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Measuring Wood Quality in Standing Trees
A Review

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Abstract

This report summarizes a state-of-the-art review conducted on the topic of field measurement of the quality of wood in trees. The foundation science of micro-resistance drilling and acoustic-based techniques for use with woody materials is presented, and use of these techniques for the detection of biodeterioration in wood is discussed. Quantification of the physical and mechanical properties of wood, in standing timber, is reviewed. Studies designed to examine the use of these techniques with trees are summarized, and a list of commercially available technologies that use these techniques is presented.

Keywords: decay, nondestructive evaluation, stiffness, trees, wood property, wood quality

Contents

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Measuring Wood Quality in Standing Trees

A Review

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Introduction

Wood production that can effectively meet the growing demand for wood supply will need to deliver more than increased volume. Efficient wood production also requires the capability of delivering the appropriate wood quality to markets to optimize wood value and business competiveness. Delivering the appropriate quality of wood poses serious challenges to the current value chain as customer requirements for specific wood quality attributes become more diverse. The current value chain has historically focused on increasing volume, which has increased yields but also has had the unintended effect of lowering many wood quality attributes. In addition, the current chain tends to extract value at each link instead of working to create more value. Accurate knowledge of wood quality is key for an optimal value chain to exist.

The beginning of the value chain is the critical point at which wood quality can be influenced by forest management and silviculture. Although there is certainly more opportunity in designing silvicultural prescriptions that include wood quality attributes, silviculture and the rest of the value chain ultimately depend on the ability to define and quantify wood quality attributes relevant to various end uses. A more comprehensive and efficient nondestructive evaluation (NDE) of wood quality in the standing tree can allow more value extraction from each tree by enabling sorting by quality as early as possible in the value chain. Assessment of ongoing silvicultural prescriptions and genetic improvement efforts can also be conducted with NDE of wood quality. With known wood quality, the potential market value of each tree can be realized. However, realizing optimal value still requires that the supply chain (working to extract value at each link) become a true value chain (working to create optimal total value).

Importance of Wood Quality

Wood quality is typically described by attributes related to either performance or appearance with relative attribute importance dependent on intended use. For centuries, wood has been assessed for quality, but with limited technologies, this was largely reliant on a visual inspection. Hence, wood quality assessment has long influenced its preferred use and optimal value. This may have even led to the rise of the aesthetic preference for wood that is free of knots because it is also structurally superior. In fact, many desirable attributes of wood quality are correlated, allowing for relatively simple field measurements and cultivation of desired attributes.

With modern technologies available to assess wood quality, a more accurate assessment of quality is possible and needed to optimize value for the thousands of end uses of wood.

Decay Detection

Decay can cause significant damage to timber in the United States. Field foresters and managers are keenly interested in learning if NDE technologies may be used to effectively detect incipient decay in standing timber at the earliest possible stage. Currently, the primary means of inspecting timber relies on visual assessment criteria. Although visual inspections are used extensively, they provide no indication of the extent of internal deterioration that may exist in timber.

A series of research and demonstration studies have been completed that were designed to determine the effectiveness of several existing NDE technologies for locating incipient decay in standing timber. Results of these studies, which are subsequently summarized, have shown that several NDE techniques are available to assist field foresters and managers in monitoring the health of the Nation's standing timber and identifying decay-infested trees in forests.

Technology Review

Time-of-Flight Stress-Wave Technique

The time-of-flight (TOF) stress-wave technique has been successfully used in decay detection in a variety of wood structures (Ross 2015) for many years. The concept of detecting decay using this method is based on the idea that stress-wave propagation is sensitive to the presence of degradation in wood. In general terms, a stress wave travels faster through healthy and high-quality wood than it does through deteriorated or low-quality wood. The TOF of the stress wave is typically used as a predictor of the physical conditions inside the wood. By measuring the TOF of a stress wave through a tree stem in the radial direction, the internal condition of the tree can be evaluated (Fig. 1).

TOF of stress waves traveling perpendicular to the grain is affected by tree species, as shown by Mattheck and Bethge (1993) (Table 1). They measured speed of sound in different species of healthy trees using a commercially available stress-wave timing unit and found that speed variation existed both within species and between species. Generally, sound travels faster in hardwood species than in softwood species. For example, the speed of sound for healthy maple trees is from 1,000 to 1,600 m/s. However, for healthy Douglas-fir trees, it ranges from 900 to 1,300 m/s. For evaluating trees of different species, Divos and Szalai (2002) provided some baseline stress-wave velocities for intact healthy trees (Table 2).

Figure 1. Time-of-flight stress-wave measurement conducted in the radial direction of a tree trunk to detect internal decay.

Micro-Drilling Resistance

Micro-drilling resistance tools are being used increasingly in the field to characterize wood properties and detect abnormal physical conditions in structural timbers and standing trees (Rinn 1994, Isik and Li 2003, Brashaw and others 2005, Gao and others 2017) (Fig. 2). Our experience on tree quality assessment using the micro-drilling resistance tool also indicated that this technique has good potential for detecting and defining the extent of incipient decay in softwood trees.

The micro-drilling resistance tool is a mechanical drill system that measures the relative resistance (drilling torque) of the material as a rotating drill bit is driven into the wood at a constant speed. It produces a chart showing the relative resistance profile for each drill path. Because it can reveal the relative density change along the drill path, it is typically used to diagnose the internal condition of structural timbers and urban trees.

Drill resistance R_D is defined as

$$R_D = T/\omega \qquad \text{(Nm s/rad)} \qquad (1)$$

where T is drilling torque (Nm) and ω angular speed (rad/s).

A micro-drilling resistance tool typically consists of a power drill unit, a small-diameter drill bit, a paper chart recorder,

Table 1—Radial stress-wave velocity and time-of-flight measured in healthy trees (Mattheck and Bethge 1993)

	Radial stress-wave velocity		Time-of-flight per unit length	
Species	m/s	ft/s	µs/m	µs/ft
		Hardwoods		
Ash	1,162–1,379	3,810–4,520	725–861	221–262
Birch	967–1,150	3,170–3,770	870–1,034	265–315
Black locust	934–1,463	3,060–4,800	684–1,071	208–326
Black poplar	869–1,057	2,850–3,470	946–1,151	299–351
Horse chestnut	837–1,557	2,860–5,110	642–1,145	196–349
Lime	940–1,183	3,080–3,880	845–1,064	258–324
Maple	1,006–1,600	3,300–5,250	625–994	191–303
Oak	1,382–1,610	4,530–5,280	621–724	189–221
Pine poplar	967–1,144	3,170–3,750	874–1,034	266–315
Plane	950–1,033	3,120–3,390	968–1,053	295–321
Red beech	1,206–1,412	3,960–4,630	708–829	216–253
Silver poplar	821–1,108	2,690–3,640	903–1,218	275–371
Sweet chestnut	1,215–1,375	3,990–4,510	727–823	222–251
Willow	912–1,333	2,990–4,370	750–1,096	229–334
		Softwoods		
Douglas-fir	905–1,323	2,970–4,340	756–1,105	230–337
Fir	910–1,066	2,990–3,830	858–1,099	261–335
Larch	1,023–1,338	3,360–4,390	747–978	228–298
Pine	1,066–1,146	3,500–3,760	873–938	266–286
Spruce	931–1,085	3,050–3,560	922–1,074	281–327

and an electronic device that can be connected to the serial interface input of any standard personal computer. The diameter of the drill bit is typically very small, from 2 to 5 mm. Therefore, any weakening effect of the drill hole on the wood cross section is negligible.

Stress-Wave Tomographic Imaging

The sensitivity of the TOF stress-wave technique is limited. A single-pass stress-wave measurement can only detect internal decay that occupies 20% or more of the total cross-sectional area (Wang and others 2004, White and Ross 2014). To increase the reliability of the inspection and define the extent and location of any internal decay, it would be practical to conduct multiple measurements in different orientations at one cross section, especially for suspect trees. Tomographic inversion of stress-wave data from multiple measurements could allow inspectors to obtain an image of the distribution of stress-wave transmission times in the cross section and help define the extent and location of internal decay with accuracy.

Stress-wave tomography is a nondestructive technique that refers to the cross-sectional imaging of an object from data collected by measuring the stress-wave properties from multiple directions in a plane (Fig. 3). Different types of stress waves can be used, but the most convenient are bulk longitudinal waves.

Tomographic images can be constructed from many stress-wave parameters, such as TOF, amplitude, frequency spectrum, and phase. The three main types of algorithms that can be used to form tomographic images from stress-wave data are transform techniques, iterative techniques, and direct inversion techniques (Bucur 2002, 2005). Divos and Szalai (2002) proposed several possible stress-wave measurement arrangements with testing points ranging from four to eight (Fig. 4). The minimum detectable defect size can be theoretically determined, assuming that the defect approximates a circle. As indicated in Figure 4, the minimum detectable defect sizes are 8%, 6%, 4%, 3%, and 1% of the cross-sectional area for 4, 5, 6, 7, and 8 test point arrangements, respectively. The reference velocity determination is a key step in constructing tomographic images. The reference velocity is defined as the velocity in the healthy wood of a tree. Because stress-wave velocity depends on anatomical directions, two or more reference values may be needed, depending on measurement arrangement.

Table 2—Reference stress-wave velocity and time-of-flight in healthy trees (Divos and Szalai 2002)

	Radial stress-wave velocity		Time-of-flight per unit length	
Species	m/s	ft/s	µs/m	µs/ft
Beech	1670	5479	599	183
Black fir	1480	4856	676	206
Larch	1490	4888	671	205
Linden	1690	5545	592	180
Maple	1690	5545	592	180
Oak	1620	5315	617	188
Poplar	1140	3740	877	267
Scotch fir	1470	4823	680	207
Silver fir	1360	4462	735	224
Spruce	1410	4626	709	216

Results from a Demonstration Study

The USDA Forest Service, in cooperation with Michigan Technological University and the University of Minnesota Duluth, conducted a laboratory investigation into the use of these three techniques to detect decay in timber (Wang and others 2005). Although the study focused on the testing of logs, the results observed are directly applicable to standing timber.

Twelve freshly cut sugar maple (*Acer saccharum*) logs representing a range of discoloration and decay were handpicked at a local mill in Houghton, Michigan, USA. The selection process segregated four classes of logs: three logs with no decay (control group), three logs with severe discoloration (light decay), three with small to medium levels of decay, and three with medium to severe levels of decay. No logs had decay along their full length, thereby permitting comparisons between healthy and decayed wood both within classes and within the same log. Logs were then shipped to the USDA Forest Service, Forest Products

Figure 2. A micro-resistance drilling tool is used to inspect the internal condition of an elm tree.

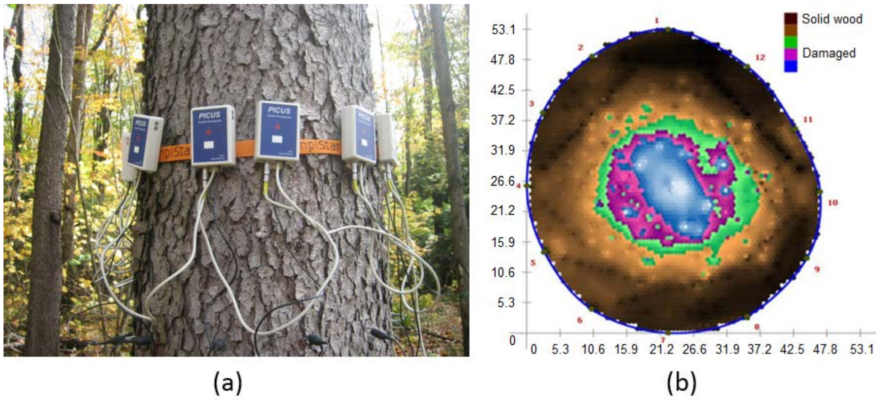


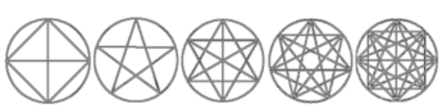
Figure 3. Stress-wave tomography test on a black cherry tree: (a) PiCUS Sonic Tomograph tool (Argus Electronic gmbh, Rostock, Germany); (b) tomogram-revealed internal rot.

Laboratory (FPL) in Madison, Wisconsin, USA, where various NDE testing procedures were performed.

The logs were randomly numbered, and the ends were marked with paint when they arrived at FPL. The log samples were all about 2.64 m (104 in.) long. The butt-end diameter ranged from 26.1 to 43.0 cm (10.3 to 16.9 in.) and the small-end diameter ranged from 25.8 to 40.5 cm (10.1 to 15.9 in.).

The instrumentation systems used included the Fakopp (Fakopp Enterprise, Agfalva, Hungary) Microsecond Timer (TOF stress-wave measurement), Fakopp 2D multichannel microsecond timer (stress-wave-based tomography), and the IML-RESI F400 (Instrument Mechanic Labor, Inc., Kennesaw, Georgia, USA) measuring instrument (micro-drilling resistance). Figure 5 outlines measurement locations and the scan path along the length of a log. Because the decay detection mechanisms of all three techniques examined are limited to provide one- or two-dimensional information only, multiplane measurements on the logs are necessary for accurate assessment. Therefore, each log was properly oriented and tested in two main directions (a–a, horizontal and b–b, vertical) and at multiple locations along the length. The butt-end of each log was more intensively scanned (15.2 cm (6 in.) apart) because decay often occurs at the lower part of a tree.

The remaining NDE measurements were taken along the length of the log with less intensity (30.5 cm (12 in.) apart). To facilitate testing, each log was supported by two concrete



Number of test points	4	5	6	7	8
Number of measurements	6	5	9	14	20
Number of reference velocities	2	1	2	2	3
Minimum detectable defect (%)	8	6	4	3	1

Figure 4. Sensor arrangements for multipath time-of-flight measurements (Divos and Szalai 2002).

blocks, one on each end, 0.9 m (3 ft) above the ground. After the log was properly oriented and secured, the upper surface of the log was marked using a chalk line according to the testing diagram. TOF measurements were conducted using a Fakopp Microsecond Timer in both horizontal (a–a) and vertical (b–b) directions at each scan location. The timer was composed of two needles (with a transducer built in to each needle) and a TOF display unit. For each measurement, two needles were inserted into the log surface through the bark and aligned in a transverse path across the center of the log. Care was taken to locate transducer probes away from obvious surface defects. The needles were connected to the timer unit. A stress wave was initiated through a hammer tap on the start transducer's back impact surface. The timer displayed the travel time of the stress wave between the two transducers.

An eight-channel stress-wave device (Fakopp 2D Microsecond Timer) was used to collect TOF data from each test plane in the logs. Figure 6 shows the use of the multichannel stress-wave measurement system in testing a log. The tomographic measurements were conducted at multiple locations for each log sample. At each test location, the diameters of the long axis and short axis and the circumference of the cross section were measured using a caliper and a tape measure. This information was used as an input for the system software to map the approximate geometric form of the cross section and determine the location of each transducer around the circumference. Eight transducers were then mounted onto the log following the sensor arrangement specified by the software. The needle probes were carefully inserted into the sapwood by penetrating the bark to eliminate the signal disturbance from bark. The transducers were then tapped one by one using a hammer, and following each tapping, an array of TOF data were collected through a data acquisition system. A complete data matrix was obtained through this measurement process at each location and saved for further tomographic image analysis.

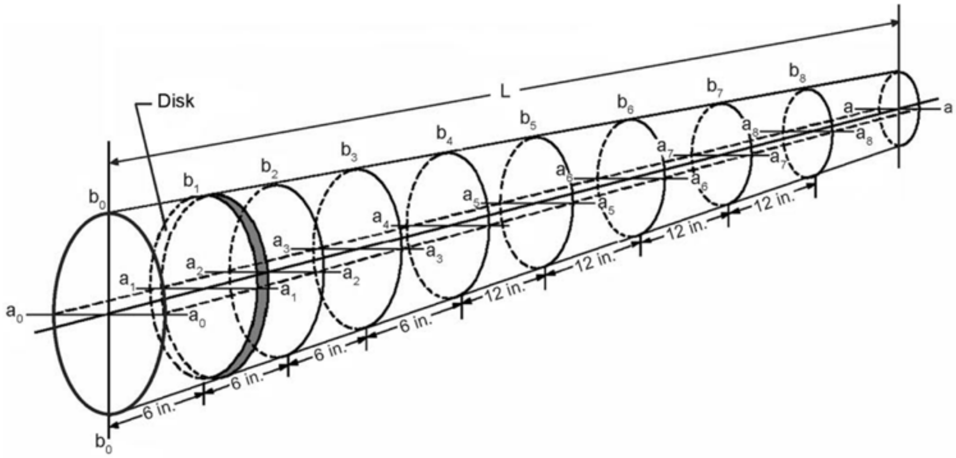


Figure 5. Measurement locations and scan path along the length of a log (L) (1 in. = 25.4 mm).

Micro-drilling resistance measurements were conducted on the log samples with the IML-RESI F400 measuring instrument (Fig. 7). As the drill bit entered and passed through the wood, the relative resistance, which was determined by the drilling torque *T* and angular speed ω, was recorded on a wax paper graph and stored in an electronic unit. Each resistance chart was properly coded to track its drilling location along the length of the log. The electronic files were transmitted to a computer after testing for further analysis. The maximum drilling depth of the tool we used was 400 mm, which was long enough to penetrate the whole cross section for most samples we tested. For the few logs with diameters slightly greater than 400 mm, the resistance information obtained from this tool was considered adequate to reveal the internal physical condition of the cross section.

After NDE measurements were completed, a 3.8- to 5-cm- (1.5- to 2-in.-) thick disk was cut from each measurement location. Ten disks were obtained from each log. Each disk was then carefully surfaced and physically examined for internal condition in terms of the discoloration and the level and location of decay. A digital picture was taken of the cross section of each disk, and the disks were mapped into different quality regions using different color lines. The color codes for mapping disks were as follows:

Blue/purple – stain (dark, deep discoloration);

Green – incipient decay (soft wood with open pores but hard to mark with fingernails);

Red – decay (severely softened wood but still in place); and

Black – hole (missing wood, complete or partial).

All disk samples were weighed after they were cut from the logs. Oven-dry weights for one disk from each log were going to be collected, but because of the rapid rate of bacterial or fungal infection and time-to-ship slowdowns, these weights were not obtained.

Based on results obtained, the following was concluded:

1. The capability of the single-path TOF method to detect incipient decay is limited because radial stress-wave velocity varies substantially and standard reference velocities for data interpretation are not readily available. This technique could be used to identify trees that have moderate and severe internal decay.

2. The results indicate that micro-drilling resistance is effective in detecting and defining the extent of internal decay, including early stages of decay if the resistance drilling device is oriented in such a way that its path goes through the decay zone. However, orienting the drill through the decay is difficult to guarantee. Considering the orientation limitation, the micro-drilling resistance method should be limited to confirm and determine the extent of

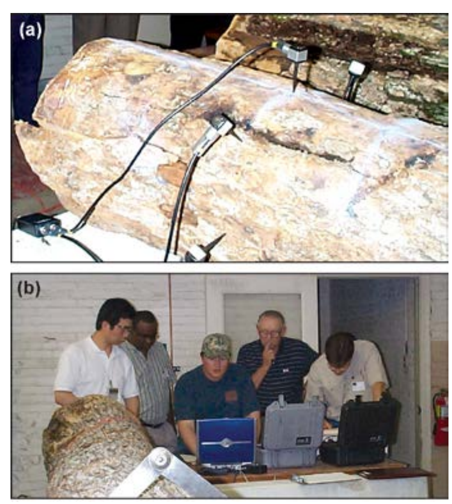


Figure 6. Multichannel stress-wave measurement system: (a) placement of transducers, (b) measurement and recording equipment.

Figure 7. Micro-drilling resistance test.

decay in trees after decay or suspect areas are detected by other techniques.

3. Compared with the single-path TOF measurement, the stress-wave tomography technique, based on multipath TOF measurements, has good potential for detecting incipient decay in standing timber.

Recent Development

The most recent development in the evolution of these techniques is the design and manufacture of a low-cost single-path TOF stress-wave unit produced by Dr. R. Bruce Allison of Allison Tree, LLC (Verona, Wisconsin, USA). This unit was specifically designed for use by field inspectors; it uses state-of-the-art electronic software and hardware to provide a robust field evaluation system (Fig. 8).

Physical and Mechanical Property Assessment Techniques

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 when 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 about reliability and the broad conservative design values associated with visual grades for structural applications led to the development of machine stress 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. 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, glue-laminated timber (glulam), and engineered trusses.

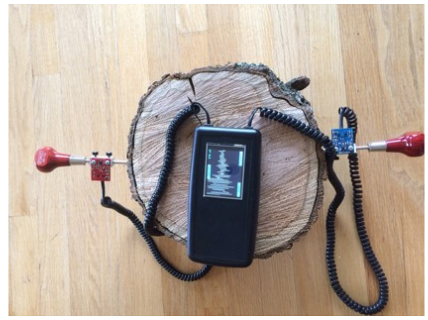


Figure 8. A low-cost stress-wave timer (Tree Check Sonic Wave Tree Decay Detector, Allison Tree, LLC, Verona, Wisconsin, USA) uses two sensors on opposite sides of the tree trunk to measure an impact-induced stress wave's transit time across the trunk (Used with permission from R. Bruce Allison).

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 mill interest 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.

Technology Review

During the past several decades, acoustic technologies have become well established as material evaluation tools and their use has become widely accepted in the forest products industry for online control and products grading. Recent research developments on acoustic sensing technology offer further opportunities to evaluate standing trees for general wood quality and intrinsic wood properties (Wang and others 2007a). The use of 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 (Wang 2013). This is particularly true in trees, in which 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).

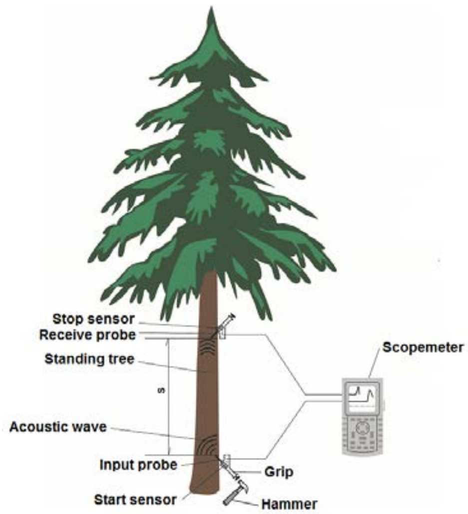


Figure 9. Time-of-flight acoustic measurement on standing trees (Wang and others 2007b).

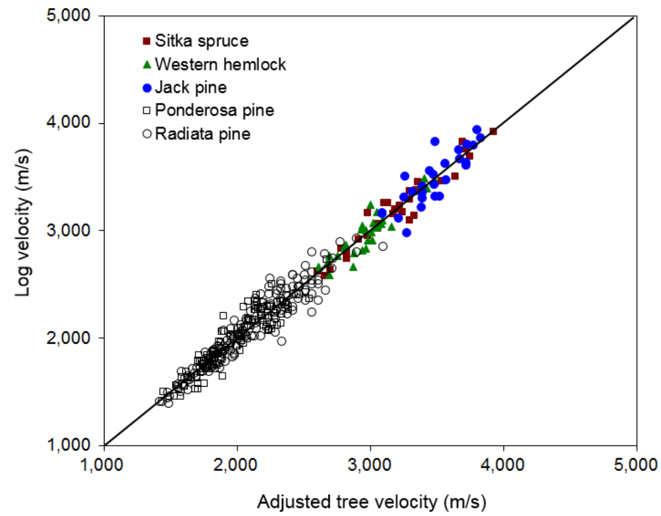


Figure 10. Tree acoustic velocity (adjusted) versus log acoustic velocity (Wang and others 2007b).

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 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 TOF using Equation (2):

$$C_{\mathrm{T}} = \frac{S}{\Delta t} \qquad (2)$$

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. 9). The lower probe is placed about 40 to 60 cm (about 16 to 24 in.) above the ground. The span between the probes is determined from a practical standpoint because they need to be positioned at a comfortable height for the person taking the measurements. The span typically ranges from 1.0 to 1.2 m (3.3 to 4 ft).

The applicability of using acoustic waves to assess intrinsic wood properties of standing trees has been validated by many researchers around the world (Nanami and others 1992a, 1992b, 1993; Wang 1999; Ikeda and Kino 2000; Huang 2000; Wang and others 2001, 2007b; Lindstrom and others 2002). 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.

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 and others 2007b). 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 good linear correlation between tree velocity and log velocity for each species tested. The relationship was 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 to be significantly higher than log velocities. The results support the hypothesis that TOF measurement in standing trees is probably 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 and others (2007b) developed two models (multivariate regression model and dilatational wave model) for the species evaluated in those trials. As an example, Figure 10 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 in decreasing the variability in velocity prediction.

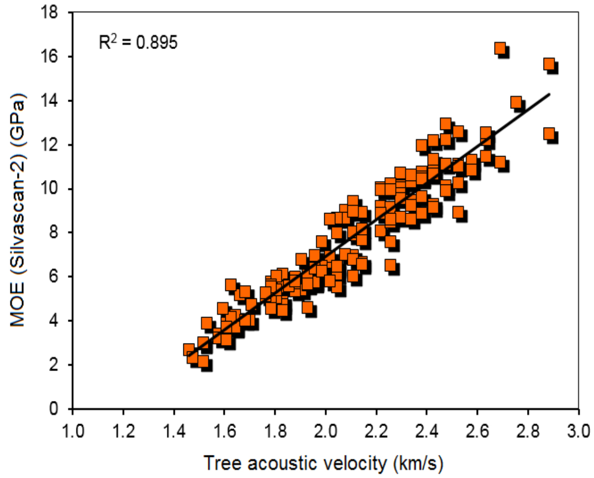


Figure 11. Relationship between tree acoustic velocity and modulus of elasticity (MOE) of the core samples measured by Silvascan-2 for radiata pine (Wang and others 2007a).

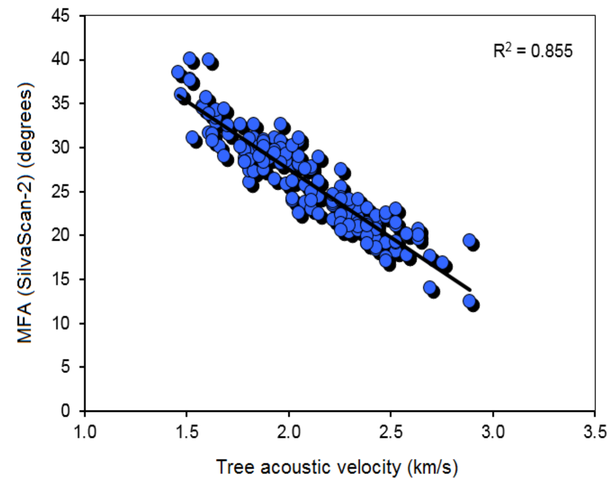


Figure 12. Relationship between tree acoustic velocity and microfibril angle (MFA) of the core samples measured by Silvascan-2 for radiata pine (Wang and others 2007a).

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 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 were the standard procedures for evaluating wood stiffness and strength. The timber owner did 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 (Wang and others 2007a). Figures 11 and 12 show the relationships between tree acoustic velocity and modulus of elasticity (MOE) and microfibril angle (MFA) of core samples from trees measured by x ray densitometry, diffractometry, and image analysis.

Applications

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 (*Abies sachalinensis*) and larch (*Larix*) trees and observed significant differences in acoustic velocities and acoustic-determined MOE for trees in forest stands at different locations and at different tree 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 acoustic and static MOE as a function of thinning regimes is illustrated in Figure 13. 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. This information will help managers select the most effective treatment for future plantations to obtain 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 contain a higher percentage of juvenile wood, thus creating a lower quality and more variable wood resource for industry to process (Kennedy 1995). Consequently, genetic improvement of juvenile wood properties is now receiving attention and getting higher priority in research. To help capture genetic opportunities,

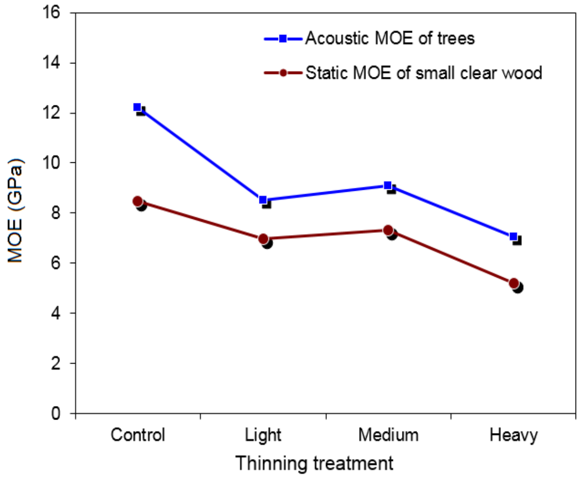


Figure 13. Modulus of elasticity (MOE) of young growth Sitka spruce in relation to thinning treatment (Wang and others 2001).

there is a need to determine wood quality at an early age (Lindstrom and others 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 traits.

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 and others 2000). 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 and others (1998) reported that with radiata pine, there was 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 and others 2003). Lindstrom and others (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 concluded that acoustic tools could provide opportunities for mass screening for stiffness of fast-grown radiata pine clones at a very early age.

Evaluation of Plantation Resources for Wood Quality

Typically, in applying acoustic technology to a plantation resource, 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 problem of relatively low stiffness of wood in the younger softwood stands that are becoming 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 subsample 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, enabling management, planning, harvesting, and wood processing to be carried out in a way that optimizes stiffness-related value from the resource.

Available Field Equipment

A range of tools are available for assessing wood quality in trees and can be obtained from a variety of equipment development firms. Table 3 lists current commercially available micro-drilling resistance and acoustic-based nondestructive testing tools. Website addresses for the companies that are manufacturing these tools are included.

Conclusions and Future Directions

Using the highest quality wood for its best and highest end use maximizes the value of wood. Optimization and decision-making to date has largely focused on increasing wood volume, and significant changes are needed in each link to transition to a value chain that includes wood quality. Accurate field assessment of key wood quality attributes is the first step in the enabling process. For a more comprehensive and useful picture of wood quality, we need to link wood quality traits to genetics and silvicultural practices that affect tree growth characteristics. This level of complexity must be modeled. Somewhat similar to tree growth models in approach, wood quality models also vary widely in methodology and success. In addition, the environmental variables driving wood quality are probably less understood and are in need of further development.

Table 3—Commercial nondestructive tools available for assessing wood quality in trees

Manufacturer	Commercial tool	Application	Website
Allison Tree, LLC, USA	Tree Check – Sonic Wave Tree Decay Detector	Decay detection	www.allisontree.com
Agricef Brazil	USLab - Ultrasound	Decay detection	www.agricef.com.br
argus-electronic gmbh, Germany	PiCUS Sonic Tomograph	Decay detection	http://www.argus-electronic.de/en
CBS-CBT, Switzerland	Sylvatest	Decay detection Property assessment	www.cbs-cbt.com
Fakopp Enterprise, Hungary	Microsecond Timer	Decay detection	www.fakopp.com
	3D Acoustic Tomograph	Decay detection	
	TreeSonic	Property assessment	
fiber-gen Limited, New Zealand	Hitman ST300	Property assessment	http://www.fibre-gen.com/
	Hitman PH330	Property assessment	
IML gmbH, Germany	Micro Hammer	Decay detection	www.imlusa.com
IML North America, LLC, USA	IML-RESI Systems	Decay detection	www.iml-na.com
Metriguard, Inc., USA	239A Stress Wave Timer	Decay detection	www.metriguard.com
RINNTECH, Inc., Germany	ARBOTOM®	Decay detection	www.rinntech.de
	RESISTOGRAPH®	Decay detection	www.rinntech.de
SIBTEC Scientific, Sibert Technology Limited, England	Digital microprobe (DMP)	Decay detection	www.sibtec.com

However, if key wood quality field measures were included in the USDA Forest Service Inventory and Analysis program, powerful linking of existing plot level data across multiple spatial scales would be enabled, which would allow increased insight into wood quality prediction and immediate utility for the wood value chain.

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