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CHALLENGES FROM INCORPORATING ACOUSTIC TECHNOLOGY ON MECHANICAL HARVESTERS/PROCESSORS FOR REAL-TIME WOOD STIFFNESS ASSESSMENT

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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. Previous research suggested that log stiffness grading based on acoustic velocity measurements could be used as a surrogate measure for potential net returns on such logs. 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.*

Ongoing research efforts, by ourselves and others, are addressing potential challenges, opportunities, and considerations from incorporating acoustic instruments on mechanized harvesters. Both resonance-based and time-of-flight based instruments are being considered and evaluated. Among other things we determined from trials undertaken in twelve Douglas- fir stands that:

- *the hold of the harvester grapple will not compromise the accuracy of acoustic velocity readings,*
- *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 will effect acoustic velocity readings,*
- *readings from the bottom portion of the stem could be used to predict acoustic velocity for the rest of the stem,*
- *prediction models may need calibration for individual stands.*

Working strategies with regard to harvest productivity impacts and processing decisions are suggested and discussed.

1. 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 additional characteristics to specify the logs they require with consideration now being given to such wood properties as stiffness, strength, density, spiral grain, extractives content, and consumption of energy for processing (Andrews, 2002). Good measurements and predictions of both the external and internal properties of the wood in each stem are essential to optimally match logs to markets. Assessing a forest stand's quality, determining its most appropriate use, time of harvest and processing technique, and consequently distributing the products to the right location are all important management decisions to achieve reduced costs and increased product values (Murphy et al., 2005).

Wood modulus of elasticity (MOE), also known as stiffness, is an important mechanical property and is the most frequently used indicator of the ability of wood to resist bending and support loads. Stiffness in raw timber material is highly variable and dependent upon site, genetics, silviculture, and location within the tree and stand. 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, have been widely used. Acoustic nondestructive testing (NDT) instruments that are compact and easy to operate have been developed and successfully used for 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). 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. The resonance technique stimulates many acoustic pulse reverberations, resulting in a very robust and repeatable velocity measurement while "the accuracy of TOF measurement depends on accurate identification of the arrival times of the acoustic wave signals, each from a start sensor and a stop sensor" (Wang et al., 2007). In regards to incorporating acoustic technology into a harvester head for real-time stiffness assessment, either of the two techniques, TOF or resonance, could be used. The TOF technique 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. Beta version TOF tools incorporated into a processor head enabling real-time optimization of log-making decisions are currently being trialed in operational conditions to validate performance (Peter Carter, pers. com.). Preliminary results suggest good operational feasibility and satisfactory performance. 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 & Murphy, 2008a), warranted a more detailed outline of the potential implications from incorporating resonance-based acoustic technology into a mechanized processor/harvester for real-time wood stiffness assessment (Amishev & Murphy, 2008b). Some machine manufacturers (Glen Murphy, pers. com.) are considering and testing resonance based acoustics to bounce a wave from a probe on the harvester back to the butt end of the log. These developments indicate the strong interest in acoustics by the machinery developers and the need for development of a variety of operational approaches and their detailed evaluation. Hence, 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 forecasted and (3) after the tree is felled by the harvester and before any further processing is done (Amishev & Murphy, 2008b). These authors determined and investigated the factors arising from incorporating acoustic instruments on a mechanized harvester head that might influence acoustic signal and velocity readings quality and also investigated the issues and considerations with the suggested working strategies in regards to harvesting productivity impacts and processing decisions.

In an ongoing research effort, in addition to further testing some of these previous findings, a study was undertaken to (a) determine the relationship between TOF acoustic velocity measured directly across a log in Douglas-fir and resonance acoustic velocity along the stem at that point in the log and (b) predict wood stiffness and acoustic velocity in Douglas-fir along the length of a tree stem with a regression model based on acoustic velocity measured at one or more points of a tree, tree wood density, and bark percentage. Additional two working procedures were suggested: (4) using the acoustic velocity measurement of the first log to predict the acoustic velocity of other portions up the stem thus eliminating the need for total tree length information; and (5) using the acoustic velocity of the first log starting 6 metres from the base of the tree (Dowding, 2010).

2. Materials and Methods

In 2006 and 2007, seven second growth Douglas-fir stands of similar age class (50 – 70 years), chosen to cover a range of elevations and tree sizes, located in the Coastal (A, D, E, F, and G) and Cascade (B and C) Ranges of Oregon (Table 1), were harvested as part of two studies evaluating novel technologies (Near Infrared and Acoustics) for in-forest measurement of wood properties. Two hundred trees from each stand were sampled, totaling 1,400 trees converted into more than 3,000 logs. Various measurements of external as well as internal tree characteristics were performed, described in detail in Amishev & Murphy (2008b). In 2009, a total of 30 trees from another five (H, I, J, K, and L) second-growth Douglas-fir stands in southern Oregon (six trees per stand) were sampled (Table 1). Trees were selected to be representative of the stand using attributes such as diameter, height, and amount of branches (Dowding, 2010). Trees with obvious defects that may affect acoustic velocity readings such as scars, rot, or conk fungi were excluded.

Table 1. Characteristics of the sample trees from the twelve sites included in the study

Site[†]	Elevation of the site (m)	Stand age (years)[‡]	Range in length to the top of trees selected (m)*	DBH range of trees selected (cm)*	Site location Latitude/Longitude
A_{200}	180	62	5.5 – 42.4 (29.8)	19.3 – 96.8 (52.2)	44° 24'N / 123° 23'W
B_{200}	900	66	7.3 – 33.8 (24.4)	16.5 – 69.6 (36.3)	43° 23'N / 123° 04'W
C_{200}	1040	56	8.2 – 35.1 (24.2)	17.5 – 79.0 (50.6)	42° 59'N / 122° 49'W
D_{200}	220	54	13.1 – 34.1 (25.3)	14.2 – 66.8 (39.5)	43° 40'N / 123° 43'W
E_{200}	120	51	13.1 – 32.6 (24.6)	15.5 – 59.4 (32.0)	43° 40'N/ 123° 45'W
F_{200}	290	53	11.6 – 35.4 (24.5)	16.3 – 77.2 (38.9)	43° 48'N / 123° 18'W
G_{200}	280	72	10.4 – 37.2 (25.8)	15.0 – 78.5 (41.6)	44° 43'N/ 123° 20'W
H_6	235	48 (41-52)	26.3 – 38.1 (33.2)	20.5 – 42.4 (34.2)	43° 43'N/ 123° 35'W
I_6	675	50 (47-58)	28.4 – 33.6 (30.3)	31.7 – 37.5 (34.9)	43° 26'N/ 123° 25'W
J_6	285	43 (39-50)	20.9 – 31.2 (26.1)	19.5 – 33.5 (28.3)	43° 20'N/ 123° 22'W
K_6	455	36 (35-78)	23.9 – 38.4 (29.6)	27.4 – 53.0 (36.9)	43° 20'N/ 123° 40'W
L_6	270	40 (37-44)	26.0 – 37.2 (31.6)	22.0 – 44.9 (32.0)	43° 43'N/ 123° 46'W

[†] - Subscript indicating number of trees sampled per stand; [‡] - Range in parentheses; * - Average tree length/DBH in parentheses;

Those 30 trees were felled, limbed, and the tops were removed at approximately 10 cm diameter (over bark. The IML Hammer TOF acoustic velocity device (IML Inc., Kennesaw, Georgia, USA) was used to measure TOF acoustic velocity. TOF acoustic velocity (km/sec) was measured directly across the tree one meter from the large end of the tree and then every one meter up the tree until the bucked top was reached. The TOF acoustic velocity signal was measured between two screws placed in each side of the tree. Distance between the tops of the screws was measured with a pair of Haglof 95 cm calipers to the nearest tenth of a cm and then the screw lengths were subtracted to get the shortest distance the acoustic velocity signal could travel. Resonance acoustic velocity (km/sec) was measured from the flat cut surface at the large end of the tree to the bucked top using the Director HM200 resonance acoustic velocity measurement device (Fibre-Gen, Christchurch, New Zealand). The tree was then bucked three meters up from the large end and resonance acoustic velocity was measured on the three meter section. Resonance acoustic velocity measurements were repeated as previously described for the new location of the large end of the tree. This process was repeated along the entire length of the tree. Disks, approximately 3 cm thick, were cut at the initial large end of the tree and every 12 m up the tree for moisture content and green density measurements. All disks were cut either the day the tree was felled or the day after. Once disks were weighed and measured for volume they were placed in a room at 30 degrees C and 20 percent relative humidity to be dried to known moisture content of 12%. Data was analyzed using SAS 9.2. Variables providing predictive capability for determining the acoustic velocity in each 3-meter log section along the length of the tree (HM200_3m) were used to build multiple regression equations using a general linear model. For all models, natural log (LN) and square root (SQRT) transformations were used to transform the dependent 3-meter section acoustic velocity (Dowding, 2010).

3. Results and Discussion

The IML Hammer across the stem TOF acoustic readings were a significant predictor of HM200 acoustic velocity of each 3 m section (HM200_3m) but accounted for less than 4% of the variation (Dowding, 2010). Moreover, it was observed by us, but not recorded, that TOF acoustic velocity signals, measured both across the stem (IML Hammer) or in the longitudinal direction using a Director ST300, varied greatly from hit to hit at the same location. This result further supported our focus on the resonance based approach as a preferred method for integration into a harvester head. 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 regards 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 the fact that the tree/log would be in the grip of a metal grapple, the relationship between acoustic velocities in the grip of a harvester/loader grapple and those on the ground with no contact to harvesting equipment was investigated (Fig. 1).

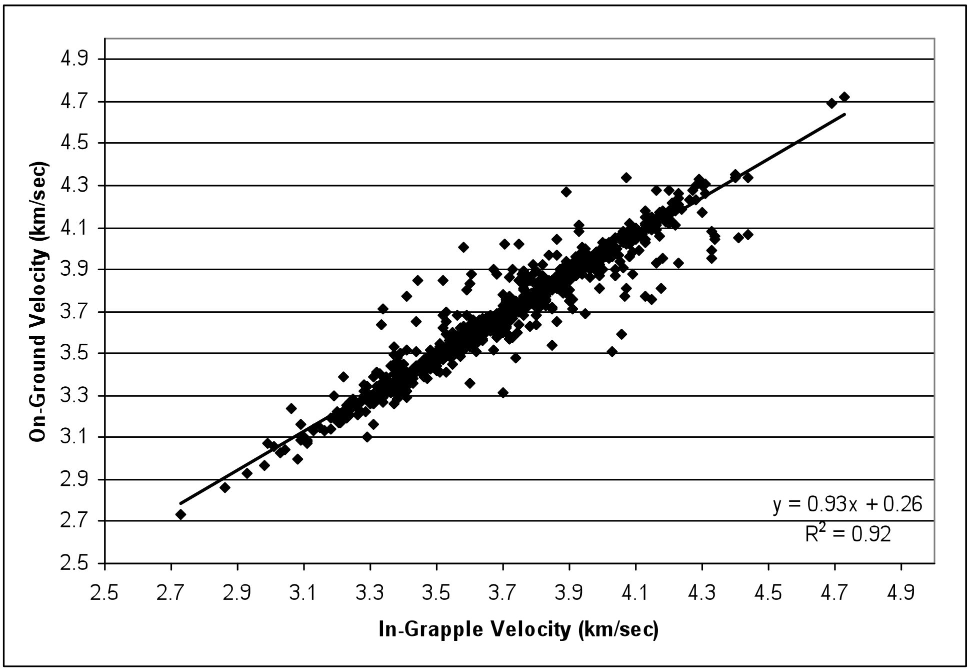

Figure 1. Relationship between acoustic velocities in the grip of a harvester/loader grapple and those on the ground with no contact to harvesting equipment.

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 strength of the grip or changing the grip position further up along 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.

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) and it decreased in each subsequent log along the length of a tree stem and the topmost log had 10% lower velocities than the whole tree (Fig. 2). 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, yielding a coefficient of determination R^2 of 0.74 (Amishev & Murphy, 2008b). The use of HM200 acoustic velocities of the initial tree length and all remaining top lengths after bucking 3 metre sections (HM200_Tree) was found to be a statistically significant and strongly correlated predictor of acoustic velocity of sections within the stem (HM200_3m). Distance of a log section from the butt of the tree (Dist) and distance of a section from the butt squared ($Dist^2$) were also found to be statistically significant and strongly correlated predictors of acoustic velocity of tree sections (HM200_3m).

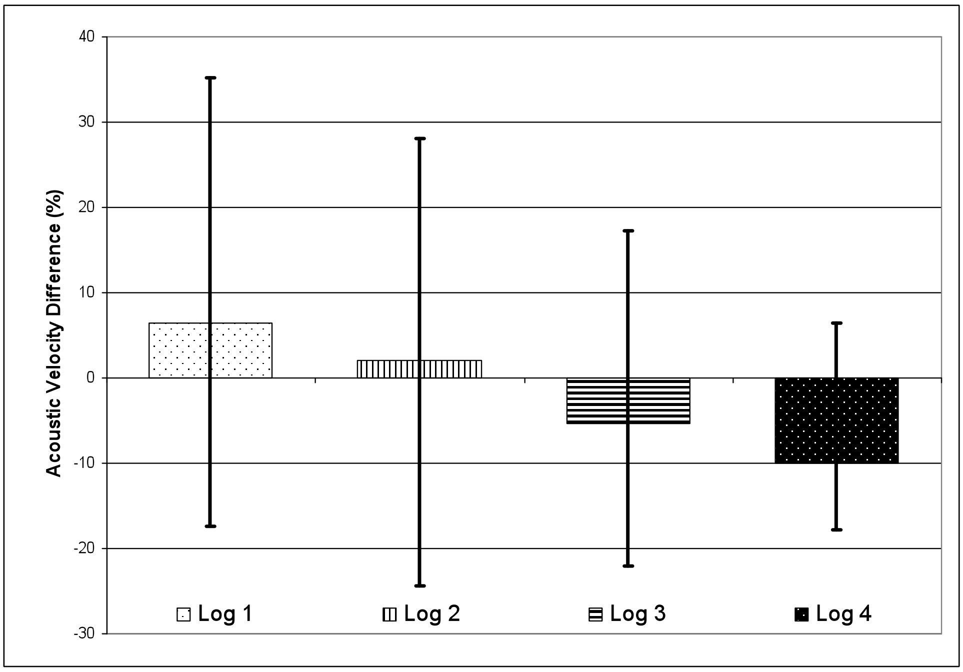

Figure 2. Average percent difference between whole tree acoustic velocities and those measured on each subsequent log produced from that tree. The "error bars" represent the range in percent difference for each log

Final models including resonance acoustic velocity measurements, distance from the butt, and distance from the butt squared were developed with high coefficients of determination (R^2 of 0.849 using all tree length acoustic velocities, R^2 of 0.827 using initial tree length acoustic velocity, and R^2 of 0.678 using initial 3 meter log acoustic velocity (HM200_Init3m) (Table 2). The models developed were found to be stand/site (S) dependent, indicating a possible need for model calibration for each stand being harvested. The use of either the single tree length acoustic velocity measurement or the first log acoustic velocity measurement with Dist and/or $Dist^2$ has the potential to increase value recovery from each log within harvested trees by predicting its stiffness. These results suggest that working procedure number four (4) would be considered as a quite reliable means of optimizing a stand while harvesting it without the need of additional tree length information. Studies on radiata pine have found that a low-stiffness wood zone forms from the base to about 2.7 m tree height (Xu et al., 2004) and our findings suggest this might be valid for Douglas-fir as well. It was found that acoustic velocity increases from 0 metres to about 6 metres up the stem and then it starts decreasing. This tree structure peculiarity should definitely be considered in designing an acoustic tester for harvester head and is a valid consideration for any working procedure employed. This is also the reason for suggesting working procedure number five (5) – to eliminate the uncertainty of identifying the point along the stem where direction of acoustic velocity change happens. This, however will inherently include at least partial processing of the harvested tree (up to 6 metres).

Table 2. HM200_3m correlation (LN transformation) with Dist and HM200_Init3m.

R-Square	Coeff Var	Root MSE	Ln_Hm200_3m Mean	
0.678	3.990	0.052	1.301	
Parameter	Estimate	Standard Error	t Value	Pr > |t|
Intercept	0.911	0.077	11.85	<.0001
HM200_Init3m	0.135	0.020	6.87	<.0001
Dist	-.009	0.000	-17.98	<.0001
S2	-.033	0.011	-2.97	0.0033
S3	-.051	0.013	-3.99	<.0001
S4	-.051	0.011	-4.65	<.0001
S5	-.034	0.011	-3.21	0.0015

If either complete or partial scanning/processing is performed, any alterations to the stem by the harvester head should be considered in regards 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 during 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 & Amishev, 2008) stands have reported that removal of bark significantly increased acoustic velocity by on average 4.1% and 4.6%, respectively. This should be accounted for to achieve a superior bucking decision for maximum value recovery from each stem.

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 & Murphy (2008a) reported that acoustic velocity for radiata pine and Douglas-fir logs with the branches still attached was 2 to 3 % lower compared to the velocity after they had been removed.

With the second (2) and third (3) suggested working procedures, 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 that it is part of. Two forecasting techniques, the regression model and the k-nearest-neighbor (NN) prediction, were evaluated (Amishev & Murphy, 2008b). 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. When a resonance-based acoustic velocity threshold value of 3.81 km/sec for stiffness quality control is assumed, the different 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/sec cutoff value, was inaccurately predicted.

Table 3. Proportion of trees (%) above a hypothetical acoustic velocity threshold value (km/sec) for stiffness quality assessment from the validation data set (VDS) of the seven trial stands. The three forecasting methods are the actual (A) percent, k-Nearest-Neighbor (NN) and linear regression (R) method, respectively.

Minimum 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

Accurately predicting the stiffness quality of more than 70% 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.

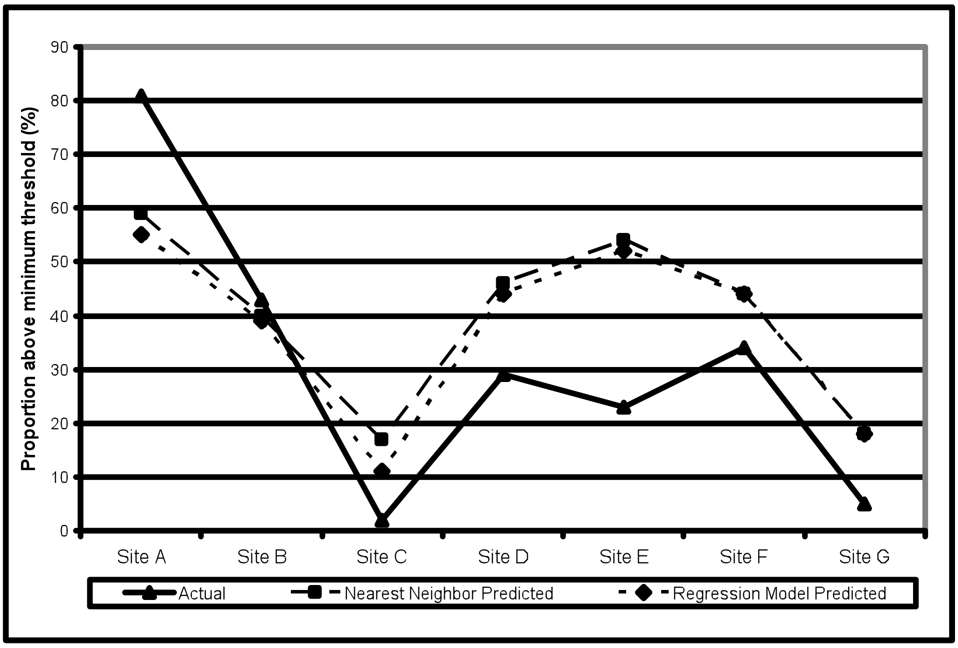

Figure 3. Percent trees above a hypothetical acoustic velocity threshold value for stiffness quality assessment from the validation data set (VDS) of the seven trial stands. The three curves represent the actual, *k*-NN and linear regression method predicted percent, respectively (Amishev & Murphy, 2008b)

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 2 cm 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.

4. Conclusions

Our continuing efforts aim to determine the most suitable acoustic technique for segregating veneer quality Douglas-fir logs as well as to investigate influential factors in regards to installing such technology on a processor/harvester head. Both the TOF and the resonance-based technique have advantages and disadvantages but research findings 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. The focus of our work was the use of resonance based acoustic velocity measurement technique.

Investigating the relationship between 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 five 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 the acoustic testing after the tree is felled by the harvester and before any further processing is done.
4. Using the acoustic velocity measurement of the first log to predict the acoustic velocity of other portions up the stem thus eliminating the need for total tree length information.
5. Using the acoustic velocity of the first log starting 6 metres from the base of the tree.

No matter 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. Velocity readings from the bottom portion of the stem could be used to predict acoustic velocity for the rest of the stem. 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. The models developed were found to be stand/site dependent, indicating a possible need for model calibration for each stand to be harvested.

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. Testing feasibility concerns with the resonance-based acoustic technique were observed if the entire stem was intact to the very top offshoot bud.

Our research efforts have significant implications for the mechanized harvesting of Douglas-fir stands. 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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