ACOUSTIC SEGREGATION OF *PINUS RADIATA* LOGS FOR SAWMILLING

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ABSTRACT

The enormous variation in wood stiffness both within and amongst trees, results in the production of low-grade solid wood products from some trees. Accordingly, it would be highly desirable to segregate logs to ensure that only those logs with predominantly high stiffness wood are processed into structural timber products. This study examined whether sound flight velocity (km/s) could be used as a measure of wood stiffness to allow such segregation. Butt logs were cross-cut from 316 *Pinus radiata* D. Don trees and measured with three non-destructive acoustic devices, before and after harvest, to establish whether there was a relationship between stress wave velocity along the wood grain and the machine stress-grades of boards sawn from those logs. The wave velocity along the grain of logs was closely correlated with wood stiffness, whilst tree size and basic density estimated from depth of pin penetration of a Pilodyn were only moderately related. The outcomes of this study indicate that non-destructive acoustics tools offer a means of sorting logs according to wood stiffness prior to milling. A highly significant and positive relationship was found for acoustic resonance measurements made on logs; a weaker, but still significant relationship was obtained for time of flight measurements from standing trees. The challenge now is to develop a non-destructive tool that is able to more accurately measure the wood quality of standing trees to assist with wood quality inventories, yield mapping, and tree selections within breeding programmes.

Keywords: non-destructive testing; acoustic tools; log sorting; sawmilling; *Pinus radiata*.

INTRODUCTION

Processors often find it difficult to consistently process wood into homogeneous quality product groups because of the wide range of properties caused through genetics, stand conditions, silviculture, and site. Generally, forest growers are in agreement with their major customers that the segregation of logs according to intrinsic wood quality and the removal of outliers (e.g., logs with defects) from within the wood supply is a key management tool for adding value to the resource (Carter & Lausberg 2002; Treloar 2002). Management of intrinsic wood quality, either in the forest or in the log yard, is critical as variation in product property only increases during milling. Many forest estate managers do not discriminate between stands with varying growth patterns (i.e., juvenile:mature wood ratios) and cutting ages (particularly relevant when production thinning operations are prescribed) in the wood supply. These variables have a great impact on total value recovery and grade yield. The current lack of suitable quick and reliable measures of wood quality means that processors are unaware of the intrinsic wood properties of logs until they are in the mill and committed to a particular cutting pattern. Accordingly, structural sawmillers struggle with the uncertainty of the quality of the wood supply at the log input stage and lose value by processing all material based on currently adopted size and visual measurements of logs, resulting in sub-optimal value recovery and low grade and poor stability yields of sawn wood (Walker & Nakada 1999).

Comparatively few studies have examined the relationship between acoustic wave velocity and machine stress grades, which take into account the effect on stiffness of knots and other defects, all of which reduce stiffness and strength (Ross 1999; Snyder *et al.* 2000). Further, there are few reported studies linking acoustic measurements of standing trees to machine stress grades of boards sawn from them. Walker & Nakada (1999) showed that acoustic measurements allowed the sorting of *P. radiata* logs according to stiffness, but their measurements were on felled trees. Clearly, it would be desirable to measure standing trees non-destructively, particularly for tree breeding and silvicultural decision-making. Only a few reported studies have successfully related acoustic measurements on standing trees and on logs to machine stress grades (Dickson *et al.* 2003).

Acoustic tools to measure time of flight (stress wave) speed along the grain of logs at the forest landing are commercially available (Carter & Lausberg 2002; Treloar 2002; Walker & Nakada 1999). Acoustic tools are ideal for undertaking stiffness measurements as they are logistically simple to operate and easy to move around. The measurements are made quickly and are relatively free of experimental error. These instruments either use a single pass measurement of time (e.g., FAKOPP) or determine the wave velocity from the natural resonance of logs using spectral analysis. Engineers have indicated they favour resonance systems as these tend to measure the average speed of a number of reverberating waves, rather than the time of arrival of a first wave front (Andrews 2000). Ultimately, the ideal situation would be to incorporate acoustic segregation tools for log processing into mechanical harvesting equipment.

The study reported here investigated the use of non-destructive acoustic measurements to estimate wood stiffness of boards sawn from standing trees and from logs of *P. radiata*. A key objective of this work was to assess the applicability of acoustic devices to measure the wood stiffness of sawn boards recorded on a machine stress grader. A secondary objective was to establish whether or not the combined effects of branch information, log dimensions, and basic density are predictors of grade recovery. The ultimate goal was to develop technical links between forest growers and wood processors, to enable integration of wood quality information and understanding into merchandising and sales systems .

MATERIALS AND METHODS

Tree Selection and Measurements

Three hundred and sixteen *P. radiata* experimental logs were milled from genetically improved trees grown in a progeny test trial (PT56) that was established by CSIRO in Compartment 19 of Tallaganda State Forest of NSW (80 km south-east of Canberra) in 1973. This trial (containing clones of 147 control-pollinated crosses of selected *P. radiata*) was designed to estimate genetic parameters such as heritability and genetic correlations for economically important traits. The genetic outcomes of this sawing study will be reported in another manuscript.

Only the nine innermost trees in all thinned plots (stocking 350 stems/ha) were selected for this study. Four plots from each replicate were available, giving a total of 316 trees. Tree numbers from 1 to 316 were blazed on sample trees to assist with identification before the harvesting began.

Conventional growth measurements were made on the sample trees including diameter at breast height (1.3 m) over bark (dbhob), height, and merchantable log classes according to MARVL. The stress wave velocity was measured on standing trees with a FAKOPP microsecond (single pass) timer. At the same time, Pilodyn (6 J and 12 J) readings were made to estimate wood density. The trees were then mechanically felled, cut into logs, and tagged to identify tree number and genetic origin. Only the butt log of each sample tree was taken to the mill for sawing.

In the standing tree FAKOPP acoustic measurements, two probes were used — namely, a transmitting and a receiving accelerometer that were driven into the wood. Stress waves were generated by tapping the transmitting probe with a hammer. Sound transit time is calculated by the difference in time of the transmission and arrival of the signal at each accelerometer. Prior to data analysis, the transit time is converted to sound flight velocity using the distance between the two probes, which were inserted 1.5 m apart and on opposite sides of the stem. There is currently no standard practice for taking acoustic measurements on standing trees but by adopting this approach (i.e., measuring acoustic velocity diagonally across the stem) it was thought that the sound waves would pass through the "lower quality" core of the tree and encounter wood characteristics which in turn would affect velocity. To give a better average value, two separate measurements were made per tree, with each probe shifted half-way around the circumference of the tree stem (180°) between measurements.

Log Measurements and Processing

Shortly after harvesting, longitudinal time of flight measurements were carried out using three acoustic tools: FAKOPP, HP 3560A dynamic signal analyser (HP), and

Hitman* to measure stress wave velocity from spectral resonance peaks on individual logs in the sawmill yard. The HP and the Hitman could not be used to test for wood stiffness in standing trees, as there were no clear end faces to enable resonance to be induced with a hammer impact. However, these resonance tools operated effectively on logs and gave very similar results to the FAKOPP.

With the HP, a microphone was used to "listen" to the acoustic signal generated by hitting the end of the log with a hammer. The unit determined the signal's fundamental frequency, which could then be used to calculate velocity knowing the length of the log. As the HP is a multi-purpose frequency response unit, it had to be correctly set up prior to use. The baseband was set appropriately to measure 5- to 6-m logs with an expected frequency range of 300–500 Hz.

The Hitman operated in a similar way except that it is a purpose-built hand-held unit with an onboard sensor (accelerometer) which, when placed firmly against the log end, picks up the signal and gives a direct reading of acoustic velocity. Naturally, the length of the log needs to be entered first into the unit to give the correct acoustic velocity reading.

Before processing, the log butts were painted with colour combinations to enable tree, log, and board identification. All 316 butt logs were cut into structural boards in the Weyerhaeuser sawmill at Tumut, NSW, Australia. The logs were sorted into 11 diameter classes and sawn using one of eight sawing patterns that depended primarily on log size. The logs were sawn into two target size-classes of boards, either 90 × 35 mm or 190 × 35 mm. The 190 × 35-mm boards were split into two 90 × 35-mm boards after drying and prior to machine grading. In total, there were 1320 boards 90 × 35 mm (22.4 m^3), and 446 boards 190 × 35 mm (16 m^3). Small-end diameter (s.e.d.) measurements were carried out at harvest and logs with s.e.d. < 20 cm were not processed through the sawmill.

Board Measurements and Processing

After sawing, the corewood ("Heart-in") and outerwood boards ("SAP") were segregated, kiln dried, and dressed. They were then stress graded using an Eldeco "DART" machine, during which dyes were sprayed on boards continuously to indicate the stress grade (MGP) at any point along the board. The colours used to mark stress grades complied with Australian Standard AS1613 (Standards Australia 1997a) and the stress grading requirements conformed to Australian and New Zealand Standard AS/NZS 1748 (Standards Australia 1997b). The stress graded values (MoE) were recorded electronically at 13-cm intervals along every board and from these the mean (Emean) and minimum (Emin) MoE values were calculated. The grades assigned by the grading machine were MGP grades 10, 12, and 15, along with F4 and reject (no colour spray applied).

To ensure the boards were stress graded correctly, all necessary diagnostic checks on the machine were undertaken by the mill at the commencement of grading. These are checks to ensure correct calibration of the grading machine and strict adherence to industry requirements with respect to accuracy, repeatability, and consistency. They are undertaken routinely which, depending on the mill production, must be performed either daily, every

* Commercial resonance instrument developed by Carter Holt Harvey for measuring stress wave velocity

shift, or when there was a change in timber size to be graded. The particular mill that graded the boards was also regularly audited by a certification body (Plantation Timber Certification – PTC), thus providing added assurance for the graded product and the results obtained in this study.

Data Analysis

Individual mean board stiffness (Emean) for each tree was collated and a mean value calculated to give an individual tree value for log stiffness (log_Emean). The data were split into two product types — "heart-in" (HI) and "outerwood" (SAP) and correlations were recalculated amongst variables for each product type. We believe this latter analysis is justified, as most pine processors segregate the two products for kiln drying under quite different drying schedules. Furthermore, it is common practice for the wood processors to visually regrade boards that failed to make a machine grade. Heart-in boards would usually make it into Heart-in stud grade as defined in the Australian Standard AS 2858 (Standards Australia 1986). The level of agreement between MoE, dbhob, log and tree FAKOPP velocities, HP and Hitman velocities for the logs, and the two Pilodyn readings was measured with the Pearsons correlation coefficient. To develop these correlations, we initially worked with velocities determined from time of flight measurements, which were shown to be an important predictor of wood stiffness. Once the significance of time of flight measurements was understood across the various product types, other variables that were thought to be related were introduced and tested.

The capacity to predict MoE (the dependent variable) by any of the variables tested by the correlation analysis was analysed by stepwise multiple regression using the PROG REG procedure (SAS Institute 1987). All the variables that were significantly correlated with MoE were included in the multiple regression. Both forward-selection and backward-selection procedures were used to confirm the findings of the stepwise model.

RESULTS

Diameter Distribution

Diameter measurements at breast height and the resulting distribution of these measurements are shown in Fig. 1.

Acoustic Velocity Distribution for Logs

The distribution of acoustic velocity for the logs according to the FAKOPP, Hitman, and HP measurements is shown in Fig. 2. Mean values were significantly different, with the FAKOPP giving the highest mean value, followed by the HP, then the Hitman. The FAKOPP velocity readings were on average around 9% higher than the Hitman readings.

Tree, Log, and Board Data

A summary of the data is presented in Table 1. Log stiffness (log_Emean) was calculated from all the sawn board Emean values originating from the same log (*see* Materials and Methods). Basic density was estimated from published relationships (Cown 1978) between Pilodyn (6 J) readings and measurements of outerwood basic density at

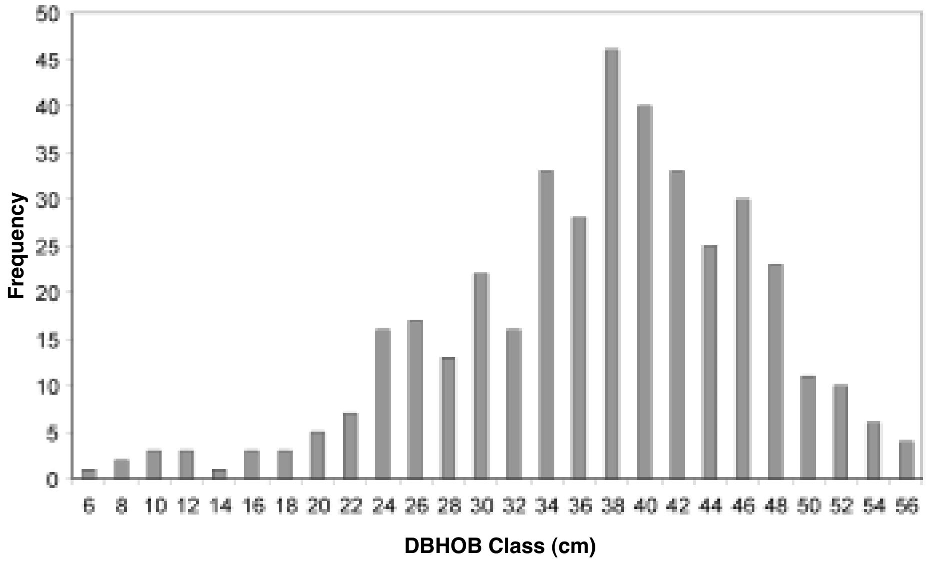

FIG. 1–Diameter (dbhob) distribution for progeny test PT56.

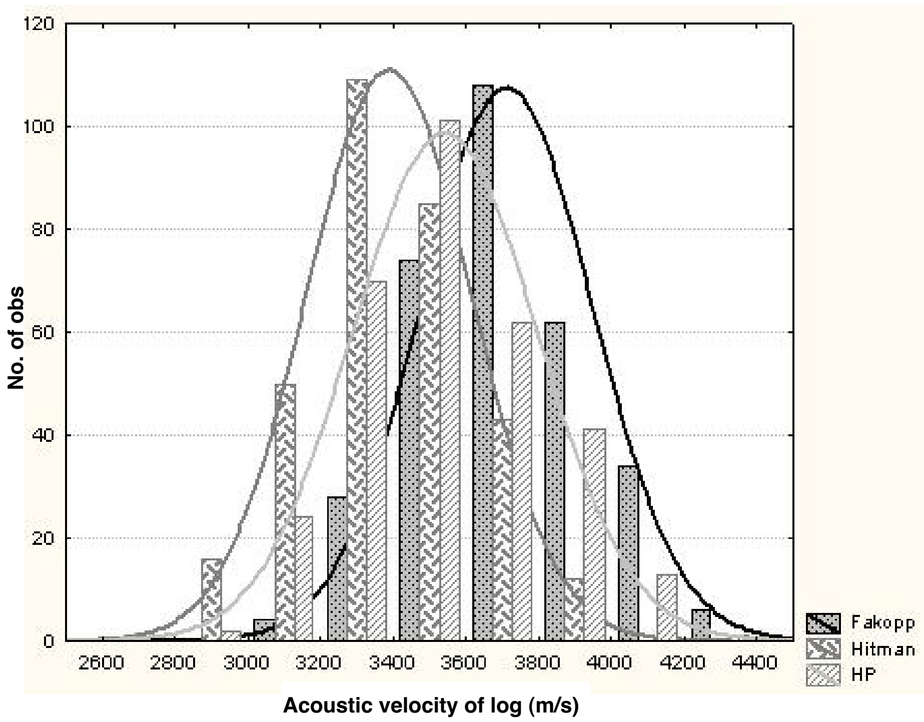

FIG. 2–Distribution of acoustic velocity for logs in the study according to the FAKOPP, Hitman, and HP measurements.

TABLE 1–Mean values for sampled tree and log measurements

Variable	Mean
Tree data:	
No. of trees	316
Dbhob (cm)	38.1
Height (m)	31.5
Pilodyn penetration-6J (mm)	12.3
Pilodyn penetration-12J (mm)	21.5
Derived outerwood basic density* (kg/m^3)	526
Tree FAKOPP velocity (m/s)	2683
Log data:	
Log FAKOPP velocity (m/s)	3706
Hitman velocity (m/s)	3385
HP velocity (m/s)	3538
Log data calculated from boards:	
Log stiffness: log_Emean (GPa)	7.98
Log stiffness (SAP only): log_Emean (GPa)	9.45
Log stiffness (HI only): log_Emean (GPa)	6.14
Grade recovery:	
MGP10 (%)	57
MGP12 (%)	1
MGP15 (%)	0
F4 (%)	13
Reject/falldown (%)	29

* Refer to Cown (1978)

breast height. This basic density value should be taken as indicative only and is subject to further work to develop site-specific relationships.

Pearson Correlation Matrix

Correlations were statistically significant between log stiffness (log_Emean) (determined from the mean stiffness of sawn boards from each log) and acoustic speed (measured using the FAKOPP and the Hitman) (Table 2). The correlations between log_Emean and the three acoustic tools were similar, although the largest correlation was for log_Emean and Hitman. The resonance tools (i.e., Hitman and HP) were not more significantly correlated with log_Emean than the single pass timing system (FAKOPP).

Considering that dynamic MoE is a function of density and sound velocity-squared (i.e., MoE = density × vel^2), the correlation between sound velocity-squared and board stiffness was also examined. The resulting correlation was practically identical to that given in Table 2. The relationship was linear for the data irrespective of whether velocity or the square of velocity was used. Adding density into the equation would not have altered the correlation appreciably — hence the reason we focused on the correlation between stiffness and acoustic velocity in this study.

Correlations improved significantly when the boards were grouped by product types (SAP and HI) from each log and the data were re-analysed. The correlations between

TABLE 2–Pearson correlation coefficient with mean log data (mean of all boards from same log).

	log_E_{mean}	log FAKOPP vel.	log Hitman vel.	log HP vel.	tree FAKOPP vel.	Pilodyn 12J	Pilodyn 6J	ddhob	log_ E_{mean} (SAP)	log_ E_{mean} (HI)
log FAKOPP vel.	0.37**									
log Hitman vel.	0.40**	0.94**								
log HP vel	0.35**	0.90**	0.91**							
tree FAKOPP vel.	0.23**	0.62**	0.66**	0.64**						
Pilodyn 12J	–0.32**	–0.56**	–0.59**	–0.54**	–0.49**					
Pilodyn 6J	–0.27**	–0.55**	–0.58**	–0.55*	–0.44**	0.80**				
dbhob	0.00	–0.69**	–0.69**	–0.69**	–0.58**	0.37**	0.44*			
log_Emean (SAP)	0.78**	0.69**	0.73**	0.66**	0.49**	–0.45**	–0.43**	–0.42**		
log_Emean (HI)	0.54**	0.60**	0.61**	0.57**	0.36**	–0.29**	–0.25**	–0.26**	0.54**	
tree height	0.23**	–0.06	–0.05	–0.07	–0.02	–0.06	0.05	0.37	0.10	0.09

significant at the 5% level;
** significant at the 1% level

log_Emean (SAP boards only) and log acoustic measurements with the FAKOPP, Hitman, and HP were 0.69, 0.73, and 0.66, respectively. A weaker, but still highly significant, correlation (*ca* 0.60) was obtained for log_Emean (HI boards only). The stronger correlation with the SAP boards suggested that the log acoustic measurements might be biased toward the stiffer outerwood from the log. An examination of the relationship between log stiffness and log acoustic measurement also found that, as log acoustic velocity increased, the average stiffness of the SAP boards increased by approximately twice as much as the HI boards (Fig. 3).

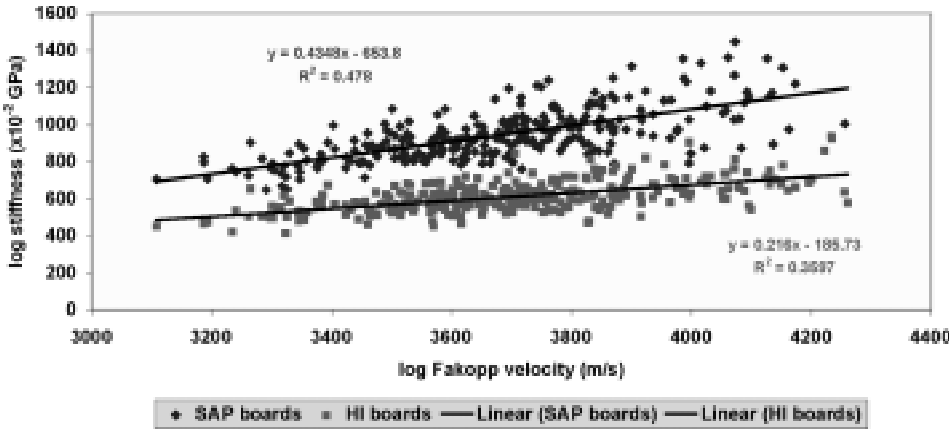

FIG. 3–Relationship between mean log stiffness (mean of all boards from each log) grouped into product type and log FAKOPP velocity, N=316.

Basic density was moderately correlated with stress wave velocity. These findings indicate that outliers within a log population can be identified using acoustics and allocated to an alternative non-structural application (Tsehaye *et al.* 1997; Walker & Nakada 1999). The resonance device (Hitman) is more convenient to use than the FAKOPP for measuring logs as only one end face needs to have a sensor attached; the FAKOPP requires a probe to be inserted at each end of a log.

When FAKOPP velocity was measured on the standing trees the correlations were reduced. This was possibly due to the shorter transmission distance (1.5 m of tree height compared with 4.2 m or 5.3 m of log) and the less direct pathway for sound to travel transversely and longitudinally through the standing tree. Interestingly, the tree correlation between the FAKOPP and the machine stress grading data (log_Emean) was stronger than that reported for a similar study carried out on trees grown adjacent to those milled in this study (Dickson & Matheson 1999). The reason for this is unclear. Nonetheless, this finding does offer some hope that the stiffness in standing trees may be measured using acoustic time of flight devices.

There was no correlation between diameter at breast height (dbhob) and log stiffness (log_Emean), and tree height was only moderately correlated with log_Emean. Tree height had no influence on either tree or log acoustic measurements (Table 2). Although dbhob had no effect on log_Emean, it had a significant effect on the acoustic measurements, which should in turn affect log_Emean. Both tree and log acoustic measurements were significantly negatively correlated with dbhob. The reasons for this are unclear; one possibility may be that as the diameter increases, the proportion of low stiffness juvenile wood also increases thereby giving rise to reduced acoustic velocity; another may be associated with the way log_Emean is determined and the possible bias of the acoustic measurements toward the stiffer outerwood. The calculated log stiffness value, log_Emean, is essentially a weighted average of board stiffness, with a higher weighting given to SAP boards, as they generally represent a greater volume of the log than the HI boards. Combining the data for the SAP and HI boards to give an overall average for log stiffness may have confounded its relationship with dbhob. This contention is supported by the fact that when the boards were segregated into product types and the data re-analysed, dbhob showed a significant (negative) relationship between the overall stiffness of the SAP boards and HI boards, albeit to varying degrees depending on product type (Table 2). Diameter at breast height over-bark was correlated strongly with the SAP boards, but only weakly with the HI boards. It is this difference in effects that may have confounded the relationship between dbhob and log stiffness (log_Emean) when all the boards (SAP and HI) were considered together. The stronger correlation between the dbhob and the stiffness of the SAP boards again suggests the acoustic measurements are biased toward the stiffer outerwood of the log. We therefore contend that dbhob as a measure of tree size influences the tree and log acoustic measurements and this in turn has an effect on log stiffness, but only when the boards are considered separately according to product type. Diameter at breast height over-bark had no direct effect on the overall stiffness of the log.

The pin penetration for both 6 J and 12 J Pilodyn tools, as measure of outerwood density, was significantly correlated with log stiffness (log_Emean), although not as well as the acoustic measurements.

Regression equations for predicting overall log stiffness (log_Emean) indicate that the best single predicting variable was log Hitman velocity which accounted for 16% of the variation in stiffness, followed closely by log FAKOPP and HP velocities (Table 3). If a measure of Pilodyn penetration was added to the equation, the amount of variation in stiffness accounted for by the regression increased only marginally. However, if dbhob was added to the equation, the amount of variation in stiffness accounted for increased by approximately two-fold to about 24–31% depending on the acoustic measurement used.

It would appear that the greatest potential for the acoustic measurements is in predicting average stiffness of the boards in a log when the boards were segregated by product types (SAP and HI). The single best predicting variable for log_Emean (SAP) was again the log Hitman velocity which accounted for nearly 53% of the variation in stiffness, followed closely by the log FAKOPP and HP velocities, accounting for about 48% and 44% of the variation, respectively. Similarly, the prediction of log_Emean (HI) with these acoustic measurements was fairly reasonable. The addition of dbhob or Pilodyn measurements in these equations did little to improve the prediction.

DISCUSSION

The key objective of this study was to explore the use of acoustic tools to indicate the stiffness of wood in standing trees and logs of *P. radiata*. A secondary objective was to

TABLE 3–Regression equations for predicting log stiffness log_Emean, log_Emean (SAP only), and log_Emean (HI only) from acoustic measurements (FAKOPP, Hitman, HP), Pilodyn 12J penetration, and dbhob. All equations significant at the 1% level.

Regression equation	$(R^2)\times100$
Overall log stiffness:	
log_E_{mean} = 1026.8 – 18.6 * Pilodyn penetration (6J)	7.2**
log_E_{mean} = 1084.4 – 13.3 * Pilodyn penetration (12J)	10.4**
log_E_{mean} = 502.3 + 0.110 * tree FAKOPP velocity	5.5**
log_E_{mean} = 150.2 + 0.175 * log FAKOPP velocity	13.9**
log_E_{mean} = 141.0 + 0.194 * log Hitman velocity	15.9**
log_E_{mean} = 267.1 + 0.150 * log HP velocity	12.1**
log_E_{mean} = 456.8 – 6.83 * Pilodyn penetration (12J) + 0.132 * log FAKOPP velocity	15.8**
log_E_{mean} = 384.2 – 5.41 * Pilodyn penetration (12J) + 0.156 * log Hitman velocity	17.0**
log_E_{mean} = 588.0 – 7.74 * Pilodyn penetration (12J) + 0.106 * log HP velocity	14.5**
log_E_{mean} = –726.7 + 7.40 * DBHOB + 0.334 * log FAKOPP velocity	26.8**
log_E_{mean} = –757.4 + 7.88 * DBHOB + 0.370 * log Hitman velocity	30.6**
log_E_{mean} = –517.0 + 7.18 * DBHOB + 0.293 * log HP velocity	24.0**
log stiffness (SAP boards only):	
$log\_E_{mean\ (SAP)}$ = 1431.4 – 39.29 * Pilodyn penetration (6J)	18.8**
$log\_E_{mean\ (SAP)}$ = 1480.7 – 24.79 * Pilodyn penetration (12J)	20.5**
$log\_E_{mean\ (SAP)}$ = 132.0 + 0.305 * tree FAKOPP velocity	23.6**
$log\_E_{mean\ (SAP)}$ = –653.8 + 0.435 * log FAKOPP velocity	47.8**
$log\_E_{mean\ (SAP)}$ = –662.7 + 0.479 * log Hitman velocity	53.0**
$log\_E_{mean\ (SAP)}$ = –390.7 + 0.381 * log HP velocity	43.6**
$log\_E_{mean\ (SAP)}$ = –347.3 – 7.03 * Pilodyn penetration (12J) + 0.393 * log FAKOPP velocity	49.0**
log stiffness (HI boards only):	
$log\_E_{mean\ (HI)}$ = 779.3 – 13.41 * Pilodyn penetration (6J)	6.4**
$log\_E_{mean\ (HI)}$ = 811.2 – 9.17 * Pilodyn penetration (12J)	8.5**
$log\_E_{mean\ (HI)}$ = 266.7 + 0.129 * tree FAKOPP velocity	13.1**
$log\_E_{mean\ (HI)}$ = –185.7 + 0.216 * log FAKOPP velocity	36.0**
$log\_E_{mean\ (HI)}$ = –147.1 + 0.225 * log Hitman velocity	37.2**

* significant at the 5% level;
** significant at the 1% level

establish whether or not log dimensions and non-destructive measurement of basic density are useful predictors of grade yield. The key finding of this study was that longitudinal acoustic sound velocity (along the grain) of *P. radiata* logs related reasonably well with the machine stress grade measurements (wood stiffness) of boards sawn from those logs. There was a strong and significant relationship between machine stress grades and velocity determined from time of flight along the grain of logs and to a lesser extent in the stems of standing trees. The wave velocity relationship was stronger with the mean stiffness grade values than the minimum stiffness grade values.

This difference in the strength of the relationships between the mean and minimum machine stress grade data and time of flight speed data may be due to the effect of defects, such as knots, which probably have a greater effect on the machine stress grade than on the acoustic measurement. Sample boards in this study did not contain significant numbers of knots and defects. Thus, these would not affect the long stress waves travelling along the grain. Conversely, the presence and position of knots and defects greatly impacts on machine stress grade and bending strength values via the significant grain distortion. Thus, the degree of variability around the regression line for the minimum stress grades and sound velocity can be attributed more to the impact of knots and defects as reflected in the stress grades than to sonic velocity values.

Impact of Outerwood and Heartwood

An interesting outcome of this study was that the relationships between sound flight speed and machine stress grade measurements varied according to whether the wood was sawn from the corewood zone (heart-in) or the outerwood (sapwood). The relationship between acoustic velocity and MoE was weaker for heart-in material than for wood sawn from the outerwood zone of the log. The reasons for this are unclear. However, there may be several causes. Firstly, the age of the trees when they were felled was close to 30 years and there would have been reasonable amounts of heartwood amongst logs in the corewood zone. Thus the prediction of stiffness on the basis of a nominal green density would be over-estimated for the drier and therefore lower green density of the heartwood core. Correction of the green density value for heartwood formation may have improved the accuracy of MoE prediction.

A second proposal for the differences in relationships between product types and acoustic velocity is that the acoustic measurements may be biased toward the stiffer outerwood of the log. This was supported to some extent by the fact that as log acoustic velocity increased, average stiffness of the SAP boards increased by twice as much as HI boards. The dbhob did not have an overall effect on wood stiffness. However, across the product types HI and SAP, dbhob was found to have a weak and strong relationship, respectively, on wood stiffness.

Standing Tree Measurements

The sound velocity measurements recorded across the stems of standing trees and along logs cut from those trees were closely correlated. However, the velocity across the stems of the standing trees was approximately half of that recorded along the logs. The reason for this is unclear. In this study, the FAKOPP probes were inserted into the tree stem on opposite sides — i.e., diagonally directly above each other. The placement of the probes on opposite sides of the stem may have resulted in measurement error if the waves travelled through the stem in straight lines across changing moisture conditions. Further, the probes were inserted at diagonal ends of the stem about 1.5 m along, i.e., about five times the size of the average tree diameter. The stress wave would most likely have travelled around a curved (longer) path, still tending to go along the grain and perhaps with some transverse skips, as the tracheids and fibres are connected to varying degrees by their side walls. Thus, the path would have been more tortuous in the standing trees compared to logs, but still relatively high compared with the radial path. In this case, the appropriate path length would be difficult to determine and it would not have been 1.5 m. We suspect this accounts to some extent for the poorer correlation of the standing tree measurements with the machine stress grade data. It would seem that placing the probes at diagonal ends was a poor choice.

Acoustic Hardware

We argue that the relationship between acoustic sound velocity and machine stress grades can be strengthened, in particular either by improved operation of the existing instruments or by development of new equipment. Essentially the accuracy of measured sound waves is dependent on the distance between the transmitting and receiving probes and the dimensions of logs. If the distance between the transmitting probe and the receiving probe is too short, then interpretation of the stress wave time may be inaccurate, as the receiving probe will receive the wave front before it has had time to spread in the radial direction. In addition, a short distance between the probes only samples a small proportion along the length of a log or stem and therefore accounts for only a small amount of the observed variation, The probes of the stress wave timer used in this study were only 1 m apart in the standing trees and this short distance may have resulted in the sound velocity being recorded less accurately; the actual path of the stress waves is still unknown. The log dimensions are also related to the effect of the distance between acoustic sound wave probes. It is thought that the length and diameter of logs affects the accuracy of stress wave measurements. In a short large log, it will take relatively longer for a sound wave to radiate in the radial dimension before it reaches the receiving probe, thus not allowing a true velocity to be measured. Conversely, in a long thin log, it is likely that a more complete wave will form before it reaches the receiving probe.

Nevertheless, our findings suggest that acoustic measurements of standing trees and logs offer an opportunity to predict machine stress grades of sawn lumber.

CONCLUSIONS

There is a significant positive relationship in *P. radiata* between acoustic wave velocity in logs and trees and the timber stiffness. This suggests there is an opportunity for segregation while the trees are still standing, enabling the selection of logs that will mill predominantly high stiffness timber. This is important for sawmills cutting structural and framing products, because logs sorted according to stiffness along the merchandising chain offer an enormous opportunity for improving grade outturn and significantly reducing down fall in the mill. Currently, broad-acre information from harvest optimisation systems gives overall estate information on merchantable wood that meets physical specification but does not take into account the wood quality of smaller harvest units, let alone the stiffness of individual stems. The key findings of this study indicate that acoustic tools may assist with individual stem segregation for the current crop and the selection of trees expressing improved wood stiffness traits for deployment into future plantings (Dickson & Matheson 1999; Matheson *et al.* 2002).

We are aware that new resonance tools are in development that are anticipated to more readily account for the hammer and log dimensional effects on the waveform (Snyder *et al.* 2000). However, the design of similar equipment for the measurement of standing trees is more challenging. This study identified scope for the development of a new generation of non-destructive acoustic tools that will predict the wood quality of stands throughout the rotation. There is real potential in using acoustic tools to make *in situ* measurements that provide relatively accurate and reliable information on wood properties in standing trees. Accordingly, this approach would greatly assist tree breeders to make early wood property trait selections and enable silviculturists to analyse the impact of stand management operations and site on wood properties. Ultimately, standing tree measurements in a pre-harvest inventory cruise would improve the accuracy of the inventory with respect to wood properties and assist with the accurate allocation of logs into the various grades. Similarly, standing tree measurements would greatly assist tree breeders in selecting stiffer trees for deployment across forest lands, and in implementation of future silviculture policy and genetic strategies. The challenge at this stage is to develop acoustic equipment that is robust enough to operate under both forest and mill conditions and to be able to be integrated into mechanical harvesting and merchandising operations, as well as to measure standing trees.

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