DEFECT DETECTION AND QUALITY ASSESSMENT OF HARDWOOD LOGS: PART 2—COMBINED ACOUSTIC AND LASER SCANNING SYSTEM[1]

*Xiping Wang**†
Research Forest Products Technologist
USDA Forest Service
Forest Products Laboratory
Madison, WI
E-mail: xwang@fs.fed.us

Ed Thomas
Research Computer Scientist
USDA Forest Service
Northern Research Station
Princeton, WV
E-mail: ethomas@fs.fed.us

Feng Xu
PhD Candidate
E-mail: xufeng@njfu.com.cn

*Yunfei Liu**
Professor
College of Information Science and Technology
Nanjing Forestry University
Nanjing, Jiangsu, China
E-mail: lyf@njfu.edu.cn

Brian K. Brashaw
Program Manager
E-mail: bbrashaw@fs.fed.us

Robert J. Ross
Project Leader
USDA Forest Service
Forest Products Laboratory
Madison, WI
E-mail: rjross@fs.fed.us

(Received January 2018)

Abstract. The 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. Using acoustic impact testing and high-resolution laser scanning techniques, 21 yellow poplar logs (*Liriodendron tulipifera*) obtained from the central Appalachian region were

---

* Corresponding author
† SWST member
[1] This article was written and prepared by US Government employees on official time, and it is therefore in the public domain and not subject to copyright.

Wood and Fiber Science, 50(3), 2018, pp. 310-322

evaluated for internal and external defects. These logs were then sawn into boards and the boards were visually graded based on the National Hardwood Lumber Association grading rules. The response signals of the logs from acoustic impact testing were analyzed to extract time-domain and frequency-domain parameters. The laser scan data of each log was processed by a defect detection system. The results indicated that acoustic velocity, time centroid, damping ratio, and the combined time- and frequency-domain parameters are all effective quality predictors of the hardwood logs in terms of internal soundness. High-resolution laser scanning is complementary to acoustic impact testing. Acoustic parameters combined with laser scanning results provide a more complete data picture of the log: 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 precisely with respect to log quality and potential board grade yields than would either method independently.

Keywords: Acoustic impact testing, laser scanning, board grades, log defects, log segregation, 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 reduce 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 the clearest and will yield the highest valued boards. The sawyer attempts to saw the log in such a way 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, to realize target profit maximization, 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.

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, and nuclear magnetic resonance offer cross-sectional images with sufficient detail 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; Li et al 1996; Guddanti and Chang 1998; Bhandarkar 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 crook, sweep, and eccentricity of the log to a fraction of a millimeter. In addition, most surface defects regarded as degrade defects by the United States Department of Agriculture (USDA) 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 also 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 and then record the reverberation of the waves within the log. At the microstructure level, energy storage and dissipation properties of the log are controlled by the 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 and 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. Part 1 of this study explored the use of the acoustic impact testing method coupled with advanced waveform analysis to classify hardwood logs in terms of log quality and potential board grade yield (Xu et al 2018). This report (Part 2) evaluates the effectiveness of using a combined acoustic and laser scanning system to rank hardwood logs and further improve the log segregation process.

MATERIALS AND METHODS

Materials

A random sample of 15 yellow poplar (*Liriodendron tulipifera*) trees was harvested from a forest leased and managed by MeadWestvaco (Richmond, VA) near Rupert, WV, in the central Appalachian region in late January 2015. Each tree was bucked to commercial lengths with three to five logs being cut from each tree, resulting in a total of 52 logs. Each log was tagged with a tree number and a log section code (A—butt log; B—2nd log; C—3rd log; D—4th log; and E—5th log). All logs were transported to the USDA Forest Service, Forestry Sciences Laboratory located in Princeton, WV, for detailed laboratory scanning and testing. Visual observation showed that 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 of 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 laboratory. 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), 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. When each log is placed on the support stands before scanning, the log is examined and the best sawing face is turned to face upward. If the log had extensive crook or sweep, features that make it difficult to safely hold the log on the sawmill, and heavily impact yield, then the log was positioned such to minimize waste and/or facilitate safe handling on the sawmill. When the positioning and proper rotation of the log had been determined, the ends of the log were marked with four colors (black, blue, red, and green) indicating the four sawing faces of the log, with black indicating the best face.

The log scanning system electronically digitizes the surface of logs with a scan line every 1.59 mm along the length. Each scan line describes the circumference of the log and consists of 250-450 points, depending on the size of the log. At each reference point, the scanner records the laser energy reflected from the surface as a 10-bit grayscale value. Average resolution around a log's circumference was three points per cm. This resolution is significantly higher than the scanner currently used in sawmills in which typically one scan line every 30-60 cm 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 (Fig 1(b)).

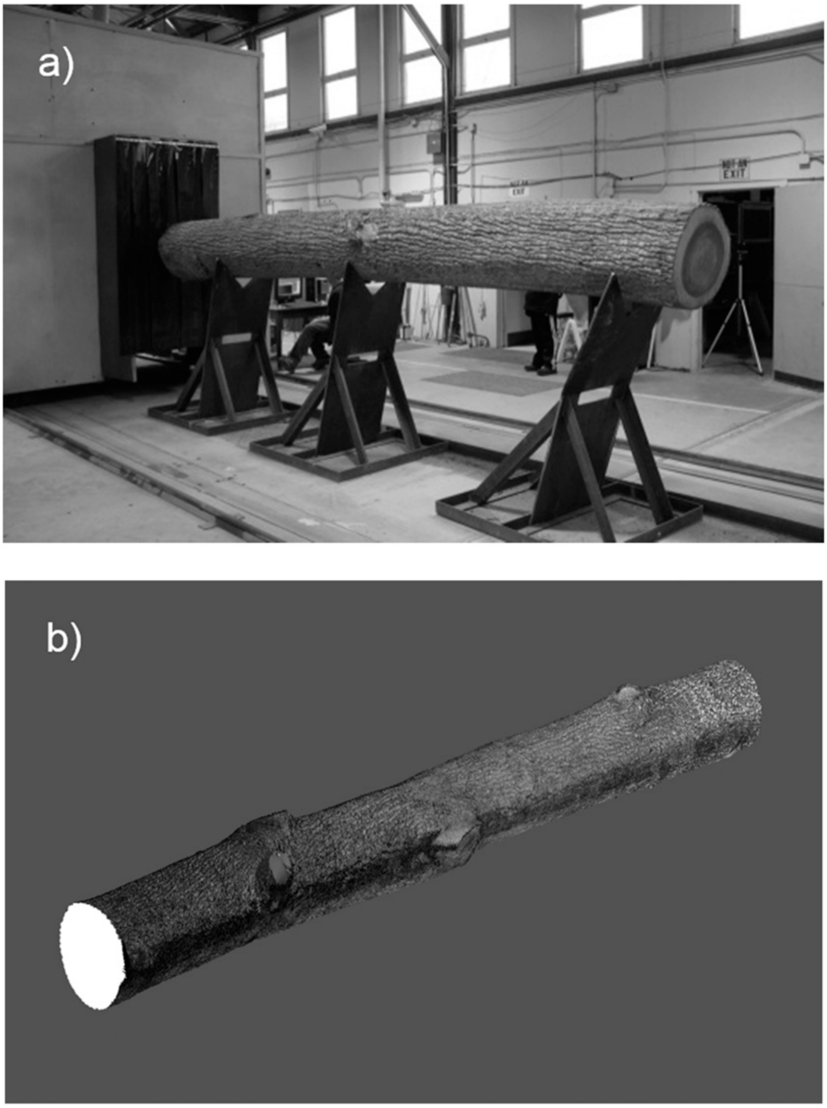

Figure 1. Laboratory laser scanning of yellow poplar logs: (a) high-resolution laser scanning system; (b) high-resolution scanned imagery of yellow poplar log (no. 12D).

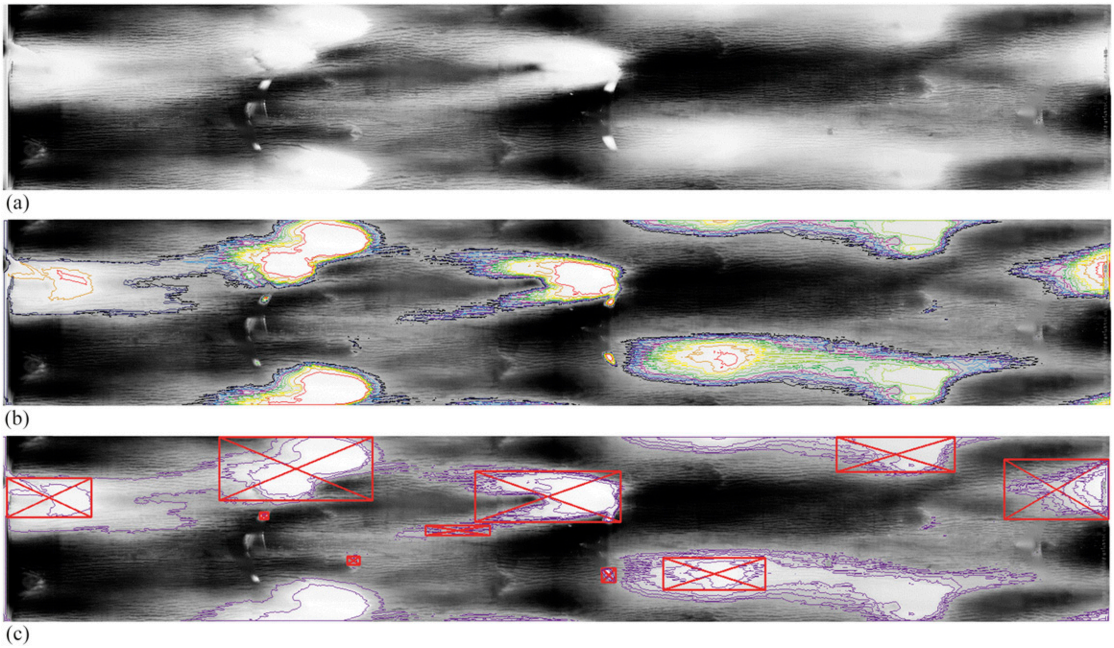

Figure 2. Defect detection results for log no. 12D: (a) residual image generated; (b) image resulting from contour analysis of residual image; (c) defects detected in contour map are identified using red boxes.

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 the mechanical impact. All acoustic tests were conducted under a condition of 21°C and 50% relative humidity (RH).

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

$$V = 2f_n L/n,$$

where f_n is the nth harmonic frequency (Hz) of the response signal, L is the full length of a log (m), 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 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 1000 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

Table 1. Physical and acoustic properties of the yellow poplar logs.

Log no.	Density (kg/m^3)	V (km/s)	E_d (GPa)	f (Hz)	Time centroid ($10^{\;2}$ s)	Damping ratio ($10^{\;2}$)	E_d/ζ^2 (10^3 GPa)	ρ/T_c^2 (10^6 kg/m^{3}s $^{\;2}$)
1C	685.4	3.34	7.65	521.74	1.74	3.59	5.93	2.26
2A	672.5	3.37	7.65	413.79	1.64	3.43	6.52	2.51
3A	885.7	3.04	8.18	382.17	1.47	3.61	6.27	4.10
3B	783.5	3.05	7.29	344.83	1.93	4.25	4.04	2.10
3D	729.5	3.27	7.81	331.49	2.08	4.26	4.31	1.68
4B	610.9	3.83	8.98	425.53	1.90	4.12	5.29	1.70
4C	614.5	3.78	8.79	372.67	1.88	4.41	4.51	1.73
4E	497.1	3.59	6.42	425.53	1.98	3.73	4.61	1.26
5A	828.8	3.65	11.05	447.76	1.41	3.16	11.04	4.14
5B	767.6	3.88	11.57	576.92	1.44	3.02	12.71	3.71
5D	760.1	3.76	10.72	560.75	1.75	3.16	10.76	2.50
5E	759.8	3.67	10.21	458.02	1.57	3.83	6.95	3.07
8A	735.4	2.91	6.22	389.61	1.80	3.88	4.14	2.27
11A	785.9	3.38	8.98	480.00	1.48	4.17	5.17	3.60
11B	810.1	2.93	6.95	560.75	1.21	3.75	6.08	5.50
11C	800.3	3.32	8.85	476.19	1.51	4.53	4.30	3.49
12D	827.0	3.23	8.64	319.15	2.04	4.27	4.75	1.98
14B	831.0	3.30	9.06	317.46	1.69	4.06	5.50	2.91
14C	827.4	2.98	7.35	428.57	1.88	4.14	4.29	2.34
15A	780.3	3.63	10.28	387.10	1.53	3.16	10.27	3.31
15B	740.5	3.73	10.31	419.58	1.70	4.13	6.06	2.54

and resonant acoustic testing results to represent the quality range of the 52 logs. The sawing was performed by an experienced sawyer who worked to maximize the yield and value of the lumber with respect to NHLA rules (NHLA 2015). The general sawing strategy was to open the log on the best face and rotate the log when the face grade of the cant dropped. 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, Fig 2 presents defect detection results for log no. 12D. This is the same log shown in Fig 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 2(a)). 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 2(b)) 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 2(c) is the graphical output from this final detection step.

The sawing process for each log was also replicated using the RAYSAW sawing simulator, a hardwood log sawing research tool that processes high-resolution 3D laser-scan data (Thomas 2013). 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 (T_c), and damping ratio (ζ), as well as two combined parameters of the response signals. The following procedures were followed in data analysis: 1) compute dynamic modulus of elasticity of the logs using one-dimensional wave equation: $E_d = \rho V^2$, 2) determine time centroid (T_c) of the response signals through first moment analysis, 3) perform continuous wavelet transform 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, and 7) rank logs based on individual and combined parameters.

RESULTS AND DISCUSSION

Table 1 shows the physical and acoustic properties of the 21 selected yellow poplar logs. The moisture contents of the wood samples were found to be 45-60%. Therefore, all acoustic parameters discussed in this report are considered green log parameters. The results of the acoustic impact test were reported in Part 1 of this study (Xu et al. 2018). 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 $E_d/\zeta\zeta^2$) were identified as log quality predictors that had positive correlation with board grade yields.

Table 2 shows the dimensional and physical measures of the 21 selected logs and the sawing results (board volume, cant volume, and board grades). It is noted that on some logs, the small end is larger than the average diameter. In most cases, this is due to a large knot being present at the end of the log. In other cases, abnormalities such as large gouges, or multiple large knots in the center of the log skew the average diameter.

Table 2. Dimensional and physical measures of the yellow poplar logs and the sawing results.

		Diameter (cm)					Volume (m^3)			Grade yield (m^3)				
Log no.	Length (m)	Large end	Small end	Avg.	Weight (kg)	Sweep (cm)	Debarked	Board	Cant	High[a]	1C	2C	3C	BG[b]
1C	3.47	46.7	43.1	47.3	419.0	4.1	0.519	0.250	0.081	0.040	0.068	0.099	0.042	0
2A	3.99	51.2	51.2	49.5	537.1	3.5	0.682	0.373	0.076	0.326	0.019	0.017	0	0.012
3A	3.99	59.2	52.0	53.9	827.6	2.7	0.801	0.517	0.070	0.441	0.045	0	0.012	0.019
3B	4.63	50.9	50.9	52.8	821.7	2.2	0.897	0.467	0.083	0.139	0.286	0.014	0.014	0.014
3D	5.00	38.1	35.1	36.4	388.2	5.4	0.441	0.156	0.080	0.071	0.038	0.047	0	0
4B	4.48	48.4	47.1	47.6	498.0	2.4	0.692	0.371	0.090	0.076	0.132	0.097	0.066	0
4C	5.12	42.7	39.1	40.7	420.4	2.1	0.574	0.274	0.104	0.054	0.165	0.054	0	0
4E	4.27	32.4	32.4	32.6	167.1	1.3	0.273	0.085	0.066	0	0.017	0.028	0.040	0
5A	4.11	48.4	43.1	45.2	548.9	2.0	0.559	0.323	0.050	0.304	0.019	0	0	0
5B	3.38	42.6	41.1	41.7	363.7	4.3	0.399	0.205	0.059	0.144	0.061	0	0	0
5D	3.38	37.9	37.9	37.9	291.0	5.3	0.319	0.085	0.079	0	0.028	0.028	0.028	0
5E	4.08	35.8	35.8	35.8	311.4	4.3	0.339	0.090	0.097	0	0.024	0.066	0	0
8A	3.81	36.2	34.5	35.7	286.9	4.2	0.324	0.142	0.074	0.090	0.014	0.009	0	0.028
11A	3.60	53.4	51.6	54.0	675.1	3.9	0.737	0.378	0.080	0.208	0.135	0.012	0.024	0
11B	2.90	52.9	52.9	52.1	643.8	3.1	0.550	0.297	0.073	0.179	0.076	0.042	0	0
11C	3.47	51.1	46.1	48.2	522.6	6.3	0.556	0.264	0.140	0.054	0.085	0.109	0.017	0
12D	5.03	43.4	38.4	40.5	548.4	4.6	0.556	0.234	0.111	0.012	0.111	0.111	0	0
14B	5.18	59.9	58.5	57.9	1202.6	2.3	1.246	0.684	0.074	0.453	0.137	0.094	0	0
14C	3.47	46.4	42.7	44.8	459.4	3.7	0.469	0.236	0.071	0.045	0.047	0.076	0.068	0
15A	4.91	44.1	37.5	39.2	474.9	4.0	0.509	0.231	0.102	0.127	0.035	0.068	0	0
15B	4.42	37.1	37.1	36.8	360.0	3.2	0.405	0.201	0.063	0.076	0.092	0.021	0	0.012

FAS, First and Seconds; FIF, FAS One Face, and Select.

[a] High includes grade FAS, FIF, and Select.

[b] BG, below grade.

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, each grade provides a measurable percentage of clear, defect-free wood. The board grades determined based on NHLA rules include high grades (FAS—First and Seconds, FAS One Face, and Select), common grades (No. 1 Common, No. 2 Common, and No. 3 Common), and below grade (BG).

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, weight, sweep, and volume of each log are listed in Table 2. 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 that has 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 USDA Forest Service hardwood log grading rules (Rast et al 1973). The USDA 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 the log should produce. As such, they provide a method of classifying logs based on their observed characteristics, regardless of whether 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.

Time centroid vs $\boldsymbol{\rho/T_c^2}$**.** 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. 11A was excluded from the high-quality class and log nos. 1C and 8A were added to the low-quality class per ρ/T_c^2 rating. Considering that log no. 11A 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 the 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 (nos. 1C and 8A) per ρ/T_c^2 rating did yield a high percentage of low-grade (3 Common and BG) boards as shown in Table 5.

Damping ratio vs $\boldsymbol{E_d/\zeta^2}$**.** In selecting high-quality logs, damping ratio and combined

Table 3. Yellow poplar logs rated as high quality and low quality based on different acoustic predictors.[a]

Predictor	Logs rated as high quality						Logs rated as low quality								
T_c	11B	5A	5B	3A	11A	14B	3D	12D	4E	3B	4B	4C	14C		
ζ	5B	$\boxed{\text{5D}}$	5A	15A	2A		11C	4C	12D	3D	3B	11A	14C	15B	4B
ρ/T_c^2	11B	5A	3A	5B	14B		4E	3D	4B	4C	12D	3B	1C	8A	14C
E_d/ζ^2	5B	5A	$\boxed{\text{5D}}$	15A	$\boxed{\text{5E}}$	2A	3B	8A	14C	11C	3D	4C	4E	12D	

[a] Logs marked with a box are abnormal cases with a false prediction.

Table 4. Volume recovery and grade yield of high-quality yellow poplar logs.[a]

	Volume (m^3)								Recovery (%)		Board grade yield (%)				
Log no.	Board	Cant	Debarked	High	1C	2C	3C	BG	Total	Board	High	1C	2C	3C	BG
5A	0.323	0.050	0.559	0.304	0.019	0	0	0	66.8	57.8	94.2	5.8	0	0	0
5B	0.205	0.059	0.399	0.144	0.061	0	0	0	66.4	51.5	70.1	29.9	0	0	0
3A	0.517	0.070	0.801	0.441	0.045	0	0.012	0.019	73.3	64.6	85.4	8.7	0	2.3	3.7
11B	0.297	0.073	0.550	0.179	0.076	0.042	0	0	67.3	54.0	60.3	25.4	14.3	0	0
2A	0.373	0.076	0.682	0.326	0.019	0.017	0	0.012	65.8	54.7	87.3	5.1	4.4	0	3.2
11A	0.378	0.080	0.737	0.208	0.135	0.012	0.024	0	62.1	51.3	55.0	35.6	3.1	6.3	0
14B	0.685	0.074	1.247	0.453	0.137	0.094	0	0	60.8	54.9	66.2	22.0	13.8	0	0
15A	0.231	0.102	0.509	0.128	0.035	0.068	0	0	65.5	45.5	55.1	15.3	29.6	0	0

[a] Logs 5D and 5E were abnormal cases and excluded.

parameter E_d/ζ^2 resulted in similar predictions with slight changes in the ranking order and inclusion of log no. 5E 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 (nos. 4B, 11A, and 15B) by damping ratio rating were not present in the E_d/ζ^2 rating, whereas two low-quality logs (nos. 8A and 4E) in E_d/ζ^2 rating were not picked up by the damping ratio. The sawing results indicated that logs nos. 8A and 4E, rated low quality by E_d/ζ^2, yielded a relatively large proportion of low-grade boards (20% BG for log no. 8A and 47.2% 3 Common for log no. 4E). Particularly for log no. 8A, which had the lowest acoustic velocity of 2.91 km/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. 8A was not picked up by damping ratio. Similarly for log no. 4E, the defects that resulted in 47.2% three 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.

Of the three logs (nos. 11A, 15B, and 4B) rated low quality by damping ratio, nos. 4B and 15B were dominated by one Common and two Common boards (61.8% and 56.5%, respectively) and were considered intermediate-quality logs and no. 11A was dominated by high-grade and one Common boards (90.6%) and was considered a high-quality log.

Tables 6 and 7 list the logs that were rated as high quality and low quality, respectively, using four

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

	Volume (m^3)								Recovery (%)		Board grade yield (%)				
Log no.	Board	Cant	Debarked	High	1C	2C	3C	BG[a]	Total	Board	High	1C	2C	3C	BG
4C	0.274	0.104	0.574	0.054	0.165	0.054	0	0	65.8	47.7	19.8	60.3	19.8	0	0
14C	0.236	0.071	0.469	0.045	0.047	0.076	0.068	0	65.5	50.3	19.0	20.0	32.0	29.0	0
4E	0.085	0.066	0.273	0	0.017	0.028	0.040	0	55.5	31.1	0	19.4	33.3	47.2	0
3D	0.156	0.080	0.441	0.071	0.038	0.047	0	0	53.5	35.3	45.5	24.2	30.3	0	0
3B	0.467	0.083	0.897	0.139	0.286	0.014	0.014	0.014	61.3	52.1	29.8	61.1	3.0	3.0	3.0
4B	0.371	0.090	0.692	0.076	0.132	0.097	0.066	0	66.6	53.5	20.4	35.7	26.1	17.8	0
12D	0.234	0.111	0.556	0.012	0.111	0.111	0	0	61.9	42.0	5.1	47.5	47.5	0	0
1C	0.250	0.081	0.519	0.040	0.068	0.099	0.042	0	63.9	48.2	16.0	27.4	39.6	17.0	0
8A	0.142	0.074	0.324	0.090	0.014	0.009	0	0.028	66.5	43.8	63.3	10.0	6.7	0	20.0
11C	0.264	0.140	0.556	0.054	0.085	0.109	0.017	0	72.7	47.6	20.5	32.1	41.1	6.3	0
15B	0.201	0.063	0.405	0.076	0.092	0.021	0	0.012	65.2	49.5	37.6	45.9	10.6	0	5.9

[a] BG, below grade.

Table 6. Frequency of positive ratings for high-quality logs using four acoustic predictors.[a]

	Logs rated as high quality									
Log no.	5A	5B	3A	11B	2A	15A	5D	14B	11A	5E
Frequency of positive rating	4/4	4/4	2/4	2/4	2/4	2/4	2/4	2/4	1/4	1/4

[a] Logs marked with a box are abnormal cases with a false prediction.

different predictors and the frequency of positive ratings. The more positive ratings, the higher the probability of the log being rated accurately. However, the logs with lower rating frequency still had a probability of being rated accurately. Overall, rating low-quality logs had better accuracy than rating high-quality logs.

Abnormal cases. Log nos. 5D and 5E were 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 3D laser scanning, 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. 5D had 7.3 cm of crook along the red blue axis (man-made mark for sawing). Log no. 5E had 4.5 cm 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- and 10.8-cm thick slabs sawn from log no. 5D. Slab thicknesses on log no. 5D were 8.6, 9.8, and 6.7 cm on the black, blue, and red faces. A similar sawing operation occurred with log no. 5E. 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, and 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 whose type and/or size will impact the grade of the log.

For each log scanned, the USDA Forest Service log grade was determined using the RAYSAW sawing analysis program (Thomas 2013). Within the USDA Forest Service grading rules, the highest grade or quality sawlog is Factory 1 (F1). Factory 2 (F2) is the middle quality level, and Factory 3 (F3) is the lowest quality level for sawlogs. As log grade or quality decreases, the number of degrade defects increases 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.

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

	Logs rated as low quality											
Log no.	4C	3D	12D	3B	14C	4E	4B	11C	8A	11A	15B	1C
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

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

Quality sort	Log no.	Log grade	Severe defect count	Defect summary
Low	4C	F2	0	Medium bark distortions
Low	3D	F3	14	Multiple wounds and knots
Low	12D	F3	7	Overgrown, unsound, and sawn knots
Low	3B	F2	1	Large overgrown crack/seam
Low	14C	F2	1	Overgrown knot
Low	4E	F3	5	Overgrown knots
Low	4B	F1	0	Several small adventitious clusters
Low	11C	F2	3	Unsound knots and an overgrown knot
Low	8A	F2	6	Wound and five overgrown knots
Low	15B	F1	1	Sawn knot
Low	1C	BG	4	Sawn knot and three overgrown knots
Average		**2.27**	**3.82**	
High	5A	F1	0	Clear
High	5B	F2	1	Large wound
High	3A	F1	0	Clear
High	11B	F2	3	Large overgrown knots
High	2A	F2	2	Large wound and a large gouge
High	15A	F1	1	Small wound
High	5D	F2	5	Overgrown knots
High	14B	F2	2	Two very large wounds on one face
High	11A	F1	0	Clear
High	5E	F3	5	Overgrown and unsound knots
Average		**1.70**	**1.90**	

Assigning numeric values to the log grades (where 1 = F1, 2 = F2, 3 = F3, and 4 = BG) allow 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 F2. For the high-grade logs, the average grade is 1.70, or slightly better than F2. 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 negates this need. In Table 8, we see that two logs, nos. 4B and 15B, in the low-quality acoustic sort were graded as F1, a high-quality visual grade. Examination of the grade yield for these two logs (Table 5) showed that the lumber produced was of a 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 (F2) logs (nos. 3B, 4C, 8A, 11C, and 14C) 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 an F2 log. The one exception was no. 8A, which had a lumber grade yield that would be expected of an F1 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 higher quality sawlogs, with two exceptions, log nos. 5D and 5E. 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 reduction.

CONCLUSIONS

Acoustic velocity, time centroid, damping ratio, and 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 indicate a sound log, but the lumber will either have significant numbers of knots or recovery will be low because of poor log shape. By contrast, a high visual grade coupled with a low-quality acoustic sort indicate a log with hidden deficiencies that will decrease lumber value and volume. Thus, a combined system would be able to discriminate much more precisely with respect to log quality and potential lumber recovery than would either method independently.

ACKNOWLEDGMENTS

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 and the USDA Forest Service, Forest Products Laboratory. Mr. Feng Xu's participation in this project was supported by the Priority Academic Program Development of Jiangsu Higher Education Institutions and the Nanjing Forestry University Innovation Grant for Outstanding PhD Dissertations (grant no. 163070682). We thank Neal Bennett and Deborah Conner for their technical assistance during the project.

REFERENCES

Bhandarkar S, Faust T, Tang M (1999) Catalog: A system for detection and rendering of internal log defects using computer tomography. Mach Vis Appl 11(4):171-190.

Carpenter RD, Sonderman DL, Rast ED (1989) Defects in hardwood timber. Agricultural Handbook No. 678. U.S. Department of Agriculture, Forest Service, Washington, DC. 88 pp.

Carter P, Briggs D, Ross RJ, Wang X (2005) Acoustic testing to enhance western forest values and meet customer wood quality needs. General Technical Report PNW-GTR642. USDA Forest Service, Pacific Northwest Research Station, Portland, OR. 121-129 pp.

Chang S (1992) External and internal defect detection to optimize cutting of hardwood logs and lumber. Transferring Technologies for Industry No. 3. U.S. Department of Agriculture, National Agriculture Library, Beltsville, MD. 24 pp.

Guddanti S, Chang S (1998) Replicating sawmill sawing with topsaw using CT images of a full length hardwood log. Forest Prod J 48(1):72-75.

Harris P, Petherick R, Andrews M (2002) Acoustic resonance tools. Pages 195-201 *in* Proc. 13th International Symposium on Nondestructive Testing of Wood, August 19-21, 2002, Berkeley, CA.

Li P, Abbott A, Schmoldt D (1996) Automated analysis of CT images for the inspection of hardwood log. Pages 1744-1749 *in* Proc. IEEE Conference on Neural Networks, June 3-6, 1996, Washington, DC.

NHLA (2015) Rules for the measurement and inspection of hardwood and cypress. National Hardwood Lumber Association, Memphis, TN. 104 pp.

Pellerin RF, DeGroot RC, Esenther GR (1985) Nondestructive stress wave measurements of decay and termite attack in experimental wood units. Pages 319-353 *in* Proc. 5th International Symposium on Nondestructive Testing of Wood, September 9-11, 1985, Pullman, WA. Washington State University, Pullman, WA.

Rast ED, Sonderman DL, Gammon GL (1973) A guide to hardwood log grading. General Technical Report NE-1. U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Upper Darby, PA. 32 pp.

Thomas L, Mili L, Thomas RE, Shaffer CA (2006) Defect detection on hardwood logs using laser scanning. Wood Fiber Sci 38(4):682-695.

Thomas LH, Thomas RE (2011) A graphical automated detection system to locate hardwood log surface defects using high-resolution three-dimensional laser scan data. Pages 92-101 *in* Fei SL, Lhotka JM, Stringer JW, Gottschalk KW, Miller GW, eds. Proc. 17th Central Hardwood Forest Conference, April 5-7, 2010, Lexington, KY. General Technical Report NRS-P-78. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA.

Thomas RE (2008) Predicting internal yellow-poplar log defect features using surface indicators. Wood Fiber Sci 40(1):14-22.

Thomas RE (2013) RAYSAW: A log sawing simulator for 3D laser-scanned hardwood logs. Pages 325-334 *in* Proc. 18th Central Hardwood Forest Conference, March 26-28, 2012, Morgantown, WV. General Technical Report NRS-P-117. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA.

Thomas RE, Thomas L, Shaffer C (2008) Defect detection on hardwood logs using high-resolution laser scan data. Pages 163-167 *in* Proc. 15th International Symposium on Nondestructive Testing of Wood, September 10-12, 2007, Duluth, MN. Natural Resources Research Institute, University of Minnesota, Duluth, MN.

Thomas RE, Thomas LH (2013) Using parallel computing methods to improve log surface defect detection methods. Pages 196-205 *in* Ross RJ, Wang X, eds. Proc. 18th International Nondestructive Testing and Evaluation of Wood Symposium, September 24-27, 2013, Madison, WI. General Technical Report FPL-GTR-226. U.S.

Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI.

Wagner F, Taylor F, Ladd D, McMillin C, Roder F (1989) Ultrafast CT scanning of an oak log for internal defects. Forest Prod J 39(11/12):62-64.

Wang X (2013) Acoustic measurements on trees and logs: A review and analysis. Wood Sci Technol 47:965-975.

Wang X, Carter P, Ross RJ, Brashaw BK (2007) Acoustic assessment of wood quality of raw forest materials—A path to increased profitability. Forest Prod J 57(5):6-14.

Wang X, Divos F, Pilon C, Brashaw BK, Ross RJ, Pellerin RF (2004) Assessment of decay in standing timber using stress wave timing nondestructive evaluation tools—A guide for use and interpretation. General Technical Report FPL-GTR-147. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. 12 pp.

Wang X, Verrill S, Lowell E, Ross RJ, Herian VL (2013) Acoustic sorting models for improved log segregation. Wood Sci Technol 45(4):343-452.

Xu F, Wang X, Thomas E, Liu Y, Brashaw BK, Ross RJ (2018) Defect detection and quality assessment of hardwood logs: Part 1—Acoustic impact test and wavelet analysis. Wood Fiber Sci (submitted).