



Acoustic Assessment of Wood Quality of RAW FOREST MATERIALS

— A Path to Increased Profitability

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Field research (top left and right) using prototype equipment helped prove the validity of acoustic assessment of wood quality in standing trees, a process now made easier with commercially available equipment shown in the bottom photos (courtesy of Fibre-gen, Inc.).

Assessment of 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, grow higher quality wood, and 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 (Pellerin and Ross 2002). 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 future plantations for desired fiber quality.

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 structural performance of the final products. With continuous advancements and refinements, this technology could assist in managing wood quality, assessing forest value, and improving the timber quality of future plantations.

Background

Traditionally, 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), and assignment to one of several possible grades is based on simple, broad, allowable ranges for the 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 since 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 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, 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 the 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 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 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.

Assessing log quality

It is well recognized that the variation in wood and fiber properties is enormous within a pile of logs that has been 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 1**

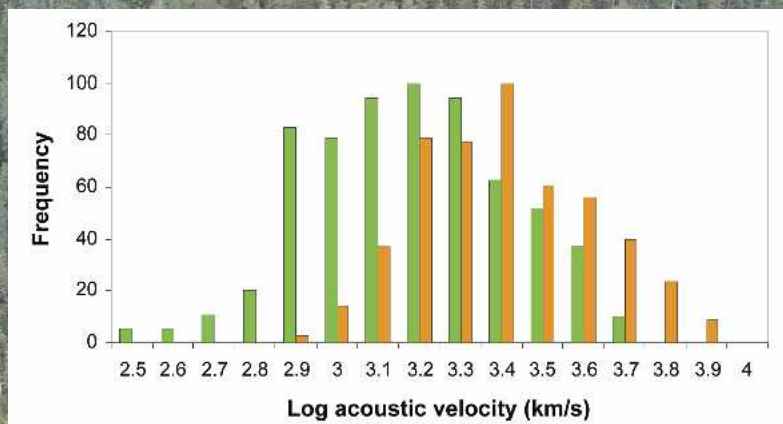


Figure 1. — The acoustic velocity (km/s) of a large sample of similar logs from two geographically distinct radiata pine forests in New Zealand demonstrating the large variability in the intrinsic wood properties of the logs (Andrews 2000).

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 the intrinsic wood properties of the logs (Andrews 2000). Clearly, there are major commercial benefits to be gained by assessing the wood properties at log level and optimizing the use of the resources through appropriate log sorting.

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 a weighted average acoustic velocity. Because the modulus of elasticity (MOE) of the log is simply equal to 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, Japanese scientists conducted 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 the close relationships 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 2** 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 unproved 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 percent stiffer than that from the group with the lowest velocity (the bottom 30%).

In a practical log-sorting process, companies can achieve benefits by developing a sorting strategy based on the log sources and desired end products. Currently, the companies implementing acoustic sorting strategies measure only the velocity of acoustic waves and segregate logs into velocity groups using predetermined cut-off velocity values. **Figure 3** shows the use of a hand-held acoustic tool for evaluating logs in a log yard. 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 4 demonstrates the increasing yield of structural grades of lumber with increasing acoustic

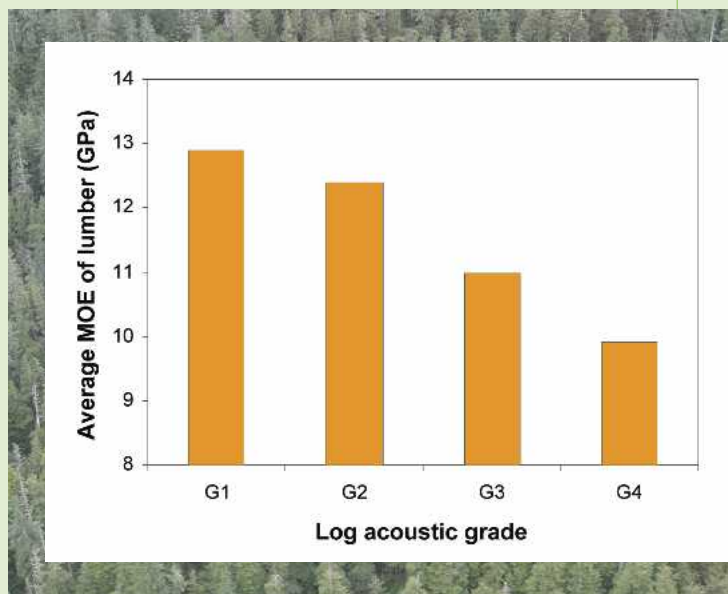


Figure 2. — Log acoustic grade versus average MOE of lumber.



Figure 3. — The use of a hand-held acoustic tool for evaluating logs in a log yard. (Photo courtesy of Fibre-gen, Inc.)

velocity of logs processed, as measured at two New Zealand radiata pine sawmills. Assuming a price differential of NZ\$200/m³ 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 percentage points. 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 5** illustrates the relationship between acoustic velocity for Southern pine log batches (10 percentile groups from log sample) and the average ultrasound propagation time (UPT) of veneer peeled from the logs. UPT is the elapsed time for ultrasound to travel between fixed roller transducers on a commercial ultrasound veneer grader.

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 3 classes, the high stiffness logs resulted in production of 52 percent premium high stiffness veneer product, compared against unsegregated logs of 24 percent. These results clearly show that segregation using acoustics results in substantially higher proportions of higher stiffness veneer being produced. Equally, if a higher grade outturn 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 to \$100 per thousand board feet, Scribner log scale) (Carter et al. 2005).

Sorting Logs for Pulp and Paper Quality

One of the challenges 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, the 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 the logs meet the quality specifications for the product outturn. If unsorted, the below-specification logs have to 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 paper mills to segregate pulp wood for pulp and paper manufacture. Albert et al. (2002) have tested the hypothesis that the acoustic measures of pulp logs are linked to the 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 pulping and testing demonstrated that fiber length, wet strength, and various handsheet properties varied systematically. The acoustic velocity of the peeler cores was found strongly related to the length-weighted fiber length and the wet zero-span tensile strength of the fibers from the peeler cores. In a larger mill study with 2,247 radiata pine logs, Bradley et al. (2005) confirmed that acoustics could 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 percent difference in energy requirement between the lowest and highest velocity logs for a given specific energy.

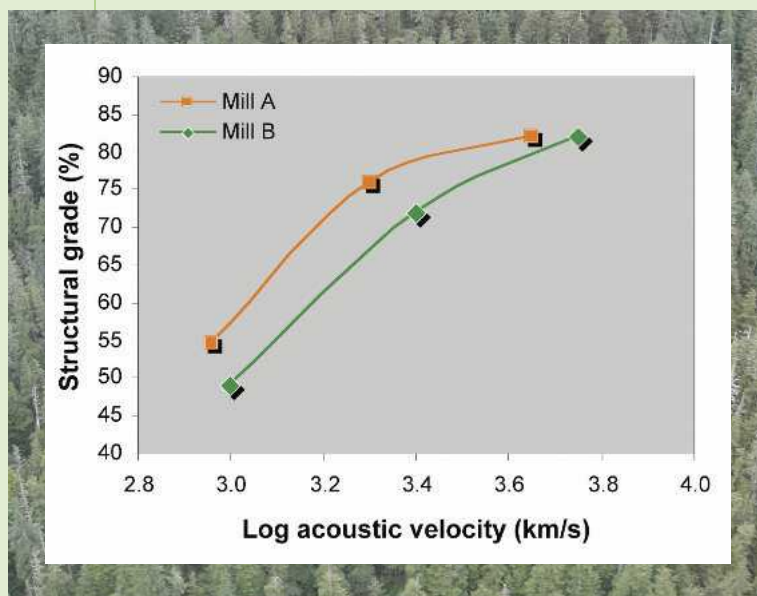


Figure 4. — Log acoustic velocity versus yield of structural grades for two New Zealand radiata pine sawmills (Carter et al. 2005).

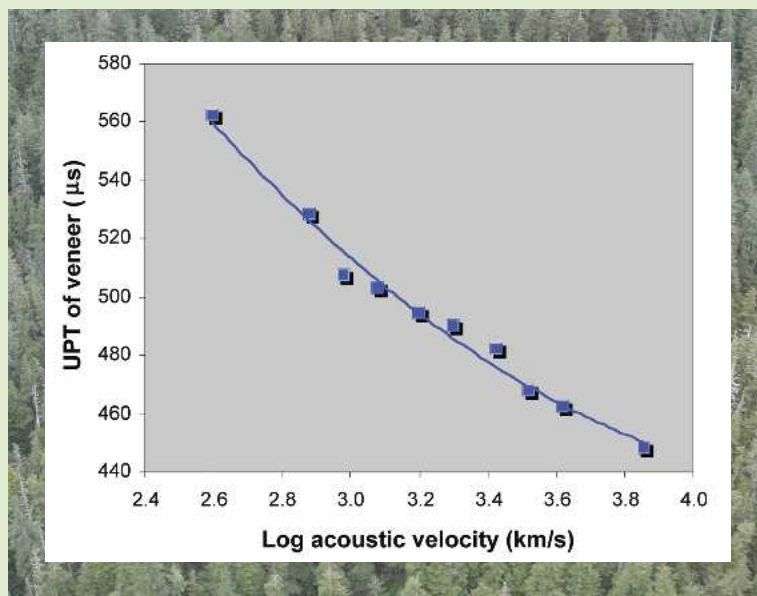


Figure 5. — Acoustic velocity of southern pine log batches versus the average ultrasound propagation time (UPT) of veneer from the logs (Carter et al. 2005).

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 as high as 150 percent down to an air-dry state of 30 to 40 percent. 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, as the standard electrical conductivity or impedance methods become inaccurate at MCs above fiber saturation 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 MC of log stockpiles as the generating companies do not want to chip and burn wood above 40 to 55 percent 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 recent 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 will be subject to a sample proof test (sampling rate: 1 in 1000). 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 tree quality

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 the intrinsic wood properties of standing trees has been validated by many research works around the world (Nanami et al. 1992a, 1992b, 1993; Wang 1999; Ikeda and Kino 2000; Ikeda and Arima 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. **Figure 6** shows the use of a portable acoustic tool for evaluating wood quality in standing trees. 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 time-of-flight (TOF) for a single pulse wave to pass through the tree trunk from the transmit probe to the receive probe.

Measuring Wood Properties of Standing Trees

Several trial studies aimed at proving the acoustic concept for measuring acoustic velocity and wood properties



Figure 6. — Assessing wood quality with a portable acoustic tool in forest. (Photo courtesy of Fibre-gen, Inc.)

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 coefficients 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 the 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 7** 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 of evaluating tree quality in terms of structural performance, Ikeda and others (2000a, b) 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 percent 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 and 9** show the relationships between tree acoustic velocity and the MOE and microfibril angle

(MFA) of core samples from the 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.

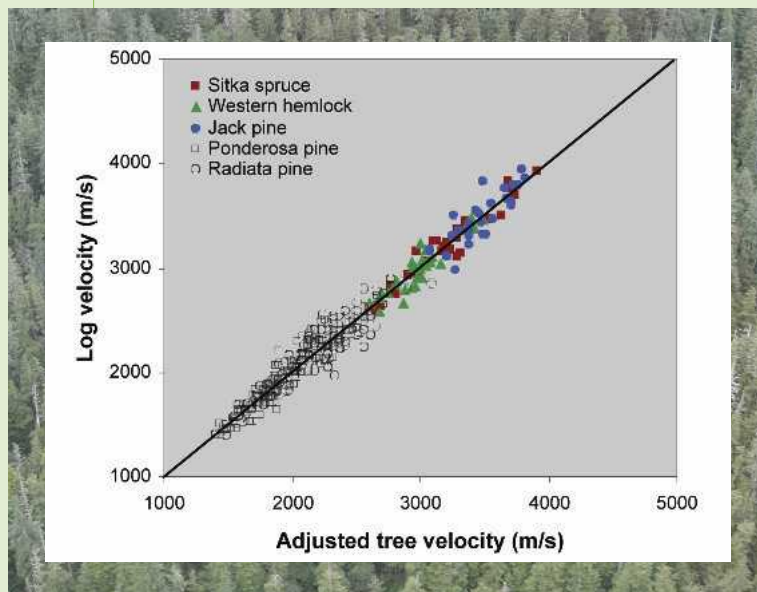


Figure 7. — Tree acoustic velocity (adjusted) versus log acoustic velocity.

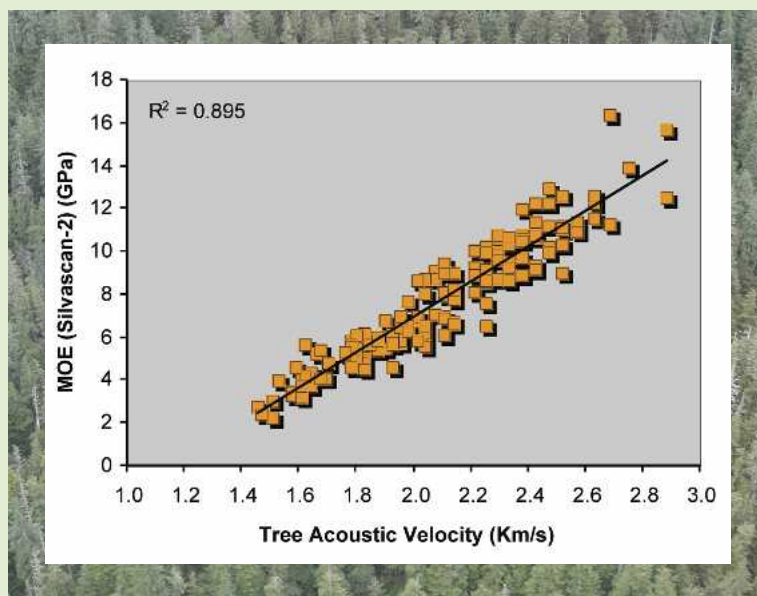


Figure 8. — Relationship between tree acoustic velocity and modulus of elasticity (MOE) of the core samples measured by Silvascan-2 for radiata pine.

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 10**. These results were encouraging and indicated that the 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 innova-

tions 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 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). 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 of nondestructively assessing the 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.

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

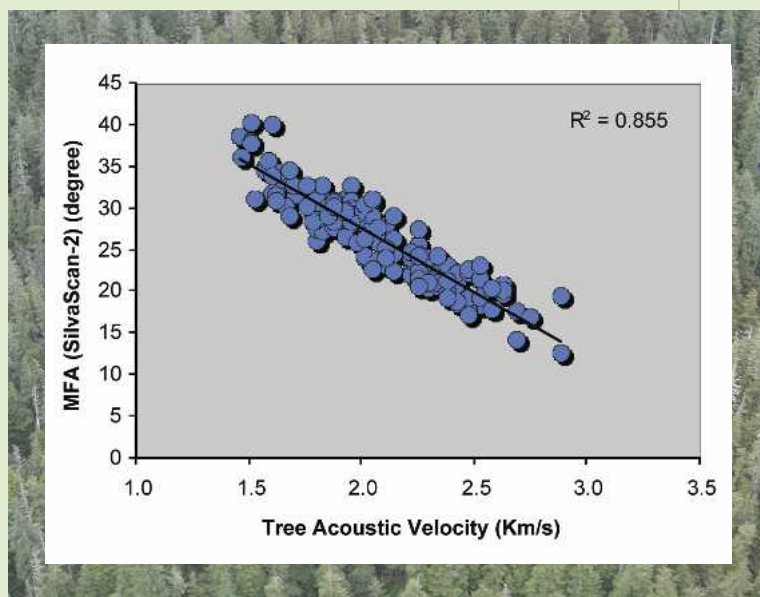


Figure 9. — Relationship between tree acoustic velocity and microfibril angle (MFA) of the core sample measured by SilvaScan-2 for radiata pine.

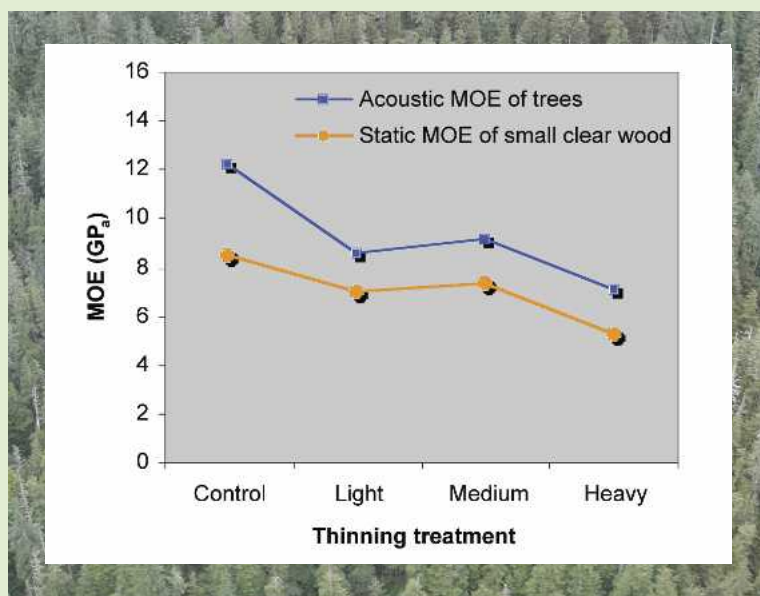


Figure 10. — Modulus of elasticity (MOE) of young growth Sitka spruce in relation to thinning treatment (Wang et al. 2000).

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 outturn, 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 11** illustrates potential application of acoustic technology through the operational value chain. New tools have been developed or are under development 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, as well as providing a very efficient means for segregation of logs based on quality and suitability for different customers or processing options.

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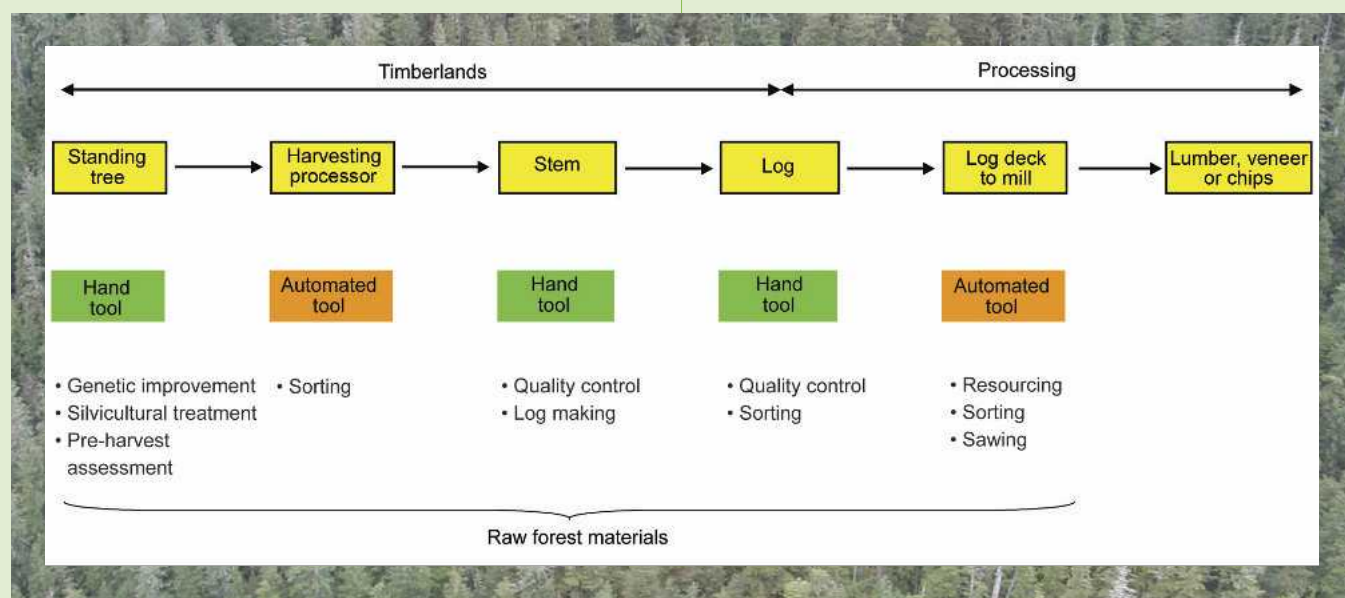


Figure 11. — Schematic outlining potential application of acoustic technology through the operational value chain.

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