Combining Acoustic and Laser Scanning Methods to Improve Hardwood Log Segregation

Xiping Wang
USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin, USA, xwang@fs.fed.us

Ed Thomas
USDA Forest Service, Northern Research Station, Princeton, West Virginia, USA, ethomas@fs.fed.us

Feng Xu
Yunfei Liu
College of Information Science and Technology, Nanjing Forestry University, Nanjing, China, xufeng@njfu.com.cn, lyf@njfu.com.cn

Victor Krause
Natural Resources Research Institute, University of Minnesota Duluth, Duluth, Minnesota, USA, vkrause@d.umn.edu

Brian K. Brashaw
Robert J. Ross
USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin, USA, bbrashaw@fs.fed.us, rjross@fs.fed.us

Abstract

The objective of this research was to examine the technical feasibility of combining acoustic wave data with high-resolution laser scanning data to improve accuracy of hardwood log defect detection and segregation. Using acoustic impact testing and high-resolution laser scanning techniques, 21 yellow-poplar logs obtained from the central Appalachian region were evaluated for internal and external defects. These logs were then sawn into boards, and the boards were visually graded based on National Hardwood Lumber Association grading rules. The response signals of the logs from acoustic impact testing were analyzed through moment analysis and continuous wavelet transform to extract time domain and frequency domain parameters. The results indicated that acoustic velocity, time centroid, damping ratio, as well as the combined time and frequency domain parameters are all effective quality predictors for segregating low-end logs. Acoustic data combined with high-resolution laser scanning data provide a more complete picture of the log in terms of size, shape, surface defects, and degree of soundness. Indications of "soundness" in a particular log allow the internal prediction system to flag suspicious defects as potentially unsound. Thus, a combined system would be able to discriminate much more exactly with respect to log quality and potential lumber recovery than either method independently.

Keywords: acoustic velocity, damping ratio, impact testing, laser scanning, log defects, wavelet analysis, yellow-poplar

Introduction

The quality of hardwood logs varies widely within species, harvest site, and even the same tree. Holes, knots, wounds, and other growth defects on logs decrease the strength and appearance of any resulting products and thus decrease the value of the log and its products (Carpenter et al. 1989). The location, type, and size of defects on hardwood logs dictate the potential grade and value of the resulting lumber. Hardwood lumber is bought and sold using National Hardwood Lumber Association (NHLA) grades reflecting the value of each board. The fewer the defects, the greater the length and width of clear areas, which results in higher lumber grade and value. Hardwood log sawing begins with the log face that is clearest and will yield the highest valued boards. The sawyer attempts to saw the log such that any defects will be on the edges of boards. Such defects can then be edged from the sides of the board to make a higher valued board. Thus, scanning systems that find defects on and inside hardwood logs could dramatically improve the sawing process and the grade and value of sawn lumber.

Another important reason for early defect detection in hardwood logs is to remove logs from the processing stream that have little or no profitability. This concept is commonly known as the “break-even log” because processing a log with quality lower than the break-even log results in a loss for the company. Ideally, logs that give no real financial return from processing should be sold to other processors that can economically process these logs into products such as railroad ties, pallet lumber, pulp, fuel, or other similar products to realize target profit maximization.

Research in the field of nondestructive testing and evaluation of wood has resulted in an array of tools for detecting internal defects. Technologies such as X-ray, computed tomography (CT), and nuclear magnetic resonance (NMR) offer cross-sectional images with sufficient details but are not cost-effective for hardwood mills and are too slow to be considered suitable for on-line implementation (Wagner et al. 1989, Chang 1992, Guddanti and Chang 1998, Li et al. 1996, Bhandarker et al. 1999). Laser scanning, however, is an inexpensive, fast, and accurate method of measuring log diameter, length, and volume. As a by-product, the scanning systems measure the crook, sweep, and eccentricity of the log to a fraction of a millimeter. In addition, most surface defects regarded as degrade defects by the Forest Service grading rules are detected during laser data image processing. This permits logs that have been laser-scanned to be sorted not only by diameter and length but by quality as well. A high-resolution laser scanning system has been developed by the USDA Forest Service (Thomas et al. 2006, 2008). This system shows promise for improving internal defect predictions and greatly improving lumber value. This system, however, has some limitations on predicting unsound areas within a log based solely on solid-appearing surface defects.

Acoustic wave methods use a mechanical impact to generate low-frequency stress waves that propagate longitudinally through a log. Then, the reverberation of the waves within the log are recorded and analyzed. At the microstructure level, energy storage and dissipation properties of the log are controlled by orientation of wood cells and structural composition, factors that contribute to stiffness and strength of wood. Such properties are observable as frequency of the wave reverberation and rate of wave attenuation. Research has shown that propagation velocity of acoustic waves in wood is a good predicting parameter for wood deterioration caused by any wood decay mechanism (Pellerin et al. 1985, Wang et al. 2004). Commercial acoustic tools are now widely accepted in the forest products industry for on-line quality control (structural lumber, veneer) and field or in-plant segregation of incoming softwood logs (Harris et al. 2002; Carter et al. 2005; Wang et al. 2007, 2013; Wang 2013).

Acoustic waves and laser scanning methods operate under different principles. Each addresses the weaknesses or inabilities of the other. The main objective of this study was to determine the technical feasibility of combining acoustic wave data with high-resolution laser scanning data to improve the accuracy of defect detection and quality assessment in hardwood logs.

Materials and methods

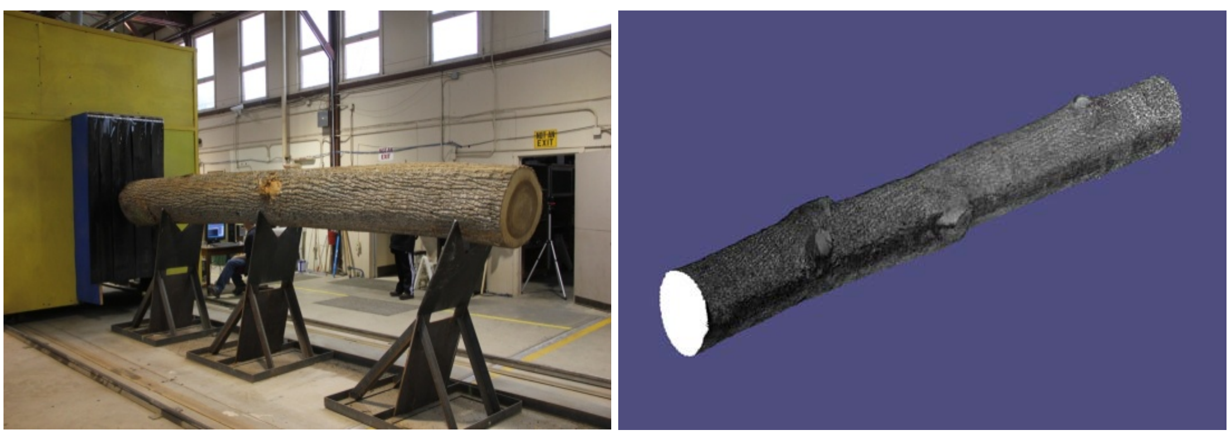
Materials

A random sample of 15 yellow-poplar (*Liriodendron tulipifera*) trees were harvested from a Mead WestVaco leased and managed forest near Rupert, West Virginia, USA, in the central Appalachian region in late January 2015. Each tree was bucked to commercial lengths with 3 to 5 logs being cut from each tree, resulting in a total of 52 logs. All logs were tagged and transported to the Forest Service wood laboratory located in Princeton, West Virginia, USA, for laboratory scanning and testing. From visual observation, these logs ranged in quality level. Some of the logs had very obvious rot after bucking, some had deeply grown wounds with significant encapsulated decay pockets, and some were very high quality.

Physical diagramming and 3D laser scanning

The yellow-poplar logs were first put on a rack for physical diagramming of all surface defect indicators shortly after arriving at the lab. All surface defects were manually located and measured according to the characteristics as defined in Carpenter et al. (1989). For each log, the following information was recorded to create a ground-truth defect map: defect type, surface width (across grain) and length (along grain), growth rate, bark thickness, and surface height rise. Photos were also taken of each log for visual documentation.

A high-resolution laser scanner (Thomas and Thomas 2011) was then used to scan each log to obtain measurements, shape, and surface data. This log scanning system electronically digitizes the surface of logs with a scan line every 1.59 mm (0.0625 in.) along the length. Each scan line describes the circumference of the log and consists of 250 to 450 points, depending on the size of the log. At each reference point, the scanner records the laser energy reflected from the surface as 10-bit grayscale value. Average resolution around a log's circumference is 8 points per inch. This resolution is significantly higher than the scanner currently used in sawmills in which typically one scan line every 30 to 60 cm (12 to 24 in.) is used. Figure 1 shows the laser scanning system and an example of a 3D rendering of log data using the laser energy data for false color. The log shape as well as defect positions and relative sizes are easily discerned.



(a) (b)

Figure 1—Laboratory laser scanning of yellow-poplar logs: (a) high-resolution laser scanning system; (b) high-resolution scanned imagery of yellow-poplar log (log no. 1161).

Acoustic impact test

Following physical diagramming and laser scanning, each log was placed on the ground and acoustically tested to obtain nondestructive parameters for potential detection of internal defects. An acoustic impact test was conducted in two different ways: (1) using a resonance acoustic tool to directly measure the acoustic velocity of each log and (2) using a laboratory impact testing system to obtain and record the response signals from each log following a mechanical impact. All acoustic tests were conducted under a condition of 21 °C (70 °F) and 50% relative humidity.

A hand-held resonance acoustic tool (Hitman HM200, Fibre-Gen, Inc., Auckland, New Zealand) was used to directly measure the acoustic velocity of each log. Following a hammer impact, the HM200 tool immediately processes the received acoustic signals through the Fast Fourier Transform (FFT) program built into the tool and calculates log acoustic velocity (V) based on the resonant frequency and log length:

$$V = 2\, f_n\, L/n \tag{1}$$

where f_n is the nth harmonic frequency (Hz) of the response signal, L is the full length of a log, and n is the order of harmonic frequency.

To collect the response signals from each log, a sensor probe (Fakopp spike sensor, Fakopp Enterprise Bt., Agfalva, Hungary) was inserted into the end grain at the log end (close to the center). The impact acoustic waves were generated through a 5.44-kg (12-lb) sledge hammer blow on the opposing end, and the response signals were recorded through a data acquisition card (NI 5132) connected to the laptop, with a sampling frequency of 20 kHz and a sampling length of 1,000 points.

Sawing and visual grading

After laboratory scanning and testing, 21 logs were selected and sawn into boards using a portable sawmill. This subsample of logs was systematically selected based on visual assessment and resonant acoustic testing results such that they represent the quality range of the 52 logs. The resulting boards were visually graded according to NHLA rules (NHLA 2015).

Data processing and analysis

Laser scan data

The laser scan data of each log was processed by a defect detection system developed to locate severe defects on hardwood logs (Thomas and Thomas 2011, 2013). As an example, Figure 2 presents defect detection results for log no. 1161. This is the same log shown in Figure 1. The defect detection begins by fitting a circle to each laser scan line. Next, a residual image is generated using the residual, or distances between the fitted circle and circular scan line (Fig. 2a). In the residual image, bumps or high spots are presented as lighter gray, whereas low areas, such as holes, are shown as darker gray. Performing a contour analysis on the residual image yields a contour map (Fig. 2b) that defines the bumps and depressions that correspond to defective areas, for example, severe log degrade defects. An expert system was developed to process the contour map and recognize, classify, and measure the defective areas. Figure 2c is the graphical output from this final detection step. The sawing process for each log was also replicated using the RAYSAW sawing simulator. The size and positions of internal defects were estimated using the models developed by Thomas (2008, 2013). These methods use the size and type of the surface indicator to predict the size and location of the internal defect. When RAYSAW processes a log, it reports the overall shape of each board, as well as the positions and sizes of all predicted defects that fall on the board faces.

Acoustic wave data

A series of physical and acoustic properties of the logs were obtained and used as potential quality indicators for predicting the soundness of the logs and grade yields of the resulting boards. The predicting parameters we examined included acoustic velocity (V), dynamic modulus of elasticity (E_d), time centroid

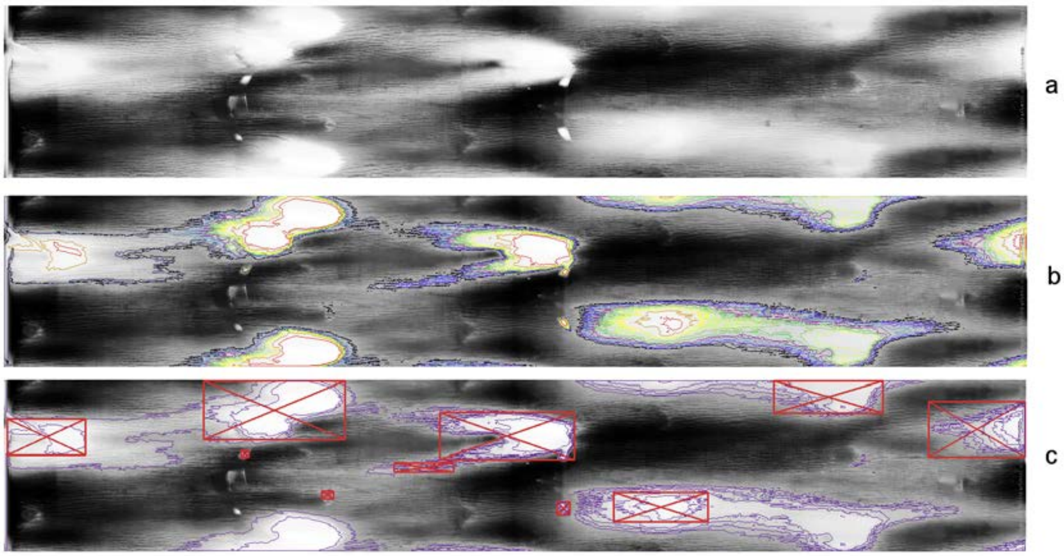


Figure 2—Defect detection results for log no. 1161: (a) residual image generated; (b) image resulting from contour analysis of residual image; (c) defects detected in contour map are identified using red boxes.

(T_c), and damping ratio (ζ), as well as two combined parameters of the response signals (Wang et al. 2016). The following procedures were followed in acoustic data analysis:

1) Compute dynamic modulus of elasticity of the logs using one-dimensional wave equation: $E_d = \rho V^2$ (2)
2) Determine time centroid (T_c) of the response signals through first moment analysis;
3) Perform continuous wavelet transform (CWT) of the response signals and compute the wavelet ridge by maximizing the modulus of wavelet skeleton at each time instant;
4) Compute instantaneous natural frequency (f_i) and damping ratio (ζ_i) according to wavelet ridge and skeleton;
5) Determine the relationships between each individual predictor and actual board grade yield;
6) Determine the relationships between the combined parameters and actual board grade yield.
7) Rank logs based on individual and combined parameters.

Results and discussion

Table 1 shows the dimenisonal and physical measures of the 21 selected logs and the sawing results (board volume, cant volume, and board grades). The NHLA rules are based on the size and number of cuttings (pieces) that can be obtained from a board when it is cut up and used in the manufacture of a hardwood product. Therefore, the grades provide a measurable percentage of clear, defect-free wood for each grade. The board grades determined based on NHIA rules include the upper grades (FAS, FIF, and Select), common grades (No. 1 Common, No. 2 Common, and No. 3 Common), and below grade (BG).

Table 1—Dimensional and physical measures of the yellow-poplar logs and the sawing results[a]

Log no.	Length (ft)	Diameter (in.)			Weight (lb)	Sweep (in.)	Volume (board footage)			Grade yield (board footage)				
		Large end	Small end	Avg.			Debarked	Board	Cant	High[b]	1C	2C	3C	BG[c]
1123	11.4	18.60	17.19	18.83	923	1.62	219.82	106	34.47	17	29	42	18	0
1126	13.1	20.39	20.39	19.72	1183	1.36	288.92	158	32.04	138	8	7	0	5
1128	13.1	23.58	20.70	21.46	1823	1.05	339.20	219	29.76	187	19	0	5	8
1129	15.2	20.27	20.27	21.02	1810	0.87	380.26	198	34.99	59	121	6	6	6
1131	16.4	15.18	13.99	14.51	855	2.13	186.80	66	34.01	30	16	20	0	0
1133	14.7	19.30	18.76	18.96	1097	0.96	293.33	157	38.29	32	56	41	28	0
1134	16.8	17.03	15.58	16.20	926	0.83	243.36	116	44.08	23	70	23	0	0
1136	14.0	12.90	12.90	12.98	368	0.52	115.58	36	28.16	0	7	12	17	0
1137	13.5	19.29	17.18	18.01	1209	0.79	236.95	137	21.25	129	8	0	0	0
1138	11.1	16.96	16.39	16.61	801	1.69	168.90	87	25.18	61	26	0	0	0
1140	11.1	15.11	15.11	15.08	641	2.09	135.31	36	33.30	0	12	12	12	0
1141	13.4	14.27	14.27	14.28	686	1.7	143.64	38	41.13	0	10	28	0	0
1147	12.5	14.43	13.76	14.23	632	1.65	137.12	60	31.25	38	6	4	0	12
1153	11.8	21.29	20.56	21.50	1487	1.53	312.18	160	33.92	88	57	5	10	0
1154	9.5	21.09	21.09	20.75	1418	1.23	233.26	126	30.95	76	32	18	0	0
1155	11.4	20.36	18.37	19.22	1151	2.48	235.54	112	59.13	23	36	46	7	0
1161	16.5	17.29	15.29	16.14	1208	1.81	235.73	99	46.90	5	47	47	0	0
1166	17.0	23.85	23.29	23.06	2649	0.91	528.00	290	31.25	192	58	40	0	0
1167	11.4	18.50	17.02	17.86	1012	1.44	198.91	100	30.20	19	20	32	29	0
1169	16.1	17.55	14.94	15.63	1046	1.59	215.58	98	43.20	54	15	29	0	0
1170	14.5	14.77	14.77	14.68	793	1.25	171.59	85	26.79	32	39	9	0	5

[a]1 ft = 0.3048 m; 1 in. = 2.54 cm; 1 lb = 0.454 kg; 1 board foot = 0.00235974 m^3.
[b] High includes grade FAS, F1F, and Select.
[c] BG, below grade.

Table 2 shows the physical and acoustic properties of the 21 selected yellow-poplar logs. The moisture contents of the wood samples were found to be 45% to 60%. Therefore, all acoustic parameters discussed in this paper are considered “green log” parameters. The results of the acoustic impact test were

Table 2—Physical and acoustic properties of the yellow-poplar logs

Log no.	Density (lb/ft^3)[a]	V (km/s)	E_d (GPa)	Scale	f (Hz)	Time centroid (10^{-2})	Damping ratio (10^{-2})	E_d/ζ^2 (10^3)	ρ/T_c^2 (10^5)
1123	42.79	3.34	7.65	115	521.74	1.74	3.59	5.93	1.41
1126	41.98	3.37	7.65	145	413.79	1.64	3.43	6.52	1.57
1128	55.29	3.04	8.18	157	382.17	1.47	3.61	6.27	2.56
1129	48.91	3.05	7.29	174	344.83	1.93	4.25	4.04	1.31
1131	45.54	3.27	7.81	181	331.49	2.08	4.26	4.31	1.05
1133	38.14	3.83	8.98	141	425.53	1.90	4.12	5.29	1.06
1134	38.36	3.78	8.79	161	372.67	1.88	4.41	4.51	1.08
1136	31.03	3.59	6.42	141	425.53	1.98	3.73	4.61	0.79
1137	51.74	3.65	11.05	134	447.76	1.41	3.16	11.04	2.59
1138	47.92	3.88	11.57	104	576.92	1.44	3.02	12.71	2.32
1140	47.45	3.76	10.72	107	560.75	1.75	3.16	10.76	1.56
1141	47.43	3.67	10.21	131	458.02	1.57	3.83	6.95	1.92
1147	45.91	2.91	6.22	154	389.61	1.80	3.88	4.14	1.42
1153	49.06	3.38	8.98	125	480.00	1.48	4.17	5.17	2.25
1154	50.57	2.93	6.95	107	560.75	1.21	3.75	6.08	3.44
1155	49.96	3.32	8.85	126	476.19	1.51	4.53	4.30	2.18
1161	51.63	3.23	8.64	188	319.15	2.04	4.27	4.75	1.24
1166	51.88	3.30	9.06	189	317.46	1.69	4.06	5.50	1.82
1167	51.65	2.98	7.35	140	428.57	1.88	4.14	4.29	1.46
1169	48.71	3.63	10.28	155	387.10	1.53	3.16	10.27	2.07
1170	46.23	3.73	10.31	143	419.58	1.70	4.13	6.06	1.59

[a]1 lb/ft^3 = 16.0185 kg/m^3.

reported in a previous report (Wang et al. 2016). Log acoustic velocity was able to identify the very low-end logs that had the most severe internal rot or other unsound defects but failed to identify the logs with poor geometry that resulted in very low recovery. The time domain parameters (time centroid and ρ/T_c^2) and frequency domain parameters (damping ratio and E_d/ζ^2) were identified as log quality predictors with positive correlation with the board grade yields.

Log visual grades based on laser scan data

The high-resolution laser scanning system was able to accurately measure all log size and shape characteristics. The size, sweep, weight, and volume of each log are listed in Table 1. By examining the center points of each scan line, the scanner can measure the departure of the log from a straight line. This allows the crook and sweep of the log to be measured. A crooked log is one with an end that has a dramatic bend to one side. A swept log has a bow to one side along the length. A log with a crook or sweep will yield less lumber than a straight log of the same diameter and length. In addition, the lumber sawn from a crooked or swept log will generally be weaker than lumber sawn from a straight log. This is because the fiber angles in swept or crooked logs are not aligned along the length of the board.

Using the log measurement data combined with the log surface defect information (position, size, and type of every surface defect) allowed the RAYSAW program (Thomas 2013) to grade each log to U.S. Forest Service hardwood log grading rules (Rast et al. 1973). The U.S. Forest Service log grades are based on the number and type of defects present on a log and the predicted impact they will have on the value and volume of lumber that log should produce. As such, they provide a method of classifying logs based on their observed characteristics, regardless if the inspection is made by machine or human.

Ranking logs based on acoustic parameters

To evaluate the effectiveness of the time domain and frequency domain parameters as log quality predictors, we ranked the 21 yellow-poplar logs using time centroid, damping ratio, ρ/T_c^2, and E_d/ζ^2, respectively. Table 3 lists the logs rated as high and low quality according to each acoustic predictor. The volume recovery and board grade yields of individual logs were tabulated in Table 4 for high-quality logs and in Table 5 for low-quality logs.

Table 3—Yellow-poplar logs rated as high quality and low quality based on different NDE predictors[a]

Predictor	Logs rated as high quality						Logs rated as low quality								
T_c	1154	1137	1138	1128	1153		1131	1161	1136	1129	1133	1134	1167		
ζ	1138	1140	1137	1169	1126		1155	1134	1161	1131	1129	1153	1167	1170	1133
ρ/T_c^2	1154	1137	1128	1138			1136	1131	1133	1134	1161	1129	1123	1147	1167
E_d/ζ^2	1138	1137	1140	1169	1141	1126	1129	1147	1167	1155	1131	1134	1136	1161	

[a]The log marked with a box indicates an abnormal case with a false prediction.

Table 4—Volume recovery and grade yield of high-quality yellow-poplar logs

Log no.	Volume (footage)								Recovery (%)		Board grade yield (%)				
	Board	Cant	Debarked	High	1C	2C	3C	BG	Total	Board	High	1C	2C	3C	BG
1137	137	21.25	236.95	129	8	0	0	0	66.8	57.8	94.2	5.8	0	0	0
1138	87	25.18	168.90	61	26	0	0	0	66.4	51.5	70.1	29.9	0	0	0
1128	219	29.76	339.20	187	19	0	5	8	73.3	64.6	85.4	8.7	0	2.3	3.7
1154	126	30.95	233.26	76	32	18	0	0	67.3	54.0	60.3	25.4	14.3	0	0
1126	158	32.04	288.92	138	8	7	0	5	65.8	54.7	87.3	5.1	4.4	0	3.2
1153	160	33.92	312.18	88	57	5	10	0	62.1	51.3	55.0	35.6	3.1	6.3	0

Time centroid vs. ρ/T_c^2

Time centroid (T_c) and combined parameter ρ/T_c^2 resulted in similar predictions in both high-quality and low-quality ratings, with the exception that when log density (ρ) was taken into consideration, log no. 1153 was excluded from high-quality class and logs no. 1123 and no. 1147 were added into low-quality class per ρ/T_c^2 rating. Considering that log no. 1153 was only marginally rated as high quality per time centroid rating and could be excluded by adjusting T_c threshold, the effectiveness of the combined parameter ρ/T_c^2 for rating high-quality logs was not substantially different from that of single parameter T_c. However, in rating low-quality logs, the combined parameter can be considered more effective because the two added low-quality logs (no. 1123 and no. 1147) per ρ/T_c^2 rating did yield high percentage of low grade (3 Common and BG) boards as shown in Table 5.

Table 5—Volume recovery and grade yield of low-quality yellow-poplar logs.

Log no.	Volume (footage)								Recovery (%)		Board grade yield (%)				
	Board	Cant	Debarked	High	1C	2C	3C	BG	Total	Board	High	1C	2C	3C	BG
1134	116	44.08	243.36	23	70	23	0	0	65.8	47.7	19.8	60.3	19.8	0	0
1167	100	30.20	198.91	19	20	32	29	0	65.5	50.3	19.0	20.0	32.0	29.0	0
1136	36	28.16	115.58	0	7	12	17	0	55.5	31.1	0	19.4	33.3	47.2	0
1131	66	34.01	186.80	30	16	20	0	0	53.5	35.3	45.5	24.2	30.3	0	0
1129	198	34.99	380.26	59	121	6	6	6	61.3	52.1	29.8	61.1	3.0	3.0	3.0
1133	157	38.29	293.33	32	56	41	28	0	66.6	53.5	20.4	35.7	26.1	17.8	0
1161	99	46.90	235.73	5	47	47	0	0	61.9	42.0	5.1	47.5	47.5	0	0
1123	106	34.47	219.82	17	29	42	18	0	63.9	48.2	16.0	27.4	39.6	17.0	0
1147	60	31.25	137.12	38	6	4	0	12	66.5	43.8	63.3	10.0	6.7	0	20.0
1153	160	33.92	312.18	88	57	5	10	0	62.1	51.3	55.0	35.6	3.1	6.3	0
1155	112	59.13	235.54	23	36	46	7	0	72.7	47.6	20.5	32.1	41.1	6.3	0
1170	85	26.79	171.59	32	39	9	0	5	65.2	49.5	37.6	45.9	10.6	0	5.9

Damping ratio vs. E_d/ζ^2

In selecting high-quality logs, damping ratio and combined parameter E_d/ζ^2 resulted in similar predictions with slight change in the ranking order and inclusion of log no. 1141 in E_d/ζ^2 rating. This could be because the defects presented in high-quality logs were too small to have a significant influence on global modulus of elasticity of the logs. However, in rating low-quality logs, the predictions of damping ratio and combined parameter E_d/ζ^2 were quite different as shown in Table 3. Three low-quality logs (no. 1133, no. 1153, and no. 1170) by damping ratio rating were not present in E_d/ζ^2 rating, whereas two low-quality logs (no. 1147 and no. 1136) in E_d/ζ^2 rating were not picked up by damping ratio. The sawing results indicated that logs no. 1147 and no. 1136, rated low quality by E_d/ζ^2, yielded a relatively large proportion of low-grade boards (20% BG for log no. 1147, 47.2% 3 Common for log no. 1136). Particularly for log no. 1147, which had the lowest acoustic velocity of 2.91 km/s (1.8 miles/s) and the largest proportion of BG boards among all the logs, defects significantly decreased the stiffness (*E*) and thus, this log was effectively rated as the second worse log. However, log no. 1147 was not picked up by damping ratio. Similarly for log no. 1136, the defects that resulted in 47.2% 3 Common boards had a significant impact on stiffness (*E*) and therefore was picked up by E_d/ζ^2 rating but not by damping ratio.

For three logs (no. 1153, no. 1170, and no. 1133) rated low quality by damping ratio, two of them (no. 1133 and no. 1170) were dominated by 1 Common and 2 Common boards (79.6% and 56.5%, respectively) and should be considered intermediate quality logs, and one log (no. 1153) was dominated by high grade and 1 Common boards (90.6%) and should be considered a high-quality log.

Tables 6 and 7 list the logs that were rated as high quality and low quality, respectively, using four different predictors and the frequency of positive ratings. The more positive ratings, the higher the probability of the log being rated accurately. However, it should be noted that the logs with lower rating frequency still have a probability of being rated accurately. Overall, rating of low-quality logs was more accurate than rating of high-quality logs.

Table 6—Frequency of positive ratings for high-quality logs using four predictors

	Logs rated as high quality								
Log no.	1137	1138	1128	1154	1126	1169	1140	1153	1141
Frequency of positive rating	4/4	4/4	2/4	2/4	2/4	2/4	2/4	1/4	1/4

Table 7—Frequency of positive ratings for low-quality logs using four predictors

	Logs rated as low quality											
Log no.	1134	1131	1161	1129	1167	1136	1133	1155	1147	1153	1170	1123
Frequency of positive rating	4/4	4/4	4/4	4/4	4/4	3/4	3/4	2/4	2/4	1/4	1/4	1/4

Abnormal cases

Logs no. 1140 and no. 1141 are abnormal cases in which the sawing results showed very low recovery (26.5%) and poor grade yields (1, 2, and 3 Common) but all acoustic predictors failed in prediction. In fact, two frequency-domain parameters (damping ratio and E_d/ζ^2) mistakenly rated these two logs as high quality. From visual examination and laser scan data, we found that these two logs were relatively small in diameter and had a significant amount of sweep or crook (Table 1).

When logs with significant amounts of crook (an abrupt bend), sweep (log is bowed in one or more directions), or taper are sawn, more wood must be removed from the surface to establish a flat board face. This piece of wood from each log face is called a slab. Log no. 1140 had 7.3-cm (2.89-in.) of crook along the red–blue axis (man-made mark for sawing). Log no. 1141 had 4.5-cm (1.79-in.) of sweep primarily along the red–blue axis, but the bow also twisted around the log toward the black face on the large end. To true up the logs, the slabs had to be cut thicker than usual with 10.5-cm- (4.125-in.-) and 10.8-cm- (4.25-in.-) thick slabs sawn from log no. 1140. Slab thicknesses on log no. 1140 were 8.6, 9.8, and 6.7 cm (3.375, 3.875, and 2.625 in.) on the black, blue, and red faces. A similar sawing operation occurred to log no. 1141. In short, these two logs had poor geometry. Significant sweep or taper always significantly decreases the volume of lumber recovered. However, the impact is much more severe on small-diameter logs. Apparently, no acoustic parameters were able to detect logs of poor geometry.

Comparison of acoustic sorting and log scanning results

Table 8 lists the logs that belong to the high- and low-quality acoustic sorts. High-resolution scanning can sense visible features such as bumps, holes, log shape, and size. These observations are based on precise and exact measurements from the laser system. For each log scanned, the number of severe or degrade defects encountered on that log are listed, along with a brief summary, characterizing the defects present. A degrade defect is a defect of a type and/or size that will impact the grade of the log.

Table 8—Defect detection results by high- and low-quality log sorts

Quality sort	Log number	Log grade	Severe defect count	Defect summary
Low	1134	F2	0	Medium bark distortions
Low	1131	F3	14	Multiple wounds and knots
Low	1161	F3	7	Overgrown, unsound, and sawn knots
Low	1129	F2	1	Large overgrown crack–seam
Low	1167	F2	1	Overgrown knot
Low	1136	F3	5	Overgrown knots
Low	1133	F1	0	Several small adventitious clusters
Low	1155	F2	3	Unsound knots and an overgrown knot
Low	1147	F2	6	Wound and five overgrown knots
Low	1170	F1	1	Sawn knot
Low	1123	BG	4	Sawn knot and three overgrown knots
Average		**2.27**	**3.82**	
High	1137	F1	0	Clear
High	1138	F2	1	Large wound
High	1128	F1	0	Clear
High	1154	F2	3	Large overgrown knots
High	1126	F2	2	Large wound and a large gouge
High	1169	F1	1	Small wound
High	1140	F2	5	Overgrown knots
High	1153	F1	0	Clear
High	1141	F3	5	Overgrown and unsound knots
Average		**1.78**	**1.89**	

For each log scanned, the Forest Service log grade was determined using the RAYSAW sawing analysis program (Thomas 2013). Within the Forest Service grading rules, the highest grade or high-quality sawlog is Factory 1 or F1. Factory 2 or F2 is the middle quality level and Factory 3 or F3 is the lowest quality level for sawlogs. As log grade or quality decreases, the number of degrade defects increase and the lengths of the clear areas between defects decrease. If enough defects are present, or the extent of crook or sweep is severe enough, the log will fail to meet the lowest grade, F3. If this happens, the log is graded as BG.

Assigning numeric values to the log grades (where 1 = F1, 2 = F2, 3 = F3, and 4 = BG) allows us to determine an average log grade within each acoustic quality sort. For the low-grade logs, the average grade is 2.27, or slightly lower than Factory 2. For the high-grade logs, the average grade is 1.78, or slightly better than Factory 2. Thus, with our small sample, there is little difference between the visual log grades of the high- and low-quality sorts. Similarly, there is little difference in the number of severe or degrade defects encountered between the samples. Therefore, it is not evident that developing a correlation between log grade or severe defects and acoustic assessment will yield a distinct advantage in sorting or processing capabilities.

Although it is difficult to correlate results from one scanning system to another, the complementary nature of the two systems negate this need. In Table 8, we see that two logs, no. 1133 and no. 1170, in the low-quality acoustic sort were graded as Factory 1, a high-quality visual grade. Examining the grade yield for these two logs (Table 5), we see that the lumber produced was much lower quality than one would expect for a high-grade sawlog. This indicates the presence of one or more internal defects that significantly impacted recovery. For the medium-quality (Factory 2) logs (no. 1129, 1134, 1147, 1155, and 1167) in the low-quality acoustic sort, most logs had lumber yields consistent with low-quality logs (Table 5), which was less than would be expected from a Factory 2 log. The one exception was no. 1147, which had a lumber grade yield that would be expected of a Factory 1 log. We have no explanation for this anomaly. For the high-quality acoustic log sort, lumber grade yields (Table 4) were what would be expected of high-quality sawlogs, with two exceptions, logs no. 1140 and no. 1141. These two logs had significant crook and sweep that drastically decreased their yields. They were also smaller logs for which any fault, shape, or surface defect caused a greater yield decrease.

Conclusions

Acoustic velocity, time centroid, damping ratio, as well as the combined time and frequency domain parameters are all effective quality predictors of hardwood logs in terms of internal soundness. Acoustic parameters combined with high-resolution laser scanning results provide a more complete data picture of the log: size, shape, surface defects, and degree of soundness. A high-quality acoustic assessment coupled with low visual grade indicates a sound log, but the lumber will either have significant numbers of knots or recovery will be low because of poor log shape. In contrast, a high visual grade coupled with a low-quality acoustic sort indicates a log with hidden deficiencies that will decrease lumber value and volume. Thus, a combined system would be able to discriminate much more exactly with respect to log quality and potential lumber recovery than either method independently.

Acknowledgment

This project was conducted under the cooperative research agreement (14-JV-11111133-089) between the Natural Resources Research Institute of the University of Minnesota Duluth (UMD) and the USDA Forest Service, Forest Products Laboratory (FPL). Mr. Feng Xu's participation in this project was supported by the Priority Academic Program Development (PAPD) of Jiangsu Higher Education Institutions and the Nanjing Forestry University (NFU) Innovation Grant for Outstanding PhD Dissertations (grant no. 163070682). We thank Neal Bennett and Deborah Conner for their technical assistance during the project.

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United States Department of Agriculture

Proceedings

20th International Nondestructive Testing and Evaluation of Wood Symposium

Madison, Wisconsin USA
2017

Forest Service, Forest Products Laboratory
Forest Products Society
International Union of Forest Research Organizations

General Technical Report
FPL–GTR–249

September
2017

Abstract

The 20h International Nondestructive Testing and Evaluation of Wood Symposium was hosted by the USDA Forest Service Forest Products Laboratory in Madison, Wisconsin, USA, on September 12–15, 2017. This Symposium was a forum for those involved in nondestructive testing and evaluation (NDT/NDE) of wood and brought together many NDT/NDE users, suppliers, international researchers, representatives from various government agencies, and other groups to share research results, products, and technology for evaluating a wide range of wood products, including standing trees, logs, lumber, and wood structures. Networking among participants encouraged international collaborative efforts and fostered the implementation of NDT/NDE technologies around the world. The technical content of the 20th Symposium is captured in these proceedings.

Keywords: International Nondestructive Testing and Evaluation of Wood Symposium, nondestructive testing, nondestructive evaluation, wood, wood products

September 2017

Wang, Xiping; Senalik, C. Adam; Ross, Robert J., eds. 2017. Proceedings: 20th International Nondestructive Testing and Evaluation of Wood Symposium. General Technical Report FPL-GTR-249. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 539 p.

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