TIME DOMAIN ULTRASONIC SIGNAL CHARACTERIZATION FOR DEFECTS IN THIN UNSURFACED HARDWOOD LUMBER

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ABSTRACT

One of the major users of thin, unsurfaced hardwood lumber is the pallet manufacturing industry. Almost all manufactured products spend part of their life cycle on a pallet during transportation. This makes pallets a critical component of both the transportation and manufacturing sectors of the economy. Many newly constructed wooden pallets, however, are not currently manufactured to deliver the best performance (strength, durability, and safety)—despite interest by pallet users and pallet manufacturers—because manual grading and sorting of parts is impractical due to processing speeds and volume, labor costs, and laborer skill. This paper describes initial work aiming to create an automated grading/sorting system for hardwood pallet parts using ultrasonic. Experiments were conducted on yellow-poplar (*Liriodendron tulipifera*, L.) and red oak (*Quercus rubra*, L.) deckboards using pressure-contact, rolling transducers in a pitch-catch arrangement. Sound and unsound knots, cross grain, bark pockets, holes, splits, and decay were characterized using six ultrasound variables calculated from the received waveforms. Our scanning system shows good data-collection repeatability, and scanning rate has little effect on the calculated variables. For each defect type, at least one ultrasonic variable demonstrated significant capability to discriminate between that defect and clear wood. Energy loss variables exhibited the greatest sensitivity to many defect types. Based on the empirical relationships identified in this study, we are now developing models to classify defects using ultrasonic signal characteristics. Scanning properties of the prototype apparatus suggest that it can readily be translated into a commercial product.

Keywords: Ultrasonic scanning, transducer, time-of-flight, wood defects; nondestructive evaluation.

INTRODUCTION

About 30–40% of sawn hardwood produced annually in the United States goes into the manufacture of wooden pallets (Bush and Araman 1998). Each year, over 400 million new wooden pallets are constructed, using 10.6 million m^3 (4.5 billion board feet) of hardwood lumber (Bush et al. 1997). A typical

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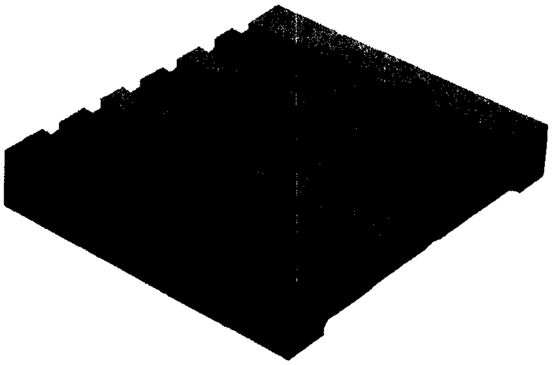


FIG. 1. A typical stringer pallet employed by the Grocery Manufacturers Association contains top and bottom deckboards and notched stringers.

wood pallet consists of two parts: (1) stringers, the structural center members that support the load, and (2) deckboards, the top and bottom members that provide dimensional stability and product placement (Fig. 1). Most pallet parts are produced from low-quality lumber or from the center cant material of logs. Because these cants originate from the defect-laden central core of logs, they have less market value for other solid wood products. Pallets are a major part of the world's transportation infrastructure, as almost all products spend a portion of their life on a pallet, either as component parts or following final assembly.

High-quality, high-performance wooden pallets require high-quality pallet parts for their manufacture. Better pallets achieve a much longer life cycle, increased material handling safety, and permit multiple trips before recycling or remanufacturing. However, individual pallets are most often constructed from a variety of wood species and from parts with differing strength properties, resulting in pallets with random and unknown strength and durability. Descriptions of allowable defects for minimum pallet component quality are shown in Table 1 (Anon 1994). By grading and sorting pallet parts prior to pallet assembly, it is possible to bound pallet performance within a well-defined range. Nevertheless, manual grading and sorting of pallet parts is a slow, inaccurate, and uneconomic process, which depends on the individual skill of the grader. Moreover, the presence, location, and extent of defects in pallet parts are often difficult to ascertain accurately, making the grading system complicated. These observations

TABLE 1. *Grading criteria employed for deckboards according to defect type, size, location, and extent.*

Defect	Description	2 & BTR	3	4
Sound knot	Maximum dimension across width of the board	¼ of board width	⅓ of board width	½ of board width
Location of knots	Knots in the edges and end 3″ of the board	½ in. diameter	¼ of board width	⅓ of board width
Unsound knot/holes	Knot holes, unsound or loose knots, and holes	⅛ of board width	1/6 of board width	¼ of board width
Cross grain	Slope of general cross grain	1 in. in 10 in.	1 in. in 8 in.	1 in. in 6 in.
	Max. dimension of local cross grain	¼ of board width	⅓ of board width	½ of board width
Splits, checks and shake	Max. length singly or in combination	¼ of board width	½ of board width	¾ of board width
	Defects 3″ or less are ignored			
Wane	Max. portion of cross section affected at point of deepest penetration	1/16 of cross section	⅛ of cross section	3/16 of cross section
Decay	Cross section deepest penetration	None allowed	⅛ of cross section	¼ of cross section

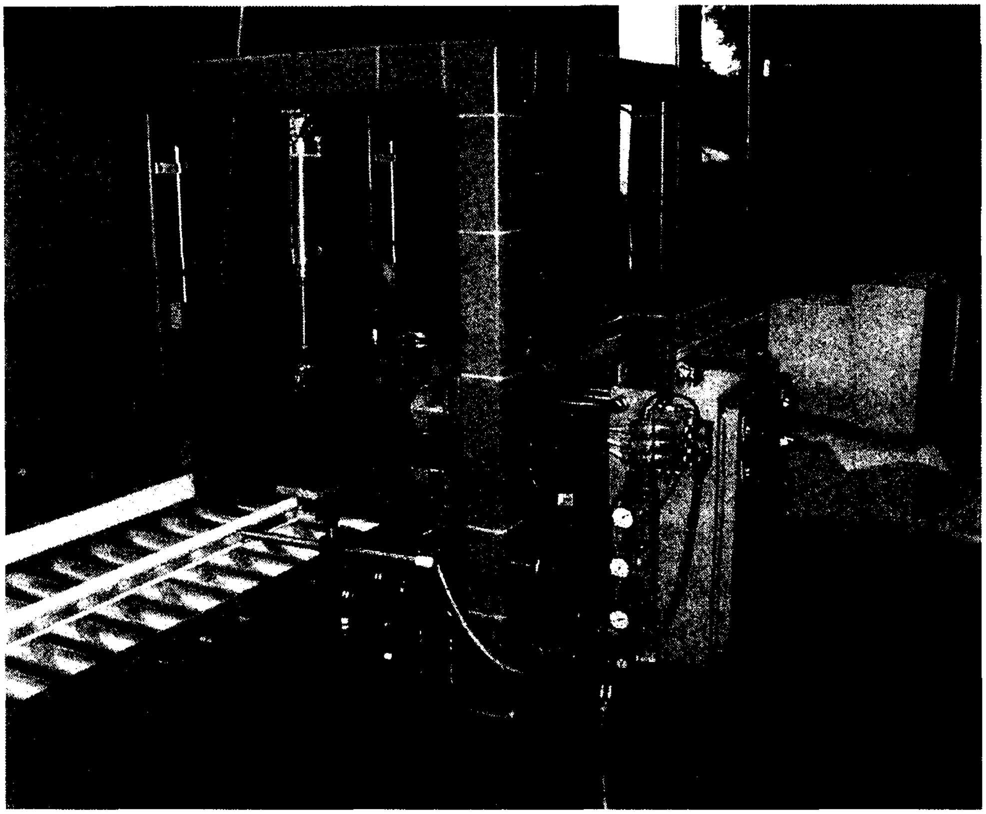


FIG. 2. Our ultrasonic scanning system includes materials handling, computer control of part movement and data collection, and ultrasound electronics.

suggest that an automated inspection system for pallet parts can be very useful, and an economic study (Schmoldt et al. 1993) has demonstrated profit potential for such an inspection system.

Detecting defects in wood nondestructively and grading wood materials have increased in importance as wood resource quality decreases and its cost increases. Defect detection systems have employed optical, acoustic/ultrasonic, microwave, X-ray, or dielectric scanning (Szymani and McDonald 1981). Each of these methods has distinct advantages and limitations. Because defects in wood alter wood structure, they also affect elastic wave propagation. Ultrasonic sensing has received con-

TABLE 2. *T-test probability values comparing ultrasonic measurements for clear wood samples to defected wood samples using yellow-poplar specimens.*

Ultrasonic parameters	Sound knots	Unsound knots	Decay	Bark pocket	Splits	Holes	Cross grain
TOF-a	0.002	*	0.001	0.005	0.060	0.005	0.230
TOF-e	*	0.001	*	0.003	0.009	0.041	*
TOF-c	0.363	0.377	*	0.001	*	0.055	*
EV	*	*	*	*	*	0.002	*
EPV	*	*	*	0.049	*	0.005	*
PL	0.041	0.061	0.028	0.030	0.001	0.130	*

* Probability value less than 0.0005.

TABLE 3. *T-test probability values comparing ultrasonic measurements for clear wood samples to defected wood samples using red oak specimens.*

Ultrasonic parameters	Sound knots	Unsound knots	Decay	Bark pocket	Splits	Holes	Cross grain
TOF-a	0.293	0.018	*	0.001	0.005	0.086	0.014
TOF-e	0.005	0.020	0.156	0.025	0.002	*	*
TOF-c	0.060	0.003	*	*	*	0.022	0.076
EV	*	*	*	*	*	0.137	0.004
EPV	*	0.002	*	*	*	0.014	0.003
PL	0.22	0.002	0.006	0.014	0.028	0.089	0.535

* Probability value less than 0.0005.

siderable attention given its relatively low cost, safety, and through-transmission capability. Individual past studies, however, have looked only at a single type of wood defect in relation to nondefected wood (clear wood), e.g., knots (McDonald et al. 1969; McDonald 1980), incipient decay (Wilcox 1988), bacterial infection (Ross et al. 1992), checks (Fuller et al. 1996), decay (Patton-Mallory and DeGoot 1990), knots (Niemz et al. 1999), incipient decay (Raczkowski et al. 1999), and knots (Karsulovic et al. 2000). These studies were additionally restrictive in using either specially prepared laboratory samples or *surfaced* lumber. Almost all of these studies measured transmission time (or propagation velocity) as the critical ultrasound quantity. In this case, all received signal frequencies are aggregated and treated as points in time—time domain analysis. Furthermore, none of these studies used high throughput material flow, as in an industrial environment.

Signal velocity alone, however, is unlikely to allow one to disambiguate all defects. For some defect types, sufficient normal wood fiber remains in the ultrasound propagation path so that transit time is unaffected; whereas, other ultrasonic signal characteristics, e.g., peak amplitude, time to peak amplitude, centroid time, pulse length, insertion loss, or frequency domain energy, show sensitivity for those same defect types. Work by Halabe et al. (1993, 1994, 1996) has reported using frequency domain analysis for simultaneously detecting decay and knots in wood. Given the variety of defect types encountered in the pallet part inspection application, it is important to examine many ultrasonic characteristics simultaneously.

Knots, cross grain, bark pockets, insect holes, splits, decay, shake, wane, etc. are the most common defects in wooden pallet parts (Table 1). In this particular application, these defects need to be located, labeled, and sized on green (freshly cut) parts that are unplaned (rough surface appearance and texture). Previous research (Schmoldt et al. 1994, 1996, 1997) and more recent efforts (Kabir et al. 2000a, 2000b) are aimed at developing an automated ultrasound inspection system for

TABLE 4. *T-test probability values comparing ultrasonic measurements for clear wood samples to defected wood samples using both species combined.*

Ultrasonic parameters	Sound knots	Unsound knots	Decay	Bark pocket	Splits	Holes	Cross grain
TOF-a	0.066	0.001	0.113	0.117	*	0.159	0.169
TOF-e	*	0.139	0.117	0.090	0.001	0.032	0.005
TOF-c	0.534	0.023	*	*	*	0.039	0.007
EV	0.003	*	*	*	*	0.005	*
EPV	0.009	*	*	*	*	0.005	0.001
PL	0.022	0.031	0.003	0.026	0.021	0.227	0.018

* Probability value less than 0.0005.

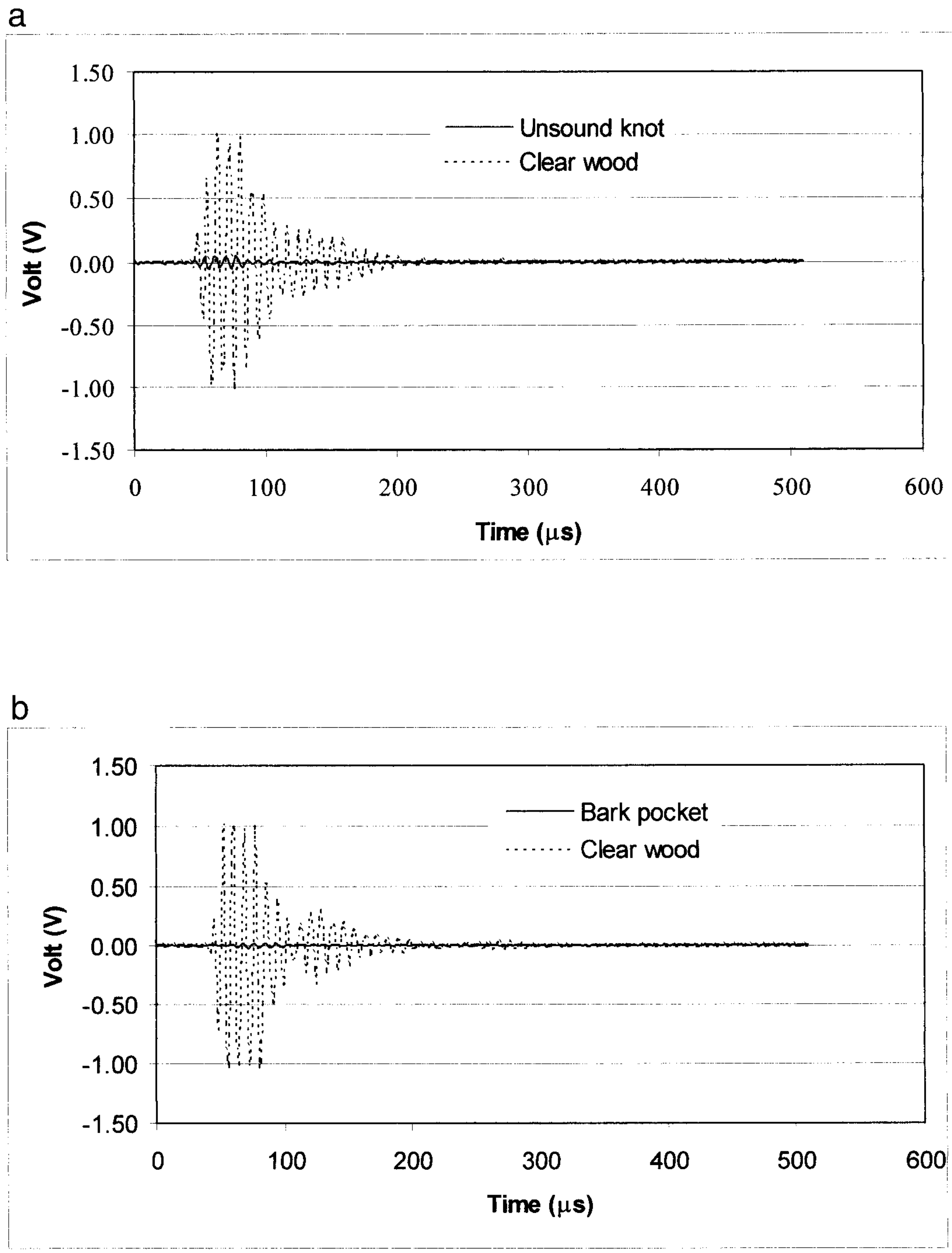
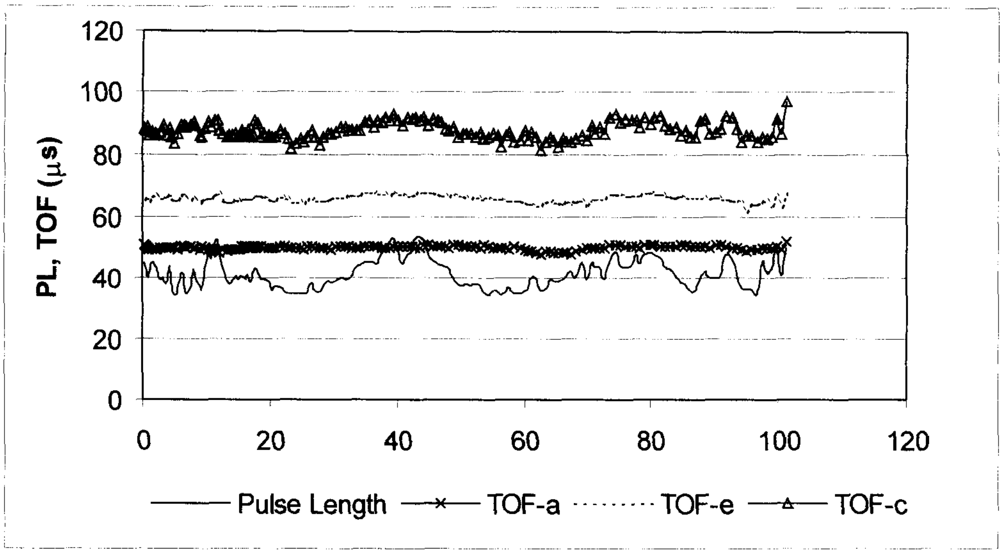
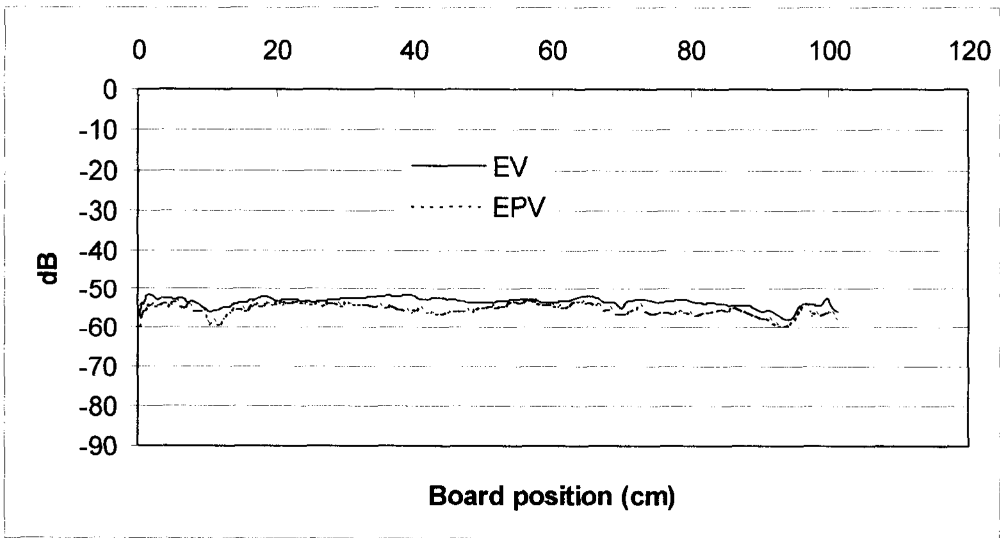


FIG. 3. Ultrasonic time-domain signals through clear and effected yellow-poplar show a dramatic loss in signal strength for unsound defects, (a) an unsound knot, (b) bark pocket.

a


PL, TOF (μs)
120
100
80
60
40
20
0
0
20
40
60
80
100
120
Pulse Length
TOF-a
TOF-e
TOF-c

b


0
20
40
60
80
100
120
dB
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
EV
EPV
Board position (cm)

c

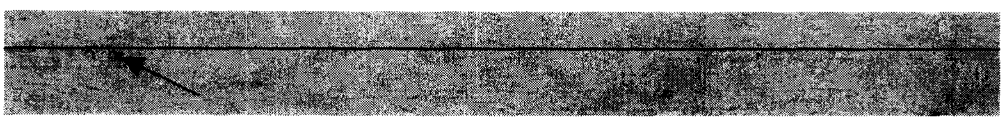


TABLE 5. *The sensitivity of different ultrasonic variables to different defect types is summarized.*

Ultrasonic variable	Defect
TOF-amplitude	Sensitive to unsound knots and splits
TOF-energy	Highly sensitive to sound knots, splits, and cross grain, with some sensitivity to holes
TOF-centroid	Highly sensitive to decay, bark pockets, splits, and cross grain, with some sensitivity to holes and unsound knots
Energy value	Highly sensitive to all defect types
Energy pulse/value	Highly sensitive to all defect types
Pulse length	Some sensitivity to all defect types except holes

grading and sorting pallet parts. The present paper describes the results of preliminary work on scanning pallet deckboards using rolling ultrasonic transducers with the species yellow-poplar (*Liriodendron tulipifera,* L.) and red oak (*Quercus rubra,* L.). These initial investigations are intended to provide important empirical data regarding different wood defect types in relation to various ultrasound signal characteristics. The current study restricts itself to those signal features lying in the time domain. Subsequent work will then use these characteristic ultrasound measurements to develop a defect classifier(s) that can be automatically applied to scan data for defect identification.

In the following section, we briefly present the equipment used, the signal features calculated, and testing procedures. Then, both graphical and statistical results are shown to indicate which ultrasonic signal characteristics are discriminating. Finally, we offer some conclusions regarding machine vision classification algorithms and prototype commercialization.

MATERIALS AND METHODS

Scanning equipment

The Ultrasonic Technology Group, Forest Products Division of Perceptron Inc, designed the ultrasonic scanning system. It consists of in-fed and out-fed roll beds, two pinch rollers for parts movement, and two rolling transducers, which are mounted in an ultrasonic scanning ring (Fig. 2). Pallet parts are driven through the system longitudinally by the motorized pinch rollers. Perceptron provided the necessary electronics and software to control material movement, signal generation, and waveform capture and analysis. Data are collected, stored, and processed by LabView™ software. The desired scanning resolution can be achieved by controlling roller speed and the number of pulses generated per second. Both transducer rollers are 9 cm in diameter and 8.9 cm in width. A plastic tier 1.9 cm in width is mounted on each of the transducer rollers to provide good contact with the sample. The transducers can be operated at a range of frequencies from 90 to 180 kHz.

Ultrasonic signal features

Each ultrasonic waveform collected was characterized using six ultrasonic variables—three involving time-of-flight (TOF), two involving ultrasound pulse energy, and one using ultrasound pulse duration. Wave energy of the received ultrasound signal can be expressed as the time integral of the voltage squared:

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FIG. 4. Ultrasonic variables are graphed for a scan line through a sound knot in a yellow-poplar deckboard, (a) Energy, PL, TOF-a, TOF-e, and TOF-c, (b) EV and EPV, and (c) board photo. The scan line is marked on the board image.

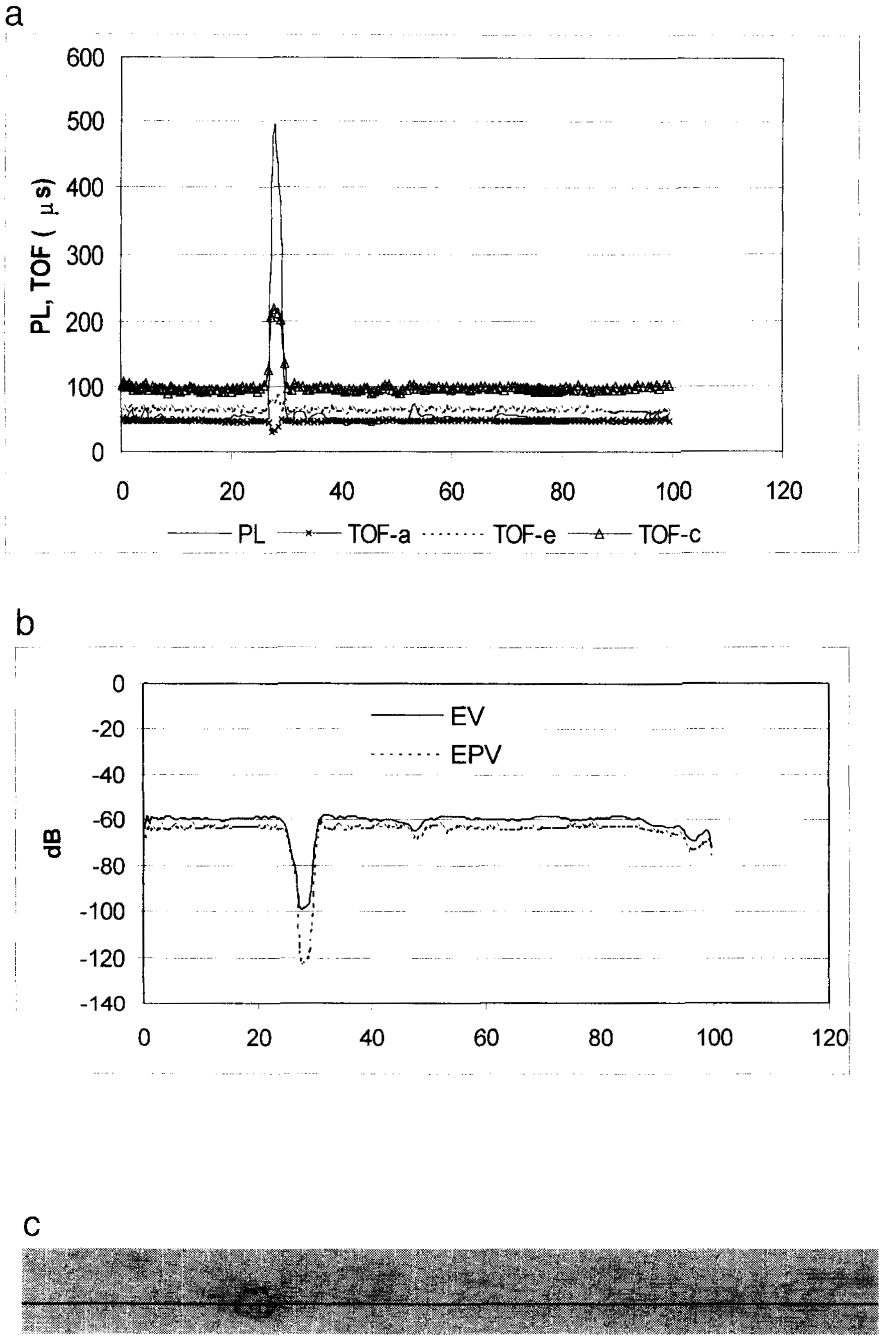


FIG. 5. Ultrasonic variables are graphed for a scan line through an unsound knot in red oak, (a) energy, PL, TOF-a, TOF-e, and TOF-c, (b) EV and EPV, and (c) board photo. The scan line is marked on the board image.

$$E = \int v^2(t)\, dt \qquad (1)$$

Due to the wide variation of transmitted energy levels between clear wood and defected wood, energy is expressed in a logarithmic scale. The energy value (EV) is derived from the energy E and is expressed as the ratio of the energy received by the receiving transducer to the energy input to the transmitting transducer. This variable is normally expressed in decibels (dB) and by convention on a logarithmic scale due to the small values involved (and hence a negative number) with lower signal ratios (containing less energy) being more negative.

The pulse length variable (in units of microseconds) is simply the time that the pulse is "on" and depends upon the transmitted ultrasound frequency. This is defined as 1.25 times the time required for the received wave energy to rise from 10% to 90% of its total received energy. Another ultrasonic parameter, which is known as energy/pulse value (EPV), has been calculated both from energy value and pulse length to provide more sensitivity to defects. Again, because of the wide range of energy levels, EPV is expressed on a logarithmic scale (dB).

TOF-energy is calculated as the time at which the energy integral (Eq. 1) crosses a threshold value, as a percentage of the final (maximum) value. If the threshold value is, for instance, 40%, then TOF-energy is simply the time at which the integral value reaches 40% of the final value. Similarly, TOF-amplitude is the time at which the amplitude of the signal first reaches 40% of the maximum amplitude. TOF-centroid is the time to the centroid of the time waveform, which is based on the ratio of the first- and zero-th order moments.

Data collection

Twenty-five deckboards were collected from a local hardwood sawmill for each of the species yellow-poplar and red oak. They were fresh cut and unplaned, which is their condition in the industrial setting. Their dimensions are approximately 9 cm wide (3.5 in.), 1.27 cm thick (0.5 in.), and 96–116 cm in length (38–46 in.). After the board samples were obtained, they were placed immediately into cold storage to reduce their drying rate and to keep their moisture content above fiber saturation point. Ultrasound signals are a function of moisture content when the moisture drops below this point. As noted above, high moisture content is the fresh-cut condition in the industrial setting and so the condition we wished to duplicate here.

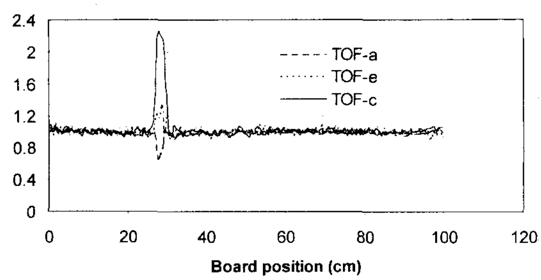


FIG. 6. Normalized TOF-a, TOF-e, and TOF-c, values are plotted for the deckboard in Fig. 5c.

Deckboard scanning was conducted in two ways. First, a line was drawn on each board through a defect of interest, and scanning was performed along the line. Each ultrasound measurement was taken through the specimen's thickness from face to face. Second, similar lines were drawn from end to end every 1.27 cm (0.5 in.) across the width of the board, and scanning was conducted along these six lines. These multiple scans lines were used to characterize the entire deckboard and produce a 2-D image. In the first series of experiments, numerous wood defects were examined, such as sound and unsound knots, bark pockets, insect holes, decay, wane, cross grain, and splits. Boards were scanned with two scanning resolutions—4 waveforms per cm (10 per in.) and 1.6 waveforms per cm (4 per in.). Each delineated scan line was repeated ten times to check the repeatability of data collection for each of the ultrasound variables calculated. All measurements were carried out

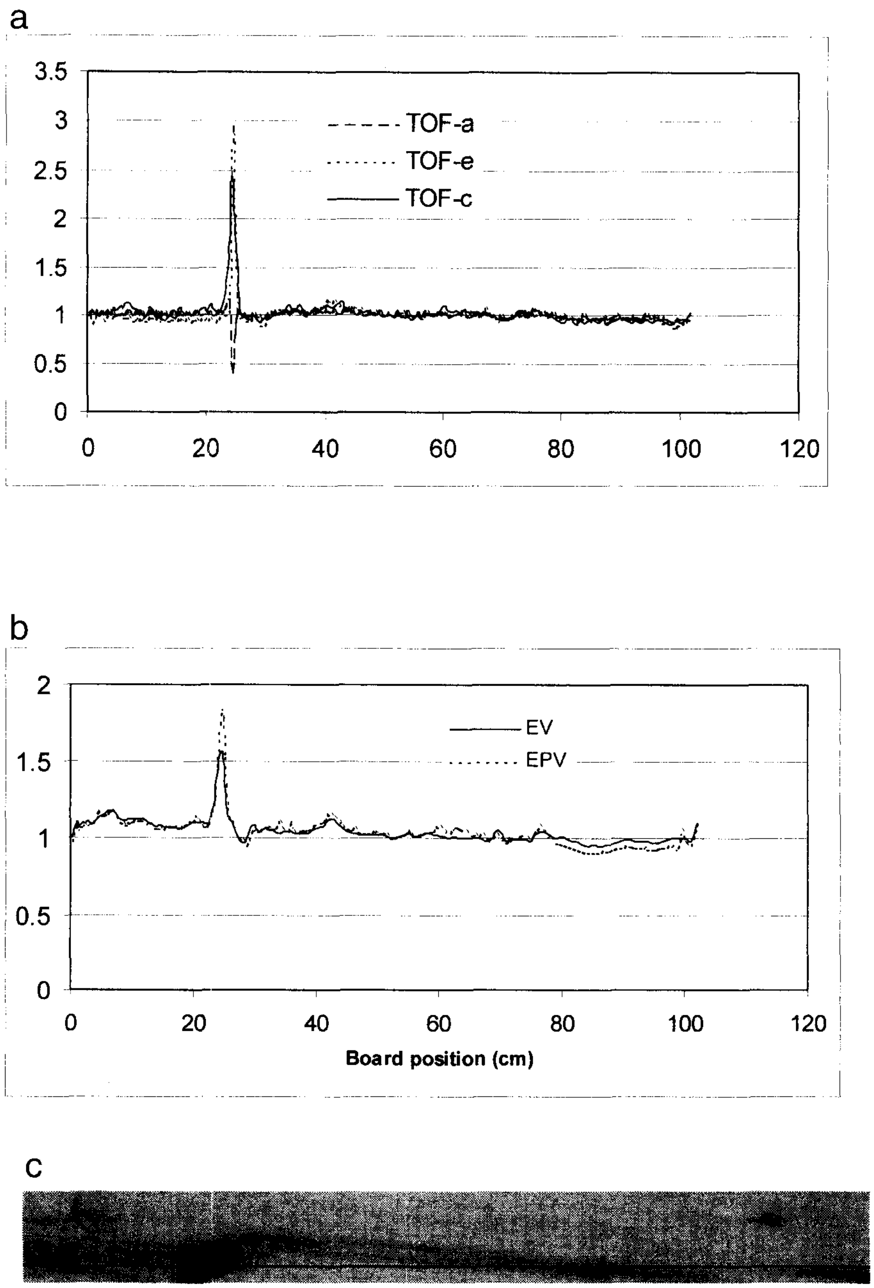


FIG. 7. Normalized ultrasonic variables are graphed for a scan line through a bark pocket in a yellow-poplar deckboard, (a) TOF-a, TOF-e, and TOF-c, (b) EV and EPV, and (c) board photo. The scan line is marked on the board image.

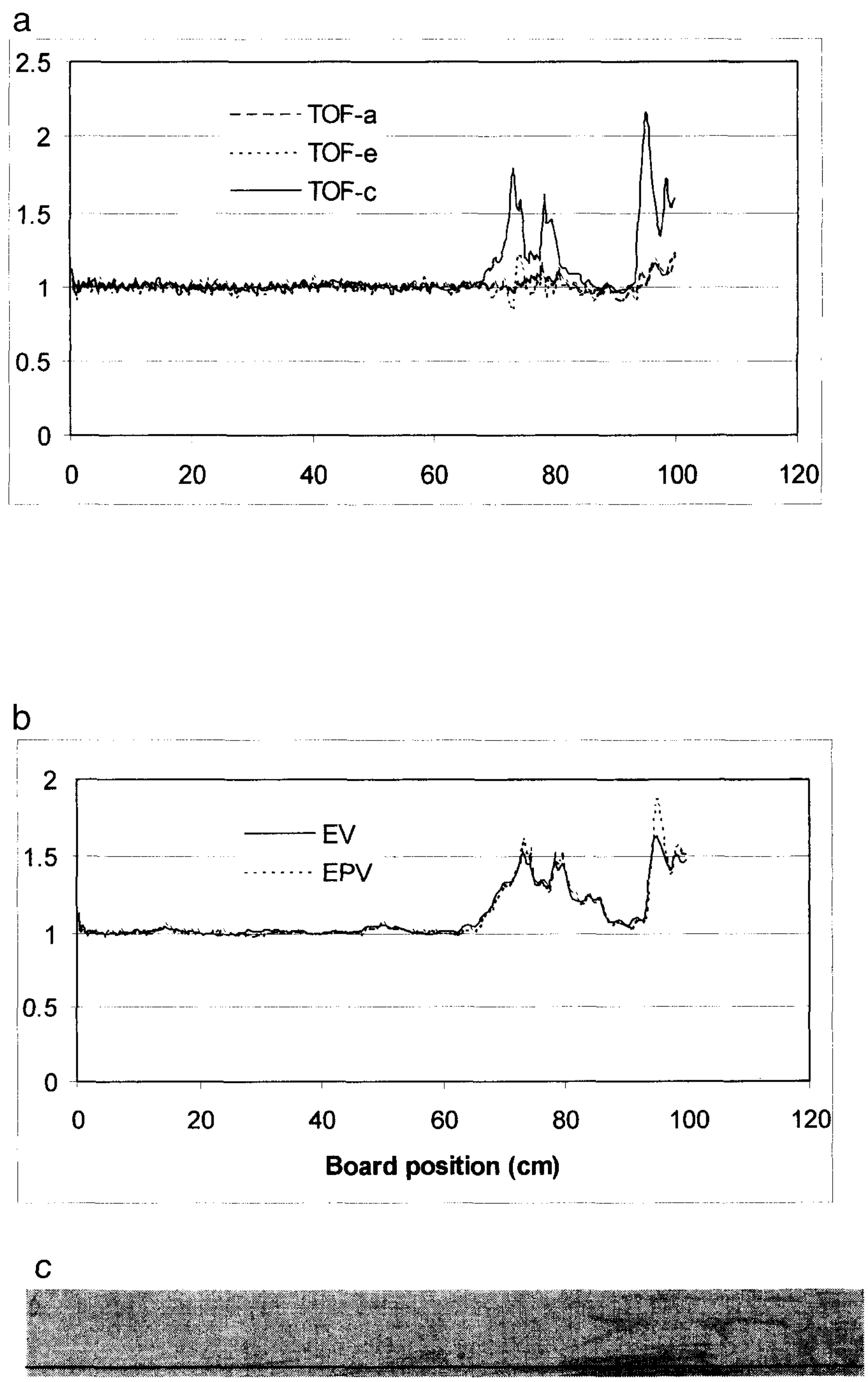
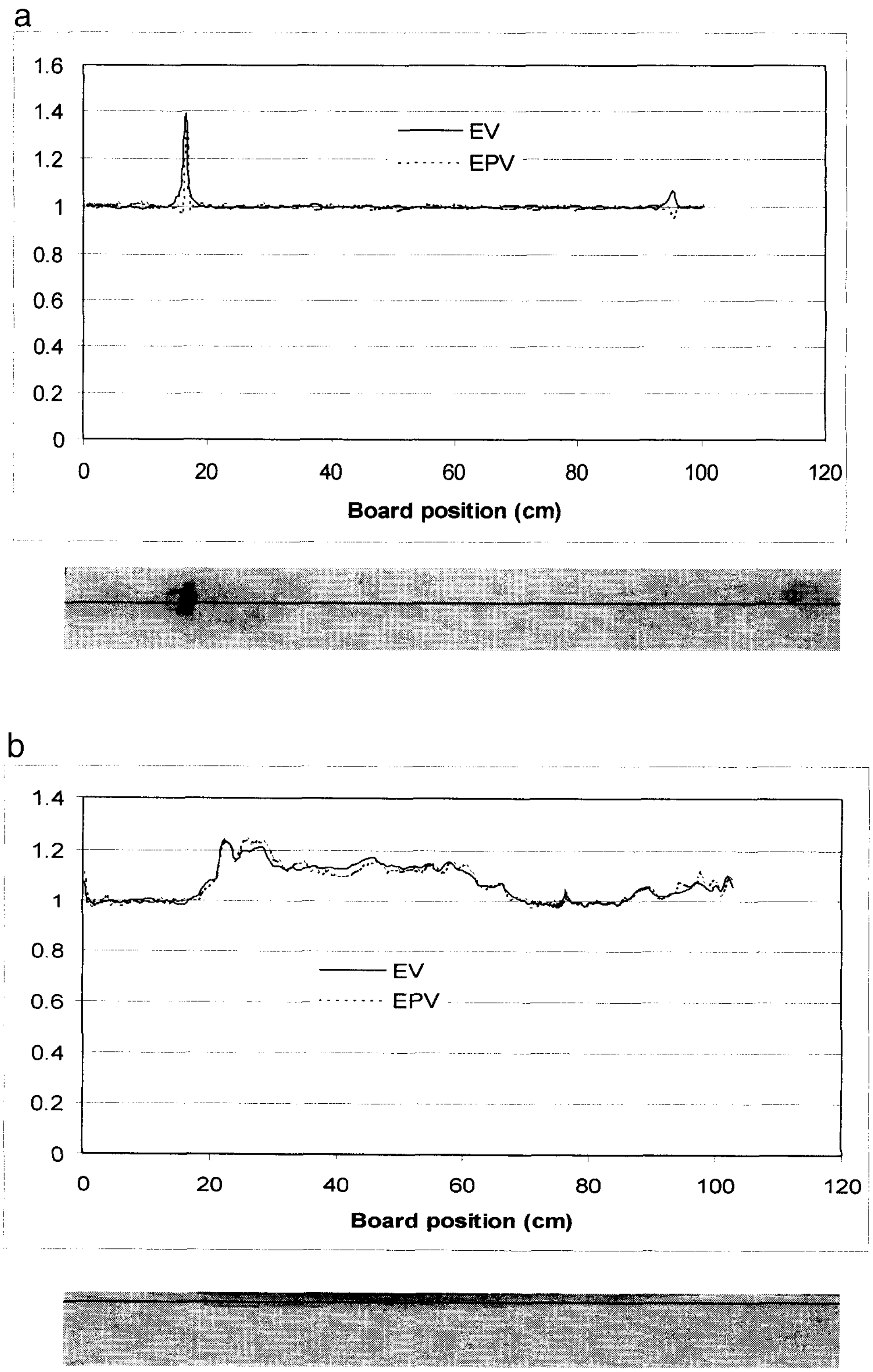


FIG. 8. Normalized ultrasonic variables are graphed for a scan line through decay in an oak deckboard, (a) TOF-a, TOF-e, and TOF-c, (b) EV and EPV. The scan line is marked on the board image.


a
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
20
40
60
80
100
120
Board position (cm)
EV
EPV
b
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
20
40
60
80
100
120
Board position (cm)
EV
EPV

at 120 kHz transmitting frequency and received signals were sampled at 500 kHz. The transmit voltage and receiver gain were 130 V and −24 to −28 dB, respectively.

RESULTS AND DISCUSSIONS

Six variables—pulse length (PL), time-of-flight-centroid (TOF-c), time-of-flight-energy (TOF-e), time-of-flight-amplitude (TOF-a), energy value (EV), and energy/pulse value (EPV)—were calculated from each ultrasound waveform captured at each measurement point. Examples of received ultrasonic waveforms through clear wood and defected wood are shown in Fig. 3a and Fig. 3b. It can be seen in this figure that defected wood, i.e., unsound knot and bark pocket, reduce the amplitude of the signal substantially.

Figure 4 illustrates the impact of a sound knot (arrow marked) on these ultrasonic variables. Sound knots represent, in effect, longitudinal fiber orientation in the sound transmission direction, that otherwise has a radial or tangential orientation. Because longitudinal transmission is nearly twice the speed of radial or tangential transmission, one would expect much reduced TOF values. In these tests, any change resulting from the sound knot is small compared to the variation present in the clear wood regions. There is a slight increase in energy loss associated with the knot (Fig. 4b), suggesting that perhaps the knot is incompletely integrated with the surrounding wood.

An unsound knot has a much greater effect on both TOF variables and energy loss variables (Fig. 5a, b). Almost all variables change abruptly in proximity to the unsound knot. Unsound knots come in two manifestations: knots that are not integrated with the surrounding wood (resulting in some wood disintegration at the knot-wood interface that produces a loose knot, or a hole, after drying) and knots that contain bark and/or decay at the center. Unsound defects exhibit some disintegration of wood material. This loss of material integrity reduces the energy transmitted (increased loss) and increases the time that it takes for the energy to move through the material. The resulting energy transmission wave is spread out more, which retards TOF-e and TOF-c measurements. Clear-wood normalized TOF values appear in Fig. 6. Normalization was done by dividing the original data by the mean of the clear wood data, which is readily determined by noting the peak in each variable's histogram. Because TOF and other variables differ for individual boards, different board thickness, and different species, clear wood values can be used as board-specific references to which other "suspect" regions (defects) on the board can be compared.

Ultrasonic responses to other unsound defects appear in Fig. 7 and Fig. 8. Figure 7 shows normalized ultrasonic variables from a scan line through a bark pocket on a yellow-poplar deckboard. Because bark is an unsound defect in wood, its ultrasonic signature is very similar to other unsound defects, e.g., unsound knots and decay. Figure 8 depicts the effect on ultrasonic signals. Both TOF and energy loss change sharply in the region of decay. Decay's effect on TOF-a and TOF-e is not as dramatic as TOF-c, and slightly different from either the bark pocket or the unsound knot.

Figure 9 illustrates the response of ultrasound to holes and wane. These are defects associated with the absence of wood (voids). Both the hole and the wane areas exhibit increased EV and EPV losses relative to clear wood. In both cases, greater energy losses result from poor transducer to wood contact induced by the voids.

Because grading and sorting pallet parts requires knowledge of defect type, size, and extent, single scans lines have limited utility. Our aim is to eventually obtain full 2-D im-

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FIG. 9. Normalized energy values and energy/pulse values are graphed for a scan line through a hole (a) and wane (b) of an oak deckboard.

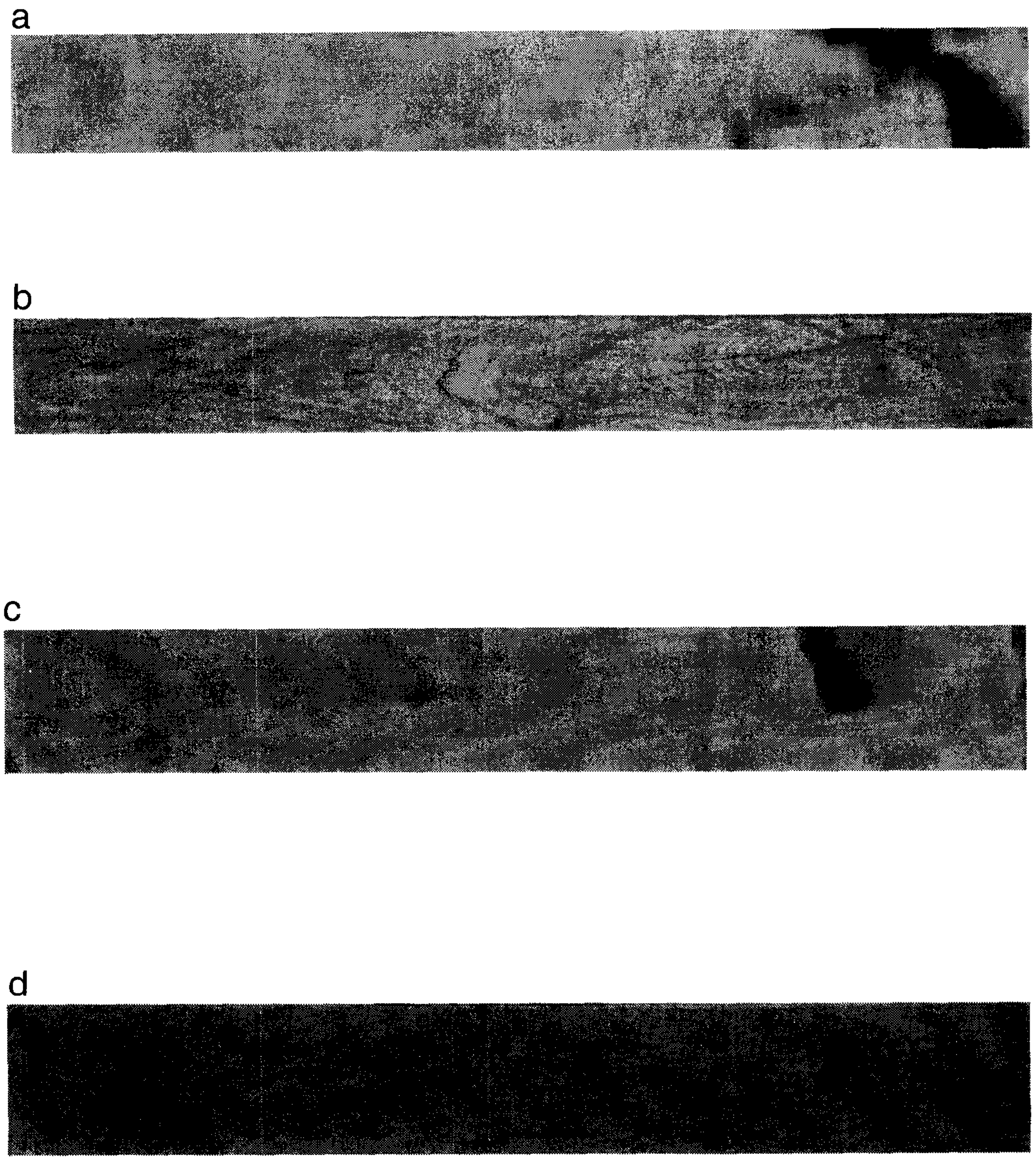
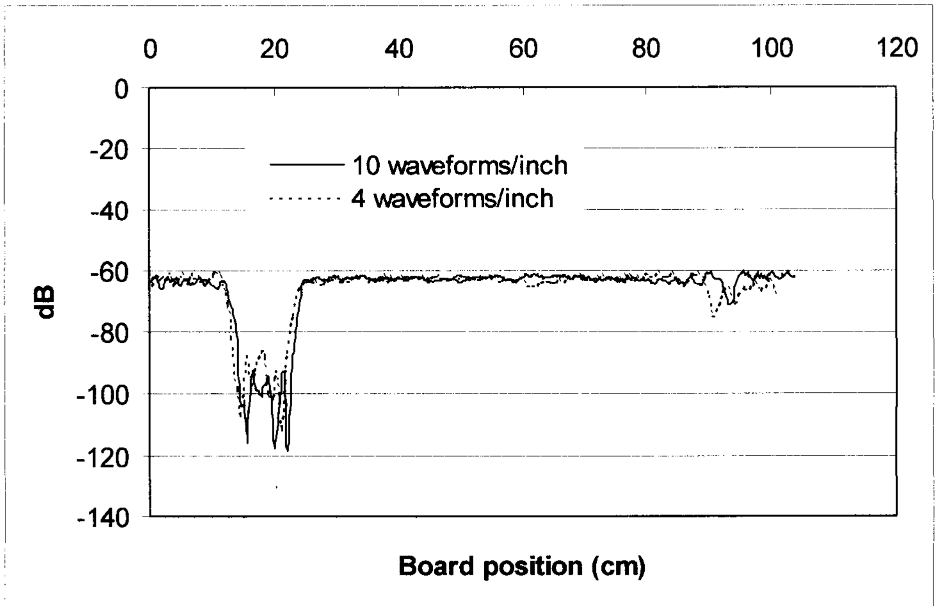


FIG. 10. Images were generated using multi-line scanning. EV values (a and c) and gray-scale photos (b and d) depict a split and a sound knot, respectively.

agery, or ultrasonic maps, where each scan will provide multiple images (one image for each ultrasonic variable). Simultaneous multiple-line scanning will be requited to achieve this. For illustrative purposes, manual multiline scanning data are presented in Fig. 10, where lines are separated by 1.27 cm. Defected areas (darker regions) can be seen quite readily.

Repeated measurement plots appear in Fig. 11. Two scanning rates—4 waveforms/cm and 1.6 waveforms/cm—for the EPV measurements are shown in Fig. 11a for red oak. This illustration suggests that scanning rate does a



b

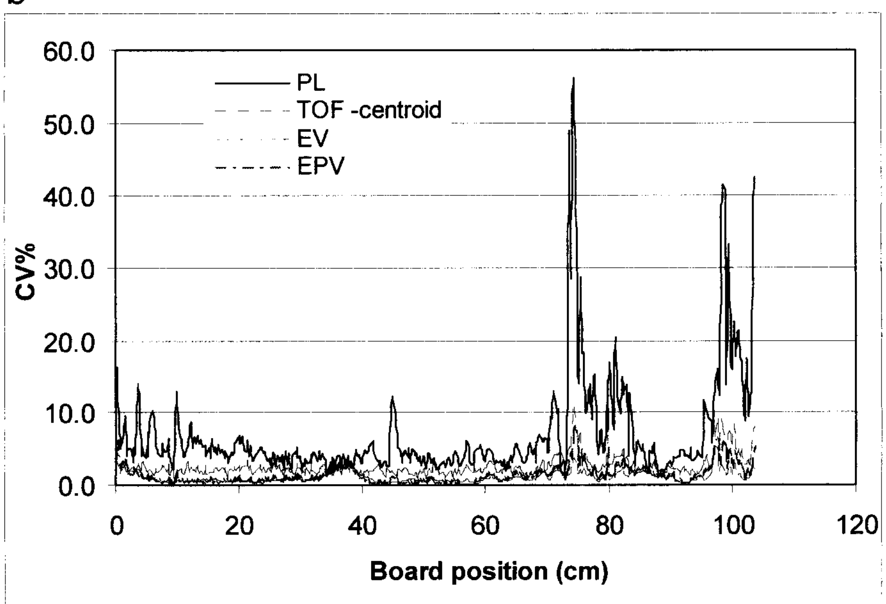


FIG. 11. Energy loss values are plotted for two different scanning rates along the same scan line on a red oak board (a). Percent coefficient of variation (CV%) is shown for several ultrasound variables using ten repeated measurements of the same scan line on a yellow-poplar board (b).

not have much effect on energy/pulse value measurements. To examine the repeatability and reliability of data collection, a set of boards was scanned ten times on the same scan line, and coefficients of variation (CVs) were calculated. The percent CV (CV%) for a decay sample on yellow-poplar is presented in Fig. 11b. Low CV% values for most calculated variables suggest that data collection repeatability is acceptable, although a high CV% was obtained for PL. The higher CV% values for PL in relation to other defects were reported earlier (Kabir et al. 2000a). The higher CV% values are confined primarily to the defected regions. This suggests that PL may be more sensitive to a shifting data collection point, which can occur with multiple scans of the same line in which repeated data points are not perfectly registered spatially.

A subset of all data points gathered were used to conduct statistical comparisons between clear wood and defected wood for all the ultrasonic variables. The data for each variable were normalized using the corresponding mean clear wood value for the specimen. Three defects of each type and at least ten sample points within each defect were used in the tests. Student's t-tests were performed separately for each ultrasonic variable and species. The probability values are presented in Table 2 and Table 3 for yellow-poplar and red oak samples, respectively. Energy variables (energy value, energy-pulse value, and TOF-e) demonstrate consistently high defect sensitivity in the yellow-poplar samples. The variable TOF-c was least sensitive, with TOF-a and pulse length showing less sensitivity than the energy variables for these same samples. For the red oak samples, the same energy values exhibited good sensitivity, although not dramatically superior to some of the other variables, e.g., TOF-c. Pulse length performed poorly for these samples. For each defect type in each species, there is at least one ultrasonic variable that distinguishes between that defect type and clear wood.

Because the data in Table 2 and Table 3 are normalized, we can also combine those data to obtain a species-independent view of ultrasonic variable sensitivity (Table 4). Again, we find that the energy variables, EV and EPV, readily distinguish between clear wood and various defects. Despite the measurement variability noted above for pulse length, it appears to discriminate quite well. Except for sound knots, TOF-c also discriminates between clear wood and all other defects. Again, as in the species-specific tests, there is at least one (in most cases, several) ultrasonic measurement whose values differ between clear wood and each defect.

Because each of Table 2, Table 3, and Table 4 contains 42 t-test values, using a typical threshold significance of 0.05 one would expect by random chance two falsely significant p-values in each table. This means that significance values of 0.01 or less should be used instead. Fortunately, there are many such values in those tables, owing to the vastly different ultrasonic measurements between clear wood and defects.

Because the primary aim of this study was to identify the sensitivity of various ultrasonic variables to different defect types, we have summarized our findings in Table 5. The energy value and energy/pulse value are the most sensitive parameters for all defect types.

CONCLUSIONS

Ultrasonic signals are greatly affected by sound and unsound knots, bark pockets, cross grain, decay, insect holes, and wane. Typically, pulse length and time-of-flight exhibit an increasing trend for most defects, whereas energy loss increases (values decrease to smaller decibel values, more negative). Energy loss is more sensitive to various defects compared to time-of-flight measurements. We suspect that this occurs because energy loss measures an attribute of the entire ultrasound signal, whereas time-of-flight variables measure a single point value (e.g., arrival time). Consequently, the former will generally be a more reliable indicator of defected wood. This suggests that we should use energy loss variables as often as possible.

Significant differences were observed between clear and defected wood for most of the ultrasonic variables. While all variables show sensitivity to some defects (and the energy variables exhibited sensitivity to all defects), it remains to distinguish between different defects using normalized values of the variables in concert. Ongoing work involves collecting spatially referenced measurements of defect samples and developing classification algorithms that will allow us to readily disambiguate different defect types.

Most pallet parts that are cut from hardwood are in a fresh-cut (green) state. Because these parts have moisture contents above fiber saturation, the moisture content dependency of ultrasonic measurements does not become an issue. Pallet parts cut from softwoods, on the other hand, are most often already dried to the point that moisture content will affect ultrasonic measurement. Therefore, the current results are applicable only to the hardwood pallet industry. The two hardwood species tested here represent two extremes in wood structure and density. Consequently, we are encouraged that the highly significant results appearing in Table 4 strongly suggest that classification algorithms should work well across several hardwood species.

The rolling transducer scanning system demonstrated good repeatability and reliability for ultrasonic data collection on unplanned (rough) pallet parts. Furthermore, the rate of data collection does not seem to affect the data values. The apparatus was able to achieve good, consistent contact between transducers and wood, without the aid of a viscous medium, such as petroleum jelly or water. These results demonstrate a realistic operational capability and the possibility to readily translate prototype scanning to commercialization.

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