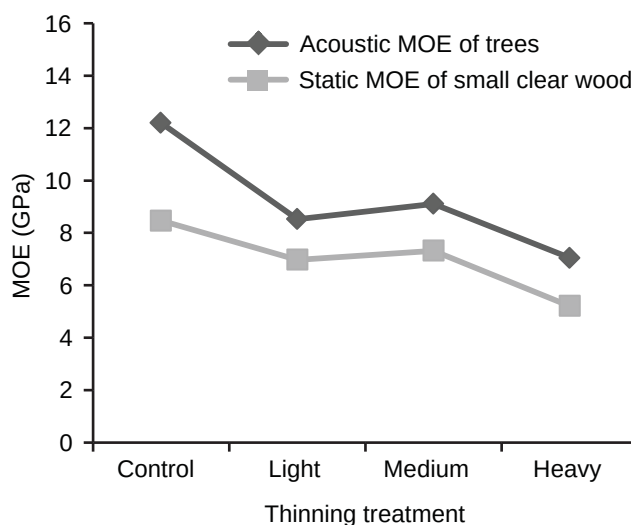


Figure 8.15—Modulus of elasticity (MOE) of young growth Sitka spruce in relation to thinning treatment (Wang et al. 2000).

Consequently, genetic improvement of juvenile wood properties is now receiving attention and getting higher priority in research. To help capture genetic opportunities, there is a need to determine wood quality at an early age (Lindstrom et al. 2002). The major challenge in operational tree improvement programs is to develop rapid and cost-effective assessment methods for selecting candidate trees with superior wood quality trait.

Wood stiffness is the most important property of structural lumber. The attractiveness of using MOE as a breeding criterion has been widely recognized in the forest industry (Addis et al. 2000a). In an investigation of sugi (*C. japonica*) clones from three different growth-rate groups, Hirakawa and Fujisawa (1995) found that juvenile wood in stiffer clones is much stiffer than mature wood of less stiff clones in all three growth categories. Similarly, Addis et al. (1998) reported that with radiata pine there is little difference in wood quality between juvenile wood of high stiffness trees and mature wood of low stiffness trees. Therefore the ability of selecting high stiffness trees opens the door to genetic improvement for future plantations.

With the ability to nondestructively assess wood properties of standing trees and raw log materials, acoustic methods have quickly been recognized as a useful tool in tree breeding programs (Walker and Nakada 1999; Huang et al. 2003). Lindstrom et al. (2002) investigated the possibility of selecting *Pinus radiata* clones with high MOE and found that acoustic measurement yielded results similar to traditional destructive and high-cost static bending methods. They conclude that acoustic tools could provide opportunities of mass screening for stiffness of fast-grown radiata pine clones at a very early age.

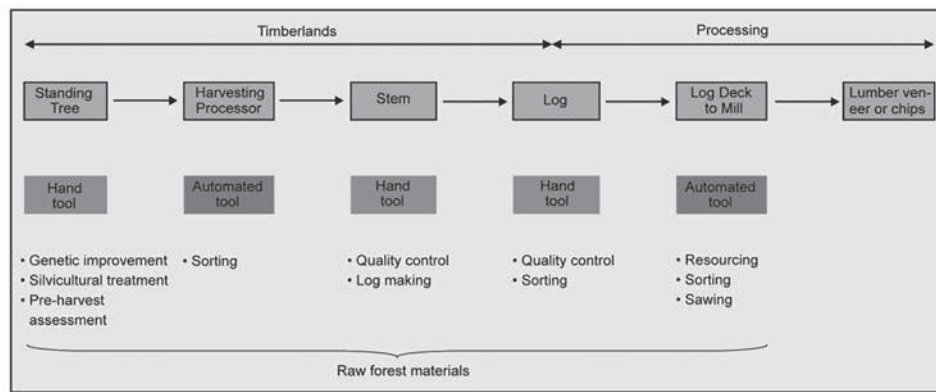


Figure 8.16—Schematic outlining potential application of acoustic technology through the operational value chain.

Evaluation of Plantation Resource for Wood Quality

In applying acoustic technology to a plantation resource, typically a number of stages will be considered. For example, a program to define wood quality for structural applications could have the goal of targeting extraction of greatest commercial value from the forest resource available, while recognizing the need to solve the problem of relatively low-stiffness wood in younger stands of much of the softwood plantation resource coming available in many countries.

Stages in a wood quality assessment program using acoustic hand tools for trial work and stand selection could include the following:

- Undertake a forest survey by mapping acoustic velocity at stand level across a range of topography, altitude, soils, ages, and silviculture (sample approximately 50 stands)
- Confirm the relationship between average standing tree velocity and average log velocity by felling 20 to 30 trees on each of 15 or more sites. Confirm velocity pattern up tree on a sub-sample of these
- Saw a sample of logs and confirm static MOE and MOR of lumber and grade out turn, relative to recorded log and standing tree velocity
- Correlate static MOE with predicted MOE from commercial testing devices (x-ray density, acoustic, mechanical bending)

By following this approach, the plantation resource can be characterized according to stiffness to enable management, planning, harvesting, and wood processing to be carried out in a way that optimizes stiffness-related value from the resource.

Operational Application of Acoustic Technology

As operational application of acoustic technology is considered, there is a recognized need for the technology to be applied at a number of stages in the operational value chain, from timberlands through to the processing site. Figure 8.16 illustrates potential application of acoustic technology through the forest-to-mill wood supply chain. Different tools have been developed to suit each specific application.

Standing tree assessment is relevant for tree breeding, pre-harvest assessment (PHA) for forest or stumpage valuation, and decision support at time of thinning, where trees cannot be cut. The harvesting processor application provides decision support for log-making as well as collation of data for subsequent forest management, harvest planning, and valuation. Felled stems can be tested to assist in optimization of value capture in log-making, while logs can be assessed for ranking of average wood quality (stiffness and related characteristics) or segregated for supply to different customers or processing options. Automated on-line log testing is relevant to valuation of log supplies, ranking of log supply sources, prediction of MSR yields for output planning, and providing a very efficient means for segregation of logs based on quality and suitability for different customers or processing options.

Automated On-Line Log Sorting/Grading

Although initial operational deployment of acoustic technology was undertaken using hand tools, automated log sorting or grading is now available, enabling log-by-log optimization of sawcut patterns to maximize the extracted value from a mixed quality log resource (IFI 2008; Carter 2011). Figure 8.17 shows the acoustic log grading operation in a sawmill where a Hitman LG640 automatic log grader is installed after the debarker where it measures logs just prior to sawing. The machine uses acoustic wave velocity to assess wood quality by swinging a hammer at the end of each log



Figure 8.17—Hitman LG640 automated log grader installed on the debarker out-feed. (Photo on the right shows the swinging hammer and microphone sensor.) (Photo courtesy of Fibre-gen Ltd.)

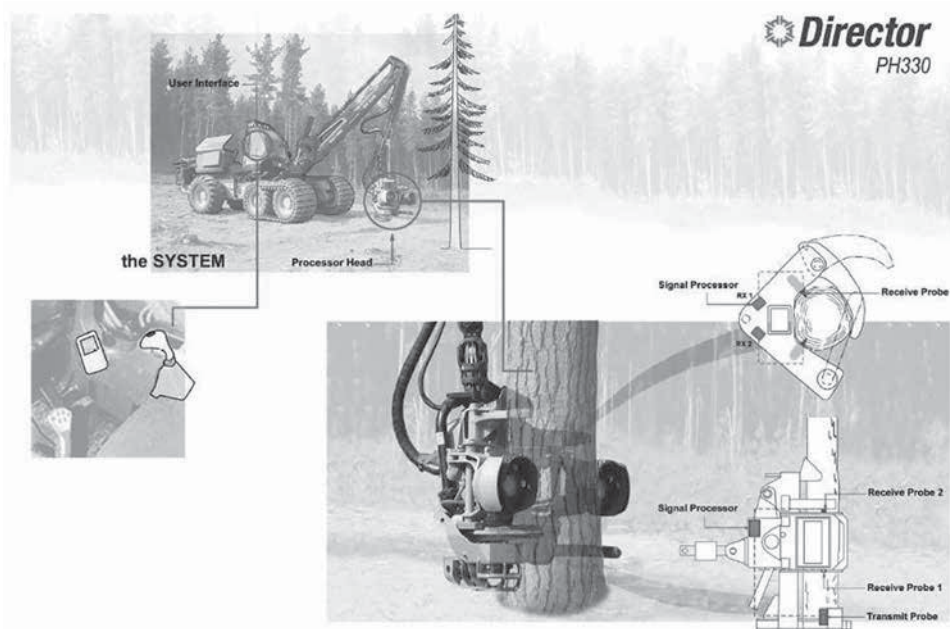


Figure 8.18—Schematics of a processor head integrated with an acoustic measurement system enabling tree quality evaluation during harvesting operation. (Drawing courtesy of Fibre-gen Ltd.)

going through the system and recording the acoustic signals using a microphone. By analyzing the resonant frequency of the longitudinal acoustic wave signals and calculating the acoustic velocity of the hit along the log, the machine is able to provide an immediate and accurate assessment of the stiffness of the wood and therefore its suitability for use as structural or nonstructural products. Logs are queued on the in-feed deck, and as each rolls into the machine infeed, its acoustic reading is displayed on the operator's control panel, which allows the operator to adjust the cut pattern to maximize the structural lumber grade out turn and profitability. The operational trial at Waimea Sawmillers in Nelson, New Zealand, has demonstrated at least a 3% gain in machine stress grading (MSG) recovery since installing the Hitman LG640 in-line acoustic grader.

Processor Head Acoustic Technology in Forest Harvest Operations

Recent research and development on acoustic technologies has brought the operational assessment of acoustic velocity as a measure of stiffness into timber harvesting and log making sectors of the forest and wood processing industry. Fibre-gen has developed a Hitman acoustic measurement system to be mounted in a processor head (Fig. 8.18). Previously reported field trials involved the integration of Hitman PH330 mechanized acoustic measurement devices into a Ponsse processor head in UK, two Waratah 626 processor heads in New Zealand, and one Waratah 624 processor head in Oregon, USA (Carter 2011). Further validation studies have been run in West Australia and Nelson, New Zealand.

The system measures the longitudinal TOF of a sound wave in the stem section held by the processor head, immediately following a cross-cut. With the acoustic velocity displayed in the cab, the operator can cut structural or nonstructural log product from the next section of stem and segregate the logs, based on a user-defined velocity threshold level. These trial studies have demonstrated the use of processor head acoustic technology in forest harvesting operations as a means to enable cutting to the correct log length and segregating logs for higher value structural markets. This avoids the need to test logs after they are cut to length and having to subsequently re-cut those logs that fail to meet the log buyer's acoustic speed specifications. Costs of sorting and re-cutting logs to a shorter length can significantly expend resources and generate waste, with the alternative of selling nonstructural logs at a discount in nonpreferred lengths.

Two alternative assessment strategies have been highlighted in recent performance validation projects: increase the average stiffness of a segregated log batch, or meet some specific minimum log velocity specifications defined by log resonance measurement (Carter et al. 2013). Processor head acoustic technology was able to identify lower stiffness sawlogs in the forest before any mill processing was undertaken. An example-based analysis of benefits and costs showed positive net benefits from the potential use of this technology to segregate structural logs from within stands otherwise considered nonstructural.

Processor head acoustic technology has now been demonstrated through a series of research, development, and validation projects over a period of 6 years and has been confirmed capable of delivering effective segregation to reliably meet a range of market and end user requirements.

Effect of Environmental Temperature on Field Acoustic Assessment of Trees and Logs

Depending on the geographic locations and the timing of forest operations, trees and logs can be acoustically tested and evaluated in different climates or different seasons. The wood temperature of trees and logs at the time of testing could range from above 30 °C to well below freezing. Previous studies on small wood samples and structural lumber suggest a direct effect of temperature on acoustic properties of wood. The observed effect of temperature on acoustic velocity in wood below fiber saturation point (FSP) is in agreement with generally accepted information on this subject, but conflicting results were reported for wood above FSP when wood temperature transitioned from above freezing to below freezing. There has been limited data showing the effect of temperature on acoustic velocity of wood measured on standing trees and logs. Little is known about the effect of seasonal temperature changes on acoustic evaluation of standing trees and freshly cut green logs. This information is important to field operations when the acoustic

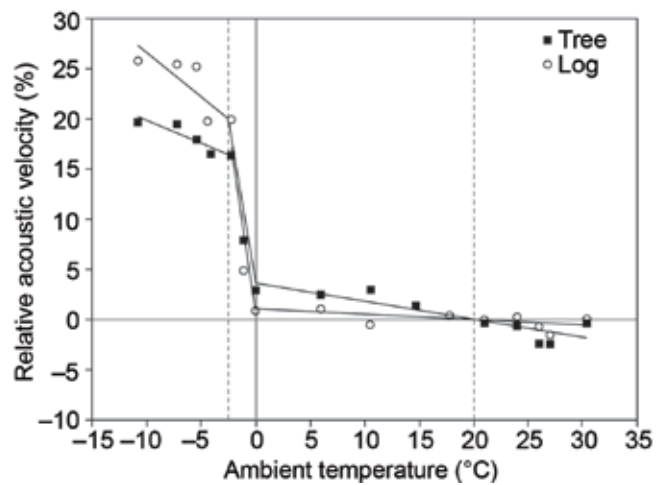


Figure 8.19—Effect of ambient temperature on change in acoustic velocity relative to 20 °C (Gao et al. 2013).

technology is used to assess the quality and values of logs, trees, and stands.

The laboratory study on red pine (*Pinus resinosa*) small clear specimens conducted by Gao et al. (2012) showed a significant change in acoustic properties of wood as wood temperature changed from –45 to 35 °C. A dramatic shift in acoustic velocity and energy loss was observed when the wood temperature changed to above or below the freezing point. Gao et al. (2013) further investigated the effects of environmental temperature on acoustic wave velocity of wood in standing trees and freshly cut logs over a duration of 12 consecutive months. Results indicated that ambient temperature had a significant effect on acoustic velocities of trees and logs in winter when temperatures were below freezing point. Acoustic velocities increased dramatically as the ambient temperature dropped below 0 °C, but then the change became less significant when the temperature decreased to below –2.5 °C. Above freezing point, acoustic velocities were found less sensitive to ambient temperature changes. Gao et al. (2013) further developed analytical models based on the change in acoustic velocity relative to a base temperature 20 °C. The relationships between the percentage of change in velocity (ΔV , %) and ambient temperature for red pine trees and logs are shown in Figure 8.19. Table 8.1 tabulates ΔV values for red pine trees and logs that were derived from the analytical models. Because acoustic velocity is more sensitive to temperature changes below freezing than above freezing, ΔV values are tabulated at a 1 °C increments from –11 to –2.5 °C and at 2 °C increments from 0 to 30 °C. From a practical standpoint, acoustic velocities of trees and logs measured well above freezing may not need a temperature adjustment, because the velocity changes observed were not large enough to have a practical significance.

From a practical standpoint, acoustic velocities of trees and logs measured at different climates or different seasons can

Table 8.1—Velocity change (ΔV) of red pine trees and logs in the range of -11 to 30 °C (Gao et al. 2013)

Ambient temperature (°C)	Tree ΔV (%)	Log ΔV (%)	Ambient temperature (°C)	Tree ΔV (%)	Log ΔV (%)
-11	21.0	27.5	6	2.5	0.8
-10	20.6	26.6	8	2.2	0.6
-9	20.1	25.7	10	1.8	0.5
-8	19.7	24.9	12	1.4	0.4
-7	19.2	24.0	14	1.1	0.3
-6	18.8	23.1	16	0.7	0.2
-5	18.3	22.2	18	0.4	0.1
-4	17.9	21.3	20	0.0	0.0
-3	17.4	20.4	22	-0.4	-0.1
-2.5	17.2	20.0	24	-0.7	-0.2
0	3.6	1.1	26	-1.1	-0.3
2	3.2	1.0	28	-1.4	-0.4
4	2.9	0.9	30	-1.8	-0.5

be adjusted to a standard temperature if measurements are conducted well above freezing temperatures or well below freezing temperatures. However, measurements conducted around freezing temperatures could cause complications in making temperature adjustments. Users should try to avoid conducting field acoustic testing when wood temperature is around the freezing point.

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