Acoustic Evaluation of Alaskan Young-Growth Wood

Xiping Wang and Robert J. Ross

Abstract

With the move to intensive forest management to meet wood demand and to preserve the environment, southeast Alaska is experiencing a period of significant change in terms of wood characteristics or wood quality. In order to responsibly manage the young-growth stands, it is important to evaluate tree quality prior to harvest and understand the product and economic potential of the wood fiber in standing trees. The research reported in this paper is a component of a larger wood quality project that was designed to address the quality concerns on the young-growth wood in southeast Alaska and grade issues regarding silvicultural treatments. The objectives of this sub-study were to investigate the applicability of a newly developed acoustic wave method for assessing wood properties of standing, young-growth western hemlock and Sitka spruce trees and to determine if the effects of pre-commercial thinning and commercial thinning on wood quality could be properly identified with this acoustic evaluation technique. Four hundred and sixty-one standing trees from nine different sites were nondestructively tested using a time-of-flight acoustic wave technique. The study sites reflected different age classes, ranging from 37 to 73 years old, and represented a range of pre-commercial thinning and commercial thinning spacings. Sample trees were subsequently harvested, sawn into logs, and then processed into structural lumber. The acoustic velocities of all mill-length logs were obtained using a resonance acoustic tool. Full-size lumbers recovered from the logs were E-rated using a transverse vibration method and then mechanically tested to failure for stiffness and strength properties. This paper only reports the results from tree-log data analysis. Acoustic data of the trees and corresponding logs were analyzed on both individual tree levels and stand levels to examine the effects of tree diameter at breast height, stand age, and thinning regime on tree acoustic velocity.

Introduction

Assessing wood quality of trees and forest stands has become an important procedure in forest operations as forestry and wood processing industries are increasingly under economic pressure to maximize the extracted value (Wang et al. 2007). The worldwide shift of wood supply from old-growth resources to intensively managed forest plantations increases the needs of evaluating tree quality prior to harvest. This is especially true in southeast Alaska where young-growth wood is becoming a main timber resource to the local forest economy.

The Tongass National Forest in southeast Alaska has nearly 400,000 acres of young-growth stands created by timber harvest that are being managed for different forest resources including timber, wildlife, recreation, fisheries, and other aquatic resources. Of the 400,000 plus acres of young-growth, the Tongass National Forest has pre-commercially thinned about 125,000 acres (Russell 2003, Lowell 2003). The bulk of the pre-commercial thinning (PCT) occurred because of the allowable cut effect (ACE) and forest health reasons. With the restructuring of the timber industry in southeast Alaska, PCT becomes very questionable from an economic timber management perspective. Previous market niche, large supplies of low-quality fiber with a small amount of high value saw timber, was based on industrial pulpwood markets.

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PCT was more important when cuts were high and before the loss of the pulpwood markets. Harvest levels are declining as a result of the decrease in capacity in timber industry. In addition, PCT usually results in fast growth and creates larger limbs/knots that may degrade wood quality in terms of structural applications (Barbour et al. 2005).

The primary question is that, with current industry outlook, is log quality being degraded for a saw milling future by continuing to PCT (Russel 2003, Lowell 2003). A similar question could also exist to commercial thinning (CT) young-growth. While there is little information available on the commercial value of the young-growth resource in southeast Alaska, information available on small-diameter timber of other species from other regions indicates that the difference in value of the timber in managed and unmanaged stands in southeast Alaska could be significant. In order to responsibly manage the young-growth stands, it is important to understand the product and economic potential of the wood fiber that is removed from PCT and CT stands and of the trees that are left behind for possible harvest in the future.

A research project was initiated in 2003 and designed to address the quality concerns on the young-growth Alaskan wood and determine how current silvicultural practices (PCT and CT) in the Tongass National Forest affect wood properties of the young-growth in terms of structural applications. This comprehensive study was jointly conducted by the USDA Forest Service Alaska Region (Region 10), USDA Forest Service Pacific Northwest Research Station, and USDA Forest Service Forest Products Laboratory. The study reported in this paper was one of the components of the overall project. Its primary objective was to investigate the applicability of a newly developed acoustic wave technique for assessing wood properties in standing, young-growth western hemlock and Sitka spruce trees. The secondary objective of this substudy was to determine if the effects of thinning on these properties could be properly identified with this technique.

Materials and Methods

Study Sites and Tree Samples

The species examined in this study were western hemlock (*Tsuga heterophylla*) and Sitka spruce (*Picea sitchensis*), located in Prince of Wales Island (PWI) and Petersburg, southeast Alaska. The study sites were selected by local foresters and represented the types of stands, timber ages, and sizes that are likely to be harvested in the future. A total of nine sites were selected to represent a range of pre-commercial thinning and commercial thinning spacings with an adjacent corresponding control stand (unthinned). Most of the sites were located near roads and on relatively flat terrain with easy access to facilitate the removal of tree samples that were planned to harvest. The silvicultural information of the sites and stands is shown in **Table 1.**

The age of the stands ranged from 37 to 73 years old. The stands in sites 1, 2, 3, and 4 received pre-commercial thinning roughly at the age of 20 and the stands in sites 5, 6, 7, and 8 received commercial thinning at the ages of 40 and 55. The thinning time for the site of Petersurg is not clear yet. At each site, one treatment stand (thinned) and one control stand (unthinned) was selected. From each stand, 10 to 15 trees per species were sampled and tested in the years of 2003 and 2004, which resulted in a total of 461 tree samples, including 207 western hemlock and 254 Sitka spruce. The tree samples were stratified by diameter at breast height (DBH) to cover the diameter range present. Each tree was uniquely identified and tagged with a tree number.

Field Measurements on Trees

The field tree measurements were conducted in the summer of 2003 and 2004 and included measuring tree DBH and conducting acoustic wave tests on each sample tree. Tree DBH was collected from each sample tree using a diameter tape. Acoustic wave propagation time was measured in the lower portion of the tree trunk using a time-of-flight measurement system (**Fig. 1**). The system includes a portable scopemeter, two probes, two acoustic sensors, and a hand-held hammer. During the Held test, a

Table 1.—*Sites and stands selected for nondestructive evaluation.*

Site no.	Site name	Year established	Stand age	Thinning treatment	Year of thinning
1	Throne Bay Dump	1963	40	12 by 12	PCT in 1983
2	12 Mile	1960	43	12 by 12	PCT in 1982
3	Maybeso	1959	44	10 by 10	PCT in 1981
4	Harris River	1963	40	16 by 16	PCT in 1980
5	Shaheen -Unit 2	1945	58	18 by 18	PCT in 1985
6	Shaheen -Unit 3	1945	58	20 by 20	CT in 1985
7	Naukati -1	1930	73	20 by 20	CT in 1985
8	Naukati -2	1930	73	25 by 25	CT in 1985
9	Petersburg	1967	37	10 by 10	PCT

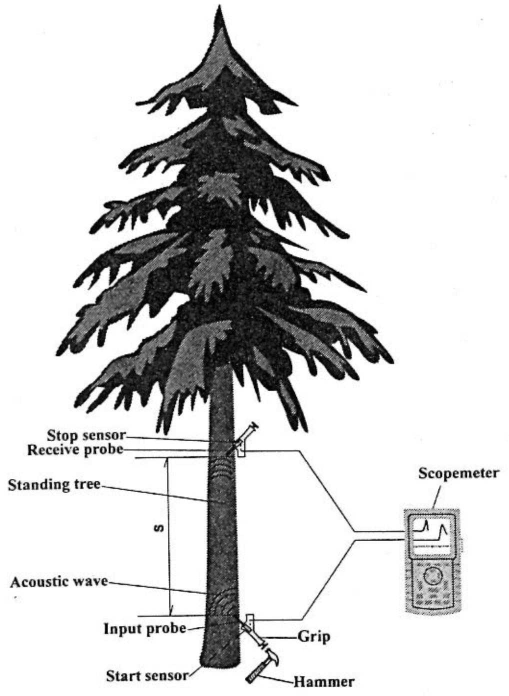

Figure 1.—*Acoustic wave system for field testing of standing trees.*

1.22-m (4-ft) testing span was roughly centered at breast height. Acoustic wave propagation time was measured at one randomly selected face for each tree.

Tree Harvesting, Log Measurements, and Mill Process

All sample trees were subsequently harvested by a local company in May 2005. Felled tree stems were then cut into mill-length logs (mostly 16-ft) and transported to a log yard at Ketchikan Wood Technology Center (KWTC) (Ketchikan, Alaska). A total of 1,801 mill-length logs were obtained from 461 sample trees.

Detailed log measurements (log scaling in cubic and Scribner rules, log grading, resonance acoustic wave testing) were obtained at the log yard of KWTC. Log grades were assigned based on current Bureau Log Scaling Rules. The acoustic velocity of each mill-length log was measured using a resonance acoustic tool (Director HM200). Cross section discs were also cut from the large end and top of the butt logs and the small end of all of the other logs for specific gravity analysis, ring counts, and estimation of juvenile wood core.

The mill-length logs were then sawn into 51-mm- (2-in.-) thick lumber that are typically marketed by the local sawmill. All lumber were kiln-dried, surfaced, and graded by certified lumber graders according to the Western Lumber Grading Rules (WWPA 1998). The identity of the logs and all of the lumber from individual logs were maintained throughout the study.

Lumber Testing

After kiln-drying, all lumber were nondestructively tested at KWTC using a transverse vibration method, according to ASTM Test Methods D6874-03 (ASTM 2003a). A dynamic modulus of elasticity (MOE) was obtained for each individual piece of lumber.

Following nondestructive testing, the full-size lumber was proof-loaded in edgewise bending and tested to failure in accordance with ASTM Test Methods D198-02 (ASTM 2003b). Edgewise bending MOE and modulus of rupture (MOR) of each lumber were calculated from load-deflection data collected during the loading process.

Data Analysis

The lumber data are currently being checked and integrated by USDA Forest Service, Pacific Northwest Research Station and Ketchikan Wood Technology Center (KWTC) and not available for analysis at this time. The results presented in this paper are considered preliminary and analysis is focused on tree data and log data only.

For acoustic data of the sample trees, three readings (wave propagation time) were collected on each tree. An average propagation time was used to calculate the acoustic velocity of the trees. The calculated tree acoustic velocity is referred to as measured tree velocity or apparent tree velocity.

Analysis of tree acoustic velocity and tree DBH was performed on both individual tree level and stand level; for both combined species and individual species. Statistic regression analysis (single variable and multi-variable regression) was used to determine the following relationships:

1. Tree acoustic velocity versus log acoustic velocity;
2. Tree acoustic velocity versus tree DBH;
3. Tree acoustic velocity versus stand age; and
4. Butt log acoustic velocity versus full-length stem acoustic velocity.

Statistical comparison analysis (t-test) was conducted to examine the acoustic velocity differences between the control stand and thinned stand for each study site.

Results and Discussions

Apparent Tree Velocity versus Butt Log Velocity

The accuracy and reliability of time-of-flight measurements on standing trees are typically evaluated through a direct comparison with the corresponding log resonance measurements. **Figure 2** shows the relationship between measured tree acoustic velocity (apparent tree velocity) and corresponding butt log acoustic velocity (butt log velocity) without species differentiation. A relatively good linear correlation is observed and supported by a coeffi-

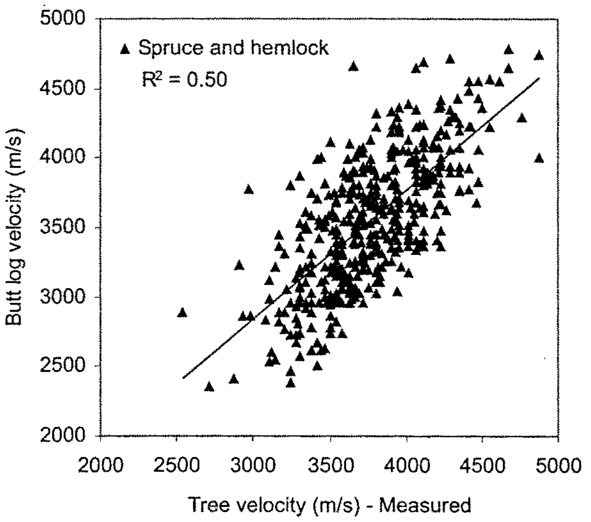

Figure 2.—*Relationship between apparent tree velocity and butt log velocity (species combined).*

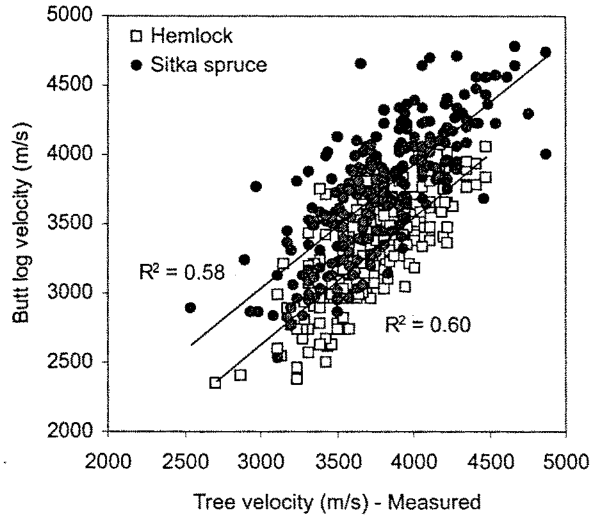

Figure 3.—*Relationship between apparent tree velocity and butt log velocity (species independent).*

cient of determination (R^2) of 0.50. This direct linear relationship, however, suffers from a large variation through the whole velocity range as shown in **Figure 2**.

Figure 3 represents the relationships between apparent tree velocity and corresponding butt log velocity with species differentiated. It is evident that species effect does exist for acoustic testing of standing trees. The strength of the relationship was improved when Sitka spruce and western hemlock were analyzed separately. The coefficient of determination (R^2) increased to 0.58 for Sitka spruce and 0.60 for western hemlock.

Apparent Tree Velocity versus Tree Diameter at Breast Height and Stand Age

Tree diameter has been recognized as a key parameter in predicting wood stiffness of standing trees with acoustic waves (Wang et al. 2007). **Figure 4** shows plots of individual tree velocity versus tree DBH where trees are grouped by stand age. There is a general trend of decreasing tree velocity versus DBH at individual tree level for all study sites. The lower apparent tree velocity with increased DBH seems associated with the higher growth rate in trees, which adversely affects specific gravity as well as strength and stiffness of the wood. The higher variability exhibited within trees of the same diameter classes may reflect the natural variation between individual trees as well as the thinning effect.

Figure 5 shows the relationships between mean apparent tree acoustic velocity per stand and stand age. Apparent tree velocity increases as stand age increases. This trend is in agreement with the current knowledge on tree growth, that is, as trees age, the outer wood gets stiffer due to decreasing microfibril angle, and the proportion of mature wood in the cross section of the tree increases. As such, the overall mechanical properties improved with aging.

It is also noted from **Figure 5** that the mean tree velocity increases at a slower rate when a stand is in older ages than it is in younger ages. One possible explanation is that as trees grow older, the percentage of mature wood increases significantly and the juvenile wood has less effects on overall properties ofthe trees. Another contributing factor could be the thinning effect. In this study, the older stands received commercial thinning (18 by 18 and 20 by 20 ft), in contrast to the pre-commercial thinning for the younger stands (10 by 10, 12 by 12, and 16 by 16 ft). The reduced stand density in older stands could result in a faster DBH growth, but less stiff mature wood.

The relationship between stand mean velocity and stand age seems to capture the changing wood quality in a stand level as trees age. This may be a useful tool for forest managers to monitor wood quality changes over a period of time and examine how trees respond to prescribed silvicultural treatments.

Multivariate Regression Model

Apparent tree velocity shows good correlation to the butt log velocity, but the strength of the relationship suffers from large variations. Similar to previous findings, apparent velocities of most sample trees also deviated from butt log velocity. To improve the prediction of butt log velocity from tree measurements, a multivariate regression model was used to make adjustment on apparent tree velocity:

$$C_{Tadj} = a + b(DBH) + C\ (age)\ dC_{Tapp}$$

where:

DBH = tree diameter at breast height (cm),

age = stand age (yr.), and

C_{Tapp} = apparent tree velocity (rn/s),

C_{Tadj} = adjusted tree velocity, and

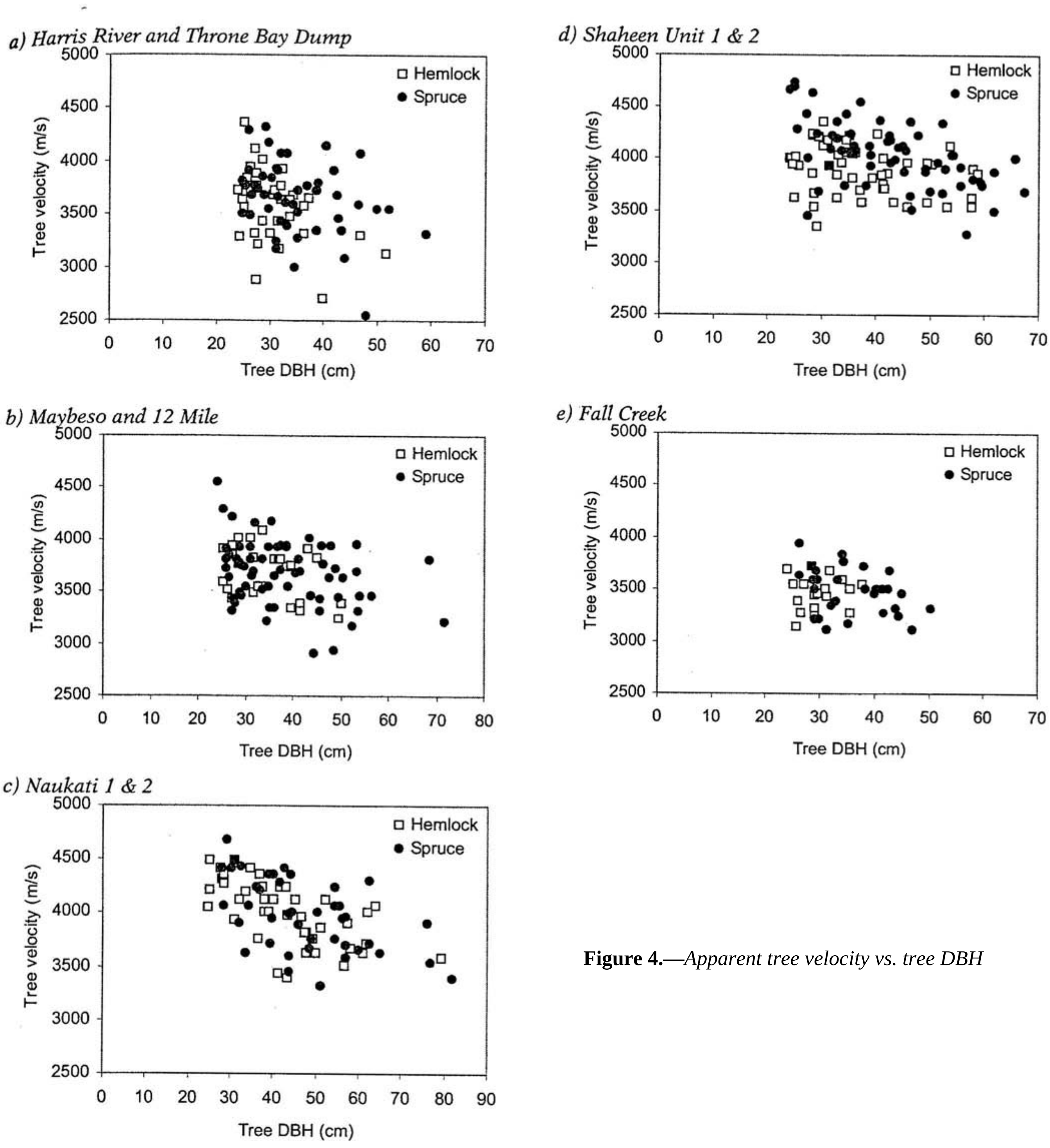

Figure 4.—*Apparent tree velocity vs. tree DBH*

a, *b*, and *c* = coefficients determined by regression analysis.

Separate regressions were developed for Sitka spruce and western hemlock. The regression results are listed in **Table 2**.

Compared with the direct linear regression between apparent tree velocity and butt log velocity, the multivariate regression showed a better correlation between independent variables (DBB, age, and Crapp) and the butt log velocity. The variability of the prediction is also significantly reduced. **Figure 6** show the relationship between adjusted tree velocity and butt log velocity for individual trees. The strength of the relationship is significantly improved when the regression analysis is performed on stand levels ($R^2 = 0.90$) (**Fig 7**).

Butt Log Velocity versus Full-Length Stem Velocity

Although a useful relationship was found between tree measurements and butt log acoustic velocity, a question remains about the validity of this acoustic wave evalua-

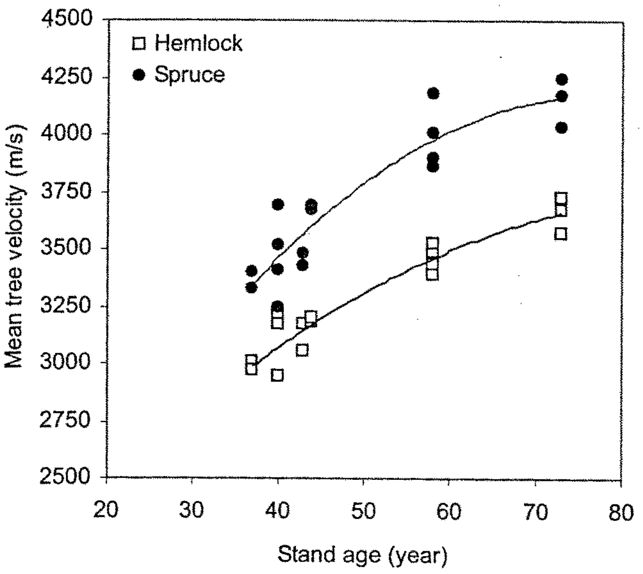

Figure 5.—*Apparent tree velocity vs. stand age.*

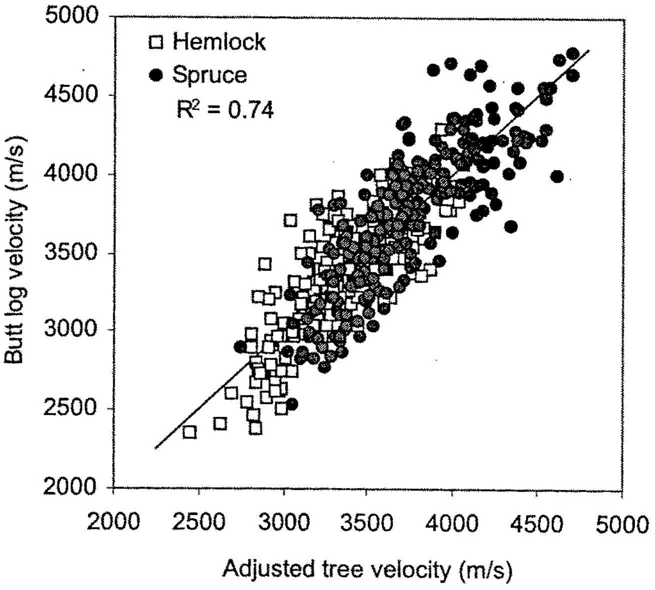

Figure 6.—*Relationship between adjusted tree velocity and butt log velocity.*

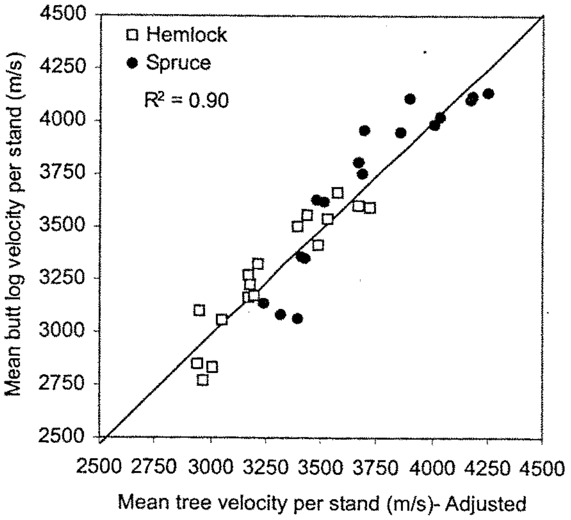

Figure 7.—*Mean tree velocity (adjusted) vs. mean butt log velocity on stand levels.*

tion approach, that is, is the tree acoustic velocity measured over a short span in the lower portion of the trunk a good indication of wood quality for the whole tree? In other words, does tree acoustic velocity or predicted butt log velocity represent the quality level of the wood for the full-length stem cut from the tree?

In this study, a total of 1,801 mill-length logs (mostly 16 ft) were cut from 461 sample trees. Each sample tree produced three to six mill-length logs, depending on tree height. To examine the distribution of log velocity along stem length, 20 trees were selected for each species and log velocity was plotted against log position (**Fig. 8**). For example, log position 1 represents the butt log, 2 represents the second log from the bottom, andso on. **Figure** 8 represents an average trend of log acoustic velocity. It was found that acoustic velocity changes along tree length in a systematic pattern: acoustic velocity is somewhat lower in the butt log than the second log; acoustic velocity is the highest at the second logs in most cases; velocity then gradually decreases as log position moves up to the top. With this consistent velocity trend, it is logical to use butt log velocity as a quality index of a full-length stem.

The effectiveness of using tree acoustic velocity as a quality measure of a standing tree can also be demonstrated by the excellent relationship between butt log velocity and mean velocity of a full-length stem (**Fig. 9**). The coefficient of determination (R^2) for the relationship is above 0.90 for both Sitka spruce and western hemlock.

Table 2.—*Multivariate regression models for adjusting tree acoustic velocity.*[a]

	$C_{Tadj} = a + b\ (DBH) + c\ (age) + d\ C_{Tapp}$					
Species	*a*	*b*	*c*	*d*	R^2	SEE
Western hemlock	374.7	9.8803	-4.1794	0.6855	0.65	226.6
Sitka spruce	901.9	15.2249	-7.0988	0.6196	0.68	259.0

[a] C_{Tadj} is adjusted tree velocity *(m/s)*; C_{Tapp} is apparent tree velocity- *(m/s)*; DBB is tree diameter at breast height (cm); age is stand age (years); *a*, *b*, c, and *d* are coefficients of regression analysis; R^2 is coefficient of determination; and SEE is standard error of estimate.

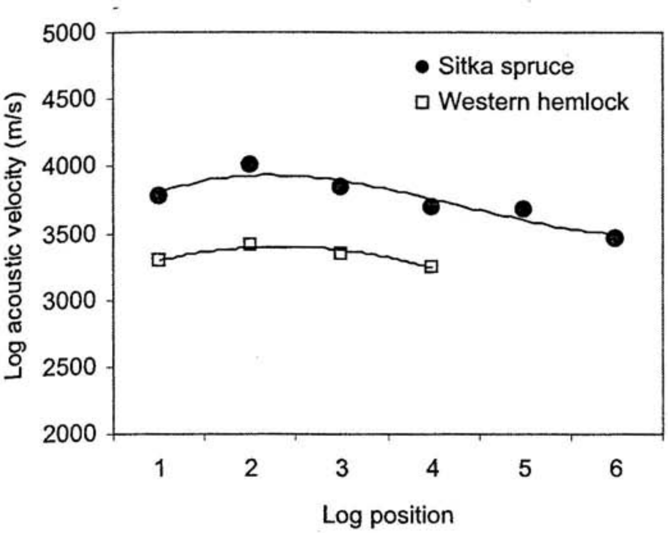

Figure 8.—*Trend of acoustic velocity along the length of tree stems.*

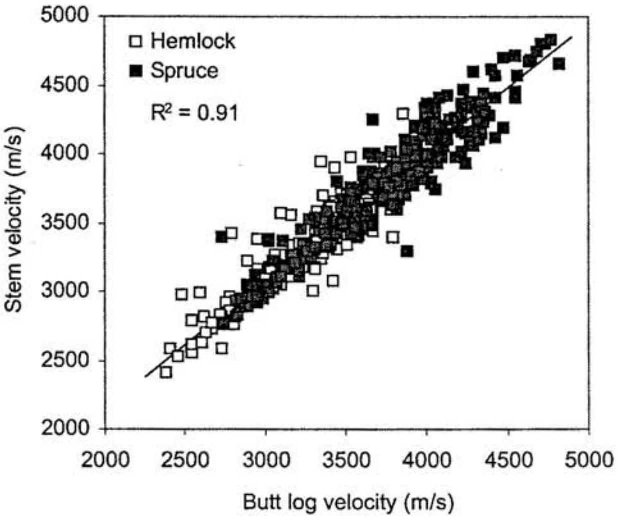

Figure 9.—*Relationship between butt log velocity and stem velocity.*

Thinning Effects on Tree Acoustic Velocity

Tables 3 and 4 summarize stand statistics of tree DBH, adjusted tree acoustic velocity, and butt log velocity for young-growth western hemlock and Sitka spruce, respectively. **Figure 10** shows a comparison of the tree acoustic velocities between the control and thinned stands. It appears that this preliminary data analysis yields some mixed results in terms of thinning effects. The first observation is that no clear trends were found for tree acoustic velocity as stands went through a range of thinning treatments. For young-growth western hemlock, one site (12 Mile) shows a significant tree velocity increase (at 95% confidence level) in the thinned stand, compared to the control stand; thinning treatments in all other sites yielded no significant effect on tree acoustic velocity. For Sitka spruce, two sites show a significant decrease (at 95% confidence level) in thinned stands; thin-

Table 3.—*Tree DBH and acoustic velocity of western hemlock.*

Site no.	Site name	Stand	Spacing	Stand age	No. of samples	DBH (cm) Mean	DBH (cm) SD[b]	Tree velocitfl (m1s) Mean	Tree velocitfl (m1s) SD	Log velocity (m1s) Mean	Log velocity (m1s) SD
			(ft)	(yr)							
1	Thome Bay Dump	Control		40	6	27.8	2.33	2948	234.1	2849	242.8
		PCT	12 by 12	40	8	30.1	6.00	2950	236.9	3049	375.1
2	Twelve Mile	Control		43	11	30.8	4.31	3053	145.1	3058	165.6
		PCT	12 by 12	43	11	34.8	8.70	3172	169.9	3164	204.6
3	Maybeso	Control		44	13	33.5	5.57	3183	192.2	3225	369.3
		PCT	10 by 10	44	13	36.6	8.66	3197	175.2	3168	323.5
4	Harris River	Control		40	11	31.3	7.59	3173	216.4	3264	411.5
		PCT	16 by 16	40	10	32.5	6.37	3214	216	3322	294.5
5	Shaheen Unit 2	Control		58	10	35.4	8.79	3493	204.6	3409	293.4
		PCT	18 by 18	58	10	38.7	11.26	3531	184.1	3534	326.8
6	Shaheen Unit 3	Control		58	15	41.0	11.58	3395	157.6	3502	209.5
		PCT	20 by 20	58	14	34.9	6.95	3439	165.6	3553	299.5
7	Naukati 1	Control		73	16	40.1	11.10	3672	231.4	3596	275.3
		PCT	20 by 20	73	12	41.6	12.51	3723	224.9	3593	296.6
8	Naukati 2	Control[c]		73	16	40.1	11.10	3672	231.4	3596	275.3
		PCT	25 by 25	73	13	48.4	13.57	3573	253.9	3660	174.0
9	Falls Creek	Control		37	7	27.9	3.83	3010	151.1	2826	211.3
		PCT	10 by 10	37	11	31.2	3.64	2973	82.4	2769	215.0

[a] Adjusted tree acoustic velocity.
[b] SD = standard deviation.
[c] Same control stand with site Naukati 1.

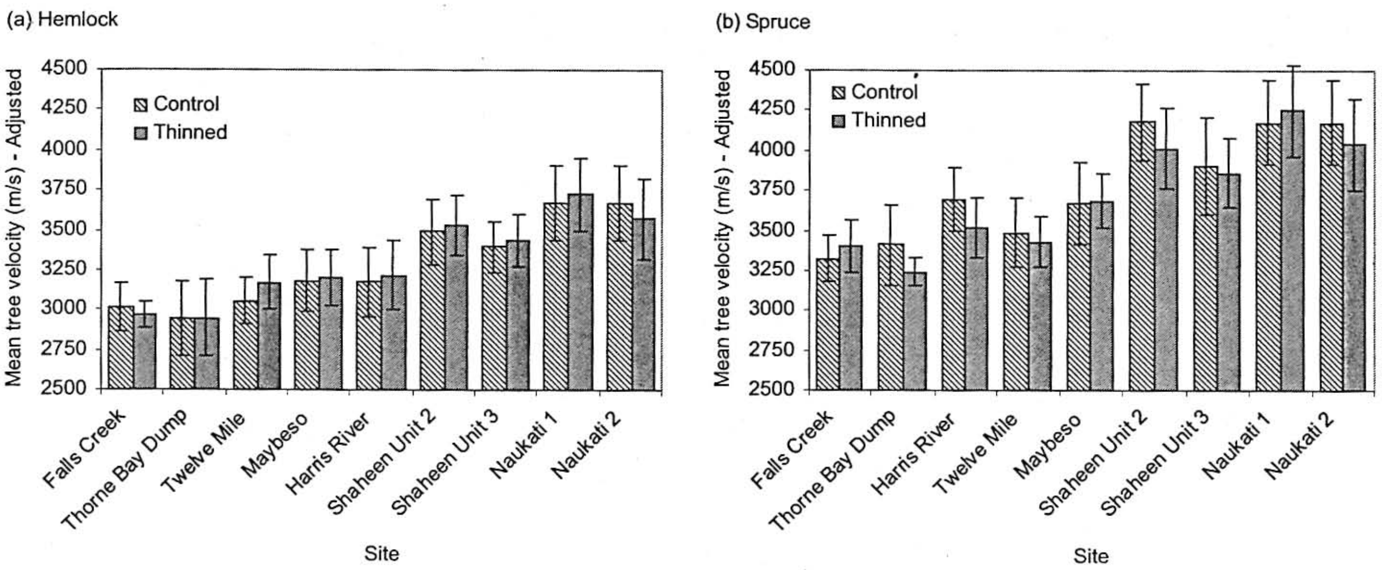

Figure 10.—*Comparison of tree acoustic velocities between control and thinned stands.*

ning treatments in the other seven sites showed no significant effect on tree acoustic velocity. The second observation is that the tree velocity variations within stands are greater than the velocity differences between the control and thinned stands, which raises concerns about the tree sample sizes of this study (mostly 10 to 17 trees per stand; four stands have 4 to 8 tree samples). The large velocity variation found within each stand is no surprise because the same has been reported by other researchers (Cater et al. 2005). This may imply that a big sample size (say 50 trees + per stand) is necessary in order to detect any significant differences in tree acoustic velocity between stands.

Conclusions

Four hundred and sixty-one young-growth western hemlock and Sitka spruce standing trees selected from nine different sites in southeast Alaska, representing a

Table 4.—*Tree DBH and acoustic velocity of Sitka spruce.*

Site no.	Site name	Stand	Spacing	Stand age	*No.* of samples	DBH (em)		Tree velocity[a] (m/s)		Log velocity (m/s)	
						Mean	SD[b]	Mean	SD	Mean	SD
			(ft)	(yr)							
	Thorne Bay Dump	Control		40	12	33	6.78	3411	252.7	3356	321.9
		PCT	12 by 12	40	4	35	3.02	3242	87.2	3137	336.2
2	Twelve Mile	Control		43	16	37	9.02	3486	217.5	3621	275.6
		PCT	12 by 12	43	15	37.4	9.07	3428	156.9	3352	220.8
3	Maybeso	Control		44	17	40.6	12.54	3671	260	3808	380.7
		PCT	10 by 10	44	15	38.5	12.2	3687	170.2	3746	258.7
4	Harris River	Control		40	14	35.7	9.05	3693	196	3952	370.2
		PCT	16 by 16	40	16	36.4	9.02	3521	185.7	3620	251.5
5	Shaheen Unit 2	Control		58	16	40.1	10.71	4182	237.7	4113	317.7
		PCT	18 by 18	58	12	46.7	10.2	4010	250.6	3982	280.6
6	Shaheen Unit 3	Control		58	16	42.3	12.35	3901	304.3	4106	327.3
		PCT	20 by 20	58	17	42	11.86	3860	213.4	3943	301.7
7	Naukati 1	Control		73	16	43.5	11.96	4176	261.5	4096	278.3
		PCT	20 by 20	73	13	47.7	14.37	4249	287.2	4136	290.8
8	Naukati 2	Control[c]		73	16	43.5	11.96	4176	261.5	4096	278.3
		PCT	25 by 25	73	15	50.6	14.6	4039	287.8	4020	295.7
9	Falls Creek	Control		37	15	36.4	6.85	3324	148.1	3078	189.8
		PCT	10 by 10	37	15	35.9	7.05	3399	165.6	3061	220.4

[a] Adjusted tree acoustic *velocity.*
[b] SD = standard deviation.
[c] Same *control* stand with site Naukati 1.

range of pre-commercial thinning and commercial thinning spacing, were nondestructively evaluated using a time-of-flight acoustic method. Acoustic velocities of the logs were then measured using a resonance acoustic tool after trees were harvested and bulked into mill-length logs. Preliminary findings from tree-log data analysis are summarized as follows:

1. Time-of-flight acoustic measurement on standing trees has a strong correlation with resonance acoustic measurement of the corresponding logs;
2. A multivariate regression model was found effective in adjusting tree velocities and reducing velocity prediction variability;
3. Tree velocity and butt log velocity are both good indicators of the wood quality of full-length stems;
4. Results on thinning effects are yet to be verified by lumber data analysis.

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