Implementing Resonance-Based Acoustic Technology on Mechanical Harvesters/Processors for Real-Time Wood Stiffness Assessment: Opportunities and Considerations

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ABSTRACT

Acoustic technology has been successfully used as a non-destructive technique for assessing the mechanical quality of various wood products and species based on stiffness. Many mechanical harvester/processor manufacturers have implemented mechanical sensors to measure tree diameter and length as well as optimal bucking algorithms on their equipment. There is a growing interest in incorporating technologies for measuring internal stem features into a harvester head. The objectives of this study, therefore, were to i) determine and investigate the factors arising from incorporating acoustic instruments on a mechanized harvester head that might influence resonance-based acoustic signal and velocity readings and quality in Douglas-fir, and ii) investigate the issues and considerations associated with suggested working strategies in regard to harvest productivity impacts and processing decisions.

After taking into account some feasibility considerations, it was determined that the hold of the machine grapple would not compromise the accuracy of resonance-based acoustic velocity readings. There were three working procedures suggested for measuring resonance-based acoustic velocity: 1) after the stem is delimbed and run through the measuring equipment, 2) once a portion of the stem is measured and the length of its unmeasured portion is forecast, and 3) after the tree is felled by the harvester but before any further processing is done.

Regardless of the working procedure, it was determined that logs produced from lower sections of the tree are stiffer than those from upper portions. If the processor head traverses the stem partially or completely, the removal of bark and branches and their effect on acoustic velocity readings should be taken into account. Forecasting routines could be developed to account for imperfect and even non-existing information about tree length with the second or third working procedure. Results yielded by the two methods used for stem height (and consequently acoustic velocity) prediction in this study (linear regression model and a *k*-nearest-neighbor) were considered rather promising. Testing feasibility concerns with the resonance-based acoustic technique were observed if the entire stem was intact to the very top offshoot bud.

Keywords: *Douglas-fir, dynamic modulus of elasticity, sound velocity, veneer quality, mechanized harvesting*

Introduction

Wood quality can be defined according to attributes that make wood valuable for a given use by society (Gartner 2005). Traditionally, tree species, log dimensions, and external quality characteristics such as knot size and distribution, sweep, taper, scarring, and decay have been used to specify a particular log-type. In recent years, however, mills and markets have begun to include wood properties such as stiffness, strength, density, spiral grain, extractives content, and consumption of energy for processing (Andrews 2002, So et al. 2002, Young 2002). These additional potential specifications add extra complexity to the already complex task of log production and sorting. Technologies capable of capturing internal log features such as microwave, X-ray, computer-aided tomography, ultrasound, near-infrared (NIR) spectroscopy, and nuclear magnetic resonance (NMR) have been investigated for their potential for log scanning (Schmoldt et al. 2000, Rayner 2001, So et al. 2004, Acuna and Murphy 2006) in sawmills.

Wood modulus of elasticity (MOE), an indicator of wood stiffness, is an important mechanical property and is the most frequently used indicator of the ability of wood to resist bending and support loads (Faherty and Williamson 1998). Stiffness in raw timber material is highly variable and dependent upon site, genetics, silviculture, and location within the tree and stand. It has long been recognized as a critical product characteristic in both solid wood and pulp and paper processing (Eastin 2005). It is a particularly important parameter in the conversion of raw timber material into veneer and plywood products, which require wood with high stiffness. With the ever growing use of engineered wood products, such as roof trusses and laminated veneer lumber (LVL), the demand for lumber and veneer with a high MOE has increased.

For many years, the sawmilling industry has utilized acoustic technology for lumber assessment and devices such as the in-line commercialized Metriguard® stress-wave grade sorter

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(Metriguard, Pullman, WA). Acoustic nondestructive testing (NDT) instruments have been successfully used for the evaluation of mechanical properties of various wood products (structural lumber, poles, pulp logs, decay detection, etc.) and species as well as in tree selection and breeding based on stiffness (Huang et al. 2003). Compact and easy to use acoustic NDT tools are based on acoustic principles that have been developed for measuring the stiffness of both logs and standing trees (Dickson et al. 2004). Dynamic MOE is a function of wood density and the velocity of an acoustic wave travelling through the wood (MOE_{dyn} = density × velocity^2). Velocity^2 is often the more variable of the two parameters. The most widely implemented acoustic techniques among industry and researchers are the time of flight (TOF) technique for standing trees and resonance-based technique for logs (Lindstrom et al. 2002).

In simple terms, for the TOF technique, two sensors are inserted a known distance apart into the tree stem and the time for a single acoustic signal to travel from one sensor to the other is recorded. For the resonance-based technique, a sensor is placed at one end of a log with a known length and the time for multiple reverberations of an acoustic signal which travels longitudinally to the other end of the log and back again is recorded. For both techniques velocity can be calculated from distance and time measurements. According to Wang et al. (2007a) who describe these techniques in more detail, "the accuracy of TOF measurement depends on accurate identification of the arrival times of [a single] acoustic wave signal, each from a start sensor and a stop sensor". The same authors also claim that the inherent accuracy of the "resonance-based" method presents a substantial advantage over a TOF system in log measurement applications, because, in contrast to TOF, the resonance technique stimulates many acoustic pulse reverberations, resulting in a very robust and repeatable velocity measurement.

While researchers around the world are in general agreement about the merits and significance of the resonance-based acoustic instruments and their potential applications for a variety of tree species and products (Ross et al. 1997, Huang et al. 2003, Joe et al. 2004, Wang et al. 2007b, Amishev and Murphy 2008), past research have reported mixed results in regard to the TOF acoustic tools. Coefficients of correlation R^2 ranging from 0.01 to 0.44 (Matheson et al. 2002, Joe et al. 2004) have indicated low predictive capabilities while Grabianowski et al. (2006) and Wang et al. (2007a) suggested that the TOF technique may be used with confidence to derive equivalent lumber stiffness values with R^2 reported in the range of 0.71 to 0.93. In terms of TOF average acoustic velocities for Douglas-fir, findings by Wagner et al. (1998, cited in Wagner et al. 2003) and Amishev and Murphy (in press b) indicate that the TOF method may be of limited value in the efforts to identify standing tree quality in regard to veneer stiffness parameters. In contrast to the robust and repetitive measurements yielded by resonance-based acoustic tools for a particular tree, the TOF acoustic instruments have been reported to produce readings with substantial inherent variability both between sides of the tree/log and between hits within each side of the tree/log and even between different devices from the same manufacturer (Toulmin and Raymond 2007, Mahon et al. in press, Amishev and Murphy 2008).

Worldwide forest harvesting has become increasingly mechanized during the last few decades. This is especially true where harvested tree size is decreasing and the capability of one or two machines to fell, delimb, buck, and sort a tree or a group of trees is an appealing advantage. This trend toward mechanization of forest harvesting operations is observed for various forest types, terrains, and climatic conditions (Raymond 1988, Nordlund 1996, Godin 2001) leading to near elimination of motor-manual felling in thinning operations and continuously increasing sales of harvesters and processors. Drivers for this shift from the traditional motor manual harvesting systems to mechanical harvesting systems generally include productivity/cost improvement goals or labor-related issues. Among other things, mechanization also provides a platform for innovative measurement systems which could lead to improved log segregation based on a wider range of wood properties (Murphy 2003a).

Most modern mechanical harvesting systems use mechanical sensors, some combining these with photocells to measure diameter and length (Andersson and Dyson 2002). Many mechanical harvester/processor manufacturers have also implemented optimal bucking algorithms on their equipment. While operators can visually assess changes in quality along the length of each stem, they are incapable of evaluating internal wood properties without the assistance of a proper scanning technology. To produce accurate optimal bucking decisions, these systems require accurate and detailed information on stem shape and quality characteristics. According to the breakeven values reported by Marshall and Murphy (2004), substantial investments could be made in improved stem scanning systems.

There is a growing interest in incorporating technologies for measuring internal stem features into a harvester head (Carter and Sharplin 2006). Ongoing research efforts are addressing potential challenges, opportunities, and considerations from installing NIR and acoustic instruments on mechanized harvesters (Murphy et al. 2007, Carter 2007). These preliminary reports indicate that, despite a number of influential factors and working protocol uncertainties, there is a great potential for these technologies to demonstrate reliable performance, and logs produced using harvesters/processors could be segregated for internal wood quality in the forest.

In regard to incorporating acoustic technology into a harvester head, either of the two techniques, TOF or resonance, could be used. Findings by Mahon et al. (in press) suggest that placing the two probes on either side of the tree instead of longitudinally on the same side may result in reduced variability and increased confidence in TOF acoustic readings. The TOF technique also does not require stem length information prior to gathering acoustic data. This is likely the reason for Carter (2007) to evaluate the performance and endeavor to improve a TOF prototype device (Director PH330) installed on a harvester head. The resonance-based approach, in contrast to the

TOF technique, would require stem length information to ensure accurate measurements. This may necessitate measuring the entire stem before an acoustic reading is taken resulting in double handling with considerable consequences for machine productivity and costs. The consistency of resonance acoustic readings and their strong correlation with veneer recovery, at least for Douglas-fir logs (Amishev and Murphy in press), supports study of the potential implications from incorporating resonance-based acoustic technology into a mechanized processor/harvester for real-time wood stiffness assessment. The resonance-based approach is the focus of the remainder of this paper.

Only a small number of research studies, all of them focusing on external stem features, have investigated the use of scanning technology with mechanical harvesting equipment (Tian and Murphy 1997, Löfgren and Wilhelmsson 1998, Möller et al. 2002, Murphy 2003b, Marshall and Murphy 2004) and the best procedures for scanning and optimal bucking with mechanized harvesters (Berglund and Sondell 1985, Näsberg 1985, Liski and Nummi 1995). There are three working procedures suggested in those studies that would also be applicable for performing acoustic measurements:

1. The first procedure would involve the complete delimbing and shape scanning of the stem after the tree is felled and subsequently performing the acoustic measurement for stiffness quality characterization of the tree. This method would guarantee a good-quality acoustic result but would require the harvester head to traverse the entire length of the tree at least twice (three times if it has to start processing from the butt) which would have considerable consequences for machine productivity and costs (Murphy 2003a, Marshall and Murphy 2004).
2. The second procedure involves delimbing and measuring a portion of the stem and forecasting the taper of its unmeasured portion for length estimation. Based on the forecast length to the top of the stem, an acoustic measurement would be performed. The acoustic measurement may be affected by the presence of branches on the undelimbed portion of the stem. Berglund and Sondell (1985) reported that, using this strategy, productivity impacts could be reduced and value losses minimized. Näsberg (1985) found that loss in value due to incomplete information was less than 2 percent using a similar forecasting procedure. Work by Murphy (2003b) later expanded by Marshall and Murphy (2004) suggested that automated partial scanning methods coupled with stem dimensions forecasting and optimization equipment have a great potential in achieving optimal value from every stem.
3. The third procedure involves measuring the acoustic velocity after the tree is felled but before any further processing is done. This method would inherently entail imperfect and even non-existing information about tree length, as well as acoustic measurements of undelimbed stems. Scandinavian researchers Liski and Nummi (1995) developed a linear mixed model that used data from previous stems plus a number of known measurements on the current stem for predicting stem curve characteristics in Norway spruce. They found that value losses decreased as the length of the known portion of the stem increased. Studies performed on Scots pine in Sweden (Möller et al. 2003) and Finland (Nummi and Möttönen 2003) on prediction models for accurately forecasting a number of wood quality characteristics during the stem processing operation also yielded promising results. With no scanning, tree height has to be predicted based on already available information from previously processed trees and measurements acquired while the tree is being felled, such as diameter at breast height (DBH) or butt diameter.

The objectives of this study, therefore, were to i) determine and investigate the factors arising from incorporating acoustic instruments on a mechanized harvester head that might influence acoustic signal and velocity readings and quality and ii) investigate the issues and considerations with these working strategies in regard to harvesting productivity impacts and processing decisions.

Materials and Methods

Study Sites and Data Collected

During the summer of 2006, six Roseburg Forest Products company (RFP) stands, located in the Coastal (A – near Bellfountain, D and E – near Elkton, and F – near Lorane,) and Cascade (B – near Sutherlin and C – near Tiller) Ranges of Oregon, were harvested as part of two studies evaluating novel technologies for in-forest measurement of wood properties. In the summer of 2007, a seventh stand (G – near Corvallis), located within Oregon State University's McDonald-Dunn College Forest, was also harvested as part of these studies. All of the sites were second-growth Douglas-fir stands of similar age class (50 to 70 years) chosen to cover a range of elevations and tree sizes (**Table 1**). Site G had been commercially thinned on three occasions. Sites A to F had no commercial thinning but may have received a pre-commercial thinning. Two hundred trees from each stand were sampled, totaling 1,400 trees converted into

Table 1. ~ *Characteristics of the seven study sites.*

Site	Site elevation	Stand age	DBH range of trees selected[a]	Latitude/longtitude of site
	(m)	(yr)	(mm)	
A	180	62	193 to 968 (522)	44° 24.04′N / 123° 23.24′W
B	900	66	165 to 696 (363)	43° 22.58′N / 123° 03.54′W
C	1040	56	175 to 790 (506)	42° 58.56′N / 122° 48.52′W
D	220	54	142 to 668 (395)	43° 40.09′N / 123° 43.19′W
E	120	51	155 to 594 (320)	43° 40.16′N/ 123° 44.58′W
F	290	53	163 to 772 (389)	43° 48.40′N / 123° 18.34′W
G	280	72	150 to 785 (416)	44° 42.55′N/ 123° 19.58′W

[a] Average DBH in parentheses.

more than 3,000 logs. Only veneer grade log lengths were cut (18, 27, and 35 ft or 5.5, 8.2, and 10.7 m, respectively); no sawlogs or pulp logs were produced. Prior to felling, each tree was numbered for unique identification and DBH was measured and recorded.

After felling, measurements included: total tree length (if broken the tree length was measured to the point of breakage), merchantable length, biggest branch diameter on each 20 ft (6.1 m) segment of the tree, acoustic velocity of the whole stem with and without the branches (using the Director HM200® tool), and acoustic velocity of each log made out of the stem. A subsample of 40 randomly selected trees was used to evaluate the impacts of harvesting equipment on acoustic velocity readings when a tree/log was in the grip of a processor/loader grapple. Sound velocities (using the Director HM200 tool) on these trees and each of the subsequently produced logs were measured both in the grip of a harvester/loader grapple and on the ground with no contact to harvesting equipment.

After the in-forest measurements on the logs were completed, the logs were transported to a veneer mill, debarked, cut into 8 ft (2.4 m) bolts, kiln-heated, shape scanned, and peeled into veneer sheets. The sheets were then scanned for defects and moisture, sorted into moisture classes, dried, and sorted into several veneer grades (G1, G2, G3, AB, C+, C, D, X, and XX) based on in-line acoustic measurement of wood stiffness using the Metriguard® grade sorter. Percent veneer recovery in all grades was calculated.

Acoustic Velocity Measurement Tools and Harvesting Equipment

The longitudinal wave velocity in logs was measured using a resonance based acoustic tool (Director HM200®, CHH Fibre-gen, New Zealand) described by Wang et al. (2007a).

Various pieces of harvesting equipment were used to evaluate the "grapple effect" on acoustic readings for the seven stands studied with the same machine being available and used throughout each particular site. Track-mounted knuckleboom loaders were used in sites A, B, and C. Sites D and E utilized a rubber-tired truck-mounted knuckleboom loader. Waratah processor heads mounted on tracked carriers were used in sites F and G.

Data Analysis

Statistical analyses of the data were undertaken following either a simple linear least squares regression analysis or a stepwise multiple regression methodology described by Ramsey and Shafer (2002). They included the following steps: graphical analysis of the data, examination of the correlation matrix, fitting of the linear model, exploration of the residuals, significance test of the variables, and improvement of the final regression model. Mean separations were examined using Fisher's least significant difference method. Both SAS® 9.1 statistical software (SAS 2004) and the Data Analysis Tool Pak of MS Excel were used for the analysis. A p-value of 0.05 was defined as the threshold for determining significance of explanatory variables. Potentially influential points were identified using both the Cook's Distance diagnostic and the studentized residual statistic test (cutoff value of 3) in SAS 9.1.

Two methods were used for stem height (and consequently acoustic velocity) prediction: a random coefficient regression model (R) and a k-nearest-neighbor (NN) prediction. For this purpose, a sample of 100 trees from each stand was designated as the training data set (TDS) and used to predict the stem height value for each of the remaining trees in that stand, referred to as the validation data set (VDS). The first method consisted of developing a linear regression model from TDS with tree height (or a function of it) being the response variable and DBH (or a function of it) being the explanatory variable. The model was then applied to predict tree height from DBH data in VDS and adjust acoustic velocity values by the predicted-to-actual tree height ratio. The NN approach involved locating the k closest members (the k-nearest-neighbors) of TDS in terms of DBH, calculating the weighted average of the corresponding tree heights, and using that value as the predicted tree height based on the DBH value for each tree in VDS. Acoustic velocity was then adjusted in the same manner as with the regression method.

Results and Discussion

Stand A produced the largest number of logs totaling 572 while Stand G yielded the least with 353 logs; the average log length was 9.2 m ranging from 8.5 m for Site F to 9.5 m in Site B; HM200 acoustic velocity averaged 3.77 km/s throughout the 3,077 total logs and ranged from 2.73 to 4.69 km/s (**Table 2**). Detailed information regarding the variation and distributions of log lengths and HM200 acoustic velocities for this study is presented in Amishev and Murphy (2008).

The apparent difference between hand-held acoustic tools and their potential counterparts integrated into a harvester head is the fact that in the latter the tree/log would be in the grip of a metal grapple. One of the challenges pointed out by Carter (2007) in regard to the TOF instrument is capturing good quality signals while the chainsaw is operating; this would certainly be an important consideration with a resonance-based tool as well. Considering similar factors in our study, the relationship between acoustic velocities in the grip of a harvester/loader

Table 2. ~ *Log summary statistics for the seven research sites.*

Study site	Total log count	Average log length	HM200 acoustic velocity		
			Average	Minimum	Maximum
		(m)	------ (km/s) ------		
A	572	9.4	3.92	3.03	4.58
B	399	9.5	3.77	2.80	4.69
C	458	9.2	3.46	2.73	4.23
D	447	9.2	3.76	2.98	4.63
E	395	9.3	3.84	2.88	4.48
F	453	8.5	3.82	2.96	4.47
G	353	9.3	3.77	2.78	4.32
Overall		9.2	3.77	2.73	4.69

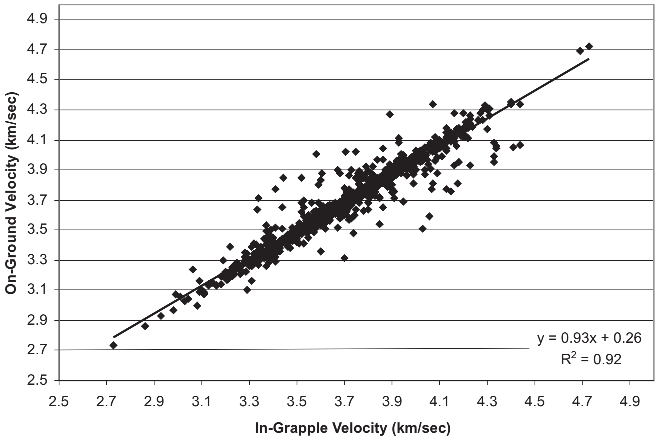

Figure 1. ~ *Relationship between acoustic velocities in the grip of a harvester/loader grapple and those on the ground with no contact to harvesting equipment for seven study sites in Western Oregon.*

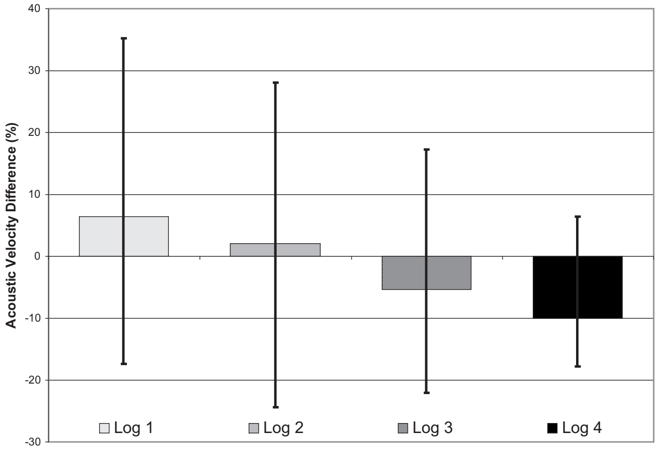

Figure 2. ~ *Average percent difference between whole tree acoustic velocities and those measured on each subsequent log produced from that tree. The "error bars" represent the range in percent difference for each log.*

grapple and those on the ground with no contact to harvesting equipment was investigated (**Fig. 1**). Yielding a significant linear model with an R^2 of 0.86, acoustic velocity readings in the grip of a metal grapple were found to be strongly correlated with acoustic velocities measured on the same tree/log laid on the ground. Potentially influential data points were identified and, after examining those, 15 out of the total 889 observations were identified as outliers and removed from the sample based on additional indications (lower confidence for acoustic readings and sampling errors) regarding the validity of those measurements. The resultant model yielded an R^2 of 0.92 meaning that the hold of the grapples does not compromise the accuracy of the resonance-based acoustic velocity readings. Although not recorded and investigated, during the study it was observed that in several cases lower confidence readings (and sometimes no readings) were produced by the Director HM200 tool while the tested specimen was in the grapples. A slight release in the strength of the grip or changing the grip position to further up the length of the tree/log was needed to warrant a good-quality signal. These factors should be taken into account in designing an acoustic device to be incorporated into a harvester head for real-time stiffness-based wood segregation in the forest.

Another aspect to be considered which is valid for all three working procedures is the effect of tree structure on stiffness. In other words, is it possible to predict stiffness characteristics for each of the logs to be produced from a tree based on a single measurement for the whole stem? The correlations between whole tree acoustic velocity readings and those taken on the logs produced were statistically significant and quite strong (R^2 ranged from 0.60 to 0.72) for all of the logs along the stem. The analysis revealed that acoustic velocities of logs produced from different sections of the tree are unequal and, on average, the butt log had the largest acoustic velocity relative to that of the whole tree (6.4% higher). It decreased in each subsequent log along the length of a tree stem and the topmost log had 10 percent lower velocities than the whole tree (**Fig. 2**). Studies on radiata pine (Xu and Walker 2004) have found that a low-stiffness wood zone forms from the base to about 2.7 m tree height. Edlund et al. (2006) report similar findings for Norway spruce. Other research suggests this might be valid for Douglas-fir as well (Amishev and Murphy in press). This tree structure peculiarity should definitely be considered in designing an acoustic tester for a harvester head and is a valid consideration for any working procedure employed.

With the first two working procedures, if either a complete or partial scanning/processing is performed, any alterations to the stem by the harvester head should be considered in regard to their influence on acoustic velocity readings. One such alteration that was observed during this study is the partial and in some cases the near-complete removal of the bark from tree stems while delimbing and shape scanning is performed. This is especially true early in the growing season when increased sap flow is initiated through the cambial layer of the trees. Studies in radiata pine (Lasserre 2005) and Douglas-fir (Murphy and Amishev, in press) stands have reported that bark removal significantly increased acoustic velocity by on average 4.1 percent and 4.6 percent, respectively. This should be accounted for to achieve a superior bucking decision for maximum value recovery from each stem. The question remains to ascertain whether bark is consistently removed by harvesting equipment across different conditions and circumstances and whether a change in the design of the feeding wheels/cutting knives of the harvester head would benefit the handling of this variance.

With the second and third working procedure, the issue of unavailable or imperfect information may be overcome by forecasting the length of the tree stem based on other already available information about the particular tree and/or the stand of which it is a part. The two forecasting techniques, the regression model and the *k*-nearest-neighbor (NN) prediction, were evaluated. For the NN method, different values for the *k* parameter were explored, and $k = 5$ was applied for the final predictions. Increasing this parameter did not result in significant prediction improvements while values lower than $k = 5$ yielded substantially poorer results. In their practice, mills and forest products companies use cutoff values for acoustic velocity to segregate different quality logs and products. In this study, when a resonance-based acoustic velocity threshold value of 3.81 km/s (12,500 ft/s) for stiffness quality control is assumed, the seven sites would yield unequal numbers of good quality trees to be accepted for veneer processing (**Fig. 3**). The two prediction methods performed similarly to each other and followed the actual distribution trend in an adequate manner. Both methods underestimated the sites with greater proportion of good quality trees and overrated the mediocre sites. Similar results were observed with other acoustic velocity cutoff values (**Table 3**). The accuracy of the velocity predictions was evaluated by calculating root mean square error (RMSE) while the accuracy of the quality prediction was expressed as the percentage of trees for which quality, based on the 3.81 km/s cutoff value, was inaccurately predicted. On average, according to the RMSE values, the regression approach performed slightly better (**Table 4**), but incorrectly predicted the quality of 0.3 percent more trees than the NN method. Accurately predicting the stiffness quality of more than 70 percent of the trees sampled could be considered as rather promising. Any breakages along the stem should also be accounted for most probably by operator inputs while processing.

If the second working procedure involves producing a log from the partially scanned portion of the stem and acquiring an acoustic velocity reading on that log, this additional information could be used for predicting acoustic velocity of the logs to be produced further up the stem. Based on HM200 acoustic readings for the whole stem with the limbs still attached to the tree and velocity measurements for the first processed log, a linear regression model was developed for the prediction of acoustic speed of the second log (**Table 5**), yielding a coefficient of determination R^2 of 0.74. Adding the length of the first log (5.5, 8.2, or 10.7 m) as an indicator variable resulted in a slight improvement of the model with $R^2 = 0.77$. Also, if another measurement is taken on the second log produced, the acoustic velocity of the third log could be predicted including this additional parameter in the model (**Table 5**). In fact, the acoustic velocity value for the first log in this case was not a significant explanatory variable and upon its removal the resultant model yielded an R^2 of 0.79.

The presence of branches attached to the tree and their effect on acoustic velocity readings may be of great importance and must be considered should the second or third working procedure for stiffness measurements be adopted. In a congruent manner, Lasserre (2005) and Amishev and Murphy (in press) reported that acoustic velocity for radiata pine and Douglas-fir logs with the branches still attached was 2 to 3 percent lower compared to the velocity after they had been removed.

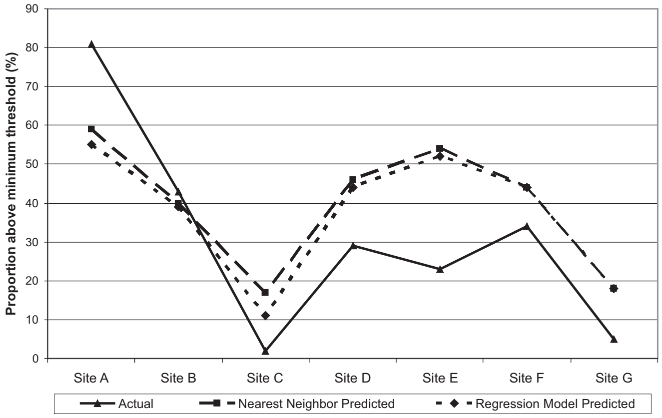

Figure 3. ~ *Percent trees above a hypothetical acoustic velocity threshold value for stiffness quality assessment from the validation data set (VDS) of the seven trial stands. The three curves represent the actual, k-NN and linear regression method predicted percent, respectively.*

Table 3. ~ *Proportion of trees (%) above a hypothetical acoustic velocity threshold value (km/sec) from the validation data set (VDS). The three forecasting methods are the actual (A) percent, k-Nearest-Neighbor (NN), and linear regression (R).*

Threshold velocity	Forecast method	Percent of trees above minimum threshold acoustic velocity						
		Site A	Site B	Site C	Site D	Site E	Site F	Site G
3.58	A	96	81	15	70	70	80	34
	NN	75	55	29	62	76	55	32
	R	74	57	17	60	69	56	29
3.73	A	87	60	7	49	39	52	16
	NN	63	46	21	49	59	49	23
	R	59	45	13	49	60	46	21
3.89	A	71	31	0	19	18	23	2
	NN	56	36	16	40	49	41	16
	R	48	31	9	40	49	39	13
4.04	A	37	12	0	8	4	8	1
	NN	44	29	11	33	39	32	7
	R	35	25	6	30	37	32	7
Number of trees in VDS		100	100	100	100	100	100	83

Table 4. ~ *The RMSE for the forecast acoustic velocity and the proportion of trees for which quality, based on a 3.81 km/sec cutoff value, was incorrectly forecasted by the k-Nearest-Neighbor (NN) and linear regression (R) method.*

Statistics parameter	Forecast method	OSU trial stands A	B	C	D	E	F	G	Overall
RMSE (km/s)	NN	0.643	0.692	0.588	0.687	0.683	0.715	0.583	0.660
	R	0.606	0.670	0.565	0.662	0.685	0.633	0.597	0.633
Incorrect prediction (%)	NN	28	40	17	35	35	30	18	29.3
	R	36	36	11	37	37	28	20	29.6

Table 5. ~ *Regression model between acoustic velocity for consecutive logs up the tree stem (response variable) and whole tree and previously produced log acoustic velocities (km/s) (explanatory variables).*

		Explanatory variables			
Predicted variable	Regression statistics	Intercept	Limbs on whole stem velocity	Log 1 velocity	Log 2 velocity
			------- (km/s)	-------	-------
Log 2 velocity (km/s)	Coefficient	0.16	0.62	0.318	--
	Standard error	0.0629	0.0238	0.02064	--
	t Stat	2.5395	26.0315	15.3836	--
	p-value	0.0112	7.64E-49	1.3E-118	--
Log 3 velocity (km/s)	Coefficient	-0.308	0.334	--	0.677
	Standard error	0.0893	0.0392	--	0.042
	t Stat	-3.4518	8.4922	--	16.1227
	p-value	0.0006	2.63E-16	--	6.1E-47

Another observation during this study which might play a crucial role in selecting a working procedure is the influence of the tree top on acoustic velocity readings. More explicitly, it was observed that if the entire stem was intact to the very top offshoot bud, resonance-based acoustic velocity readings could not be acquired or they had a low confidence level (not recorded). Severing the very top portion of the tree (up to at least 20 mm in diameter) was necessary to ensure a good quality acoustic velocity measurement. This might be due to the dissipation of the acoustic wave energy into the smallest offshoots and not rebounding back to the signal receiver. Many of the trees in the study had broken tops; although mechanized felling tends to reduce the incidence of breakage, it does not eliminate it, particularly in large trees. If resonance-based acoustics are to be used on harvester heads, work procedures will have to be developed for trees with unbroken tops. These could include procedures whereby the machine operator purposefully breaks a small piece of the top while handling the stem (in which case a stem height adjustment will need to be made), or the complete tree is delimbed, shaped scanned, and topped prior to an acoustic measurement being taken.

The research reported in this paper has primarily focused on the use of resonance-based acoustic technology for in-forest evaluation of internal properties of Douglas-fir trees/logs in terms of their veneer quality. There are number of factors to be accounted for if this technology is to be implemented on a mechanized harvester/processor for real-time stiffness evaluation and an optimal working method to be adopted with it. Some of them were identified and examined in this paper.

Conclusions

The objectives of this study were to determine the most suitable acoustic technique for segregating veneer quality Douglas-fir logs, to investigate influential factors in regard to installing such technology on a processor/harvester head, and to evaluate suggested working procedures based on feasibility and productivity considerations. Both the TOF and the resonance-based technique have advantages and disadvantages but research findings by others have suggested that the resonance-based acoustic method is a more reliable option in this particular case unless improved TOF instruments are developed and utilized.

Investigating the relationship between resonance-based acoustic velocities in the grip of a harvester/loader grapple and those on the ground with no contact to harvesting equipment revealed that the hold of the machine grapple would not compromise the accuracy of the resonance-based acoustic velocity readings with proper attention given to some feasibility concerns.

There were basically three working procedures examined:

1. Measure acoustic velocity once the stem is delimbed and run through the measuring equipment.
2. Measure a portion of the stem and forecast the taper of its unmeasured portion for length estimation. Based on this information an acoustic measurement would be performed.
3. Perform acoustic testing after the tree is felled by the harvester and before any further processing is done.

Regardless of the working procedure, it was revealed that logs produced from upper sections of the tree are less stiff than those from lower portions which is important if optimal bucking decisions based on stiffness are to be accomplished. If the processor head traverses the stem partially or completely, the removal of bark and branches and their effect on acoustic velocity readings should be taken into account.

If the second or third working procedure is selected, it would inherently entail imperfect and even non-existing information about external tree characteristics and particularly tree length. Forecasting routines could be developed to accommodate this issue and the two methods used for stem height (and consequently acoustic velocity) prediction in this study (linear regression model and a *k*-nearest-neighbor) were considered as rather promising. Feasibility concerns with the resonance-based acoustic technique were observed if the entire stem was intact to the very top offshoot bud. Stems with their tops intact would require the development of additional work procedures.

This research has significant implications for the mechanized harvesting of Douglas-fir stands. Further research needs to be undertaken to determine how broadly these findings and considerations can be applied. Much more work needs to be carried out to examine the costs, benefits, the technical feasibility, and economic viability of this challenging endeavor.

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