Mason et al. New Zealand Journal of Forestry Science (2017) 47:16
DOI 10.1186/s40490-017-0098-y

New Zealand Journal of Forestry Science

RESEARCH ARTICLE Open Access

Validation of ultrasonic velocity estimates of wood properties in discs of radiata pine

Euan G. Mason[1*], Michael Hayes[2] and Nigel Pink[1]

Abstract

Background: Measurement of microfibril angle (MFA) in the S2 layer of the cell walls of wood using speed of sound in wood has become a common way to estimate wood stiffness and stability. Measurements across the radius of a disc can be critical, but sonic testing needs to be validated against direct measurements of MFA.

Methods: A robotic machine that uses two transducers to detect the speed of sound through discs of wood from tree stems was validated by comparing its measurements with wood MFA, air-dry density, and modulus of elasticity assessed by X-ray diffractometry through the "Silviscan" system.

Results: Ultrasonic velocity (USV) was highly correlated with MFA but not with air-dry density. Variable moving averages were assessed in order to estimate the resolution of the USV measurements, and it appeared that the diameter of the swath detected by the transducers was between 23 and 30 mm.

Conclusions: It was concluded that MFA in wood samples can be assessed rapidly and cheaply using USV measurements but at lower resolution than assessments using X-ray diffractometry.

Keywords: Wood quality, Microfibril angle, Wood density, Modulus of elasticity

Background

The cores of conifer logs often contain wood with relatively low stiffness and instability during drying (Walker & Nakada, 1999), and so finding efficient ways to assess these properties can help researchers and forest managers to select genotypes, silvicultural operations, or growing sites that minimise this problem.

Dynamic modulus of elasticity (MOE) generally increases radially within *Pinus radiata* D.Don logs (Tsehaye et al., 1995), and so the "corewood" zone has become a focus of research in an attempt to improve stiffness. Cave (1968) found that MOE of wood was strongly correlated with the angle from vertical of cellulose microfibrils, known as the "microfibril angle" (MFA), in the S2 layer of the cell wall of gymnosperms, and so finding ways to reduce MFA in the corewood zone is an important focus of wood quality research.

Instability during drying arises from differential shrinkage. Shrinkage in the three anisotropic dimensions varies with MFA (Harris & Meylan, 1965; Megraw et al., 1998; Pentoney, 1953). Longitudinal shrinkage is critical for stability of wood, because wooden boards have much longer longitudinal dimensions, and shrinkage in this direction increases with MFA (Harris & Meylan, 1965). MFA diminishes most rapidly with radius in the corewood zone, and so wood derived from this zone tends to be more unstable than wood nearer the outside of a large log.

Cave (1968) assessed MFA using X-ray diffractometery, and more recently an automated system for measuring MFA, air-dry density, and predicting MOE with X-rays has been developed (Evans, 1998; Evans, Downes et al., 1995; Evans & Ilic, 2001). The system can deliver extremely high resolution (<2 mm) estimates of variation in these properties across a small radial sample of wood. The system, known as "Silviscan" is relatively expensive for clients, but it has been extensively used by researchers to compare wood quality samples.

Assessment of the velocity of sound through wood is relatively inexpensive and has become a common technique for assessing wood properties of logs (Harris & Andrews, 1999; Harris et al., 2003) and also living trees

* Correspondence: euan.mason@canterbury.ac.nz
[1]School of Forestry, University of Canterbury, Private Bag 4800, Christchurch, New Zealand
Full list of author information is available at the end of the article

(Andrews, 2000; Chauhan & Walker, 2006; Legg & Bradley, 2016). Moreover, ultrasonic velocity (USV) has been shown to be a good measure of MOE across radial cores of trees (Bucur, 1983). However, using theoretical relationships between time-of-flight ultrasonic velocity, density, and MOE has been found to result in substantial overestimates (Hassan et al., 2013).

A robotic machine was built at the School of Forestry, University of Canterbury, to detect USV across disc sections of stems of trees. It used two Harisonic HDC-8703-0 (10 mm diameter) 500-kHz transducers which were placed on either side of a disc and stress waves were transmitted between them. Either the transducers (version 1, Fig. 1) or the disc (version 2, Fig. 2) could be moved so that the machine automatically delivered maps of USV across any given disc. Details of the design will be published in a separate article, but it is relevant to record that the pressure exerted by the transducers on the disc is 124 kPA.

The objectives of the study described here were to determine:

1. Which wood property variables, among MFA, air-dry density, and MOE, ultrasonic velocity was correlated with
2. How good the correlations were
3. The spatial resolution of USV measurements obtained by the machine

Method

Twenty *Pinus radiata* D.Don trees were harvested from a 17-year-old plantation in Canterbury (43° 35′ 54″ S and 172° 18′ 46″ E). Two adjacent 60-mm discs were cut from the stems at 1.4, 2.5, and 8 m from ground level. A band saw was used to cut a small, northern radial section from the first of each pair of discs. These were then prepared for Silviscan assessment using prescribed protocols (Evans, 1999; Evans & Ilic, 2001). X-ray diffractometery was used to assess MFA and MOE every 2 mm and air-dry density every 0.025 mm along the radius. The second disc was sanded to make both top and bottom surfaces smooth on a radial section that matched the one sent for Silviscan analysis. This second disc was then used for USV assessment at 2-mm intervals along the radius using a robot.

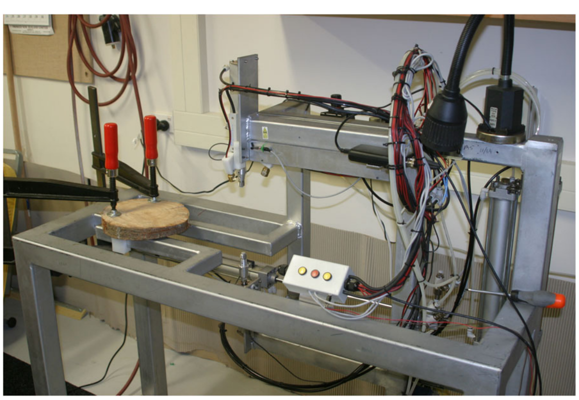

Fig. 1 Version I of the USV robot. With this version, the disc of wood was held fixed and the frame holding the transducers moved at pre-programmed intervals to make a radial measurement

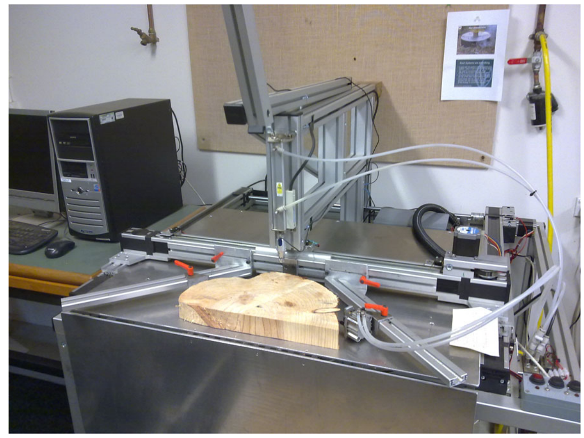

Fig. 2 Version 2 of the USV robot. In this version, the frame with the transducers is fixed and the table holding the disc can be moved in any direction, allowing any layout of measurement points. A camera automatically detects the edge of the disc

As the radial sections of the pairs of discs were of slightly different lengths, USV and Silviscan positions were matched up in two different ways. Firstly, matches were made by using the distance from pith along each radius, and excluding any overhang produced by either USV or Silviscan. Secondly, the shortest radius was stretched by the ratio of the two radii with the degree of stretching increasing with distance from the pith. Correlations between Silviscan and USV measurements were used to determine which matching technique was most effective.

In order to determine the diameter of the stem section being measured by the robot's transducers at each measurement point, moving averages of differing lengths were made from the Silviscan MFA, MOE, and air-density data at each USV measurement point. Data points obtained within 20 mm at each end of the radii were excluded, and then 19 moving averages from 2 to 38 mm in width were calculated, at 2-mm intervals. Tables of correlations were

Table 1 Summary of data available between 20 mm from the pith and 20 mm from the cambium

Variable	Minimum	Mean	Maximum
USV (km/s)	2.72	4.04	5.17
MFA (degrees)	12.3	27.1	49.7
MOE (GPa)	0.80	6.06	15.82
Air-dry density (kg/m^3)	254	424	755

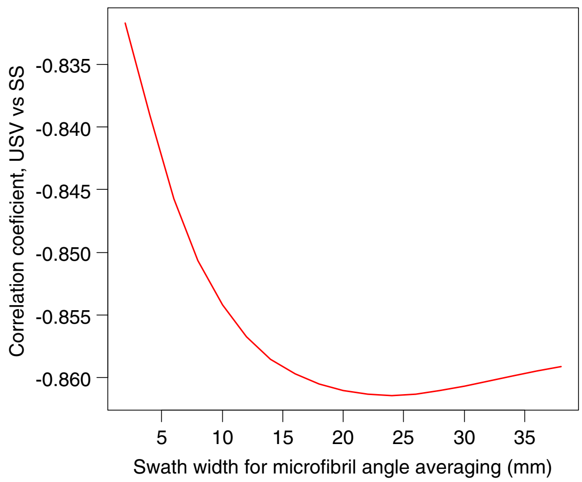

Fig. 3 Correlation coefficient between Silviscan (SS) measurements of MFA and USV versus length of moving average with absolute position data

examined to find at what length of moving average correlations between Silviscan and USV measurements were maximised.

Finally, mixed effect models were used to enable conversions to be made between USV and Silviscan estimates for variables found to be strongly correlated with USV. Trees and discs were random effects in these models, and average coefficients were reported for users of the USV robot to employ.

Results and discussion

Ranges of measurements within the measurement zone used in each radius (20 mm from each end) are shown in Table 1.

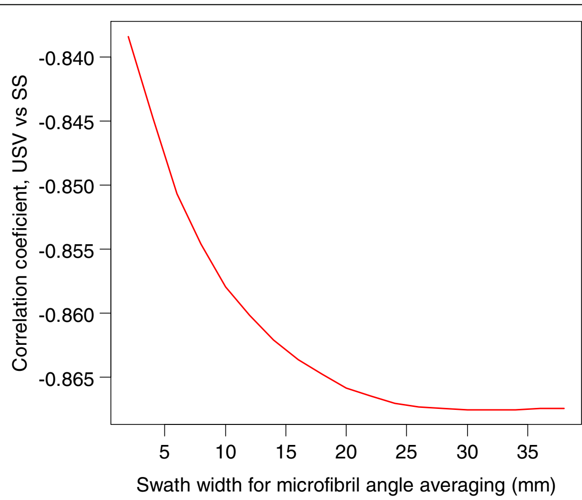

Fig. 4 Correlation coefficient between Silviscan (SS) measurements of MFA and USV versus length of moving average with stretched position data

Table 2 Highest correlations (*r*) between USV (km/s) and Silviscan measurements of wood quality variables for data stretched to ensure a complete match between discs

Variable	Highest correlation	Moving average length (mm)
MFA (degrees)	−0.86753	30
MOE (GPa)	0.85110	26
Air-dry density (kg/m^3)	0.03227	18

USV measurements were most strongly correlated with Silviscan estimates of MFA and MOE and were not significantly correlated with air-dry density. Correlations with MFA were maximised at swath diameters of 23 mm for absolute distances from the pith, and at 30 mm for the stretched matches. Fluctuations were visible across the radius (particularly near the pith) when USV estimates were plotted versus radial distance for single discs, but no clear growth rings were observed (Fig. 5), which is consistent with our estimates of effective USV swath diameter. Stretched match correlations were slightly higher than those of absolute distances, indicating that the stretched matches were probably better at matching wood grown at equivalent times in the two discs of each pair (Figs. 3 and 4). Correlation coefficients for points of maximum correlation for each variable are shown in Table 2.

Models of MFA and MOE versus USV were created using swath widths of 30 mm and stretched data. Scaled power transformations (Cook & Weisberg, 1999) were used to normalise frequency distributions of each variable. Model coefficients, *P* values, lambda values for the scaled power transformations, and model standard errors are shown in Table 3.

These results corroborate earlier findings that USV measurements of wood sections were correlated with MFA and MOE (Bucur, 1983, 1985; Bucur, Herbe, & Nosei, 1994; Chuang & Wang, 2001; Hassan et al., 2013; Karlinasari et al., 2008) but not with wood density (Hassan et al., 2013) (Fig. 5).

What is new about these findings is that we have characterised the diameter of swath detected by the transducers, and for 60-mm discs with 10-mm diameter transducers it was between 23 and 30 mm. These estimates may have been influenced by small differences between USV disc and Silviscan disc radii, and they

Table 3 Parameters, standard errors, *P* values and lambda values for models of MFA and MOE versus USV (km/s, λ = 1.86) using running averages for MFA and MOE of optimum length

Dependent variable	λ	Intercept	Slope	Standard error	*P* value
MFA (degrees)	0.54	13.274082	−0.644517	1.84°	<0.0001
MOE (GPa)	0.76	−1.4949208	0.7942896	0.81 GPa	<0.0001

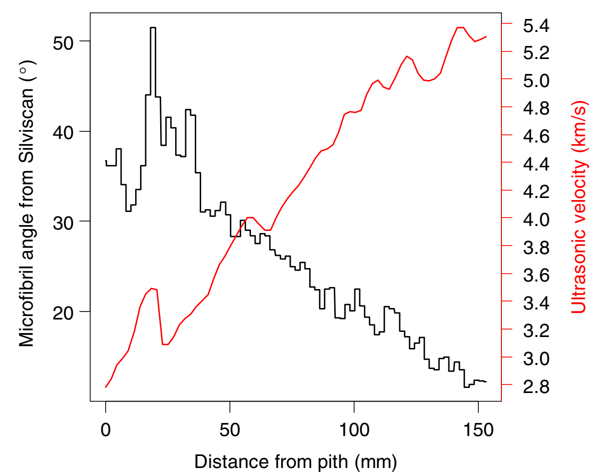

Fig. 5 Example plot of microfibril angle (*jagged line*) and ultrasonic velocity (*smooth line*) on two samples at 1.4 m in one tree

therefore indicate an upper limit of the likely range of resolution of the device, but the impacts of small differences in disc radii are likely to be minor. Smaller-diameter transducers and/or small-diameter discs may reduce the effective swath diameter of USV measurements. We have also produced some models so that users can transform USV measurements into MFA and MOE estimates with defined uncertainties.

USV measurements with machines such as the one employed for this study are likely to be much cheaper than X-ray diffractometry measurements. The cost of scanning a whole disc (Fig. 6) with the USV machine was 35% of the cost of scanning only one radial section with X-rays at the time this study was undertaken. The capacity to scan more of a disc at lower cost may mean

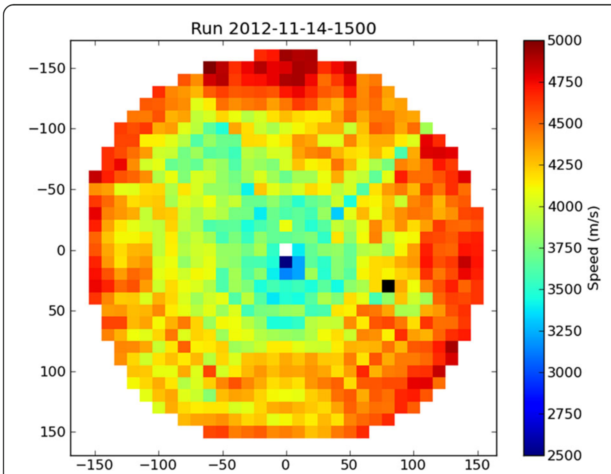

Fig. 6 An ultrasonic velocity scan of an entire disc. Such a scan is potentially much cheaper than even one radial scan with Silviscan X-ray diffractometery. The ultrasonic velocity is shown in metres per second and disc dimensions are in centimetres

that for many studies USV is a preferred option despite the lower resolution of USV scans.

Conclusions

USV measurements of stem discs were highly correlated with MFA estimates from X-ray diffractometry in adjacent discs. A model to predict MFA from USV measurements was created with a standard error of 1.84°.

The swath width for estimates of MFA was estimated to be approximately 30 mm in diameter.

Abbreviations

MFA: Microfibril angle; MOE: Modulus of elasticity; USV: Untrasonic velocity

Acknowledgements

Many thanks are due to Mr. Gofred Sialumba, who should be a co-author, but we have been unable to contact him. He helped collect the samples and made the USV measurements. Thanks also to Alan Leckie for his assistance with field work. We are very grateful for funding from the New Zealand Wood Quality Initiative and for earlier design of a non-robotic version of the machine by staff at Scion Research.

Funding

Funding for this study was obtained from the New Zealand Wood Quality Initiative.

Availability of data and materials

Data and materials are available on request from the corresponding author.

Authors' contributions

NP helped with the machine design and constructed it. MH designed the machine. EM supervised data collection, performed all analyses and wrote most of the manuscript. All authors read and approved the final manuscript.

Ethics approval and consent to participate

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Author details

[1]School of Forestry, University of Canterbury, Private Bag 4800, Christchurch, New Zealand. [2]Department of Electrical and Computer Engineering, University of Canterbury, Private Bag 4800, Christchurch, New Zealand.

Received: 24 November 2016 Accepted: 26 July 2017
Published online: 11 August 2017

References

Andrews, M. (2000). *Where are we with sonics? Paper presented at the Wood Technology research Centre workshop – 2000: Capturing the benefits of forestry research*. Christchurch: University of Canterbury.

Bucur, V. (1983). An ultrasonic method for measuring the elastic constants of wood increment cores bored from living trees. *Ultrasonics, 21*(3), 116–126.

Bucur, V. (1985). Ultrasonic velocity, stiffness matrix and elastic constants of wood. *Journal of the Catgut Acoustical Society, 44*, 23–28.

Bucur, V., Herbe, C., & Nosei, G. (1994). Annual ring characteristics of Pinus taeda measured by ultrasonic and X-ray techniques. *IAWA Journal, 15*(2), 121–132.

Cave, I. D. (1968). The anisotropic elasticity of the plant cell wall. *Wood Science and Technology, 2*, 268–278.

Chauhan, S. S., & Walker, J. C. F. (2006). Variations in acoustic velocity and density with age, and their interrelationhips in radiata pine. *Forest Ecology and Management, 229*, 338–394.

Chuang, S. T., & Wang, S. Y. (2001). Evaluation of standing tree quality of Japanese cedar grown with different spacing using stress-wave and ultrasonic-wave methods. *Journal of Wood Science*, *47*, 245–253.

Cook, R. D., & Weisberg, S. (1999). *Applied regression including computing and graphics*. New York: John Wiley and Sons.

Evans, R. (1998). Rapid scanning of microfibril angles in increment cores by X-ray diffraction. In B.G. Butterfield (Ed.) Proceedings of the IAWA/IUFRO international workshop on the significance of microfibril angle to wood quality, Westport, November 1997, International Association of Wood Anatomists, International Union of Forestry Research Organisations.

Evans, R. (1999). A variance approach to the X-ray diffractometric estimation of microfibril angle in wood. *Appita, 52*(4), 283–289.

Evans, R., & Ilic, J. (2001). Rapid prediction of wood stiffness from microfibril angle and density. *Forest Products Journal*, *51*, 53–57.

Evans, R., Downes, G., Menz, D., & Stringer, S. (1995). Rapid measurement of variation in tracheid transverse dimensions in a radiata pine tree. *Appita*, *48*, 134–138.

Harris, P., & Andrews, M. (1999). Tools and acoustic techniques for measuring wood stiffness. Paper presented at the 3rd Wood Quality Symposium – Emerging technology for evaluating wood quality for wood processing, Rotorua, New Zealand. Westport, New Zealand, November 1997, International Association of Wood Anatomists, International Union of Forestry Research Organisations, Edited by B.G. Butterfield

Harris, P., & Meylan, B. A. (1965). The influence of microfibril angle on longitudinal and tangential shrinkage in *Pinus radiata*. *Holzforschung*, *19*, 144–153.

Harris, P., Petherick, R., & Andrews, M. (2003). Acoustic resonance tools. In F. C. Beall (Ed.), *Proceedings 13th international symposium on nondestructive testing of wood*. Richmond. 19-21 August 2002: University of California.

Hassan, K. T. S., Horacek, P., & Tippner, J. (2013). Evaluation of stiffness and strength of Scots pine wood using resonance frequency and ultrasonic techniques. *BioResources, 8*(2), 1634–1645.

Karlinasari, L., Wahyuna, M. E., & Nugroho, N. (2008). Non-destructive ultrasonic testing method for determining bending strength properties of gmelina wood (*Gmelina arborea*). *Journal of Tropical Forest Science*, *20*(2), 99–104.

Legg, M., & Bradley, S. (2016). Measurement of stiffness of standing trees and felled logs using acoustics: A review. *Journal of the Acoustical Society of America, 139*, 588–604 doi: http://dx.doi.org/10.1121/1.4940210.

Megraw, R. A., Leaf, G., & Bremer, D. (1998). Longitudinal shrinkage and microfibril angle in loblolly pine. In B.G. Butterfield (Ed.) Proceedings of the IAWA/IUFRO international workshop on the significance of microfibril angle to wood quality, Westport, November 1997, International Association of Wood Anatomists, International Union of Forestry Research Organisations.

Pentoney, R. E. (1953). Mechanisms affecting tangential vs radial shrinkage. *Journal of Forest Products Research, 3*(2), 27–33.

Tsehaye, A., Buchanan, A. H., & Walker, J. C. F. (1995). Stiffness and tensile strength variation within and between radiata pine trees. *Journal of the Institute of Wood Science*, *13*, 513–518.

Walker, J. C. F., & Nakada, R. (1999). Understanding corewood in some softwoods: A selective review on stiffness and acoustics. *International Forestry Review*, *1*, 251–259.