Acoustic segregation of Australian-grown *Pinus radiata* logs for structural board production

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Revised manuscript received 11 August 2004

Summary

The wood quality of sawlogs is highly variable and poorly reflected by log physical dimensions. Current log grading rules for structural timber, based purely on physical appearance, result in a significant loss of value to growers and processors. Growers and processors both require tools that are able to rapidly sort logs to yield timber of a uniform quality.

Ninety-two radiata pine (*Pinus radiata*) logs harvested from Green Hills State Forest, NSW, were measured at the Hyne and Son sawmill at Tumbarumba, NSW. Two non-destructive longitudinal stress wave acoustic devices, a FAKOPP single-pass transit-time tool and a WoodSpec resonance tool, were used to characterise the logs. The sampled logs were sorted into three sound speed classes: slow (<3.5 km s^{-1}), medium (3.5–3.7 km s^{-1}) and fast (>3.7 km s^{-1}).

The relationship between measurements of acoustic velocity in logs and the stiffness of the boards milled from the tested logs was established. The boards recovered from logs sorted into the fast sound class had a mean stiffness of 10.5 GPa. The boards recovered from the logs segregated in the medium and slow sound classes had mean stiffnesses of 9.3 GPa and 8.9 GPa, respectively. The acoustic segregation patterns were similar for each of the acoustic tools tested, with the coefficient of variation of repeated measurements with WoodSpec being 2.2% lower than with the FAKOPP, suggesting that the WoodSpec tool was more precise. This study indicates that acoustic measurement of wood stiffness in the field and in the mill may improve value recovery.

Keywords: log grade; wood properties; wood density; wood strength; juvenile wood; quality; grading; stress grading; outturn; instruments; acoustic properties; *Pinus radiata*

Introduction

Timber production from Australia's planted forests is expected to double over the next decade. Economics is a major factor in the development of existing and future plantation forests. Implementing effective measurement of the quality of wood in the resource is a key step in reducing cost and adding value to forest products.

The variation in wood quality within stands in plantations of radiata pine (*Pinus radiata*) is large. As a consequence, the wood quality of logs is also highly variable. Current log grading rules are based on log diameter, which is known to be a poor predictor of intrinsic wood properties (Walker and Nakada 1999). Currently, the processing industry has difficulty in producing products to specification. An ability to assess wood quality at the beginning of the timber stream (in the forest or log yard) offers potential economic gains. Managing wood quality variation by non-destructive measurement of wood properties, enabling log segregation, will allow improved matching of end-use requirements with wood supplies both from existing stands and from new or replacement crops (Matheson *et al*. 2002). Furthermore, data on wood quality provide a means by which silviculturalists can understand the effects of site, silviculture and genetics on the stand, thus guiding prudent silvicultural policies and genetic strategies (Bunn 1981).

Reducing the harvesting age of pine increases the proportion of low quality, juvenile wood in the wood supply. It is known that acoustic velocity is strongly related to fibre strength and length, and possibly microfibril angle (MFA) (Walker and Nakada 1999; Albert *et al*. 2002; Downes *et al*. 2002). Acoustic measurements may offer an opportunity to segregate logs that are stiffer and possibly more stable in the corewood: models have demonstrated an association between timber stability and stiffness (Astley *et al*. 1998). Acoustic velocity may also be a practical method for identifying wood prone to longitudinal shrinkage during drying (Jugo Ilic, CSIRO, *pers. comm*.).

Acoustic tools are logistically simple to operate, and measurements can be quickly taken and are relatively free of operator bias. Two acoustic tools currently available are of different types — a single-pass transit-time measurement system (FAKOPP[1]) and a multi-pass resonance system (WoodSpec[2]). Recently, engineers have indicated that they favour resonance systems for log sorting, as they measure a number of reverberations of the plane acoustic wave from which a dynamic modulus of elasticity (MoE) can be quantitatively determined, compared to the speed of a single expanding wave front that is correlated with MoE (Andrews 2000).

The primary objective of this study was to compare the stiffness of timber resulting from acoustically segregated logs. A secondary

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[1] FAKOPP is available commercially through its manufacturer in Hungary

[2] WoodSpec was developed by Industrial Research Ltd, New Zealand.

objective was to gain experience in the use of the two acoustic tools and identify any differences in the measured data.

Materials and methods

Log measurement and sorting

Ninety-two commercial logs, 6.1 m long, were selected from a log supply at the Hyne & Son sawmill, Tumbarumba, in New South Wales, Australia. The logs originated from a single clearfelled stand of 35-y-old thinned radiata pine grown in Green Hills State Forest (Compartment 407) located south-west of Tumut, NSW. The trees were a mix of low- and high-pruned stems. To minimise the number of sawing patterns used, the selection was restricted to logs with a small-end diameter of 24–35 cm under bark. The logs were mechanically debarked before being placed on skids (unstacked) in the mill yard for the acoustic measurements. The diameters of both the small and large end of each log were measured and recorded.

The longitudinal acoustic velocity of each log was determined with the two instruments, the FAKOPP microsecond timer and the WoodSpec.

The FAKOPP has two probes, one a transmitting accelerometer and the other a receiving accelerometer. Measurements were made by inserting the transmitting probe in one end of the log and the receiving probe in the other end. Stress waves were then propagated by lightly tapping the transmitting probe. The transit time for the wave front to reach the receiving probe was recorded and used to calculate the acoustic velocity (FAKOPP velocity = log length/ transit time). For each log, a second measurement was taken by re-inserting the two probes in different areas of the log ends.

In contrast, the acoustic velocity determined by the WoodSpec is based on resonance. The instrument generates a reading from many hundreds of reverberations of an acoustic signal within a log, providing a highly accurate measurement of the plane wave acoustic velocity. The acoustic signal was generated by tapping one end of the log with a hammer and at the same end detecting the reverberations with the accelerometer. The WoodSpec determined the fundamental frequency of vibration for the log and calculated the acoustic velocity (WoodSpec velocity = 2 × log length × fundamental frequency). We made two measurements per log.

For sawing, the logs were sorted into three broad classes according to their acoustic velocities as determined by WoodSpec. The acoustic velocity cut-off points for each class were established simply by dividing the range of values obtained equally to give the following sound speed classes: Slow <3.5 km s^{-1}, Medium 3.6–3.7 km s^{-1}, and Fast >3.8 km s^{-1}. The logs were painted on the ends with a unique colour for each of the sound classes to enable identification during conversion.

Mill conversion and machine stress grading

All logs were sawn using one of Hyne and Sons' standard sawing patterns. The green sawn output was predominantly 100 mm × 38 mm and 200 mm× 38 mm boards; the latter were split to produce 100 mm × 38 mm pieces. Board of two other sizes (100 mm × 50 mm and 75 mm × 50 mm) were also produced but were not included in the study as they represented only a small fraction of the total sawn output. In the green chain, the boards were segregated into two classes, Heart-in (HI) and standard (STD), principally for drying purposes. The HI boards were those containing corewood, whilst the STD boards were mainly outerwood. All boards were kiln dried at high temperature using standard industry drying practice for radiata pine, dressed to a finished size (90 mm × 35 mm) and grouped into one of the three sound speed classes, with the HI and STD boards segregated within each sound class to ultimately make six classes in all.

Grading was carried out according to the Australian and New Zealand Standard AS/NZS 1748 (Standards Australia 1997) using a Metriguard CLT stress grader at the mill. Stiffness (MOE) was measured at regular intervals along the board by bending it in two directions using a 'double-bending' system and averaging the forces required to achieve a preset deflection. A stress grade was then assigned to each board on the basis of the lowest MOE along the length. The grades assigned were 'Machine stress grade pine' MGP 15, MGP 12, MGP 10, F4 or reject. The information on stress grade and the mean and minimum MOE values for each board were recorded electronically using the mill's data capture system linked to the stress grader. All data were saved to a separate file at the end of each class graded.

Basic density measurement

Basic density of logs like those used in the acoustic study was determined by sawing a disc 50 mm thick from either end of 92 logs from a neighbouring stand ('nearby logs') used in a separate unpublished carbon accounting study. The logs used for both that study and this report were harvested at the same time. The basic densities for the discs were determined gravimetrically in accordance with the Australian/New Zealand Standard, AS/NZS 1080.3:2000 (Standards Australia 2000).

Data analysis

Analysis of variance (ANOVA) was used to identify any significant differences amongst the three log acoustic velocity classes. If the analysis indicated significant statistical differences, an *a posteriori* test (Tukey HSD multiple comparisons) established where the differences existed. The Tukey HSD test has the simplicity of the least significant difference (LSD) test in having a constant yard-stick with which to test all pairs of treatment means.

Correlations between the acoustic measurements and wood stiffness were calculated to examine the strength of the relationship and thus indicate the potential for predicting timber outturn.

Results and discussion

Table 1 presents a summary of the mean values of the log and board measurements together with the grade recoveries. The logs segregated reasonably well across the three acoustic velocity classes. There was no statistically significant difference in mean diameter of logs (either at the small end or large end) across the three acoustic velocity classes. The total green log volume in each class was 16.2 m^3 (slow), 10.4 m^3 (medium) and 20.5 m^3 (fast). The volume of boards recovered was similar across the classes (19–25% of log volume).

Table 1. Summary of the mean values of log and board measurements

Sample and variable	Stiffness class			Units
	Low	Medium	High	
Logs				
No of logs	32	21	39	
Diameter, small end	29.1	29.1	30.1	cm
Diameter, large end	35.2	34.8	35.7	cm
Volume	16.2	10.4	20.5	m3
FAKOPP velocity	3.84	4.09	4.34	km s^{-1}
WoodSpec velocity	3.35	3.58	3.78	km s^{-1}
All boards				
No. of boards (90 x 35 mm only)	215	134	205	
Volume recovery (90 x 35 mm only)	25.5	24.6	19.2	%
Mean stiffness (E_{mean})	8.9	9.3	10.5	GPa
Min. stiffness (E_{min})	6.8	6.7	7.2	GPa
Grade recovery:				
MGP 15	4.7	6.0	12.2	%
MGP 12	40.5	39.6	41.0	%
MGP 10	46.5	41.0	35.6	%
F4	7.4	13.4	10.7	%
Reject	0.9	–	0.5	%
STD boards only				
No. of boards (90 x 35 mm only)	114	65	117	
Volume recovery (90 x 35 mm only)	13.5	12.0	11.0	%
Mean stiffness (E_{mean})	9.80	10.53	11.80	GPa
Min. stiffness (E_{min})	7.69	7.53	7.94	GPa
Grade recovery:				
MGP 15	8.8	10.8	16.2	%
MGP 12	58.8	53.8	53.0	%
MGP 10	28.9	27.7	24.8	%
F4	3.5	7.7	6.0	%
HI boards only				
No. of boards (90 x 35 mm only)	101	69	88	
Volume recovery (90 x 35 mm only)	12.0	12.7	8.2	%
Mean stiffness (E_{mean})	7.93	8.21	8.89	GPa
Min. stiffness (E_{min})	5.72	5.92	6.16	GPa
Grade recovery:				
MGP 15	–	1.4	6.8	%
MGP 12	19.8	26.1	25.0	%
MGP 10	66.3	53.6	50.0	%
F4	11.9	18.8	17.0	%
Reject	2.0	–	1.1	%

The mean acoustic velocity (±SD) for all 92 green logs measured with the FAKOPP and WoodSpec was 4.1 km s^{-1} (±0.3) and 3.6 km s^{-1} (±0.2), respectively. For the slow, medium and fast log classes the FAKOPP recorded an average sound velocity of 3.8, 4.1 and 4.3 km s^{-1} respectively, and corresponding WoodSpec values were 3.3, 3.5 and 3.8 km s^{-1}.

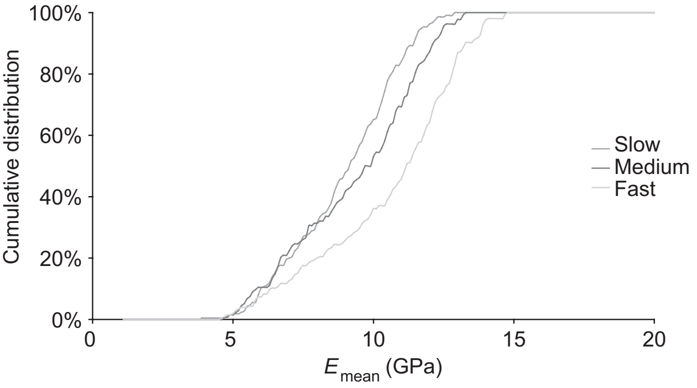

Figure 1. Cumulative distribution for the three acoustic velocity classes for boards

The results in Table 1 indicate that for both acoustic instruments there was a discernable relationship between the acoustic velocity of the green logs and the average modulus of elasticity (E_{mean}) of the sawn boards in bending as determined by the stress grader. The cumulative distribution of E_{mean} of boards (HI and STD combined) for each of the three acoustic velocity classes demonstrates the effect of the segregation (Fig. 1). At greater stiffness values (9–12 GPa) clear differentiation (20–40%) is achieved by the acoustic segregation of the logs.

This relationship was less convincing for the board minimum MOE (E_{min}) as indicated by the mechanical stress grading (MSG) results (Fig. 2). This weaker relationship is likely to be due to localised defects (such as knots) within individual boards. Grain distortion around a knot can extend at least five knot diameters and induce a zone of severe stress concentration. Usually, board samples incorporating knots and other defects have a bending strength that is substantially less than that of clearwood specimens. Furthermore, cross grain is known to greatly reduce bending strength (Bodig and Jayne1982). The E_{min} vs E_{mean} scatter plot for the timber (Fig. 3) clearly indicates this (E_{min}=0.71E_{mean}, r^2 = 0.66). The plot does confirm that E_{min} is proportional to E_{mean}, with 95% of the data within ±25% of the regression line. Clearly there is significant scatter. Acoustic tools account for deviated

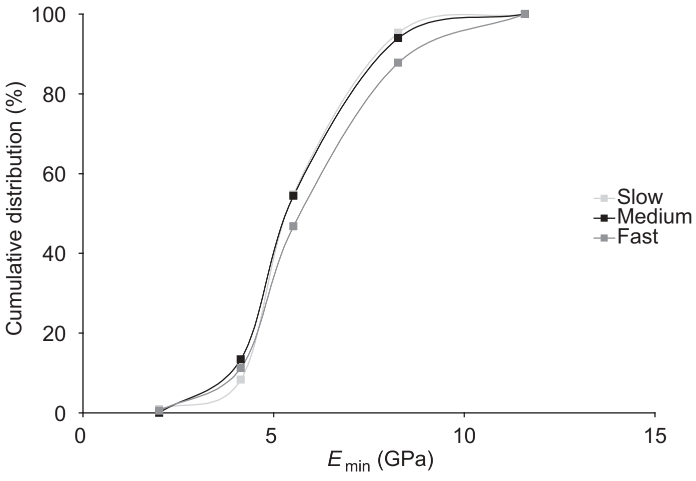

Figure 2. Cumulative distribution of the MSG grades for the three acoustic velocity classes

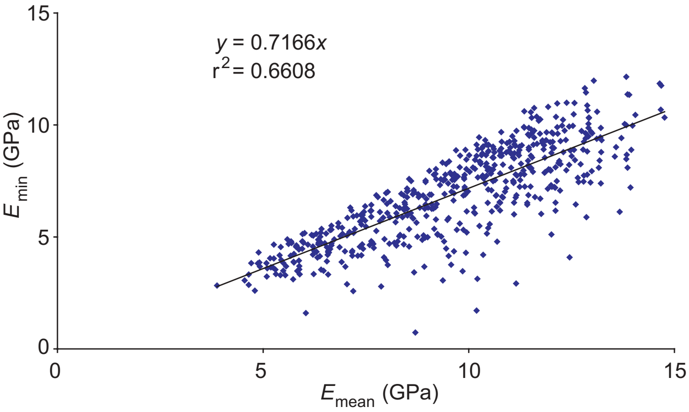

Figure 3. E_{min} vs E_{mean} scatter plot for the timber samples

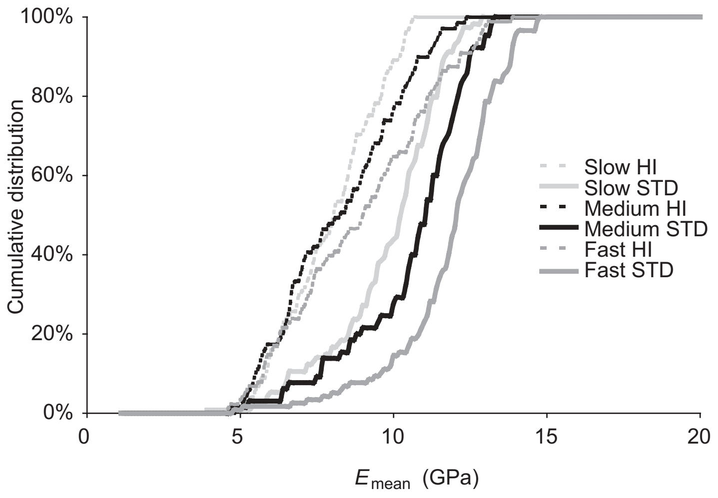

Figure 4. Cumulative distribution for the three acoustic velocity classes and HI or STD boards

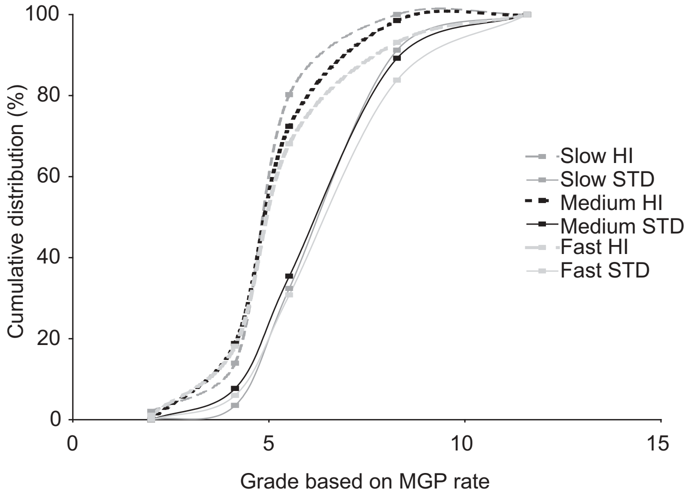

Figure 5. Cumulative distribution of the MSG Grades for the three acoustic velocity classes and HI or STD boards

grain arising from knots and defects only in their effect on the average for the board. Conversely, the presence and position of knots and defects greatly affects the MSG values because it is dominated by localised E_{min} values. This is indicated in Figure 2, which shows the cumulative distribution of the MSG grade outturn.

Despite the good segregation evident in Figure 1 based on the E_{mean} values, the final grade outturn showed poor segregation, with only about 10% differentiation of the high MGP grades achieved in the fast class. Unfortunately, grading for strength, whether by visual or mechanical (MSG) means, necessarily involves identifying the 'weakest' point (e.g. E_{min} or largest knot) along the board and assigning a grade for the whole board based on the assumed strength at that weak point. Moreover, for further structural safety, the derivation of design properties for strength for a graded population is based on strength values of the lower percentiles (usually the lower 5th percentile) and not on an average value. Nonetheless, within a graded population (e.g. MGP 10), the stiffness requirements must also be satisfied. This value is based on the graded population average (and not minimum) and herein lies the usefulness of acoustic segregation for satisfying grade requirements.

Recently it has been observed within the industry that radiata pine mills are able to demonstrate compliance for strength but are struggling to meet stiffness requirements, resulting in a change in perspective regarding design properties for possible new grades. Essentially, the industry is wishing to ensure that the average stiffness of a consignment of boards meets any agreed stiffness thresholds. Acoustic segregation of logs may achieve this outcome by assisting mills to comply with grading rules, whilst maintaining production targets. Furthermore, acoustic segregation of logs may be employed prior to incurring processing costs, thus maximising plant throughput.

The effect of the acoustic segregation and the radial stiffness profile is clearly demonstrated for the HI and STD boards E_{mean} cumulative distribution (Fig. 4). The three acoustically-segregated log classes show a nearly linear increase in the HI boards' cumulative distribution. This implies a broad range in wood stiffness in the core increasing steadily in a radial direction, and a plateauing of properties in the typical radial profile from about the corewood–outerwood boundary, and reflected in the abrupt increase in the STD boards' cumulative distribution at about 10–12 GPa. Note that the log segregation provides significant gain in both the core and outerwood, and achieves a gain of >40% in the outerwood. Overall, Figure 4 indicates that substantial gains can be achieved by adapting a sawing pattern to account for the average acoustic velocity for a specific log and the typical radial stiffness profile (by segregating boards cut from corewood from those cut from outerwood). A plot of the MSG outturn distinguishing the HI and STD boards re-emphasises this point, indicating that the effect of defects does not mask the radial profile effect, although it does diminish the segregation effectiveness (Fig. 5).

Wood basic density

The mean basic wood density of the samples from the 'nearby' logs was 463 kg m^{-3} (Table 2). This is on the high end of the basic density scale for *Pinus radiata* (Cown and McConchie 1983). These density data alone indicate that such logs would yield a high proportion of boards of MGP 10 or better. A separate unpublished study of a neighbouring stand ascertained that the branch index (BIX)[3] was 3–4 cm (C. Raymond, Forests NSW, *pers. comm.*). Based on the wood density data from the current

Table 2. The basic wood density of samples from 92 ‘nearby’ logs from North Green Hills State Forest, New South Wales (F. Ximenes, Forests NSW, *pers. comm.*)

Statistic	Value (kg m^{-3})
Mean	463
Minimum	415
Maximum	521
Standard deviation	±23.6
Confidence interval (95%)	456–469

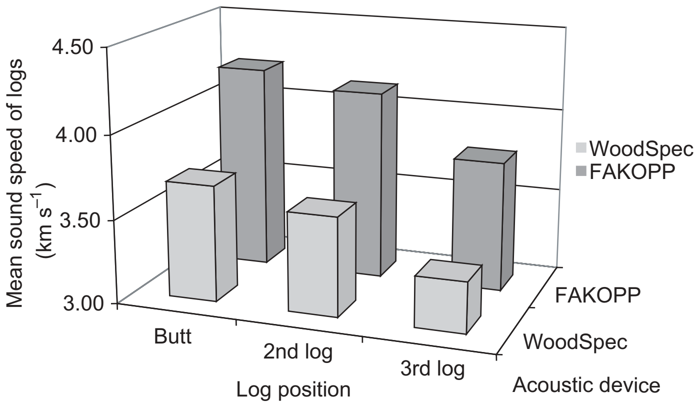

Figure 6. Effect of log position and acoustic tool on the average sound velocity of logs

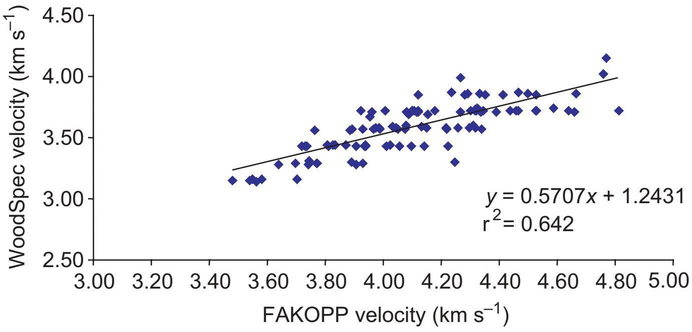

Figure 7. Relationship between the WoodSpec and FAKOPP acoustic velocity

study and a BIX of 4 cm, past research would suggest that the total sawn recovery of boards making MGP10 or better should have been above 70% (Cown *et al*. 1987). In our study, the actual grade yield data show that across the slow, medium and fast log classes, 92%, 87% and 89% respectively of the sawn board recovery made MGP 10 or better.

It could be argued that as basic density is high there is little point in segregating this resource. However, wood properties vary hugely amongst trees of the same stand, between stands and across regional forests (Bunn 1981; Donaldson 1992). Thus there is merit in seeking opportunities to identify and sort high- and low-quality logs within stands, enabling the extraction of stems suitable for structural timber from a resource of low to medium quality (C.Treloar, *pers. comm.*). Although density was not specifically assessed in this study, there is evidence that it does not necessarily predict stiffness (Lindstrom *et al.* 2002; Maclaren 2002). During recent years published information has indicated wood microfibril angle (MFA) is associated with wood stiffness, and acoustic measurements are thought to be related to variation in MFA (Tsehaye *et al.* 2000; Downes *et al.* 2002).

Impact of corewood

The average acoustic velocity was found to be slower for the top logs than for butt logs (Fig. 6). This trend may be explained by changes in the proportion of juvenile or corewood, since in the top logs the fraction of juvenile wood is greater and this has lower stiffness (Zobel and Sprague 1998) and therefore lower acoustic velocity. Low-stiffness juvenile wood (HI) has a high propensity to warp and twist, so acoustic sorting of logs for stiffness may be useful as a screen for quality control. In processing logs, low volumes of juvenile wood are not noticeable in grade yield. However, in southern pines (e.g. lobolly pine and slash pine) when juvenile wood content approaches 10–20%, there is an important effect on both the yield and characteristics of the final product (Zobel and Sprague 1998). As the age at clear-felling is reduced, the segregation of juvenile wood in the wood supply may become economically desirable.

Hardware and methods

We found significant differences ($P < 0.001$) in the flight velocity of sound recorded by the two instruments when used on the same group of logs (Table 1). The FAKOPP instrument consistently determined a higher velocity along logs than the WoodSpec (Fig. 7). The FAKOPP measures the transit time of the initial disturbance, whereas the WoodSpec measures intervals between multiple reverberations of the reflected wave. It is generally known that the initial disturbance travels faster than subsequent reverberations, settling to the plane wave speed (Andrews 2000).

In this trial, the logs were selected within a narrow range of diameter, resulting in a log length:diameter ratio of about 20:1. One would intuitively expect close agreement between the results of the two methods. The fact that this is not the case implies that the initial disturbance travels over large fractions of the length of the 6.1 m logs without reflections from the walls of the logs, resulting in the plane wave condition. For a log diameter of 0.3 m, this is a surprising result.

In spite of the differences between results from the two instruments, the relationship between the two sets of estimates was highly significant ($r^2 = 0.64$) (Fig. 7). An analysis of how the logs were sorted by the two instruments is presented in Figure 8. Of the 92 logs, 66% were sorted into the same sound velocity class by both instruments. The remaining logs were ‘borderline’ cases, with the disparity in classification occurring between either the slow- and medium-speed classes, or the medium- and fast-speed classes. This was an encouraging result.

The duplicate estimates of the acoustic velocity by WoodSpec were consistently in good agreement, irrespective of how hard, or where, the log ends were tapped. The ability of the two instruments

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[3] Branch index (BIX) is the mean diameter of the four branches representing the largest branch in each of four quadrants of a log.

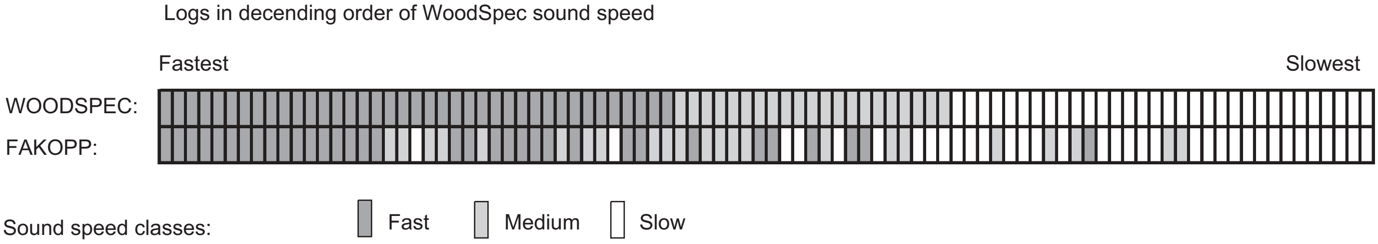

Figure 8. Comparison of how logs were sorted into the three sound speed classes using WoodSpec and FAKOPP. Logs are ranked from highest to lowest sound speed according to WoodSpec.

to give stable acoustic signatures for individual logs differed — the repeatability of the readings by the WoodSpec was far superior to that of readings by the FAKOPP. If we define repeatability as the difference between the two velocity readings for each log expressed as a percentage of the mean reading, then the overall repeatability of all the log measurements with the FAKOPP was about 2%, with a range of 0–8%. In contrast, the Woodspec repeatability was 0%: the same reading was obtained for a log each time.

Conclusions

This study indicates that there is scope to improve value recovery by acoustically segregating logs in the forest or mill yard. Application of this technology offers a cost-effective means of upgrading structural yields by identifying logs of a quality appropriate for structural purposes. It offers an opportunity for mills to hedge against the impact of reducing clearfell age, which increases the fraction of juvenile wood in the wood flow. Combining the average log acoustic velocity of a log parcel, segregated by the acoustic instruments, with grading reflecting the typical radial stiffness profile, significantly improved value recovery.

In future crops, acoustic tools may be used to make judicious tree improvement and silvicultural decisions to produce logs that yield greater fractions of stiffer wood. The use of non-destructive tools to measure intrinsic wood properties of either standing trees or logs has real merit, and potentially offers significant economic gain to growers. These instruments can inform forest growers about wood stiffness as it affects the wood quality of their estate, thus guiding the implementation of silviculture policy and genetic strategies. The challenge will be to find a system to effectively gather this information at the stand level and then ensure the information has relevance and an accepted value in the market place.

This study indicates that WoodSpec has advantages over FAKOPP for making log measurements. Resonance sweep technology employed by WoodSpec provides accurate information from reverberating waves and offers the advantage of needing access to only one end of the log to obtain measurements, which has logistical appeal.

Acknowledgements

The authors would like to thank Hyne & Son in Tumbarumba, NSW, who allowed this study to be undertaken in their sawmill; the sawmillers' cooperation and support was greatly appreciated. The authors also acknowledge the assistance of Lindsay Nicks and Ian Hides of Forests NSW Research & Development Division with the acoustic readings of sawlogs at Hyne & Son.

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