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Measurement of stiffness of standing trees and felled logs using acoustics: A review

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This paper provides a review on the use of acoustics to measure stiffness of standing trees, stems, and logs. An outline is given of the properties of wood and how these are related to stiffness and acoustic velocity throughout the tree. Factors are described that influence the speed of sound in wood, including the different types of acoustic waves which propagate in tree stems and lumber. Acoustic tools and techniques that have been used to measure the stiffness of wood are reviewed. The reasons for a systematic difference between direct and acoustic measurements of stiffness for standing trees, and methods for correction, are discussed. Other techniques, which have been used in addition to acoustics to try to improve stiffness measurements, are also briefly described. Also reviewed are studies which have used acoustic tools to investigate factors that influence the stiffness of trees. These factors include different silvicultural practices, geographic and environmental conditions, and genetics.
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I. INTRODUCTION

There can be significant variation in the properties of wood, even within trees in the same stand.[1,2] Examples of wood properties of interest include stiffness, density, microfibril angle, fiber length, spiral grain, reaction wood (compressional or tension wood), shrinkage, checking, and resin pockets. The importance of measuring wood properties is discussed in Refs. 3–10. A significant amount of effort has, therefore, been put into developing non-destructive testing (NDT) techniques for measuring these properties.

One of the main wood properties of interest to the wood industry is stiffness, which is related to the Modulus of Elasticity (MOE) or Young's modulus. Structural grade timber should have high stiffness levels. By performing segregation at the standing tree or log stage, considerable saving can be achieved in terms of reduction in wastage of wood and reduced manufacturing costs. Also, measurements of stiffness can be used to improve breeding, planting, and silviculture practices so that future forests have higher stiffness characteristics.

Bending tests can be used to measure the static modulus of elasticity of samples cut from logs. Saw milling production line bending tools have been developed for lumber. However, performing segregation at this stage in the production process can potentially cause significant wastage in wood and manufacturing costs. It is, therefore, desirable to measure the stiffness at the log or standing tree stage using NDT methods.[6] Techniques have been developed for standing trees, which either physically bend a tree stem[11] or measure the natural frequency of tree stem sway.[12] However, these techniques do not appear to be commonly used.

The stiffness of wood can also be estimated by measuring other wood properties. The SilviScan[13] estimates stiffness by measuring the average microfibril angle using x-ray diffraction for cylindrical cores taken from trees.[14] However, it has been reported that this technique has the disadvantage of being more costly than alternative techniques such as acoustics and requires samples to be sent away for testing.[15] Near infrared (NIR) spectroscopy has also been used for profiling the stiffness distribution in sawmilling application.[16] X-ray tomography has shown the ability to provide good imaging of the density and internal structure, such as knots, of logs but also has the disadvantage of being relatively expensive and not suited to field based measurements.[17]

Acoustic techniques have been developed for measuring the stiffness of wood. They are among the most commonly used techniques because they are relatively inexpensive, fast, robust, and easily used in the field. Acoustic techniques are used for segregation of existing forests by measuring the stiffness of standing trees, felled logs, or sawn timber. They are also used for improving the stiffness of future forests in breeding studies. Commercial acoustic tools have been developed for either measuring the stiffness of logs or standing trees. These tools can be hand held devices, installations in saw milling or timber processing plants, or more recently harvester head attachments.

There are books and review papers on the acoustics of wood.[18–26] Bucur's book provides an extensive review on this topic.[24] Similarly there are books and review papers on NDT of wood, that includes the use of acoustics.[27–37] While they do mention the use of acoustics for stiffness measurements of tree stems, they do not focus in any great detail on this topic and may be in need of updating. Literature reviews have been written relating to the stiffness of wood,[34,38,39] but these have not specifically focused on the use of acoustics. Walker and Nakada provided a review on stiffness and acoustics.[40] However, this was written some time ago and there has been significant work performed on this topic since then. Wang *et al*.[41] reviewed studies relating to differences

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in measured stiffness that were obtained for acoustic velocity measurements made on standing trees and logs. No paper/book was found that provided a full/extensive review specifically on the use of acoustics for measuring the stiffness of wood. This paper was written in response to this gap in the literature.

This paper provides a review on literature relating to the use of acoustics for measuring the stiffness of wood in standing trees and felled logs. An overview of the properties of wood that affect acoustic velocity and how this relates to stiffness/MOE are discussed in Sec. II. Different types of acoustic waves, which propagate in tree stems and lumber, and their relative sound speed characteristics are also described. In Sec. III, methods, hardware, and errors for measuring the acoustic velocity in trees and logs are described. The systematic overestimation for measurements made in trees compared to logs and corrections are described in Sec. IV. Theories that have been proposed to explain this overestimation are discussed. Other techniques that have been used with acoustics for improving stiffness measurements are briefly outlined in Sec. V. In Sec. VI, literature is reviewed that have used acoustic tools to study factors influencing the stiffness of trees, such as silvicultural practices, geographic and environmental conditions, and genetics.

II. FACTORS INFLUENCING ACOUSTIC VELOCITY IN WOOD

The speed of sound in wood is related to a number of factors including mechanical properties, moisture content, temperature, and variations in grain angle. The acoustic wave speed also depends the type of waves that are propagating; dilatational (bulk) waves or "rod waves" (guided waves). This section provides an overview of the factors which affects acoustic velocity in wood.

A. Mechanical properties of wood

1. Hooke's law

Hooke's law describes the strain γ that occurs when a stress $\boldsymbol{\sigma}$ is applied to a sample. This is can be expressed as

$$\gamma_{ij} = S_{ijkl}\sigma_{kl}, \tag{1}$$

where $\boldsymbol{S}$ is the compliance tensor and the subscripts i, j, k, and l have values of 1, 2, or 3. The convention for $\boldsymbol{\sigma}_{kl}$ is that index k defines which face the stress is applied to (face 1 is in the 2–3 plane for an orthogonal system) and l is for the direction of the stress force (see Fig. 1). If symmetry is assumed, then $\sigma_{kl} = \sigma_{lk}$ and there are only six distinct stress components; σ_{11}, σ_{22}, σ_{33}, σ_{23}, σ_{13}, and σ_{12}. If these are written as a 6×1 vector $\hat{\boldsymbol{\sigma}}$, then Eq. (1) becomes

$$\hat{\gamma} = \hat{\boldsymbol{S}}\hat{\boldsymbol{\sigma}}, \tag{2}$$

where $\hat{\gamma}$ is a 6×1 vector and $\hat{\boldsymbol{S}}$ is a 6×6 matrix (refer to Ref. 42).

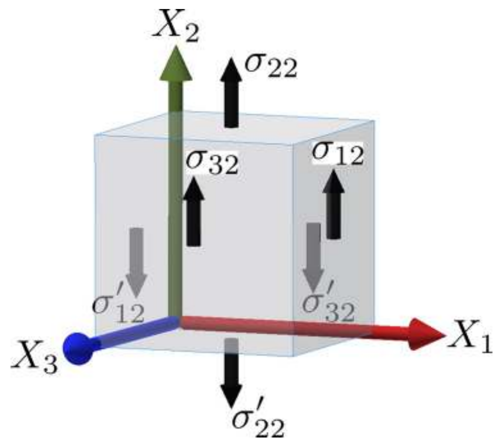

FIG. 1. (Color online) Diagram reproduced from Ref. 42 showing compressional and shear stresses in the X_2 axis direction for a small cubic sample at equilibrium.

2. Orthotropic mechanical properties of wood

Wood is an orthotropic medium, which means its properties vary in three orthogonal directions. For trees, it is convenient to use a cylindrical coordinate system, with orthotropic axes directions being in the longitudinal, radial, and tangential directions, respectively (see Fig. 2). Instead of using axes indexes 1, 2, and 3 it is common to instead use the corresponding indexes L, R, and T. This convention will be used in this work.

The compliance tensor for wood may be written as a 6×6 matrix

$$\hat{\boldsymbol{S}} = \begin{bmatrix} \frac{1}{E_L} & -\frac{\nu_{RL}}{E_R} & -\frac{\nu_{TL}}{E_T} & 0 & 0 & 0 \\ -\frac{\nu_{LR}}{E_L} & \frac{1}{E_R} & -\frac{\nu_{TR}}{E_T} & 0 & 0 & 0 \\ -\frac{\nu_{LT}}{E_L} & -\frac{\nu_{RL}}{E_R} & \frac{1}{E_T} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{RT}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{LT}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{LR}} \end{bmatrix}, \tag{3}$$

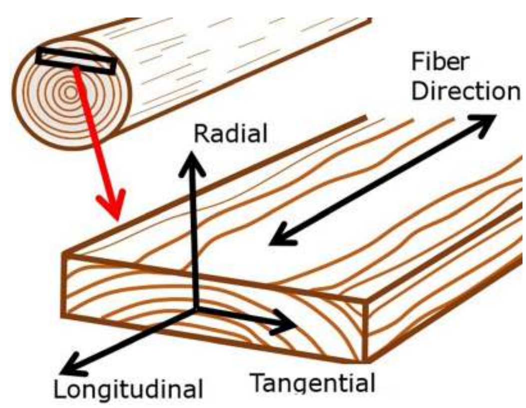

FIG. 2. (Color online) Diagram showing the orthotropic axes for wood.

TABLE I. Example Poisson's ratios for wood.

	ν_{LR}	ν_{LT}	ν_{RT}	ν_{TR}	ν_{RL}	ν_{TL}
Softwood average (Ref. 42)	0.37	0.42	0.47	0.35	0.041	0.033
Sitka spruce (Ref. 276)	0.372	0.467	0.435	0.245	0.040	0.025
Douglas fir (Ref. 276)	0.292	0.449	0.390	0.374	0.036	0.029

where E_L, E_R, and E_T are the Young's moduli in the longitudinal, radial, and tangential directions, ν_{RL}, ν_{LR}, ν_{TL}, ν_{LT}, ν_{TR}, and ν_{RT} are the Poisson's ratios, and G_{RT}, G_{LT}, and G_{LR} are the shear moduli. Table I provides some example Poisson's ratios for wood found in the literature. Bodig and Jayne[42] states that ν_{RL} and ν_{TL} are typically much lower than the other Poisson's ratios and are, therefore, subject to large measurement errors.

It should be noted that the above compliance tensor is different from that for an isotropic medium, such as steel, which has a single Young's modulus E, shear modulus $G = E/[2(1+\nu)]$, and Poisson's ratio ν. For the isotropic case, $\hat{\boldsymbol{S}}$ becomes[42]

$$\hat{\boldsymbol{S}} = \frac{1}{E}\begin{bmatrix} 1 & -\nu & -\nu & 0 & 0 & 0 \\ -\nu & 1 & -\nu & 0 & 0 & 0 \\ -\nu & -\nu & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2(1+\nu) & 0 & 0 \\ 0 & 0 & 0 & 0 & 2(1+\nu) & 0 \\ 0 & 0 & 0 & 0 & 0 & 2(1+\nu) \end{bmatrix}. \tag{4}$$

The compliance matrix is also commonly expressed in terms of its inverse $\hat{\boldsymbol{C}} = \hat{\boldsymbol{S}}^{-1}$, which is referred to as the stiffness matrix. For an orthotropic medium, this has the form

$$\hat{\boldsymbol{C}} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{21} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{31} & C_{32} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix}. \tag{5}$$

Both the compliance and stiffness matrices are usually assumed to be symmetric, $\hat{S}_{kl} = \hat{S}_{kl}$ and $\hat{C}_{kl} = \hat{C}_{lk}$.

The key parameter that is used for determining if wood is of structural grade is the stiffness, which is related to the longitudinal modulus of elasticity E_L. The longitudinal stiffness and acoustic velocity in the longitudinal direction has been related to a range of wood properties such as the microfibril angle (MFA),[43–47] tracheid dimensions,[48] and density.[46,49–54] Huang *et al.* provides a review on this topic and its relationship to the acoustic velocity in wood.[55] In general, longitudinal stiffness, and hence longitudinal velocity, increases with reduced MFA and increased density. However, some studies have cautioned against using density alone as a measure of MOE[56,57] or have reported no correlation of MOE and density.[58,59]

B. Relationship between mechanical properties and speed of sound in wood

1. Dilatational (bulk) waves in wood

The orthotropic nature of wood means that the speed of sound depends on the direction of propagation. The sound speed in the longitudinal orthotropic axis direction is the highest, while that in the tangential axis direction is the lowest (see Fig. 3).[24,47] Also, the acoustic attenuation is lowest in the longitudinal direction.[60] This attenuation is significantly higher than steel, for example, and increases with frequency.[60] These factors mean that the first arrival of an acoustic signal tends to follow the wood grain.[61–66]

The velocity of an acoustic signal in a medium for a particular direction is related to the medium's mechanical properties. This may be described by the Kelvin-Christoffel equation

$$\begin{bmatrix} \Gamma_{11} - \rho c^2 & \Gamma_{12} & \Gamma_{13} \\ \Gamma_{12} & \Gamma_{22} - \rho c^2 & \Gamma_{23} \\ \Gamma_{13} & \Gamma_{23} & \Gamma_{33} - \rho c^2 \end{bmatrix} \begin{bmatrix} p_1 \\ p_2 \\ p_3 \end{bmatrix} = 0, \tag{6}$$

where Γ_{ik} is the Kelvin-Christoffel matrix, p_m is a polarization vector, which indicates the direction of vibration, and ρ is the density.[67] For an orthotropic medium,

$$\begin{aligned} \Gamma_{11} &= n_1^2 C_{11} + n_2^2 C_{66} + n_3^2 C_{55}, \\ \Gamma_{22} &= n_1^2 C_{66} + n_2^2 C_{22} + n_3^2 C_{44}, \\ \Gamma_{33} &= n_1^2 C_{55} + n_2^2 C_{44} + n_3^2 C_{33}, \\ \Gamma_{12} &= n_1 n_2 (C_{12} + C_{66}), \\ \Gamma_{13} &= n_1 n_3 (C_{13} + C_{55}), \\ \Gamma_{23} &= n_2 n_3 (C_{23} + C_{44}), \end{aligned} \tag{7}$$

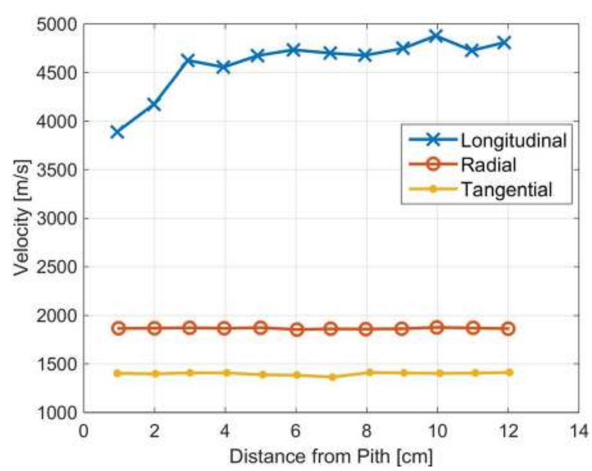

FIG. 3. (Color online) Figure reproduced from Ref. 47 showing variations in the acoustic velocities in three orthotropic directions for Japanese cypress as a function of distance from the centre of the tree (pith).

where n_j are propagation direction cosines. This equation can be used to calculate the velocity of shear and compressional dilatational (bulk) waves in different propagation directions relative to the orthotropic axes.[68–75] Other models, including the Hankinsen's model, have been proposed for the speed of sound in wood as a function of grain angle in the radial/tangential[76–78] and longitudinal[79] directions.

The Kelvin-Christoffel equation can be used to calculate the theoretical speed of an acoustic dilatational wave (in an infinite unbounded medium). The speed of a wave propagating along the longitudinal orthotropic axis may be calculated, using $n_1 = 1$ and $n_2 = n_3 = 0$, as

$$c_L = \sqrt{\frac{C_{11}}{\rho}} = k\sqrt{\frac{E_L}{\rho}}, \tag{8}$$

where k is a term greater than one that is related to the Poisson's ratios of wood. For an orthotropic medium, the Kelvin-Christoffel equation gives

$$k = \sqrt{\frac{1-\nu_{RT}\nu_{TR}}{1-\nu_{RT}\nu_{TR}-\alpha}}, \tag{9}$$

where $\alpha = 2\nu_{RL}\nu_{TR}\nu_{LT} + \nu_{TL}\nu_{LT} + \nu_{RL}\nu_{LR}$. Refer to Sec. 4.1 of Ref. 24 and Sec. 1.3 of Ref. 67 for more details. Note that if all six Poisson's ratios were equal (a single Poisson's ratio), one would get the isotropic case

$$k = \sqrt{\frac{(1-\nu)}{(1+\nu)(1-2\nu)}}. \tag{10}$$

Equation (8) provides a theoretical dilatational wave speed in an unbounded medium (in the longitudinal direction).

The acoustic velocity in wood also varies with moisture content (MC), which may change with the season of the year.[47,80–90] The longitudinal velocity has been reported to reduce with increased MC, while the radial and tangential velocities may vary (decrease and increase) as MC was varied.[83] In addition, the density of wood increases with MC. Both these factors will have an effect on the measured MOE obtained using acoustic techniques.[87] Corrections for moisture content in MOE calculations using acoustic velocity have been investigated by several authors.[86,89] Temperature also influences the acoustic velocity in wood.[82,86,88,91–96] The velocity decreases with increased temperature. There is an abrupt change in velocity around the freezing point.[97–100]

2. Rod waves in tree stems

An acoustic signal initially propagates in a log as bulk or dilatational waves.[101,102] The first arrival times for a 3D stress wave propagating through a tree stem has been investigated experimentally in several papers.[103–106] Searles reported that the first arrival times could initially be explained by elliptical wave fronts, with the semi-axes being obtained from the orthotropic velocities in the longitudinal and radial directions.[106] Zhang *et al.* states that the first arrival wave fronts become approximately planar after the wave has propagated about ten stem diameters from the impact point on the side of the trunk.[103] It is generally assumed that after propagating sufficient distance the first arrival of this compressional wave in the tree stem becomes a 1D "rod wave" with a velocity of[20,101,102,107]

$$c_L = \sqrt{\frac{E_L}{\rho}}. \tag{11}$$

This equation is used to calculate the elastic modulus E_L of a tree stem from measurement of the acoustic velocity. Generally a fixed density is assumed for a given tree type. For example, the density of radiata pine is often chosen to be about 1050 kg/m^3. This can lead to errors in the calculated MOE values since the actual density of the tree stem may be different to this assumed value and will vary within the tree stem. However, generally errors in velocity are considered to be the main source of error in MOE values, since the dynamic MOE is proportional to the square of velocity. It should be noted, however, that Eq. (11) is an approximation of one type of vibration in a isotropic, homogeneous, thin rod.[108] Tree stems, however, are actually orthotropic, non-homogeneous, and have a finite diameter and a taper. This has the potential to lead to errors in stiffness measurement.

3. Acoustic/ultrasonic guided waves in tree stems

Waves which propagate along tree stems are often referred to as "rod waves." However, these appear to be what are more generally referred to as acoustic guided waves. An elongated structure such as a rod or plate acts as a wave-guide for an acoustic signal if the diameter of the structure is approximately proportional to the wavelength of the signal. The signal initially propagate as dilatational (bulk) waves. However, after propagating sufficient distance, guided waves will be generated, which would be expected to be composed of multiple wave modes. For a rod like structure, these would be longitudinal, flexural, and torsional wave modes. These propagate at different speeds and are generally dispersive; having wave speeds, which vary with frequency and diameter of the structure. For example, if the diameter of a steel rod (or plate) was reduced, the velocity of a longitudinal wave mode at a given frequency would be expected to change. Also, the number of wave modes that can propagate for a given frequency range might change with the diameter.

The study of acoustic/ultrasonic guided waves is well established for homogeneous materials such as metal pipes, rod, and plates and some anisotropic materials such fiber glass or carbon fiber sheets.[109–112] For objects with simple geometries, such as steel plates and rods, commercial software has been developed for obtaining the phase and group velocities as a function of frequency (dispersion curves). For objects with more complex geometries, finite element analysis (FEA) software may be used.

For tree stems, the high anisotropy and inhomogeneity of wood make the wave propagation more complex than in homogeneous, isotropic materials such as steel rods. Only a few studies were found which had investigating guided waves in timber[113,114] or logs.[115–118] There have been several other papers that have described guided wave phenomena, though have not specifically referred to them as being due to guided wave effects. Marra *et al.* stated that, as the dimensions of a piece of timber approach the wavelength of the acoustic signal, the velocity becomes a function of wavelength and these dimensions.[119] Others have also reported the acoustic/ultrasonic wave velocity in timber being dependant on the frequency and dimensions of the timber.[24,77,119–123] The complex signals measured in wood have been attributed by some as being due to different modes or dispersion, though little detail has been provided. Generally only the first arrival time of the signal is measured while the remainder is ignored. This complex signal following the first arrival may be the result of different guided wave modes. More research in this area is needed.

C. Additional factors affecting acoustic velocity in tree stems

Variations in stiffness, density, and MC within a tree can affect the acoustic velocity. The longitudinal MOE and the density of a log, when dried, increases from pith outward toward the bark (see Fig. 4).[56,124] However, this effect is offset to some degree by the higher moisture content at the core of the log than in the outerwood. This results in the longitudinal wave velocity increasing from pith to bark,[45,47,49,124,125] though not as much as might be expected from dry wood density alone.[107] The acoustic velocity is also reported to decrease with height up the tree stem.[57,126–129] However, some studies have reported that the longitudinal acoustic velocity in radiata pine initially increased to a maximum a few meters up the tree and then decreased with height.[107,126,130]

Reaction wood within the tree stem can also cause variations in acoustic velocity measurements.[131] Also, variations in grain angle, including knots/branches and spiral grain, can reduce the measured velocity observed in wood.[58,106,126,132–136] Gerhards showed that the wave front of an acoustic signal tends to follow the grain and flow around knots, potentially resulting in measurements of reduced acoustic velocity.[133]

Acoustic velocity has also been reported to have a negative correlation with diameter at breast height (DBH), for the same age of tree.[137,138] Some have stated that this correlation of DBH and stiffness, and hence velocity, can be inconsistent due to variations in growth rates between different locations. Instead it is suggested that tree stiffness should be compared against stem slenderness (taper), which is the ratio of height/DBH. A strong correlation of slenderness with stiffness has been reported for mature[1,50,59,139–142] and juvenile[143,144] trees. This increased stiffness with the slenderness has been suggested as being a natural mechanism to prevent buckling of tree stems.[145] Wind exposure appears to have an effect on the stiffness of trees.[1] Also, the acoustic velocity increases with the age of the tree.[58,124,146–148] Auty and Achim[146] proposed a non-linear model

$$E_L(\text{age}) = \beta_1 \left[\frac{\text{age}}{\beta_2 + \text{age}}\right] + \beta_3, \qquad (12)$$

to take into account the effect of age on MOE for Scots pine. Similar models are provided in reference.[149] Gonçalves *et al.* reported that the rate of acoustic velocity increase with age for *Pinus elliottii* was highest in younger trees.[147]

III. MEASUREMENT OF THE STIFFNESS OF WOOD USING ACOUSTIC SENSORS

Acoustic NDT techniques have been developed to estimate the longitudinal modulus of elasticity (often referred to as the dynamic modulus of elasticity), E_L, of standing trees and logs. This is achieved by exciting stress waves in the tree stem and measuring the velocity c_L in the longitudinal direction. The dynamic MOE of a tree stem is calculated from Eq. (11) using the measured acoustic velocity and the wood density.[20] There are two methods used to measure acoustic velocity; acoustic resonance and time of flight (TOF).

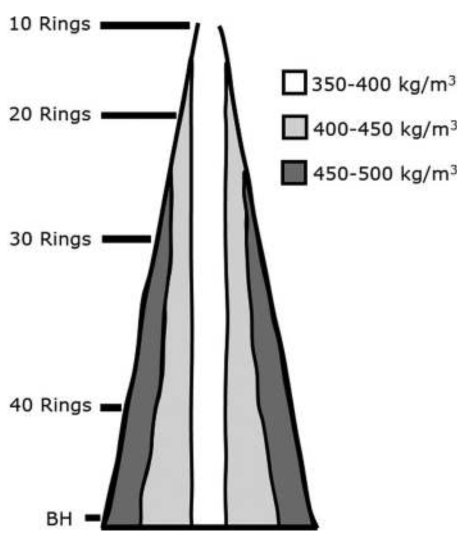

FIG. 4. Figure reproduced from Ref. 131 showing within tree variation in air dry density for radiata pine.

FIG. 5. (Color online) Diagram of an acoustic resonance tool used for measuring the acoustic velocity in logs.

A. Acoustic resonance tools for measuring the stiffness of logs

Transverse vibration techniques have been developed for measuring the stiffness of lumber, which use transverse vibrations generated by an impact near the middle of the sample.[108,119,150–153] The longitudinal vibration technique, however, is more common and is used for measuring the stiffness of both logs and lumber. It utilizes vibrations, which are predominantly in a direction parallel to the grain of the wood. Longitudinal stress waves are generated by an impact from a hammer or similar object at one end of the log or timber (see Fig. 5). The resulting stress waves are reflected from each end of the log many times and standing waves are generated. The signal is recorded and a fast Fourier transform (FFT) of the signal is obtained. The frequencies at which peaks occur in the signal are measured. The longitudinal acoustic velocity may be calculated from the nth resonance frequency f_n using

$$c_{\mathrm{RES}} = \frac{2Lf_n}{n}, \qquad (13)$$

where L is the length of the log. Early work using resonance for measuring the stiffness of logs was performed in Japan.[154–158] Harris *et al.*[159] and Lindstrom *et al.*[160] used an alternative technique for exciting resonance. Rather than using a hammer hit, a transducer and a chirp signal (swept frequency) were used to generate longitudinal resonance.

Acoustic resonance tools have been developed for sorting logs in sawmilling installations.[161] A study on the potential of resonance based tools for installation on a harvester head is provided in Refs. 162 and 163. However, the need for knowing the length of the log before calculating the MOE appears to limit the practical use of resonance for harvester head application. Acoustic resonance measurements have also been made for seedlings or juvenile trees.[12,160]

1. Example commercial acoustic resonance hardware

There have been a number of hand held resonance tools for measuring the acoustic velocity in logs. Fibre-gen[164] have developed the HITMAN HM200.[165–167] This is a newer version of the Director HM200 provided by Carter Holt Harvey fibre-gen. Achim *et al.* provides a description of the design of a hand-held longitudinal resonance tool.[167] Fakopp[168] have a similar tool referred to as Resonance Log Grader.[169] Fiber-gen have developed the HITMAN LG640 for sorting logs in sawmilling installations.[170] There have also been a range of production line acoustic resonance tools for measuring the stiffness of lumber.[171–173]

2. Acoustic resonance tool errors

Studies have shown that there is a strong correlation between the MOE values calculated using the acoustic resonance technique and those obtained using mechanical bending of boards[34,44,127,159,160] (see Fig. 6). It has been suggested this technique provides MOE measurements, which are an average through the cross-section of the log.[124,159,174] This has been associated with the fact that it uses an acoustic signal that has propagated many times through the length of the log due to multiple reflections from each end. However, there are a few factors that have been suggested as potential sources of errors in resonance measurements.

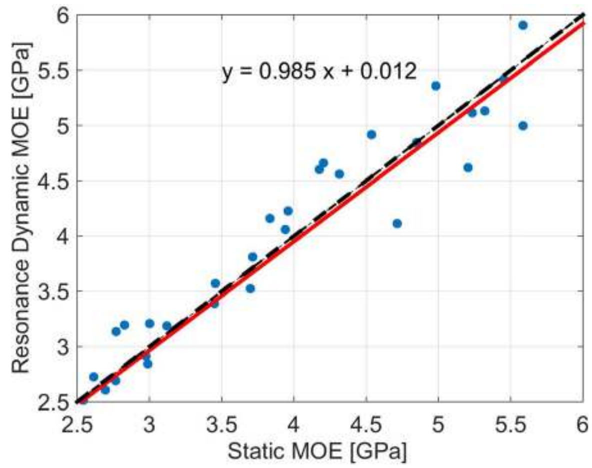

FIG. 6. (Color online) Correlation between the static (bending) and dynamic (resonance) modulus of elasticity. Figure reproduced from Ref. 160.

There has been some discussion on the optimal way of exciting resonance in logs. In a paper describing their swept frequency resonance device, Harris *et al.* raises questions of the potential for errors for resonance devices that use hammer hits.[159] They performed time frequency analysis of the signal induced by hitting the end of a log with a hammer. The resonant frequencies varied with time but the overall spectrum was dominated by the first few reverberations due to attenuation. It was also questioned whether a hammer hit is the optimal way of exciting resonance. Andrews suggests there is the potential for the resonance frequencies of the log to be outside the main frequency components generated by the hammer hit (mainly around 1 kHz for wet logs).[175] It should be noted, however, that Chauhan and Walker provides a comparison of acoustic velocities obtained using two different resonance devices, which excite the logs using either a hammer hit or a frequency sweep transducer (Hitman HM300 and WoodSpec), and a good correlation was observed.[58]

Some studies have looked at which harmonic should be used for resonance measurements. Andrews reported that the measured resonance peaks may not be harmonics of each other.[107] He stated that the taper of the tree can affect the resonance frequency, particularly for the lower frequency vibration. Chauhan and Walker reported that the acoustic velocity measured using the first and second harmonic can vary by as much as 11%.[58] It was suggested that the second harmonic was more accurate and appeared to be that used by Hitman HM300. The location of knots may also affect some resonance frequencies.[58,135]

The presence of bark on a log can cause errors in acoustic velocity measurements using resonance techniques. Lasserre *et al.* reported that removing the bark on a tree stem increased the resonance velocity measured MOE value by 8% on average.[176] Similarly, Hsu reported that bark removal increased the acoustic velocity by 7.2% for logs from the base of the tree.[126] This effect increased with height in the tree, with a maximum of 22.6% near the top. This appears to be related to the fact that the proportion of bark to wood mass increased with height. A similar increase in velocity with bark removal was observed by Emms *et al*. for juvenile trees.[177] The increase in sound speed reported in these references ranged from 3% to 22%.

The presence of branches on a log has also been reported to cause errors in the acoustic velocity measured using resonance. Lasserre *et al*. found that removing branches increased the measured MOE obtained using resonance by on average 5.4% but this value varied from 24% to 0%.[176] Similarly, in a study on the potential of the using resonance for harvester head segregation, Amishev also observed an increase in resonance velocity with removal of branches for Douglas fir.[163]

3. Damping measurement from acoustic resonance data

Acoustic resonance raw data obtained using a hammer hit can be analyzed to obtain more information on wood properties, such as damping. Damping can be measured in the time domain from the rate that the signal amplitude drops off with time. In the frequency domain, it has been related to the narrowness of the resonance peaks. This can be expressed as a Q-factor using

$$Q = \frac{f_c}{f_2 - f_1}, \tag{14}$$

where f_c is the central frequency of the resonance and f_1 and f_2 are upper and low frequencies where the peak has dropped a certain amount (perhaps $-3\,\text{dB}$) below the peak. The Q factor can be related to a damping factor $\xi = (2Q)^{-1}$. Damping will vary with frequency due to the fact that higher frequencies experiencing more attenuation rates.[135] This is likely to be the cause of the change in resonance peak frequency with time that Harris *et al*. observed[159] and may influence the resonance frequencies obtained using acoustic resonance. Damping has been relating by several studies to the stiffness of wood.[135,178] However, damping measurements do not appear to be commonly used for wood stiffness evaluation and is more commonly used for detecting rot in tree stems.[179–184]

B. Acoustic time of flight tools for measuring the stiffness of standing trees

The stiffness of standing trees cannot be measured using the acoustic resonance technique, since this method requires two cut ends. Instead the stiffness of standing trees may be estimated by measuring the acoustic velocity in the stem using TOF techniques. TOF velocity measurements are generally made using stress waves excited by an impact from a hammer on a metal spike inserted into a tree stem.[185,186] Two spikes/probes are generally inserted on the same side of the tree ("same face"), which are separated vertically by about a meter. They are usually orientated at an angle of 45°

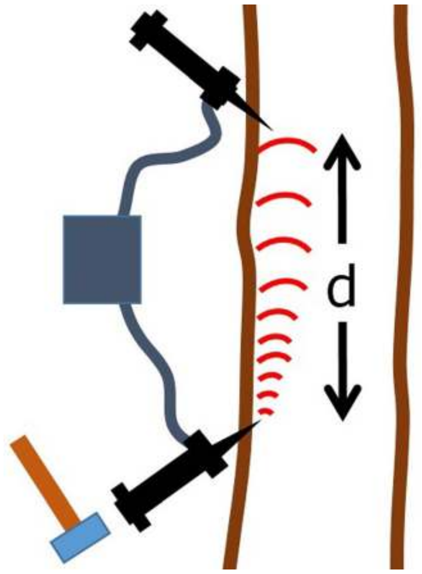

FIG. 7. (Color online) Diagram of an acoustic TOF tool used to measure the velocity in standing trees.

to the stem with the tips facing each other. One probe is hit with a hammer and the time T that it takes for the stress wave to first reach the second probe is measured, see Fig. 7. The acoustic velocity is then calculated using

$$c_{\text{TOF}} = \frac{d}{T}, \tag{15}$$

where d is the separation between probes. A description of a design of this type of TOF tool can be found in the patents.[187,188] An slightly different measurement technique was used by Toulmin and Raymond[189] and Woods[190] who used three probes: one for hitting with a hammer and the other two for receiving. A harvester head TOF device has recently been developed.[191] TOF velocity measurements have also been performed using ultrasonic transducers instead of a hammer hit.[192–194]

It has been reported that TOF methods overestimate the stiffness compared to bending and resonance techniques (see Sec. IV). An alternative technique has, therefore, been tried that has the transmit and receive probes on different sides ("opposite faces") of the tree, with the probes separated vertically by about a meter.[195–200] This was performed to try to measure an average stiffness through the entire tree stem. Mahon[199] and Mahon *et al*.[200] investigated different propagation paths through the tree stem to allow for variations in the diameter of the tree when calculating the TOF velocity. A problem that has been reported with this technique was that the results underestimated the MOE. This appears to be due to the fact that these studies have not allowed for the anisotropy of the wood, where the velocity in the radial direction is significantly lower than in the longitudinal direction.

A few studies have used the TOF technique to measure the stiffness on logs. This generally involves using a hammer hit[201–210] or an ultrasonic transducer[211] to generate an acoustic signal at one end of a log, and measuring the TOF to the other end of the log. However, this technique is rarely used for measuring the stiffness of logs since it is considered to be less accurate than acoustic resonance techniques and leads to an overestimation of stiffness. TOF acoustic velocity tools have also been developed for measurements of the stiffness of seedlings and juvenile trees in breeding studies.[12,160,212] Emms *et al*. developed a technique for measuring the TOF acoustic velocity in seedlings using cross-correlation of the signals measured on two spatially separated sensors using a pinhead strike as a sound source.[177,213]

1. Example commercial acoustic TOF hardware

Many of the TOF tools are composed of two probes and a hammer. A description of the design of this type of TOF tool can be found in the patents.[187,188] Commercial versions of this tool is the produced by Fibre-gen[164] in the form of the HITMAN (Director) ST300. A harvester head version of the ST300 is the HITMAN PH330.[214] Other commercial hand held tools include the TreeSonic and Fokopp 2D,[202,215] which were developed by Fakopp,[168] Metriguard,[216,217] and IML Micro Hammer.[218]

There have also been several tools which use ultrasonic excitation to measure the acoustic velocity in trees and logs. These include Fokopp's Ultrasonic Timer,[219] Agricef USLab,[220] CBS-CBT Group's Sylvatest Duo and Sylvatest Trio,[192,193,221] and an ultrasonic device produced by the University of Canterbury.[194] The Krautkramer USD10-NS Ultrasound flaw detector[222] is referred to in Ref. 12. There have also been a range of production line ultrasonic TOF tools used for grading of lumber[173,193,223,224] and veneer.[225,226]

2. Acoustic TOF tool errors

Studies have shown that there is a good correlation of stiffness measurements made using the TOF technique and other methods, such as bending and resonance. TOF velocity measurements, however, are considered be less accurate than those obtained using the acoustic resonance technique. As will be discussed in Sec. IV, TOF techniques produce stiffness measurements that are overestimated compared to those obtained using acoustic resonance and bending techniques. Also, the fact that signal used in the TOF technique has propagated a relatively short distance (about a meter) compared to that used for resonance (many reflections from the ends of log), has been attributed to TOF measurements being more sensitive to errors resulting from local inhomogeneousness in the wood properties and measurement errors. Variations in grain angle, including that due to knots/branches and spiral grain, can reduce the measured TOF velocity observed along a tree stem.[58,106,126,132–136] Reaction wood and non-symmetric variation in stiffness within the tree stem can also cause variations in acoustic TOF measurements. To compensate for these effects, multiple measurements may be made at different points around a tree to try to obtain an average velocity measurement.[176,227] Variations in results have also been reported with individual hammer hits. This can be compensated for by averaging over multiple measurements.[41]

Several studies have provided data that appear to indicate that TOF velocity measurements are more closely correlated with outerwood MOE than that of the corewood. Grabianowski *et al*. made TOF measurements of lumber at different positions in logs.[124] They found that TOF acoustic velocity measurements had a higher correlation to resonance velocities in the outerwood than in the corewood. Chauhan and Walker state that their TOF measured MOE values were more correlated with SilviScan MOE measurements than that obtained using resonance.[58] Mora *et al*. also compared TOF calculated MOE values with those made using a SilviScan at different depths in the tree.[228] They reported that the difference in the MOE values increased with depth from the bark. A similar result was obtained by Hong *et al*.[229] Paradis *et al*. reported that the measured TOF acoustic velocity can vary with the depth that the probes are inserted into the tree stem.[230]

IV. SYSTEMATIC DIFFERENCE BETWEEN TOF AND RESONANCE

Studies have found that the TOF method provides measured values of MOE which are higher than those obtained using resonance for standing trees and logs[58,101,124,126,127,176,228,231–233] (see Fig. 8). Wang provides a review on this topic.[41] The overestimation of TOF compared to resonance velocity has also been reported to occur even if the TOF velocity measurements were made from pith to pith at each end of the log.[126,209] Yin *et al*.[232] and Chiu *et al*.[127] reported that dynamic MOE values obtained using both TOF and resonance were higher than static MOE calculated using bending tests, though the resonance value was closer to the static values.

The higher TOF velocity compared to resonance velocity has been expressed as the ratio

$$k = \frac{\overline{c_{\text{TOF}}}}{\overline{c_{\text{RES}}}}, \tag{16}$$

where $\overline{c_{\text{TOF}}}$ is the average TOF velocity measured in trees and $\overline{c_{\text{RES}}}$ is the average resonance velocity measured in logs. The individual resonance and TOF velocity data points have been fitted by many using

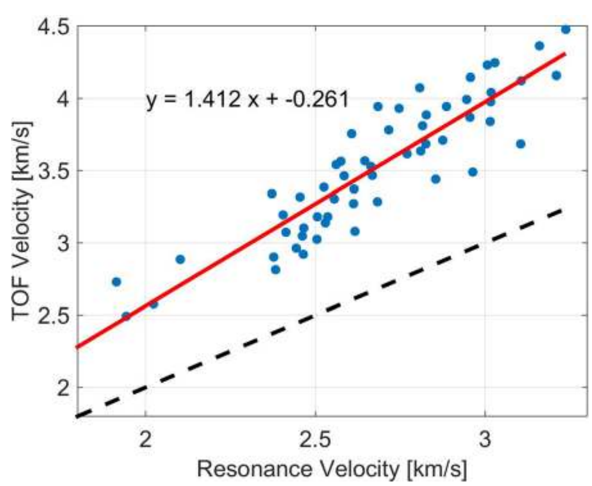

FIG. 8. (Color online) Figure is reproduced from Ref. 228 showing overestimation of TOF in standing trees compared to resonance velocity in logs cut from the trees.

$$c_{RES} = a + bc_{TOF}, \quad (17)$$

which is the same as Eq. (16) if $a = 0$ and $b = 1/k$. A range of studies have investigated the overestimation of TOF compared to resonance for radiata pine in New Zealand.[58,101,124,126,176,234] They show some variability in the fitted parameters a and b and provide k values which ranged from 1.07 to 1.31 with a mean of about 1.15.

The diameter of a tree has been reported by some papers to have an effect on the overestimation of TOF velocity c_{TOF} in standing trees compared to bending[138] and resonance.[58,101,138] An empirical multi-variable model, developed by Wang *et al.*,[138] models the resonance acoustic velocity in a tree stem in terms of the TOF velocity as

$$c_{RES} = a\left(\frac{\mathrm{DBH}}{\rho}\right)^{b} c_{TOF}^{g}, \quad (18)$$

where DBH is the diameter at breast height, a, b, and g are least squares fitted parameters, and ρ is the density and would reduce to Eq. (16) if $a = 1/k$, $b = 0$, and $g = 1$. This was used to provide an empirical correction for TOF data.[102,138,234] Chauhan and Walker noted that the difference between TOF and resonance velocities tended to be greater in the older and larger diameter trees.[58] A few studies, however, have reported not observing any significant effect of diameter on the difference between TOF and resonance.[176,228] Gonçalves *et al.* looked at several tree species and reported that the dependence on tree diameter was only observed for some of these species.[233]

Several papers have stated that the presence of bark on a tree stem can cause the measured resonance velocity on a log to be lower than it would be without bark and thereby cause an underestimation of the MOE of a log. The presence of bark on logs has, therefore, been attributed to causing the measured value of k to be higher than it should be.[58,124,176] It was reported by Lasserre *et al.* that values of MOE obtained using resonance measurements with and without bark were, respectively, on average 38% and 33% lower than MOE values obtained using TOF with the bark on the tree stem.[176]

A. Explanations for the overestimation of TOF compared to resonance and corrections

There have been several explanations provided in the literature on the reason for the overestimation of TOF compared to resonance and some corrections. This section provides a review of these explanations.

1. Viscoelastic properties of wood explanation of TOF overestimation

It has been suggested that the higher MOE values compared to resonance and bending are related to the viscoelastic nature of wood.[235,236] Static bending was considered to be a vibration with a very low frequency. Therefore, static bending, resonance, and ultrasound were regarded as three forms of vibration with, respectively, three increasing levels of vibrational frequencies. Increased MOE measured values obtained with the three different techniques were related to an increase in velocity with increased frequency (dispersion). Ouis reviewed this idea and provided mathematical models.[236]

2. Variation in stiffness from pith to bark explanation

The longitudinal stiffness of wood increases from pith to bark. It has been assumed that the resonance technique provides an average stiffness measurement through the entire cross-section of the tree stem. In contrast, it is suggested that the TOF technique provides results which are biased toward outerwood MOE.[58,126,138,176] Hsu suggested that the fact that TOF velocity measurements, which were made from pith to pith at opposite ends of logs, were still higher than that obtained using resonance, was because the fastest propagation path would involve the acoustic signal propagating in the stiffer outer-wood for some part of the travel time.[126] Chauhan and Walker assumed that the overestimation with diameter was due to the oldest stands and larger diameter trees having a large difference in stiffness between outerwood and corewood.[58]

Some studies have performed TOF and resonance tests on timber samples. These studies also reported that the velocities obtained using TOF were higher than those obtained using longitudinal resonance[237–239] and flexural resonance.[235,237,240,241] Others have reported that TOF measured dynamic MOE values for timber samples were higher than static MOE values calculated using bending tests on these samples.[185,186,208,235,237,242,243] Hassan *et al.* reported that dynamic MOE obtained using flexural vibration, longitudinal vibration, and ultrasound (TOF) where greater than those of static MOE values by 13.8, 22.3, and 30.9%, respectively.[239] Similar results were reported by Yang *et al.*[237] Searles measured TOF velocity for stress wave propagation along a thin billet cut from a log.[106] He reported that a reduction in velocity was observed with propagation distance. He proposed that the overestimation of TOF compared to resonance was related to boundary effects and not due to changes in material properties.

3. "Bulk" and "rod" velocity explanation

An explanation of the difference between TOF and resonance is related to the wave propagation through the log. For the TOF technique, the effective propagation distances are typically only about a meter, while for resonance the propagation distance may be many lengths of the log. Andrews[101] and Wang *et al.*[102,234] suggested that, for the TOF velocity measurement technique, the acoustic signal will propagate at a "dilatational" speed. Assuming an infinite, unbounded, isotropic medium, they give this dilatational speed as

$$c_{TOF} = \sqrt{\frac{C_{11}}{\rho}} = \sqrt{\frac{(1-\nu)}{(1+\nu)(1-2\nu)}}\sqrt{\frac{E_L}{\rho}}, \quad (19)$$

coming from Eqs. (4), (5), (8), and (10), where ν is the Poisson's ratio. However, for the acoustic resonance technique, where the acoustic waves have propagated a significant distance involving many reflections from the ends of the log, they assumed that the signal propagates at a "rod" speed [see Eq. (11)]

$$c_{\mathrm{RES}} = \sqrt{\frac{E_L}{\rho}}. \tag{20}$$

It is, therefore, suggested that the overestimation of TOF compared to resonance is given by the ratio of Eqs. (19) and (20) giving

$$k = \frac{c_{\mathrm{TOF}}}{c_{\mathrm{RES}}} = \sqrt{\frac{(1-\nu)}{(1+\nu)(1-2\nu)}}. \tag{21}$$

For example, Wang *et al.*[102] observed that the TOF velocity for Sitka spruce was 1.22 times that for resonance and used Eq. (21) to calculate an isotropic Poisson's ratio of 0.331.

For TOF measurement in trees, it is suggested that the wave propagation is dominated by dilatational waves and that this effect increases with diameter causing the higher velocity for TOF compared to resonance. The MOE values obtained using TOF for standing trees were corrected for this dilatational speed effect using

$$E_L = \left(\frac{c_{\mathrm{TOF}}}{k}\right)^2 \rho, \tag{22}$$

where k was determined from experimental measurements from trees of the same species.[41,102,234,244] It was reported that the corrected TOF dynamic MOE values were well correlated with those obtained using resonances. This method requires a calibration data set of TOF and resonance velocities for calculating k. Since factors such as age, DBH, and genome type has been reported to influence the overestimation k, a range of different calibration data sets might be beneficial.

Mora *et al.*[228] extended Eq. (22) to include a correction for the effect of moisture content on density

$$E_L = K\left(\frac{c_{\mathrm{TOF}}}{k}\right)^2 \times \rho\left\{1 - \frac{(1-k)(\mathrm{MC} - \mathrm{MC}_{\mathrm{FSP}})}{100 + \mathrm{MC}}\right\}, \tag{23}$$

where MC is the moisture content (%), $\mathrm{MC}_{\mathrm{FSP}}$ is the moisture content at fiber saturation (30% is used), κ is the mobility of free water (0.6 is used), and K is a constant 9.84×10^{-10} used to incorporate gravitational acceleration and conversion constants to express stiffness in GPa. They reported that including the moisture content correction resulted in improved dynamic MOE values, which compared well with static MOE values obtained using bending tests. Other studies that have investigated correction of MOE values for moisture content can be found in Refs. 86 and 89.

B. Discussion

Most of the studies comparing TOF measurements on trees with resonance measurements on felled logs have generally only compared TOF and resonance velocities. Only a few of the studies have provided comparison with other techniques. Generally this comparison was only made with TOF measurements and not those obtained using resonance. It would be beneficial if any future studies on this topic included more comparisons with other techniques, such as static bending tests, and made this comparison with resonance as well as TOF. Also, ideally these studies would include measurements made with the bark and branches removed from the felled logs before making the resonance tests, since these have been shown to cause errors in resonance measurements. Future studies could also compare k measurements with tree slenderness (tree height/DBH), since this characteristic of trees has been reported to have a strong correlation with stiffness.[1,50,59,139–144]

One of the ideas to explain the higher TOF measurements compared to resonance is variation from pith to bark of the tree stem. Several studies have reported that MOE values obtained using TOF techniques have higher correlation with outerwood MOE than that closer to the pith. However, other studies have reported that the overestimation also occurs in thin timber samples. This appears to indicate that the variation in stiffness may contribute to, but probably is not the main mechanism of, the overestimation.

Andrews[101] and Wang *et al.*[102,234] suggested that the TOF method measures the dilatational (bulk) wave speed, while the resonance technique measures the "rod" speed of the log. Equation (21) was used to explain the overestimation of TOF compared to resonance and provide TOF corrections.[102,234] This appears to be a good explanation for the overestimation. However, Eq. (21) uses isotropic wave propagation theory with a single Poisson's ratio, while wood is an orthotropic material and has six Poisson's ratios. Equation (9) provides an orthotropic version of Eq. (21). Using the six orthotropic Poisson's ratios for Sitka spruce given in Table I, a theoretical value of $k = 0.02$ is obtained. Because of the low values of ν_{RL} and ν_{TL}, this value is significantly smaller than the measured overestimation of $k = 1.22$ reported by Wang *et al.*[102] for Sitka. It is possible that the orthotropic Poisson's ratios used are not correct (ν_{RL} and ν_{TL} are usually not measured) or that Eq. (9) does not accurate represent the wave propagation. More work on this topic, incorporating the orthotropic nature of wood, would be beneficial.

It is likely that the signals used by resonance are guided waves. Could the variation in overestimation of TOF with diameter be related to a guided wave effect? Also, could dispersion be playing a role? The longer propagation distance for the signals used for resonance means that more of the higher frequency components of that signal will have been filtered out compared to TOF. Could different frequency components in the signal be propagating at different speeds? It may be that more work on guided waves in tree stems may provide improved understanding of the difference between TOF and resonance velocity and potentially more accurate stiffness measurements.

V. OTHER TECHNIQUES COMBINED WITH ACOUSTIC TOOLS FOR MEASURING STIFFNESS

The use of other techniques with acoustics has been investigated for increasing the accuracy of stiffness measurements. Wang *et al*. reported that, for Douglas fir, the combination of log diameter or log position (height) in the tree with longitudinal acoustic velocity were better predictors of average lumber MOE and visual grade yield than log acoustic velocity alone.[129] Acoustic velocity has been reported to be related to slenderness (height/DBH).[139,245] It has been suggested that slenderness could be used for initial sorting of timber. Laser scanning of a log's surface to automatically measure the shape of a log in saw milling plants can also be utilized to measure slenderness and knots.[246] Ridoutt *et al*. reported that for radiata pine the inclusion of branch size with longitudinal stress wave velocity resulted in improved sorting compared to velocity alone.[205]

VI. IDENTIFYING FACTORS INFLUENCING THE STIFFNESS OF TREES

Acoustics tools have been used to try to improve the stiffness of future forests. This has been done by trying to identify silvicultural practices or environmental conditions that affect stiffness. Acoustic tools have also been used in breeding/genetic studies to try to improve properties such as stiffness of future breeding stock. This section provides a review on some of these studies.

Studies using acoustic tools have reported that the initial planting spacing can affect stiffness. Stand spacing density has been reported to be positively correlated with acoustic velocity/stiffness for radiata pine[59,130,137,140,247,248] and Japanese cedar.[249] It has been suggested that the correlation of stand planting density and stiffness may be related to higher density stands experiencing less wind stress.[137] Lasserre *et al*. found that close initial stand spacing (2500 compared to 833 stems ha^{-1}) significantly increased the dynamic modulus of elasticity of radiata pine from 3.4 to 4.6 GPa. It also significantly reduced MFA and ring width, while significantly increased fiber length, latewood percentage and cell wall thickness. Density and fiber width were reported to not be significantly different between spacing treatments.[59] Similar results were observed for juvenile (6 year old) trees.[143] However, others have reported not observing this increase in acoustic velocity with stand density.[1,144,250] Watson reported that, while radiata pine show significant increase in stiffness with planting density, *Eucalyptus nitens* did not show any significant correlation. This may indicate that the effect of stocking on MOE may vary with species.[148]

Several studies have reported that stands that were thinned were less stiff than unthinned stands.[57,251–253] Raymond *et al*. reported that radiata pine trees growing on thinned sites were, on average, 3% lower in stiffness at each height in the stem.[57] However, Lowell *et al*. in a study on Douglas fir found no evidence to suggest that thinning reduces stiffness.[142] Wang *et al*. reported that medium pruning provided higher MOE values than unpruned or heavily pruning.[251,252] Carson *et al*. reported that trees in the unpruned 500 stems/ha treatment had larger DBH, lower outerwood density, and lower stress-wave velocity than trees in the 400 stems/ha pruned treatment.[248] The effect of fertilizer has also been studied with mixed reported results.[50,254]

Geographic location appears to play a role in the properties of wood. For example, Palmer *et al*. provide a map of the variation in density (related to stiffness) of radiata pine in New Zealand, where large differences can be observed with geographic location.[255] This variation has been suggested to be related to factors such as mean air temperature, rainfall, and soil chemistry such as total soil phosphorus.[50]

Genetics plays a large part in the properties of wood such as stiffness. Considerable effort is put into studies on improving the breeding stock. Acoustic techniques are, therefore, used to identify trees that have desirable characteristics such as high stiffness to be used for breeding. Many of these studies are performed on juvenile trees to enable outcomes of breeding trials to be obtained in a shorter time frame. Studies which have used acoustics to obtain stiffness measurements on juvenile trees include references.[12,44,143,144,160,177,213,256–267] Many of these have investigated the effect of stress such as tilting or drought. Investigations using acoustic velocity for more mature juvenile trees include references.[12,268–275]

VII. CONCLUSION

This paper provides a review on the use of acoustics for measuring the stiffness of standing trees and felled logs. The elastic properties of wood and how these relate to velocity were presented. Other factors which influence the speed of sound in wood are described. This is reported to include the type of waves, which propagate in tree stems or lumber. Variations in stiffness and acoustic velocity with location in trees were outlined. Acoustic methods and tools used to measure stiffness and their errors were discussed. Ideas on differences between tree and log acoustic measurements and potential corrections were then presented. More study on acoustic or ultrasonic guided wave in logs/tree stems could provide a better understanding of the wave propagation and potentially help to obtain improved formulas for calculating the stiffness of tree stems. Additional techniques, which can be used in conjunction with acoustics, are briefly discussed. An overview was then provided of studies relating to the effect of silvicultural practices, geographic and environmental conditions, and genetics on acoustic velocity and hence stiffness.

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