Estimating Within Tree Spatial Changes in Acoustic Velocity in Felled Douglas-fir Stems

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Abstract

Sorting logs for stiffness in the woods using acoustic devices mounted on harvesters and processors could improve the allocation of logs to their most appropriate processing destinations. Estimating spatial changes in acoustic velocity in felled stems, based on a limited number of measurements, will be essential if they are not to unduly impact harvesting or processing productivity and costs.

The effect of five variables (length from butt, bark percentage, moisture content, green density, and oven dry density) and four velocity measurement approaches (time of flight [TOF] across the tree bole, resonance of the full tree length, resonance of the first 3 m butt log segment, and resonance of a log segment between 6 and 9 m above the butt) on the ability to estimate spatial changes in acoustic velocity were evaluated in felled Douglas-fir stems from five stands in southwestern Oregon.

Distance from the butt was a significant predictor of acoustic velocity along the stem. TOF acoustic velocity measured across the bole had little value in predicting the longitudinal resonance acoustic velocity of a section of the tree. Full tree length resonance acoustic velocity, or single log acoustic velocity (either 3 m butt log or 3 m log 6 m above the butt) were found to be statistically significant and strongly correlated predictors of acoustic velocity of a section of a tree (R^2 ranging from 0.68 to 0.89). The models were found to be stand-dependent, indicating a possible need for calibration for each stand to be harvested.

Keywords: Wood stiffness, Douglas-fir, acoustic velocity, Oregon, mechanized harvesting.

Introduction

To compete with other building materials, the wood products industry must find a way to increase value and lower costs (Amishev 2008). One way to increase value is to properly allocate logs to their processing location. This decreases shipping costs because logs do not have to be reshipped if they are delivered directly to their final processing location, and increases value recovery because only logs that are fit for the end use are processed.

Currently, trees are mainly sorted by visual grading, but wood properties vary greatly between logs that have been given the same grade based on visual grading (Wang et. al. 2007a). Wood stiffness is one of the most important mechanical properties for most wood uses (Xu et. al. 2004). The structural use of wood depends on its engineering properties and stiffness is an important engineering property because it can be used as an indicator of the ability of wood to support loads and resist bending (Amishev 2008) but wood stiffness cannot be reliably predicted by visual grading (Edlund et. al. 2006). Acoustics can be used to non-destructively test wood for stiffness (Grabianowski et. al. 2006) and thus properly allocate logs to their end uses. Sorting logs by stiffness allows the exclusion of low stiffness logs at sawmills and veneer mills where high stiffness end products are desired. This exclusion of low stiffness wood can help mills avoid producing low quality/value structural lumber and veneer (Edlund et. al. 2006) because these products are more valuable when they have higher stiffness.

Acoustic velocity in wood can be used to predict wood stiffness according to the equation modulus of elasticity (MOE), which is proportional to wood density*velocity² (Grabianowski et. al. 2006). Wood density is weakly correlated with acoustic velocity because thicker cells are denser and have a higher proportion of the stiff S2 cell layer (Chauhan

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and Walker 2006). Two methods are used to measure acoustic velocity in wood; the resonance method and the time of flight (TOF) method. Both methods have been used to measure acoustic velocity in Douglas-fir (Amishev 2008).

Resonance acoustic velocity is measured by the time it takes for a generated shear wave to leave the transducer, travel longitudinally through the log, reflect off the opposite end of the log, and then return to the transducer. A known log length is used to calculate a log's acoustic velocity. "With acoustic resonance the entire cross section is assessed by the resonating wave and the calculated stiffness is for the cross sectional weighted average" (Grabianowski et. al. 2006). Resonance acoustic velocity is not based on a single acoustic pass; multiple passes are involved (in some instances many hundreds) and excellent measurement repeatability is a consequence of this (Grabianowski et. al. 2006). Because resonance acoustic velocity is an average of speed throughout the log, it takes into account the speed of sound in bark which has few fibers and low stiffness and thus lowers the average acoustic velocity measurement for a tree (Chauhan and Walker 2006). Due to the low frequency of the sound waves involved with resonance acoustic velocity, defects such as knots do not affect speed of sound measurements (Grabianowski et. al. 2006).

TOF acoustic velocity is a measurement of the time it takes for a single generated shear wave to travel between two metal probes inserted into a log with a known distance between them (Wang et. al. 2007a). The known distance and time of travel is used to calculate acoustic velocity. TOF acoustic velocity of longitudinal shear waves has been measured with probes inserted on the same side of a tree with distance between the probes being in the longitudinal direction and transverse shear waves have been measured with probes inserted in opposite sides of a tree with the distance between them in the radial and longitudinal direction. TOF acoustic velocity has not been studied using probes inserted directly across the stem of a tree with the main distance difference in the radial direction. TOF acoustic velocity measured across the log with distance in the radial direction will travel fastest around the log in the stiff outer wood of the tree and not straight through the log through the less stiff juvenile wood (Mahon et. al. 2009). Further information on how acoustic waves travel through wood can be found in Chauhan et al. (2005) and Wang et al. (2007a).

Hand-held tools for measuring acoustic velocity in felled tree stems and logs are being used operationally or in trials in log yards and forests around the world; particularly in New Zealand, Australia, North America and the United Kingdom (Matheson et al. 2002, Wang et al. 2007b). These tools can be used directly by log-makers for manual processing operations. They could also be used by log-graders for mechanized operations as per the approach used in the two machine mobile log merchandizing plant described by Dick (2007); the log-grader would pre-record the acoustic velocity of each marked stem on a hand-held computer, and then transfer the information to the on-board computer of the processing machine for later use when the stem is bucked into logs.

The use of mechanized harvesters and processors is increasing around the world. The ability of these systems to recover value from trees tends to be less than that of manual bucking, although not consistently so (Marshall and Murphy 2004). With mechanization, on-board computers can provide a platform for novel measuring systems, such as acoustic velocity measurement, and optimal bucking. Devices that measure acoustic velocity and their applications on harvesters and processors are currently being studied by the forest products industry (Carter 2007).

Measurement of the acoustic velocity of logs after they have been cut can indicate whether they meet the minimum acoustic velocity thresholds specified for a particular log grade. This approach is also likely to lead to wastage and value loss if the acoustic velocity is found to be too low and the lengths of these logs do not exactly match alternative log products. A better approach would be to predict what the likely acoustic velocity of a log is before a saw cut is made. Understanding how acoustic velocity varies spatially within a tree should improve the chances of cutting the right logs and lead to the proper sorting of logs to their end uses and to increased product quality and value. Amishev (2008) has shown that acoustic velocity tends to decrease with height up the stem for Douglas-fir. Xu et al. (2004) have shown, however, wood stiffness increases for the first 3 m of a stem and then decreases with height.

The successful application of acoustic velocity measuring devices, whether it be for use with manual log making systems or for use on harvester and processor heads, will rely on the ability to accurately predict wood stiffness along the length of a tree's bole. A regression model that predicts stiffness along the length of a tree stem based on an acoustic velocity measurement at one or more locations of the stem would improve the utility of acoustic velocity measurement devices. To the best of our knowledge there is no model to predict the stiffness of wood in Douglas-fir logs based on acoustic velocity measurements at one or more points of the log.

The goal of this study was to determine if four increasingly more difficult-to-measure variables (length from the butt, bark percentage, green wood density and oven dry density), in conjunction with a measurement of acoustic velocity at one or more points on the stem, could be used to predict the acoustic velocity along the length of a tree in Douglas-fir and thus improve the utility of acoustic devices as tools for the optimal bucking of trees into logs which have been sorted according to stiffness.

Four approaches for measuring acoustic velocity were also evaluated: TOF measurements across the tree bole, resonance measurement of the full tree length, resonance measurement of the first 3 m butt log segment, and resonance measurement of a log segment between 6 and 9 m above the butt (i.e. beyond the initial zone where the acoustic velocity may initially increase). The first approach was selected since it requires a measurement of stem diameter but not stem length. The second approach was selected since it requires stem length to be measured, with likely impacts of harvesting productivity, or estimated, with likely impacts on acoustic velocity accuracy. The third and fourth approaches were selected since they only require a partial measurement of stem length.

Materials and Methods

Sample Selection

Trees were obtained from five stands owned by Roseburg Forest Products in southern Oregon. Five stands were selected in order to determine if acoustic velocity relationships were stand independent. Six trees were selected from each stand. Trees were selected to be broadly representative of the stand using attributes such as diameter, height, and amount of branches. Trees with obvious defects that may affect acoustic velocity readings such as scars, rot, or conk fungi were excluded. Tree selection was performed with the assistance of a contract supervisor from Roseburg Forest Products. Trees tested had ring counts of 36 to 78 years at the diameter breast height (DBH) measurement point. Tree DBH, total height, height to live crown, and age can be seen in Table 1. The longitude, latitude and elevation of the site that the trees originated from can be seen in Table 2.

Table 1. Characteristics of the sample trees for the five sites included in the study.

Stand Name	Stand Number	Tree ID	DBH (mm)	Total Height (m)	Height to Live Crown (m)	Age (yrs.)
Paradise Flats	1	1	205	26.3	18.7	41
		2	424	38.1	22.4	48
		3	368	33.6	17.2	49
		4	421	36.9	19.0	48
		5	279	30.6	20.6	45
		6	355	33.9	22.1	52
Rock Island Green	2	1	375	33.6	20.0	53
		2	330	29.0	18.4	47
		6	317	28.7	16.6	47
		7	365	29.0	17.5	58
		8	335	28.4	17.8	50
		9	373	33.0	18.1	52
Oliphant Returns	3	1	309	30.3	21.5	44
		4	297	20.9	10.3	43
		5	274	26.6	18.1	41
		6	335	31.2	19.0	50
		7	195	20.9	12.1	39
		8	287	26.9	14.2	46
Kirken-dalli Lama	4	1	292	23.9	13.3	35
		3	309	29.0	11.8	35
		4	530	38.4	15.1	78
		5	495	30.3	15.1	73
		8	314	29.6	17.8	36
		9	274	26.6	16.3	37
Vincent 28 Flats	5	3	309	30.9	19.6	42
		4	449	37.2	22.1	40
		5	350	33.6	22.1	44
		6	231	26.0	20.3	38
		7	363	34.2	10.3	40
		8	220	27.8	22.1	37

Measurement and Processing Procedures

Tree Processing

Trees were manually felled, limbed, and the tops were removed at approximately 10 cm (~ 4”) diameter (over bark). This was done to eliminate the effect that limbs and treetops can have on adding variation to the measured speed of resonance acoustic velocity (Amishev 2008). We recognize that delimbing and topping each tree before acoustic measurements were taken would not be a preferred operational practice since harvesting productivity and costs would be negatively impacted due to additional handling requirements (Marshall and Murphy 2004). Controlling some of the causes of variation in this study was necessary because of the small sample size for each stand. In many cases, however, treetops broke at diameters larger than 10 cm over bark when the tree was felled. When this happened the treetop was cut before the break and the diameter was recorded.

Acoustic Velocity

A mechanized harvester was not available while fieldwork for this study was being undertaken. The acoustic velocities of trees and 3 m log segments cut from the trees were, therefore, measured when the trees were laying on the ground and, where possible, separated from other trees. If trees to be measured were touching other trees this was noted.

The IML Micro Hammer TOF acoustic velocity device (IML Inc., Kennesaw, Georgia, USA; www.imlusa.com/html/ml_micro_hammer.html - accessed July 1, 2011) was

Table 2. Stand locations.

Stand Name	Longi-tude	Latitude	Eleva-tion (m)
Paradise Flats	43° 43' N	123° 35' W	235
Rock Island Green	43° 26' N	123° 25' W	675
Oliphant Returns	43° 20' N	123° 22' W	285
Kirkendalli Lama	43° 00' N	123° 40' W	455
Vincent 28 Flats	43° 43' N	123° 46' W	270

used to measure TOF transverse acoustic velocity. TOF acoustic velocity (km/sec) was measured directly across the tree 1 m from the large end of the tree and then every 1 m up the tree until the bucked top was reached. The TOF acoustic velocity signal was measured between two 60 mm screws inserted through the bark and into the sapwood on 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.

Longitudinal 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; www.fibre-gen.com/hm200.html - accessed July 1, 2011). Prior experience with the HM200 tool indicated that readings do not vary when measurements are taken from the large or small end of the log or when the transducer is placed on the sapwood or heartwood of the log. The tree was then bucked 3 m up from the large end and resonance acoustic velocity was measured on the 3 m section. This process was repeated along the entire length of the tree. Tree and log lengths were measured using a measuring tape. Diameter over and under bark to the nearest 1 cm was measured after bucking using a hand-held measuring tape for the wide and narrow cross section of the tree trunk every 3 m up the tree at the bucking point. Diameters over and under bark were used to determine the bark percentage.

Moisture Content, Green Density and Oven Dry Density

Disks, approximately 3 cm thick, were cut at the initial large end of the tree and at 12 m and 24 m from the base of the tree. All disks were cut either the day the tree was felled or the day after. If the end of the disk was cut from had been exposed for over four hours, the disk was taken after the end had been trimmed to reduce the impact of drying on wet moisture content measurements. This was only a concern with the butt end of the tree because all other disks were cut soon after the tree was bucked.

Wedges, which were representative of the area-weighted sapwood and heartwood content of each disk, were then cut from the centers to the outer edges of these disks and placed in plastic bags until they could be weighed. All wedges were weighed in their plastic bags to account for moisture that escaped the wedges. Wedges were weighed either the same day or the day after they were cut and plastic bags were kept in the shade before weighing.

To obtain green density at the time of acoustic velocity testing volume measurements were obtained using the Archimedes principle after the wedges had been saturated to return them to green volume. Green density is the mass of the wedge divided by the green volume.

Once wedges were weighed and measured for volume they were placed in a room at 30 degrees C and 70 percent relative humidity to be dried to a known moisture content of 12%. After drying the wedges were reweighed and oven dry densities (zero moisture content) calculated. Moisture content percentages are expressed on an oven dry wood basis.

Data Analysis

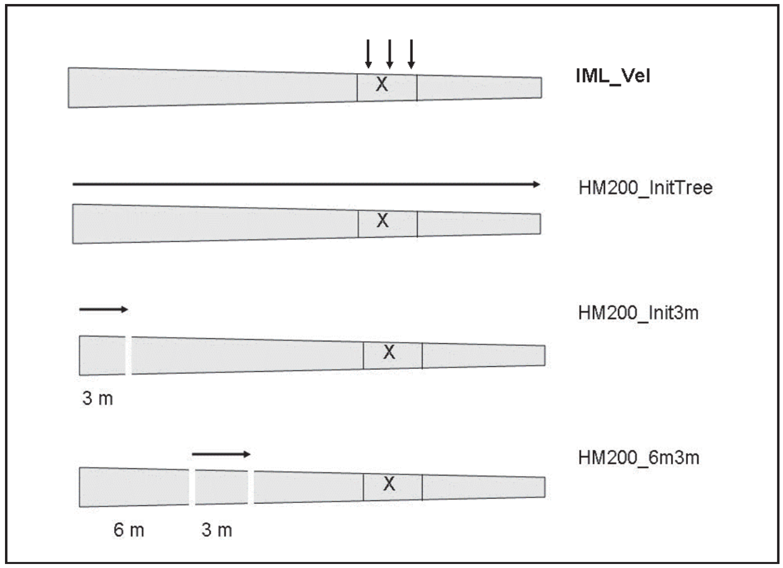
Data was analyzed using SAS 9.2. The dependent variable was the HM200 resonance acoustic velocity of each 3 m section (HM200_3m); this measurement was selected as the dependent variable because it provides an indicator of average stiffness for the stem section and has excellent measurement repeatability (Grabianowski et. al. 2006). A number of variables were individually examined to determine their utility for predicting the HM200_3m acoustic velocity along the length of the tree. These variables included:

- Diameter over bark (DOB) at the small end of the log
- Wood moisture content percent on an oven dry basis (MC) for each disk
- Green wood density (Green Density) for each disk
- Oven dry density (OD Density) for each disk
- Average bark percentage based on the cross sectional areas of the small and large ends of each log (Bark)
- Distance from the butt of the tree to the large end of the log (Dist).
- Distance from the butt of the tree squared ($Dist^2$).
- IML Micro Hammer acoustic velocity across tree (IML_Vel) (see Figure 1) at the large end of the log
- HM 200 initial tree length acoustic velocity (HM200_InitTree) (see Figure 1)
- HM 200 acoustic velocity for the first 3 m section from the butt of the stem (HM200_Init3m) (see Figure 1)
- HM 200 acoustic velocity for the first 3 m section after the bottom 6 m section has been removed (HM200_6m3m) (see Figure 1)

The justification for evaluating the predictive utility of acoustic velocity measured at four locations on the stem (IML_Vel, HM200_InitTree, HM200_Init3m, and HM200_6m3m) is provided in the "Discussion" section of this paper.

Variables providing predictive capability were used to build multiple regression equations. As part of the process to select the best final models, we evaluated many combinations of transformed (natural log, square root and inverse) and non-transformed dependent variables (HM200_3m) in conjunction with transformed (natural log, square root, and squared) and non-transformed distance from the butt predictors, non-transformed acoustic predictors (HM200_InitTree, HM200_Init3m and HM200_6m3m), and binary stand variables (S1 to S5). Transformations were evaluated since there appeared to be a non-linear acoustic velocity pattern with distance in the data (Figures 2 and 3) particularly in the bottom portion of the stem where a paired t-test showed significant differences ($p < 0.001$) between the acoustic velocities of the first and second 3m log segments of each stem. Differences between stands were tested for both intercept and slope using stepwise backward regression techniques. Three models (one for the initial tree length HM200_InitTree reading, one for the initial 3 m log HM200_Init3m reading, and one for the 3 m log above the first 6 m segment HM200_6m3m reading) were found to be the most significant by calculating the root mean square error of the predicted acoustic velocity for each 3 m segment. Root mean square error was calculated once the predicted value had been back transformed if transformations were used.

Figure 1. Four approaches for predicting acoustic velocity in a section of stem based on prior measurements. The objective is to predict the acoustic velocity of the section of stem marked X, where X can be located anywhere further up the tree. In the top approach a prior TOF measurement is taken across the tree bole with an IML Micro Hammer (IML_Vel). In the second approach a prior acoustic velocity measurement is taken from the butt of the stem to the top with a Director HM200 (HM200_InitTree). In the third approach the bottom 3 m section of the tree is removed, then a prior acoustic velocity measurement is taken from the butt of this section to the top of the section (HM200_Init3m). In the fourth approach the bottom 6m section is removed, then a 3 m section is removed and a prior acoustic velocity measurement taken of this 3 m section (HM200_6m3m).



Results

Summary statistics for the variables measured can be seen in Table 3.

A graph of IML Micro Hammer transverse acoustic velocities as a function of distance from the butt can be seen for Stand 5 in Figure 2; this stand was selected as being representative of the five stands. IML Micro Hammer velocities decreased as the distance from the butt increased, decreasing more so above 10 m from the butt than below 10 m. A graph of HM 200_3m longitudinal velocities as a function of distance from the butt can be seen for Stand 5 in Figure 3. HM200_3m velocities increased from the first 3 m section and were greatest in the second and third 3 m sections. HM200_3m velocities then decreased with height in the tree. On average, HM200_3m resonance velocities were about three times faster than IML TOF velocities; 3.69 and 1.18 km/sec respectively.

Table 3. Summary statistics for variables measured.

	DOB (cm)	MC (%)	IML_Vel (km/sec)	Green Density (g/cm³)	Bark (%)	Oven Dry Density (g/cm³)	HM200 InitTree (km/sec)	HM200 Init3m (km/sec)
Ave.	28.3	82	1.19	0.85	12.5	0.47	3.65	3.81
St. Dev.	9.2	23	0.14	0.08	3.6	0.04	0.19	0.23
Min.	7.6	51	0.61	0.69	7.7	0.39	3.17	3.32
Max.	59	152	1.49	1.05	23.6	0.55	4.01	4.25

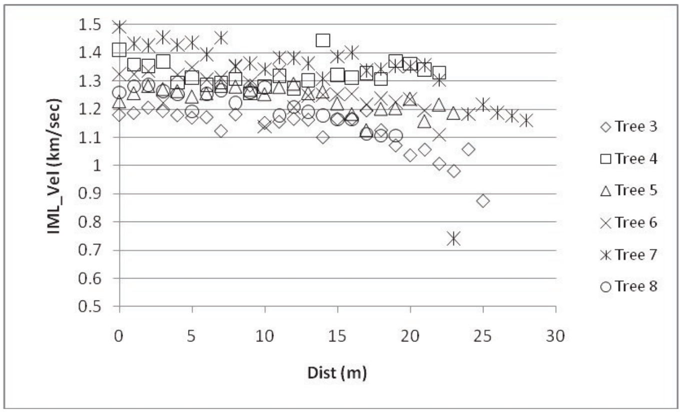
Note: DOB = diameter over bark, MC = moisture content, IML_Vel = acoustic velocity across the stem measured by an IML Micro Hammer, HM200_InitTree = acoustic velocity for the full tree length as measured by a Director HM200, HM200_Init3m = acoustic velocity for the first 3m of the tree as measured by a Director HM200.

Single-Predictor Models

Diameter over bark was significant ($p < 0.0001$) in predicting resonance acoustic velocity of the 3 m sections but had a low R^2 value (0.130). When diameter over bark was added with other variables in the final model the R^2 increased from 0.796 to 0.799. This increase was very small and in order to keep the final model simple diameter over bark was not included.

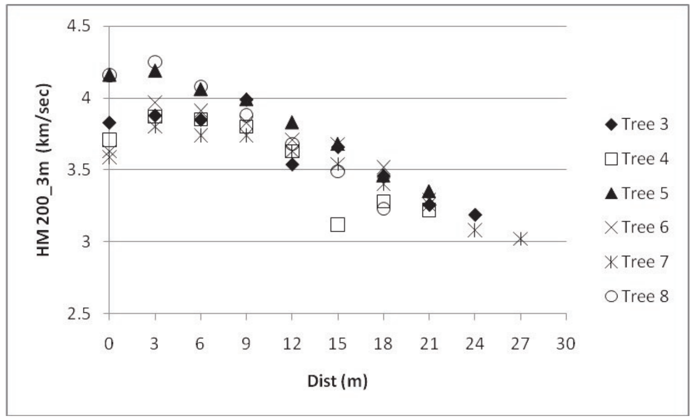
Wood moisture content ($p = 0.162$), green wood density ($p = 0.162$), oven dry density ($p = 0.907$), and bark percentage ($p = 0.965$), were not significant in predicting resonance acoustic velocity of the 3 m sections and were not included in the final model.

Figure 2. IML Micro Hammer TOF Acoustic Velocity (IML_Vel) from Stand 5.



Note: Dist = distance from the base of the tree to the IML measurement point.

Figure 3. HM200 Resonance Acoustic Velocity (HM200_3m) from Stand 5.



Note: Dist = distance from the base of the tree to the Director HM200 measurement point.

The IML Micro Hammer transverse acoustic velocity readings were a significant ($p = 0.004$) predictor of longitudinal resonance acoustic velocity of the 3 m sections but due to a low R^2 (0.036), they were not included in the final model.

Distance of the 3 m section from the butt of the tree was statistically significant ($p < 0.0001$), had a relatively high R^2 value (0.479), and was included in the final model to predict resonance acoustic velocity of the 3 m sections (HM200_3m).

Multi-Variable Models

Multi-variable models were initially constructed by ignoring potential differences between stands.

The model shown in Table 4 was the initial multi-variable model selected. This model was highly significant ($p < 0.0001$) and was able to explain 75% of the variation of the 3 m section acoustic velocity readings. This model was built using only one tree length reading, the acoustic reading from the butt of the tree (HM200_InitTree), along with distance from the butt as an additional predictor. Compared with a single variable model that included distance from the butt, adding HM200_InitTree increased the percent of the variation explained from 48% to 75%.

In order to see if the HM200_3m acoustic velocity could be predicted using a reading from the first log, the reading from the 3 m butt section of the tree (HM200_Init3m) was used with distance from the butt as an additional predictor. The model shown in Table 5 was produced. This model was highly significant ($p < 0.0001$) and was able to explain 65% of the variation of the 3 m section acoustic velocity readings. Compared with a single variable model that included the distance from the butt, adding HM200_Init3m increased the percent of the variation explained from 48% to 65%. This shows that the 3 m section acoustic velocity can be predicted using

Table 4. HM200_3m correlation with Dist and HM200_InitTree.

Parameter	Estimate	Standard Error	t Value	Pr > |t|
Intercept	0.662	0.216	3.07	0.0024
HM200_ InitTree	0.918	0.059	15.61	<.0001
Dist	-0.032	0.002	-20.52	<.0001
R-Square	Root MSE			
0.749	0.163			

Note: HM200_3m = acoustic velocity for each 3m log up the stem as measured by a Director HM200, HM200_InitTree = acoustic velocity for the full tree length, Dist = distance from the base of the tree to the large end of each 3m log of interest.

Table 5. HM200_3m correlation with Dist and HM200_Init3m.

Parameter	Estimate	Standard Error	t Value	Pr > |t|
Intercept	1.749	0.221	7.90	<.0001
HM200_ Init3m	0.593	0.058	10.29	<.0001
Dist	-0.032	0.002	-17.02	<.0001
R-Square	Root MSE			
0.645	0.194			

Note: HM200_3m = acoustic velocity for each 3m log up the stem as measured by a Director HM200, HM200_Init3m = acoustic velocity for the first 3m of the tree, Dist = distance from the base of the tree to the large end of each 3m log of interest.

only the acoustic velocity from the first log of the tree and the distance from the butt.

A model that used HM200_6m3m acoustic readings and distance from the butt was constructed (Table 6). The model was highly significant (p<0.0001) and was able to explain 86% of the variation in HM200_3m velocities above 6m from the butt of the stem.

Table 6. HM200_3m correlation with Dist and HM200_6m3m.

Parameter	Estimate	Standard Error	t Value	Pr > |t|
Intercept	0.849	0.195	4.35	<.0001
HM200_ 6m3m	0.086	0.049	17.46	<.0001
Dist	-0.046	0.002	-26.34	<.0001
R-Square	Root MSE			
0.857	0.122			

Note: HM200_3m = acoustic velocity for each 3m log up the stem as measured by a Director HM200, HM200_6m3m = acoustic velocity for the third 3m of the tree, Dist = distance from the base of the tree to the large end of each 3m log of interest.

$Dist^2$ and binary stand variables were added to the HM200_InitTree model in an attempt to account for the lower acoustic velocity of the initial 3 m sections and to test for differences between stands. The final model can be seen in Table 7. $Dist^2$ was significant in this model but not Dist. This model found the intercepts of Stands 4 and 5 to be significantly different from the other three stands (p = 0.0004) but not from each other. Slopes from Stands 1, 4, and 5, interacting with $Dist^2$, were found to be significantly different from slopes from the other two stands (p = 0.0123, 0.0002, and 0.0001 respectively). This model had a high R^2 of 0.827 and a RMSE of 0.137.

The final model using the initial 3 m log (HM200_Init3m) reading, distance from the butt, and stand binary variables as predictors for HM200_3m velocities is shown in Table 8. The intercepts of Stands 2 to 5 were found to be significantly different from Stand 1. The intercepts of Stands 2 and 5 were not significantly different from each other. Similarly, the intercepts of Stands 3 and 4 were not significantly different from each other. $Dist^2$ was not significant in this model. The model had an R^2 value of 0.683 and a RMSE of 0.184.

The final model using HM200_6m3m acoustic readings, distance from the butt, and stand binary variables as predictors for the HM200_3m velocities above the first 6 m of the tree is shown in Table 9. This model found the intercepts of Stands 2 and 4 to be significantly different from the intercept of Stand 3 (p = <0.0001 and 0.0366 respectively).

Table 7. HM200_3m correlation with $Dist^2$, HM200_InitTree and Stand Binary Variables.

Parameter	Estimate	Standard Error	t Value	Pr > |t|
Intercept	0.751	0.189	3.98	<.0001
HM200_ InitTree	0.878	0.051	17.08	<.0001
$Dist^2$	-0.002	0.000	-18.74	<.0001
S4 of S5	-0.092	0.026	-3.58	0.0004
$Dist^2$*S1	0.0003	0.0001	2.52	0.0123
$Dist^2$*S4	0.0006	0.0001	3.74	0.0002
$Dist^2$*S5	0.0005	0.0001	3.91	0.0001
R-Square	Root MSE			
0.827	0.137			

Note: HM200_3m = acoustic velocity for each 3m log up the stem as measured by a Director HM200, HM200_InitTree = acoustic velocity for the full tree length, $Dist^2$ = the square of distance from the base of the tree to the large end of each 3m log of interest. S1, S4 and S5 are binary variables for Stands 1, 4 and 5 respectively. The value of the variable was 1 if the stem was from that stand, and 0 otherwise.

Table 8. HM200_3m correlation with Dist, HM200_Init3m and Stand Binary Variables.

Parameter	Estimate	Standard Error	t Value	Pr > |t|
Intercept	2.214	0.244	9.09	<.0001
HM200_ Init3m	0.503	0.062	8.10	<.0001
Dist	-0.032	0.002	-18.18	<.0001
S2 or S5	-0.119	0.033	-3.64	0.0003
S3 or S4	-0.181	0.035	-5.13	<.0001
R-Square	Root MSE			
0.683	0.184			

Note: HM200_3m = acoustic velocity for each 3m log up the stem as measured by a Director HM200, HM200_Init3m = acoustic velocity for the first 3m of the tree, Dist = distance from the base of the tree to the large end of each 3m log of interest. S2, S3, S4 and S5 are binary variables for Stands 2, 3, 4 and 5 respectively. The value of the variable was 1 if the stem was from that stand, and 0 otherwise.

The intercepts of Stands 1 and 5 were not significantly different from the intercept of Stand 3. Slopes from Stands 1 or 5, and from Stand 4, interacting with Dist, were found to be significantly different from the slope of Stand 3 (p = <0.0001 and 0.0002 respectively). The slope from Stand 2, interacting with Dist, was not significantly different from Stand 3. The slopes from Stands 1 and 4, interacting with Dist, were not significantly different from each other. This model had a high R^2 of 0.887 and a RMSE of 0.110 when predicting HM200_3m velocities after the first 6 m of the tree.

Table 9. HM200_3m correlation with Dist, HM200_6m3m and Stand Binary Variables.

Parameter	Estimate	Standard Error	t Value	Pr > |t|
Intercept	1.264	0.194	6.52	<.0001
HM200_ 6m3m	0.760	0.049	15.58	<.0001
Dist	-0.055	0.002	-25.60	<.0001
S2	0.129	0.028	4.60	<.0001
S4	-0.120	0.057	-2.11	0.0366
Dist*(S1 or S5)	0.011	0.002	6.02	<.0001
Dist*S4	0.016	0.004	3.85	0.0002
R-Square	Root MSE			
0.887	0.110			

Note: HM200_3m = acoustic velocity for each 3m log up the stem as measured by a Director HM200, HM200_6m3m = acoustic velocity for the third 3m of the tree, Dist = distance from the base of the tree to the large end of each 3m log of interest. S1, S2, S4 and S5 are binary variables for Stands 1, 2, 4 and 5 respectively. The value of the variable was 1 if the stem was from that stand, and 0 otherwise.

It should be noted that Shapiro-Wilks tests of residuals for all of the models shown in Tables 4 to 9 indicated that the residuals were not normally distributed. It should also be noted that chi-square test of residuals for all the models shown, except the model shown in Table 9, indicated that the residuals were heteroscedastic. None of the data transformations evaluated improved normality or heteroscedascity of the residuals. Removing outliers can improve normality and heteroscedasity. Since there was no justifiable reason to discard any of the potential outliers, we can only point out that the true error coefficients for the models may be larger than shown in Tables 4 to 9.

Discussion

To increase the value recovery from mechanical harvesters, it has been suggested that the industry should look at improved scanning, forecasting, and optimization systems to assist operators in log making (Marshall and Murphy 2004). A forecasting system that more accurately forecasts both stem form and quality may yield higher net value recovery (Marshall and Murphy 2004). In this study we have looked at models for forecasting acoustic velocity as a surrogate for wood stiffness.

Single-Predictor Models

Diameter over bark was significant in predicting longitudinal resonance acoustic velocity of the 3 m sections but had a low R^2 of 0.130. The significance of diameter over bark in predicting acoustic velocity of the 3 m sections can likely be attributed to the relationship that diameter has with height and that height has with microfibril angle. Microfibril angle is responsible for a rapid increase in stiffness in the vertical direction (Xu et al. 2004) and is a major determinant of wood modulus of elasticity (Evans and Ilic 2001). Acoustic velocity of the 3 m sections was shown to decrease with a decrease in diameter. This relationship would be expected because as you move further toward the top of a tree the diameter decreases and the proportion of juvenile wood with a high microfibril angle increases.

Wood moisture content percentage was not significant in predicting resonance acoustic velocity of the 3 m sections for freshly felled trees. Acoustic velocities are lower in wet wood as compared to dry wood but with MC% above 40%, there is little effect on acoustic velocity (Carter et al. 2004). Wedge moisture content varied from 51 to 151% on an oven dry basis. The finding that moisture content is not a good predictor of acoustic velocity agrees with Carter et al. (2004).

Green density of the wood wedges was not a significant predictor of the resonance acoustic velocity of the 3 m sections. The green densities of the wedges measured varied from 0.69 to 1.05 g/cm^3 and with this large of a spread of densities it would be expected that if there were a substantial effect of density on acoustic velocity it would have emerged.

Oven dry density was not significant in predicting resonance acoustic velocity of the 3 m sections. This finding agrees with that of Lachenbruch et al. (2010) who found that density at 12% MC (density at 12% is directly related to oven dry density) had a poor correlation (R= 0.36) with acoustic velocity.

Bark percentage of the cross-sectional area was not significant in predicting the resonance acoustic velocity of the 3 m sections. These findings did not agree with previous studies. A small experiment in a mill yard on 81 Douglas-fir logs found an average increase in resonance acoustic velocity of 4.6% for debarked logs (Amishev 2008) and another study found that removal of bark increased dynamic MOE by an average of 8.3% in 11 year old radiata pine (Lasserre et al. 2007). Grabianowski et al. (2006) found that bark slows resonance acoustic velocity readings. In these previous studies the same logs were compared with and without bark. In this study logs were not debarked but the percentage of their cross-sectional area that was bark was recorded. This percentage varied up the trees but for butt logs average bark percentage varied from 13 to 23%. It is likely that other differences between trees, such as microfibril angle, had a much larger effect on acoustic velocity than bark and the effect that bark would have was dominated by other factors in this study.

Distance of the 3 m section from the butt of the stem was significant in predicting longitudinal resonance acoustic velocity of the 3 m sections and accounted for almost 48% of the variation in HM200_3m readings. Acoustic velocity of the 3 m sections was shown to decrease with increasing distance from the butt of the log. This decrease in acoustic velocity as you move toward the top end of the tree is logical because microfibril angle is a major determinant of wood modulus of elasticity (Evans and Ilic 2001) and as you move further toward the top of a tree the proportion of juvenile wood with a high microfibril angle increases causing a decrease in acoustic velocity. Lachenbruch et al. (2010) have shown a significant negative relationship between microfibril angle and acoustic velocity in Douglas-fir.

The IML Micro Hammer TOF transverse acoustic readings were a significant predictor of HM200_3m longitudinal resonance acoustic velocity but the relationship was weak, accounting for less than 4% of the variation. This finding did not agree with previous research by Wang et al. (2007a) who noted that "a strong relationship was found between tree velocity (TOF) and log velocity (HM200)" nor by Grabianowski et al. (2006) who found a correlation coefficient of 0.96 between TOF and resonance velocities on the same logs. Our research did agree with that of Amishev (2008), however, who found that, for Douglas-fir, there was a weak "coefficient of determination of 0.25 between sound velocities of 698 standing trees measured by the TOF method ([Fibre-Gen] ST300 tool) and the corresponding speed in the butt logs, measured by the resonance based method (HM200 tool)." One possibility for the difference in the results between studies may relate to how TOF acoustic velocity was measured. In this study the TOF measurement was across the stem (radial and/or tangential direction) but it was along the stem (longitudinal direction) in the three previously mentioned studies. Acoustic velocity in wood is usually slower in the tangential direction (Maurer et al. 2006) and higher in the longitudinal direction (Chauhan et al. 2005) than in the radial direction. Another possibility for the difference relates to the inherent accuracy and robustness of the resonance method in comparison with TOF method (Wang et al. 2007b). It was observed by us, but not recorded, that the resonance method yielded repeatable results for the same location while the TOF results varied greatly. Amishev (2008) also observed that substantial variability occurred from hit to hit using a TOF tool.

Multi-Variable Models

In order to develop a practical model for predicting the resonance acoustic velocity of individual sections of a tree, three multi-variable models, based on a single resonance acoustic velocity measurement, were evaluated. The first model used HM200_InitTree and the distance of the 3 m section from the butt as predictor variables. This model was highly significant and accounted for close to 75% of the variation in acoustic velocity. With the use of this model a tree could have one acoustic velocity measurement taken from the butt along the entire length of the tree to the breakpoint or top cut and, with a known length, the acoustic velocity in any portion of the tree could be predicted. This would be highly advantageous for an acoustic velocity device mounted on a harvester or processor head because the tree would only have to be handled once to determine an acoustic velocity profile along the stem. Often, however, the length of a tree to the breakpoint or top cut is not known when it is being handled by a harvester or processor. In this case an acoustic velocity reading on a whole tree would have to be based on a measured tree length (requiring additional handling of the tree and harvesting costs) or an estimated tree length (which would add to any errors associated with the model).

A second multi-variable model was, therefore, developed that uses the longitudinal acoustic velocity of the first 3 m section of the tree (HM200_Init3m) and the distance from the butt to determine acoustic velocity down the length of the tree. This model was also highly significant and accounted for almost 65% of the variability in HM200_3m acoustic velocity. With the use of this model an acoustic velocity profile could be developed for a tree with only the acoustic velocity of the first log and the known distance of a section of the tree from the butt. It would also require, however, that a potentially suboptimal log length be cut for the first log from the stem in order to provide information needed for optimal bucking based on acoustic profiles of the remainder of the stem. Alternatively, multiple models based on measured acoustic velocities of first logs of varying lengths could be developed. The harvester operator could decide what log length should be cut first based on non-acoustic stem features, then measure the first log's acoustic velocity and finally select the appropriate acoustic model for predicting the acoustic profile of the remainder of the stem.

Sheng-zuo and Wen-zhong (2003) reported that both fiber diameter and length increased from the base of the poplar trees they measured to about 6 m and then decreased towards the top of the tree. Xu et al. (2004) also noted that there is a cone of low stiffness wood in radiata pine, with the wide base of the cone at the butt of the tree – stiffness first increases with height to about 3m and then decreases. To overcome possible errors in prediction based on measurements of the atypical butt zone of the tree, a third multi-variable model was constructed based on a resonance acoustic velocity measurement of a log 6 m from the butt (HM200_6m3m). This model accounted for 89% of the variability in HM200_3m acoustic velocity measurements above 6 m from the butt of the tree. It was also superior (lower RMSE) to a model based on HM200_Init3m measurements for predicting velocity measurements above 6 m from the butt of the tree. Similar to the HM200_Init3m model, there are implications for suboptimal bucking of the stem that come from cutting first a 6 m butt log and then a 3 m log for measuring acoustic velocity. These problems could be overcome, however, with the development of multiple models for varying log lengths.

Analysis of the data showed that there were also statistically significant differences in the predicted acoustic velocity profile between stands for all three final models that were constructed. For the model using HM200_Init3m as a predictor variable the differences were constant and did not depend on the distance from the butt. For the models using HM200_InitTree and HM200_6m3m as predictor variables stand differences were also linked to distance from the butt. Additional analyses, not described above, showed that the increase in RMSE, when stand differences were not accounted for, was 0.004 to 0.011 km s^{-1} (equivalent to 0.1 to 0.3% of the mean HM200_3m acoustic velocity). If these differences are deemed to be practically significant it may be necessary to develop a simple procedure for calibrating acoustic profile models for each stand to be harvested. Such a procedure could include pre-felling and measuring a small sample of trees to determine whether prediction errors were within acceptable bounds. If not, additional stem information may need to be collected and a new regression equation would have to be developed.

The applications of the results of this study are limited to Douglas-fir because it was the only species tested. All five stands were located in southwest Oregon and due to within species variation by geographic region the results of this study should be used with care when applying them to Douglas-fir in other geographic regions. Trees tested varied in age from 36-78 years and this study may not be applicable to trees outside of this age range. Trees tested were selected to be free of visible defects such as sweep, rot, and scarring, and trees with these characteristics may have different acoustic velocity profiles due to their defects. All trees were tested either the day they were felled or the day following felling. In production operations trees often are left in the brush for weeks before being brought to the landing where they can be tested for acoustic velocity. Due to drying, acoustic velocity profiles may differ if trees are not tested immediately after felling. Acoustic measurements were taken while stems were laying on the ground, rather than in the grip of a harvester head, because a harvester was not available at the time of the study. Amishev (2008) has shown, however, that there is less than a 3% average difference between acoustic measurements of a stem laying on the ground and within a harvester head. Stems were delimbed prior to acoustic measurements being taken to reduce the impact of variability in measurements from having a small sample size. In practice this would be likely to result in double handling of stems, reduced harvesting productivity and increased costs. Amishev (2008), however, has shown that there is a 3% average reduction in acoustic measurements between delimbed and undelimbed stems within a harvester head.

Future research should be directed to mitigate the limitations of this study. Species other than Douglas-fir should be tested to determine how acoustic velocity profiles vary between species. Douglas-fir trees should be tested from regions with growing conditions that differ from those in southwest Oregon to see if regional differences in trees affect acoustic velocity profiles. Trees with defects such as sweep, rot, and scarring, should be tested to see how these defects affect acoustic velocity profiles. Trees should be tested for acoustic velocity at varying times after felling to see how acoustic velocity profiles vary over time after a tree is felled.

Conclusions

Distance of a log section from the butt of the tree (or distance squared) and a single acoustic velocity measurement gathered in the bottom portion of the felled stem were found to be statistically significant and strongly correlated predictors of acoustic velocity of tree sections. Final models were developed with high coefficients of determination (R^2 ranging from 0.68 to 0.89). The models developed were found to be stand-dependent, indicating a possible need for model calibration for each stand to be harvested.

Of the four approaches which used a single measurement of acoustic velocity as the basis for predicting spatial distribution of acoustic velocity in Douglas-fir stems, the three that used resonance acoustic velocity measurements showed the most promise. Measuring TOF acoustic velocity across the bole of the tree had little value in predicting the longitudinal resonance acoustic velocity of a section of the tree.

The development of a reliable acoustic measuring device that could be mounted on a processor or harvester head and the use of acoustic profile models would facilitate sorting of Douglas-fir logs for stiffness while they are being processed and more effectively match logs to their best end-use.

References

Amishev, D. Y. 2008. In-forest log segregation based on acoustic measurements of wood stiffness. A Dissertation Submitted to Oregon State University. 272 pp.

Carter, P. 2007. Development of the Director PH330 sonic tester for harvesting head. FWPA PN07.2038 project update. Forest and Wood Products Australia Leading Edge Newsletter. 5(4). 8pp.

Carter, P., Briggs, D., Ross, R.J., and Wang, X. 2004. Acoustic testing to enhance Western forest values and meet customer wood quality needs. In: Harrington, C. H. and Schoenholtz, S., (eds.) Productivity of Western forests: a forest products focus. USDA Forest Service PNW Research Station General Technical Report. PNW-GTR-642. pp. 121-129.

Chauhan, S.S., Entwistle, K. M., and Walker, J. C. F. 2005. Differences in acoustic velocity by resonance and transit-time methods in an anisotropic laminated wood medium. *Holzforschung*. 59(4):428-434.

Chauhan, S.S. and Walker, J. C. F. 2006. Variation in acoustic velocity and density with age, and their interrelationships in radiata pine. *Forest Ecology and Management*. 229: 388-394.

Dick, A. 2007. The Logmaister log merchandizer. Paper presented to the Log Measurement Society, October 17, 2007. Available from http://www.timbermeasure.com/Longview_2007/logmaister.pdf accessed 15 September 2010 [accessed September 15, 2010].

Edlund, J., Lindstrom, H., Nilsson, F., and Reale, M. 2006. Modulus of elasticity of Norway spruce logs vs. structural lumber grade. *Holz als Roh-und Werkstoff*. 64 (4):273-279.

Evans, R. and Ilic, J. 2001. Rapid prediction of wood stiffness from microfibril angle and density. *Forest Products Journal*. 51(3):53-57.

Grabianowski, M., Manley, B., and Walker, J. 2006. Acoustic measurements on standing trees, logs, and green lumber. *Wood Science and Technology*. 40(3):205-216.

Lachenbruch, B., Johnson, G.R., Downes, G.M., and Evans, R. 2010. Relationships of density, microfibril angle, and sound velocity with stiffness in Douglas-fir. *Canadian Journal of Forest Research*. 20(1):55-64.

Lasserre, J.P., Mason, E. G., Watt, S. W. 2007. Assessing corewood acoustic velocity and modulus of elasticity with two impact based instruments in 11-year-old trees from a clonal spacing experiment of *Pinus radiata* D. Don. *Forest Ecology and Management*. 239(1-3):217-221.

Mahon, J.M., Jr., L. Jordan, L.R. Schimleck, A. Clark III, and R.F. Daniels. 2009. A comparison of sampling methods for a standing tree acoustic device. *Southern Journal of Applied Forestry*. 33(2):62-68.

Marshall, H.D., and Murphy, G.E. 2004. Economic evaluation of implementing improved stem scanning systems on mechanical harvesters/processors. *New Zealand Journal of Forestry Science*. 34(2):158-174.

Matheson, A.C., Dickson, R.L., Spencer, D.J., Joe, B., and Ilic, J. 2002. Acoustic segregation of *Pinus radiata* logs according to stiffness. *Annals of Forest Science*. 59(5-6):471-477.

Maurer, H., Schubert, S. I., Bachle, F., Clauss, S., Gsell, D., Dual, J., and Niemz, P. 2006. A simple anisotropy correction procedure for acoustic wood tomography. *Holzforschung*. 60(5):567-573.

Sheng-zuo, F. and WenZhong, Y. 2003. Interclonal and within tree variation in wood properties of poplar clones. *Journal of Forest Research*. 14(4):263-268.

Wang, X., Ross, R.J., and Carter, P. 2007a. Acoustic evaluation of wood quality in standing trees. Part I. Acoustic wave behavior. *Wood and Fiber Science*. 39(1):28-38.

Wang, X., Carter, P., Ross, R. J., and Brashaw, B. K. 2007b. Acoustic assessment of wood quality of raw forest materials – a path to increased profitability. *Forest Products Journal*. 57(5):6-14.

Xu, P., Donaldson, L., Walker, J., Evans, R., and Downes, G. 2004. Effects of density and microfibril orientation on the vertical variation of low-stiffness wood in radiata pine butt logs. *Holzforschung*. 58(6):673-677.

Xu, P., Walker, J. C. F. 2004. Stiffness gradients in radiata pine trees. *Wood Science and Technology*. 38(1):1-9.