Comparing usefulness of acoustic measurements on standing trees for segregation by timber stiffness

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Abstract

The paper presents a comparison of standard procedures to measure acoustic stiffness of standing trees and logs. The aim is to see how useful they are for predicting the properties of dry, sawn, timber for the purposes of resource segregation in industrial practice. Stress wave time-of-flight (TOF) measurements were made on 36 trees of four species. The TOF data were analyzed and compared with resonant frequency measurements made on cut logs and sawn dry timber, and, as the ultimate measurement, static stiffness measured by four point bending tests. A simplified model of segregation is used to examine the relative performance of the methods to sort the better grade timber; in this case defined by mean static bending stiffness. The research reveals that lengthening the TOF distance from 1 to 2 meters improves the performance for segregation in this case, particularly when segregating the higher stiffness proportion of the timber.

Keywords: resonance, time-of-flight, sawn dry timber, stiffness, grading, segregation, indicating property.

Introduction

Portable acoustic devices can be used for early segregation of timber, prior to making decisions about forest management, harvesting and processing into wood products. When segregating trees, it is less important that the acoustic measurement be a good predictor of the quality of the timber that can be made from that specific tree, than it is that the acoustic measurement can discern, specifically, the lower quality material that is unsuitable for timber. Therefore the common statistical comparisons of NDT methods, based on linear regression, are not so useful in comparing the actual practical performance of different NDT methods in industrial practice.

Acoustic tools currently used in forestry measure the speed of propagation of a sound wave in the wood, either by direct “time-of-flight” (TOF) measurement between two points (a technique which can be applied on standing trees, logs or sawn timber), or by impact excitation resonant frequency (which can be applied to logs and sawn timber, but not standing trees). The use of these techniques is particularly important in the UK, where stiffness is typically the limiting property when it comes to grading structural timber (Moore et al. 2011) and the ability to divert the lower stiffness timber to other markets at an early stage could reduce the cost of grading rejects after processing and drying.

It is already known that estimation of sawn timber quality can be achieved more successfully using the resonance of a log (Wang, 2013), but this can only be done after felling and cutting the log to length for a certain intended wood product. This study, aims to make better use of standing tree acoustic measurements in making decisions about the most appropriate end products. The method commonly used in research and industrial practice, measures the TOF of a stress wave between transducers, which for practical reasons are usually about 1m apart on the same side of the tree at about breast height. However, the correlation between the TOF measurements made on individual trees and the stiffness of the timber cut from those trees is often weak. It has previously been suggested that this is because the short measurement distance of only 1m is not representative of the wood stiffness throughout the log and that a ratio of tree diameter to measurement length should be 0.1 or below (Zhang et al. 2011). The implication here is that if the measurement is over too short a distance, or the distance is not standardized, the measurements are confounded by other factors such as tree age, diameter and sapwood depth.

This study, conducted as part of a PhD, compares the performance of different standing tree TOF measurements for segregation on the basis of wood stiffness, comparing also to log and timber measurements and the ideal standard of a “perfect” machine simulated by use of the measured static stiffness (the best possible performance). The research is ongoing, but there is already sufficient data to make some preliminary recommendations for best practice standing tree measurement in the future.

Material and methods

This study uses material from four tree species, noble fir (*Abies procera*), western hemlock (*Tsuga heterophylla*), Norway spruce (*Picea abies*) and western red cedar (*Thuja plicata*), grown in even-aged plantations in Scotland, UK. For the exercise in this paper, the species are treated together, even though this would not normally happen in industrial practice because the species have different properties. This was done in order to provide more data over a wider range of wood stiffness.

Three trees were selected from three replicate plots for every species covering the range of diameter classes in each plot. Multiple TOF measurements using a Fakopp Tree Sonic device were collected on each of the 36 trees (nine per species), with a fixed origin over a measurement distance of 1, 2 and 3m on the north facing side (0 to 1, 0 to 2, and 0 to 3 in Figure 1). Further arrival times are compared on the south facing side of the tree with vertical distance between the transducers of 1m (A to B in Figure 1).

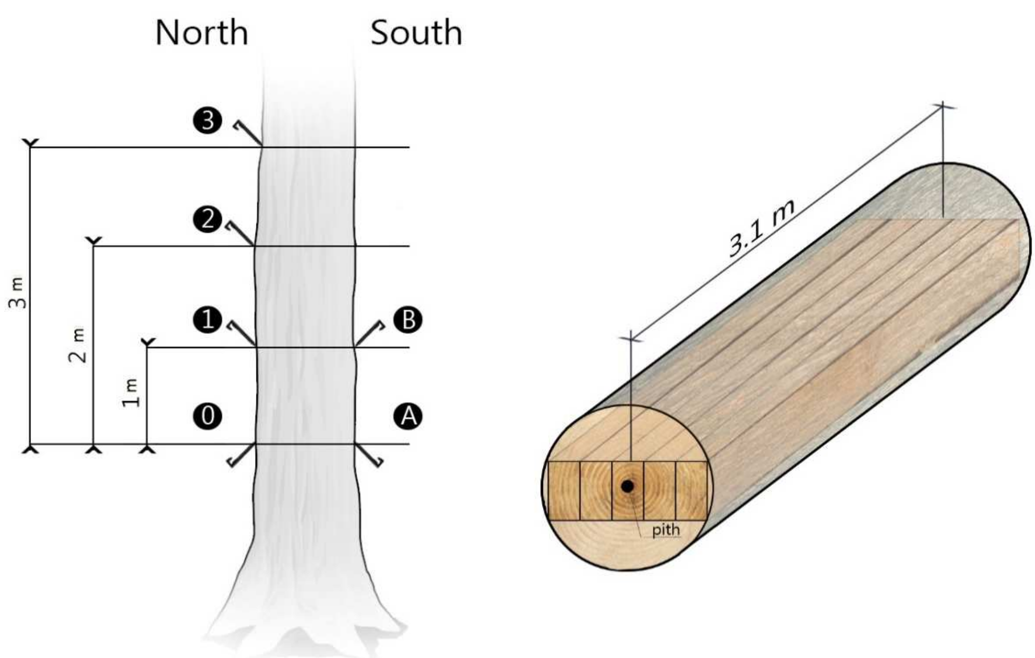

Figure 1—Left: Representation of TOF measurements collected per tree: 0-1; 0-2; 0-3; and A-B. Right: Cutting pattern of structural timber.

The trees were shortly after felled, and longitudinal resonance velocity of the logs (one per tree) measured with a HM-200 “Hitman” (Fibre-gen, Auckland, New Zealand). For the log resonance measurement the log length was 5 m for all species except the western red cedar, which was 3.1 m.

Dynamic modulus of elasticity (MOE_{dyn}) was calculated from measurements of wave speed using equation (1):

$$MOE_d = \rho V^2 \qquad (1)$$

where ρ is the density and V is the speed of sound. In the case of TOF, V is calculated from straight line distance divided by time delay, and in the case of longitudinal resonance it is calculated from the frequency of the fundamental mode multiplied by the wavelength (twice the log or batten length). Wood density for standing trees and freshly felled logs was assumed to be 1000 kg/m^3 for all the trees.

Logs were next cross cut to 3.1 m length (retaining the lower part) and then processed into structural sized timbers, following a bark to bark pattern, with nominal cross sectional dimensions of 100x50 mm (Figure 1 right).These samples were aligned so as to match the orientation of the TOF measurements. The purpose of cutting bark to bark was to examine the radial trend in properties within the wider research project. This is not a normal industrial cutting pattern, but it is expected this will nevertheless provide good mean values per log. A total of 226 battens were obtained by this process: 47 noble fir, 51 Norway spruce, 61 western hemlock and 67 western red cedar.

The noble fir, Norway spruce and western hemlock material was kiln dried to 12%, whereas western red cedar was kiln dried to 20% due to the concerns over the risk of drying collapse for this species. The timber was then conditioned towards 12% and longitudinal resonance acoustic velocity was measured with a timber grading machine MTG960 (Brookhuis Microelectronics BV, Holland) with a connected balance to obtain whole batten density (in combination with manually measured dimensions). Finally, the specimens were subjected to destructive four point bending tests in accordance with EN408:2010, using a Zwick Z050 universal testing machine (Zwick Roell, Germany). The bending stiffness measurements used in this paper are the, as measured, “global” measurement adjusted to the reference conditions (12% moisture content), but not pure bending stiffness as in EN384:2010. Moisture content was measured by the oven dry method on the density samples cut from each batten immediately after testing. The measurements made with the MTG were not adjusted for moisture content (representative of a typical production scenario for this machine, grading a batch of timber within a moisture content range). Bending strength and density were also measured, but these data are not used for this paper.

For this paper, segregation means a process undertaken to sort trees and logs into categories based on wood properties. It can be used to improve grading of structural timber in the sawmill by diverting the lower quality material to other products so as to reduce grading rejects.

Like grading, segregation does not operate at the level of predicting the properties of individual trees or battens. Instead, segregation operates on the basis of predicting the characteristics of the portion of the population that passes a certain threshold “indicating property” (IP) measurement, which could be based on NDT, visual criteria, or category description.

Strength grading of structural timber is concerned with strength, stiffness and density, but this example is concerned only with stiffness. The reasons for this are simplicity, and because consideration of all three properties requires more data to work correctly, and may not work across a mix of species. Stiffness is the property that is most closely related to the acoustic measurements made, and it is also usually the critical (most limiting) property for production of graded timber in the UK. The relevant characteristic value for stiffness for this analysis is the mean of the static modulus of elasticity (after adjustment to 12% moisture content) of the timber passing the IP threshold.

The four species differed in average stiffness, so the most basic kind of segregation can operate on removal of species in ascending order of average static stiffness (Table 1). Any non-destructive measurement that performs less well than simple species segregation is not particularly useful.

In order that the NDT approaches can be compared to the simple species segregation, three grade targets have been defined to correspond with the result of the simple species segregation on this dataset with its particular ratio of species. The "low" grade has a target mean stiffness of 7947 N/mm^2, which corresponds to the result of removing the western red cedar. The "medium" grade has a target mean stiffness of 8358 N/mm^2, which corresponds to the result of also removing the noble fir. The "high" grade has a target mean stiffness of 8803 N/mm^2, which corresponds to the result of also removing the Norway spruce so that only the western hemlock remains. The low, medium and high grades are alternative levels of segregation (it is not segregation into three categories). NDT has the potential to outperform the species segregation because there is some overlap of wood stiffness within the species (even western red cedar contains some higher stiffness timber).

The best possible segregation that could be done is with an NDT machine that has perfect knowledge of the dry wood stiffness ("perfect segregation" being the equivalent of a "perfect grading machine", operating on trees rather than on battens as grading does), which can be simulated here because this has been measured. Real segregation approaches can be compared to the yield of perfect segregation to assess their performance.

Table 1—Summary of static bending stiffness for the four species

Species (in ascending order)	Mean static MoE [st dev] Adjusted to 12% mc (N/mm^2)	Mean moisture content at time of bending test (%)
Western red cedar (THPL)	6521 [1604]	12.0
Noble fir (ABPR)	6967 [1360]	9.3
Norway spruce (PCAB)	7826 [1426]	9.0
Western hemlock (TSHT)	8803 [2019]	15.7

Results

The correlation between the standing tree measurement and stiffness of the sawn dry timber is relatively weak. Figure 2 shows the apparent dynamic MOE calculated from the 1 and 3 m TOF measurements compared to the static MOE of the immediately adjacent (north side) batten (Figure 2, left) and the mean static MOE of all battens from that tree. The relationship is better for the 3 m measurement, and even more so for the mean static MOE of battens for that 3 m measurement. This is consistent with the wave propagating both up and outward, and not only through the sapwood in the outer part as Searles (2012) explains: "*when the excitation is initiated, the stress wave starts propagating both up toward the top probe and outward across the tree's cross section. It is not yet a plane wave but possibly, by the time it arrives at the top probe 1.0 – 1.5 m away, a measure of more of the tree's wood properties than simply the area directly between the probes*". The question to be answered is: are these correlations useful for segregation, and does the 3 m measurement afford any additional practical usefulness over the 1m measurement that would justify the additional effort required to make the measurement in practice.

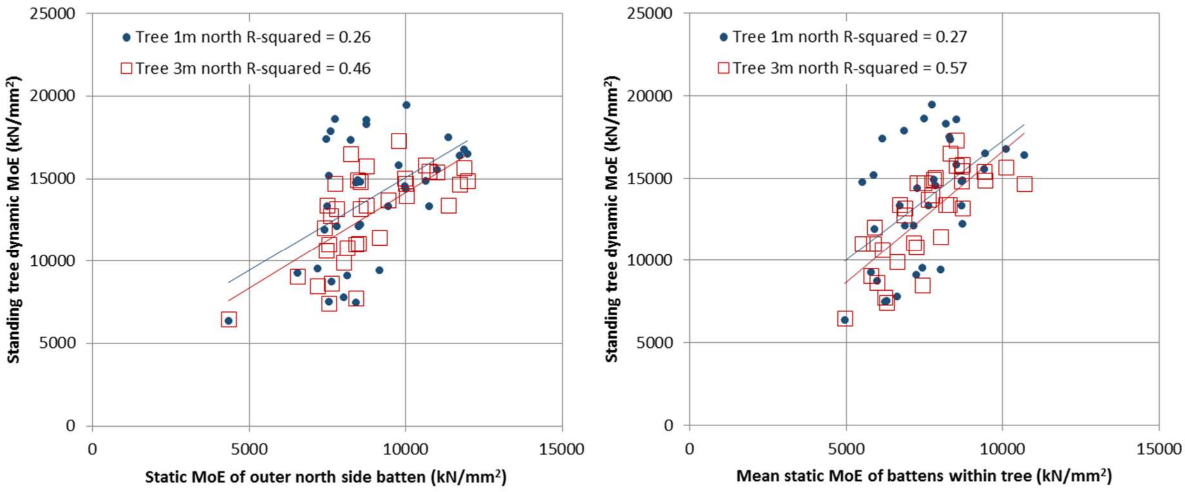

Figure 2—Comparison of 1m and 3m north side TOF measurements with the static MOE of the north side outer batten (left) and mean static MOE of all battens from the tree (right).

Correlation coefficients for each of the IP (indicating property) types against static MOE of individual battens are listed in Table 2. Ten segregation/grading approaches are assessed. This includes a perfect grading machine sorting individual battens (IP is static MOE) and perfect segregation sorting battens grouped by tree (IP is mean static MOE of battens within the tree), which are used as a reference to evaluate the effectiveness of the real world approaches.

Table 2—Effectiveness of different acoustic measurements to segregate timber.

Indicating property	R^2 vs Static MoE (note 1)	Segregation to "Grade" (note 2) Yield as a % of the perfect method yield [absolute yield %] Low	Medium	High
On standing tree / log				
Sorting by species	-	88% [70%]	79% [50%]	67% [27%]
1m TOF north side	16% (27%)	88% [70%]	51% [32%]	0% [0%]
1m TOF north & south	18% (31%)	92% [73%]	48% [30%]	0% [0%]
2m TOF north side	27% (50%)	88% [70%]	86% [54%]	80% [32%]
3m TOF north side	31% (57%)	92% [73%]	88% [55%]	47%* [19%]
Hitman velocity of log	35% (63%)	94% [76%]	79% [50%]	95% [38%]
Perfect tree segregation (mean)	*53% (100%)*	*100% [80%]*	*100% [63%]*	*100% [40%]*
On sawn dry timber				
MTG frequency only	63%	97% [84%]	96% [69%]	88% [49%]
MTG frequency & density	91%	99% [86%]	99% [71%]	94% [52%]
Perfect grading machine	*100%*	*100% [87%]*	*100% [72%]*	*100% [56%]*

Note 1: The R^2 value relate to correlations on a batten by batten basis. Values based on the mean of batten MOE per tree given in brackets

Note 2:Standing tree / log IP yields are compared to perfect tree segregation, batten IP (i.e. MTG) yields are compared to the perfect grading machine

* nearly achieves 89% [36%] (being just 0.4% short of the required mean stiffness at this yield)

Figure 3 shows the outcome of the thresholds of the different IPs being progressively increased to segregate the higher stiffness timber, described by the mean static stiffness of the timber passed (y-axis) and the simple proportion of the battens passing (x-axis). The figure also shows the MTG operating in frequency only mode on the battens, and in frequency plus density mode, the latter of which is close the performance of the perfect grading machine – indicating a high performance of this approach to grade timber (as expected when the only grading criteria is stiffness, as in this example) and also confirming that the relationship between dynamic and static stiffness is suitably similar for all species for the purposes of this analysis. Segregating trees cannot perform as well the (real or perfect) grading machine because the trees contain substantial variation of wood stiffness within them, but it can be seen that the perfect tree segregation works better than simple segregation by species - a near trivial kind of segregation in practice. Segregation by Hitman (log resonance) works better than by species, but not as well as perfect tree segregation.

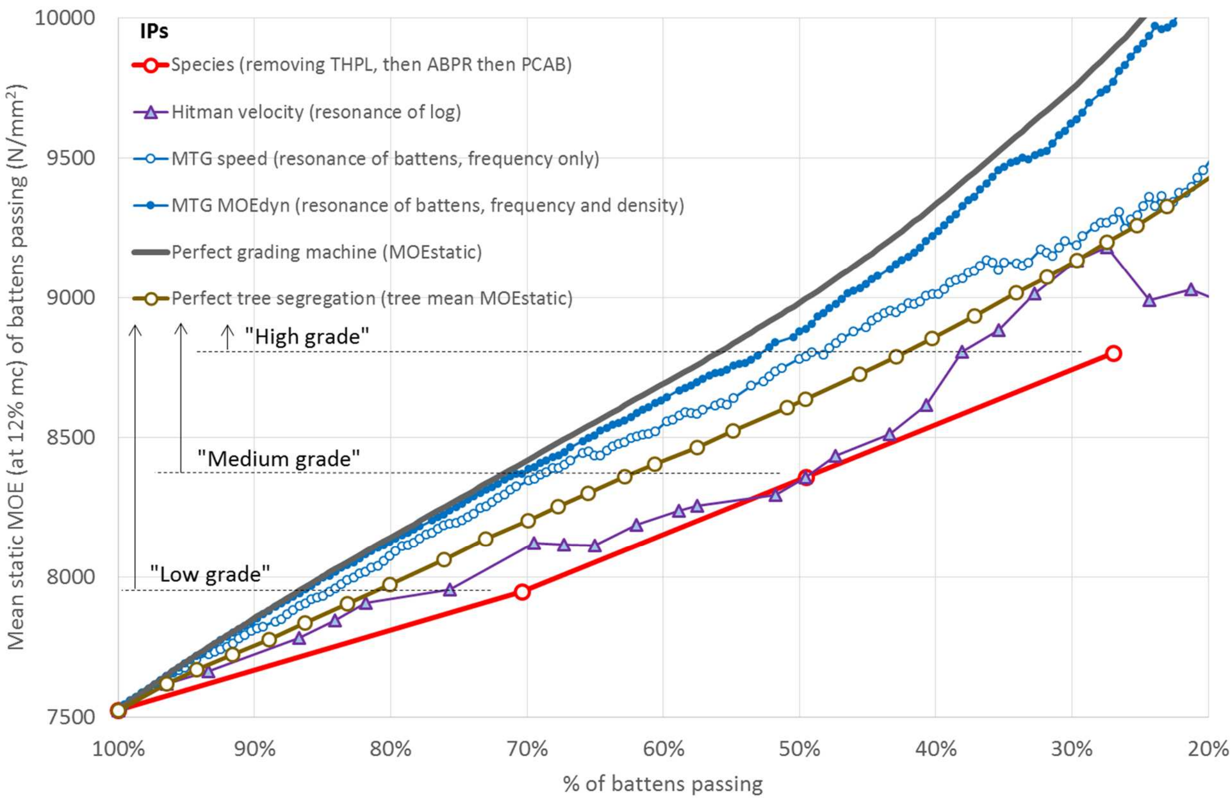

Figure 3—Segregation performance (for static stiffness) of the perfect grading machine, perfect tree segregation, MTG, Hitman, and simple species approach.

The performance of the standing tree measurements is shown in Figure 4, which indicates that the 2 and 3 m TOF measurement outperform the 1 m TOF measurement, except when segregation passes (approximately) more than three quarters of timber. When segregating the stiffest half of the timber, the 1 m TOF measurement performs less well than simple species segregation. This is consistent with the speed of stress wave propagation in trees being more similar to log resonance when TOF is made over more than a meter. This suggest a larger influence of the properties of the entire cross section as the distance increases rather than solely the outer part of the tree. In line with previous research, it is consistent with a change in the wave behavior from a dilatational or quasi-dilatational wave with short spans, to a one dimensional plane waves with longer spans (Wang et al. 2007; Andrews, 2003).

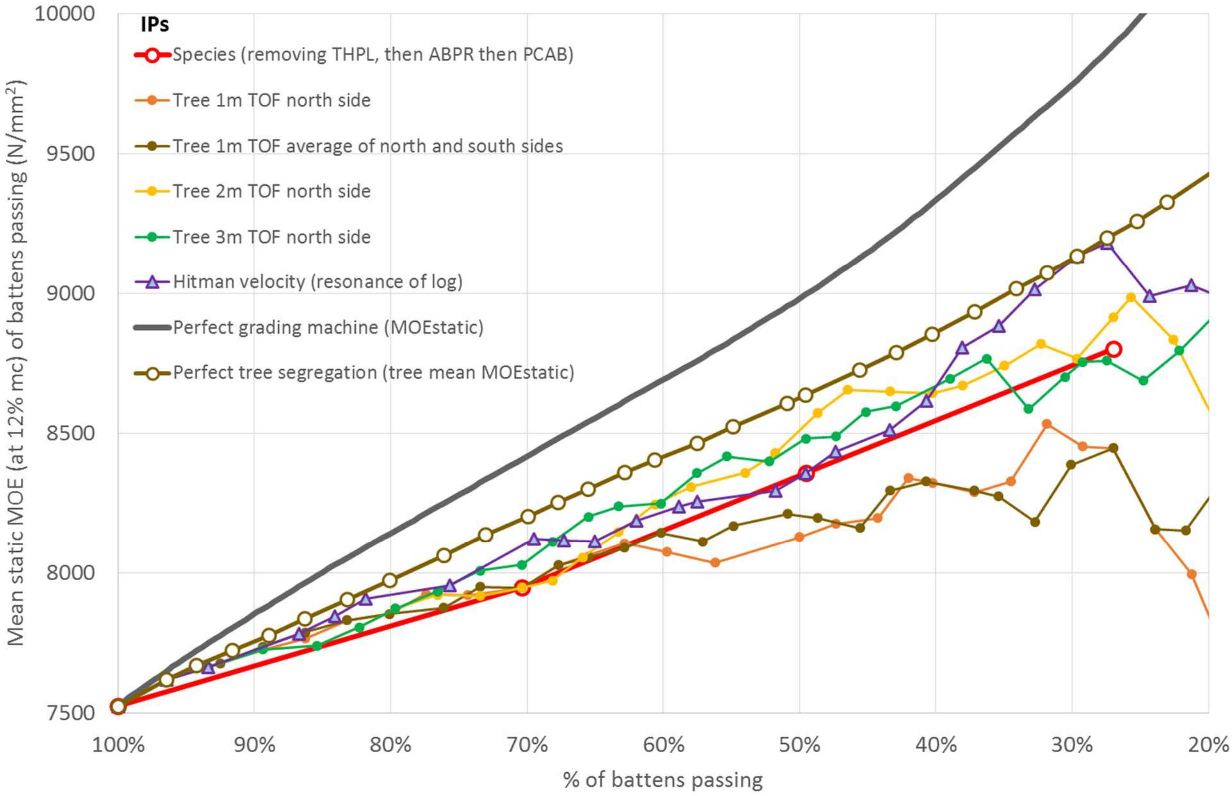

Figure 4—Segregation performance (for static stiffness) of the standing tree TOF measurements, compared to the simple species approach and perfect segregation.

To better illustrate the relative performance, three ‘grades’ were created that are equivalent to what is obtained by a simple species sort. The ‘low’ grade has a mean stiffness requirement equal to that of the timber when western red cedar is removed, ‘medium’ when noble fir is additionally removed, and ‘high’ when only western hemlock remains (see materials and methods above). Table 2 lists yields for these grades (when segregation to one grade only) expressed as a percentage of the yield obtained by the perfect segregation (in the case of the tree and log IP) and the yield of the perfect grading machine (in the case of the MTG, which operates on sawn dry timber rather than logs). The 2 and 3 m TOF measurements on the trees are seen to be similarly good, superior to simple segregation by species, and almost as good as resonance measurements on the logs. The case of the 3 m TOF yield for the high grade is special in that it very narrowly misses the required stiffness with a much higher yield (see table footnote), which is likely a random statistical effect of the low number of specimens for the high grade and an under representation of the performance.

Conclusions

As expected, the tree measurements are not as good as the log measurements, especially when the measurement distance is the usual 1 m. Increasing the measurement distance to 2 m is sufficient to add useful segregation potential, although, in this example, even a 1 m measurement performs as well as other standing tree measurements when it is desired to sort only the lower quarter of the timber.

Despite the variability of wood properties within a tree, the use of portable acoustic tools can help to segregate timber from standing trees and logs, and the correlations need not be strong if the requirement is only to segregate out the very worst timber. By establishing relationship between an indicating property and characteristic grade-determining property (which will depend on growth area and species) it is possible to set thresholds that would improve grading machine yields later down the line, and divert the less good timber to non-structural products.

This study also provides confirmation that stress wave do not travel only in the outer part of the tree, between the two probes, but likely up and across the tree's cross section with increasing measurement length.

Future work will take this approach further, adding more data to bring in consideration of cutting pattern, the performance within a single species, consideration of strength and density, and the more direct avoidance of machine grader rejects.

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