

Application of ultrasound nondestructive evaluation to grading pallet parts

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Abstract

High-quality pallets are easier to repair and last longer. To obtain the high-quality parts necessary to build durable pallets requires grading and sorting by an automated inspection system. Ultrasonic sensing was selected for this application because 1) it is relatively inexpensive; 2) it can penetrate and characterize internal features of wood specimens; and 3) its effectiveness has been demonstrated for certain features of wood. This study has sought to 1) determine the ultrasonic parameters that are most sensitive to pallet part defects; and 2) specify which aspects of ultrasonic response signals best characterize defect size and location. Time-of-flight measurements appear reliable for delineating knots from clear wood. Also, preliminary indications are that peak amplitude may be sensitive to areas with splits/checks/shake. Results from this work and subsequent studies will be applied to the development of an industrial prototype that automatically detects defects and grades parts according to established visual grading rules.

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Introduction

Wood pallets are the largest single use of sawn hardwood logs in the United States. Unfortunately, millions of wood pallets are discarded annually due to damage or because their low cost makes them readily disposable. High-quality wood pallets, on the other hand, have a much longer life-cycle and promote reuse. However, building durable pallets requires high-quality pallet parts. Because manual grading and sorting of pallet parts is not feasible, we have a long-term goal to develop an automated pallet-part inspection system. We envision that it will scan moving parts in a production environment, locate and identify defect areas, and grade the parts according to established visual grading rules.

Most wood pallets are constructed from two types of pallet parts (Fig. 1): 1) stringers, the structural center members that support the pallet load; and 2) deckboards, the top- and bottom-facing materials that provide dimensional stability and product placement. There are many variants of this basic design, but most pallets contain solid wood components that are produced from lumber or from the center cant material of logs. Cant material has a high percentage of defect area and is generally not highly valuable for other solid wood products.

Ultrasonic testing has been used by other investigators to examine wooden objects. Previous work has established that knots can be detected in hardwood and softwood lumber (5,6), decay is detectable in structural timbers (7,9), beams can be graded for strength in situ (8), dry-coupled transducers can be used to detect knots and decay

in timber bridge members (2,3), knots, decay, and cross grain are detectable in small laboratory samples (4), and wooden art objects can be examined for small cracks and other degradation (1). In most of these studies, softwood species, such as southern yellow pine (*Pinus* spp.), Suisse spruce, Douglas-fir (*Pseudotsuga menziesii* (Mirb.) France), and white fir (*Abies concolor* (Gord. and Glend.) Lindl. ex Hildebr.), were examined. With some exceptions (2,3, 5,6), reports on the application of ultrasound to hardwood species is limited. Physical and mechanical properties of hardwoods differ from softwoods, and previous ultrasonic examination methods for softwoods may not directly translate to hardwood applications. Because many different hardwood species are used in pallets, inspection methods must be adaptive to interspecific dissimilarities. Additionally, pallet parts are rough cut, and therefore wood surfaces can vary greatly in smoothness and in reflectance of elastic waves.

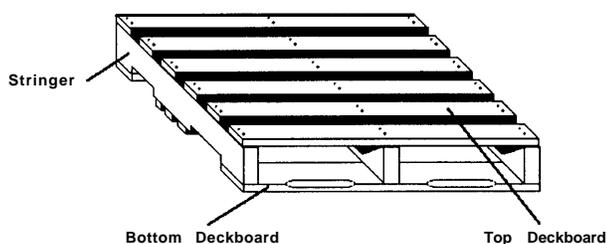


Figure 1. — A typical stringer class wood pallet containing three load-supporting stringers in the center and five to seven deckboards on the top and bottom.

Previous successes in ultrasonic testing of wood and its ability to characterize internal as well as surface features led us to select it for this application. Visual grading of pallet parts, however, requires that defects be described in very specific terms. For example, Table 1 contains an abbreviated set of grading rules that categorize pallet stringer quality into grades 2 & Better, 3, and 4. Cross-sectional extent of defects is an important descriptor in these grading rules. Therefore, this study has sought to 1) determine the ultrasonic parameters (mode and frequency of excitant, couplant, scan pattern) that are most effective for circumscribing pallet part defects; and 2) specify what aspects of ultrasonic response signals (time of flight (TOF), RMS voltage, amplitude, etc.) best mirror actual defect size and location and the descriptors (e.g., cross section) used to measure them.

Methods

To understand the interaction of wood and ultrasound, it is important to know something about the structural geometry of wood. The wood raw material consists of cellulose and hemicellulose fibers oriented with the axis of the stem (longitudinal). A new layer of wood is added to the circumference of the tree annually. This creates a radial axis, and perpendicular to the radial direction there is a tangential axis. Figure 2 depicts these three axes in relation to a typical piece of lumber. The velocity and magnitude of ultrasound signals has been shown to differ with respect to travel in these three axial directions (5,6).

Depending on how lumber is cut from a log, the tangential and radial axes may rotate 90° with

Table 1. — Partial list of grading criteria employed for stringers.

Defect	Description	2 & Better	3	4
Sound knots	Maximum portion of cross section affected	1/4 of cross section	1/3 of cross section	1/2 of cross section
Location of knots	Over notch or in 6-inch end of the stringer	1/2 inch maximum diameter	1/4 of cross section	1/3 of cross section
Unsound knots/holes	Knot holes, unsound or loose knots, and holes	1/8 of cross section	1/6 of cross section	1/4 of cross section
Cross grain	Slope of general cross grain	1 inch in 10 inches	1 inch in 8 inches	1 inch in 6 inches
	Maximum dimension of local cross grain	1/4 cross section	1/3 cross section	1/2 cross section
Splits/checks/shake	Maximum length singly or in combination Defects 3 inches or less are ignored	1/4 of length of part	1/2 of length of part	3/4 of length of part

respect to lumber dimensions. Because pallet parts are often cut from the center cant material of a log, this geometry varies drastically from piece to piece. The rotation of these two axes across different pieces of wood makes ultrasonic examination extremely variable. Ultrasound response signals used to characterize defects must be more sensitive to the defects than to the geometric variation of wood.

Ultimately, we need to define those ultrasonic parameters that will be useful for this pallet part inspection problem. There are many parameters to consider: scanning orientation, ultrasound signal (frequency and amplitude), scanning resolution, sensor type, couplant, and pulse-echo versus pitch-catch sensing. It is hoped that a "best" set of parameter settings can be found for the types of defects present in pallet parts. Parameter settings will be judged on their ability to provide diagnostic response signals.

Therefore, our first task is to identify ultrasonic response signals that show strong relationships to wood defects. We conducted a series of experiments to determine which ultrasound response signals could be useful for detecting various defects. The three experiments increased progressively in sensitivity and level of resolution. Each experiment attempted to extend the results of the previous one.

Experiment 1

Our first experiment was designed to identify,

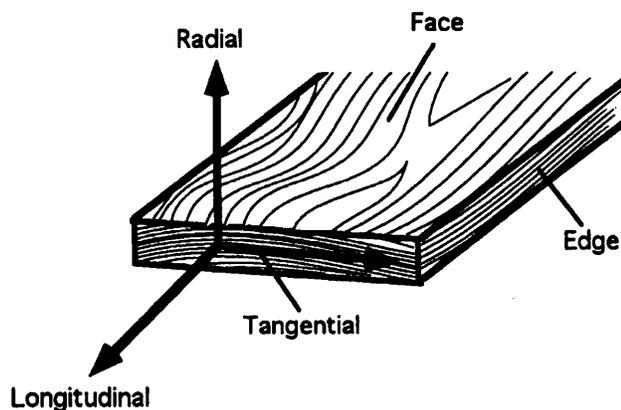


Figure 2. — A typical piece of lumber has three orthogonal components that are derived from the structure of wood fibers in a tree. Orientation of the radial and tangential directions will vary (up to 90°) with respect to lumber dimensions depending on the log sawing pattern and where in the log the lumber is cut.

in a very general way, those response signals that might be impacted by different types of defects. The experimental arrangement depicted in Figure 3 was used. An ultrasonic sine pulse was generated every 10 milliseconds at 250 kHz and 0.3 volts in a through-transmission arrangement. Petroleum jelly was used as a couplant. Peak amplitude and TOF were measured. Time of flight was measured as the time to receipt of the first part of the signal. On the basis of material thickness measurements, propagation velocity was then calculated.

Samples of rough cut, undried northern red oak (*Quercus rubra* L.) were obtained from a local pallet manufacturer. There were seven stringers measuring 52 inches long by 3-1/4 inches wide ($\pm 1/8$ in.) by 1-11/16 inches thick ($\pm 1/16$ in.). The nine deckboards measured 36 inches long by 3-3/16 inches wide ($\pm 1/16$ in.) by 11/16 inches thick ($\pm 1/16$ in.). Edge-to-edge through-transmission of ultrasonic pulses was applied every 2 inches along their length. Because of the way in which pallet parts are cut from cant material, the direction of ultrasound transmission varies from radial to tangential within each piece sampled. We selected edge-to-edge scanning because of its simplicity and the ability to sample many types of defects fairly quickly. Edge-to-edge scanning would be advantageous in an industrial setting because this method would only require two stationary transducers and pallet parts could move between them.

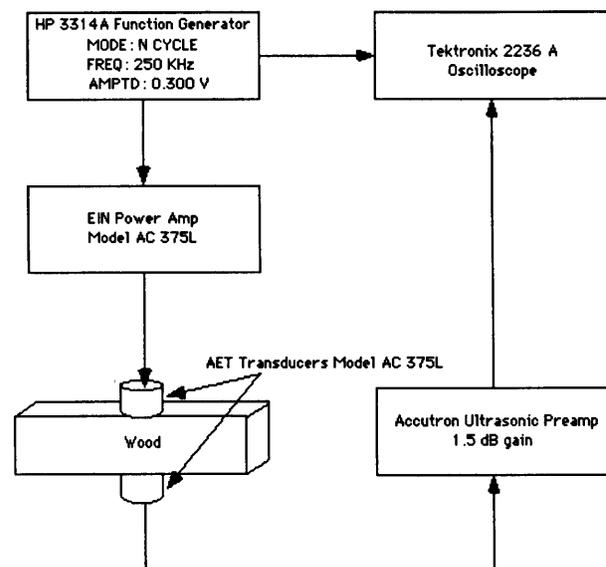


Figure 3. — A through-transmission arrangement was used to scan pallet part samples.

Experiment 2

After identifying several general relationships between defects and ultrasound signals, we investigated those relationships more closely for sound-knot defects. We performed this second experiment using a single deckboard. The sample was again red oak with dimensions 36 by 3-1/4 by 11/16 inch. The experimental apparatus was identical to the first experiment (Fig. 3). In this case, however, the sample was scanned in a face-to-face manner. Through-transmission measurements were taken every 1 inch in a raster fashion across the face of the deckboard. Measurements were taken every 1/2 inch near defect areas. In addition to TOF and peak amplitude measurements, time-to-peak amplitude was also recorded. From these, velocity and velocity-to-peak amplitude were calculated. Only one type of defect (sound knots) was present on this board.

Experiment 3

While results from the previous two experiments were encouraging, they did not provide us with an unambiguous diagnostic procedure for reliably discerning knots from clear wood. Based on previous work by (1,4,5) we decided to increase our ability to resolve knot defects by increasing the frequency of the ultrasound signal. We used the experimental setup depicted in Figure 4. Three, small (3-5/8 by 4 in.) samples of red oak deckboards were immersed in a water bath. A 5 MHz focused transducer was used to transmit an ultrasound signal and a point-ducer was used as the receiving transducer. A 3-axis, computer

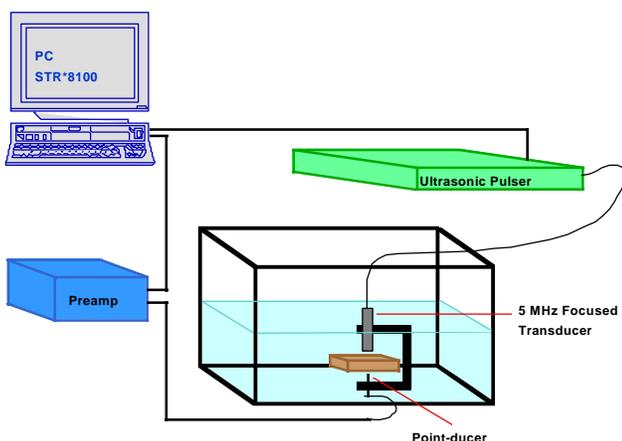


Figure 4. — To better delineate the effects of knots on ultrasonic signals, a high-frequency focused transducer was used, scanning at very high resolution.

controlled scanning unit moved the transducer pair in 0.01 inch increments. Approximately 2-1/2-by 3- inch areas of the samples were scanned in a face-to-face, pitch-catch arrangement. TOF to peak amplitude and peak amplitude measurements were automatically recorded at each scan point by a computer using a real-time data acquisition board. Both TOF and amplitude are recorded as 8-bit data values in the range 0 to 255.

Results

In the first experiment, actual values for velocity and amplitude varied considerably from sample to sample. To analyze the response of these signals to different wood characteristics, however, we needed to pool the data from all deckboards and from all stringers. Therefore, we normalized the amplitude and velocity values within each sample. We then aggregated the normalized values for all deckboards and also for all stringers. Figure 5 contains plots of normalized amplitude versus normalized velocity for all deckboards with respect to different wood characteristics, namely clear wood, sound knots, unsound knots, cross grain, and splits/check/shake. Similar plots were obtained for the stringers tested.

The data for the second experiment were also normalized to make them visually similar to those in Figure 5. Figure 6 depicts pairwise plots of velocity, peak amplitude, and velocity to peak amplitude. Results are consistent with those derived from the first experiment, but otherwise provide little additional benefit.

Because of the high resolution, two-dimensional nature of the third experiment, we were able to generate 2D images of each sample (Fig. 7). A scale in each image distinguishes high versus low TOF measurements. The image to the left in each figure is a line-scan camera image of the actual wood sample for comparison. Because these two images (TOF and camera) were generated at two different scales, they do not register perfectly in the figure.

Knots consistently relate to low TOF values in each image. Slightly higher TOF values correspond to those areas of the board that have radial geometry. Much higher TOF values are associated with wood having tangential geometry. In these three samples, the knots visible from this side extend through the wood obliquely to the other side. This is reflected in low TOF values outside of the knot regions visible. Histograms for each of the images in

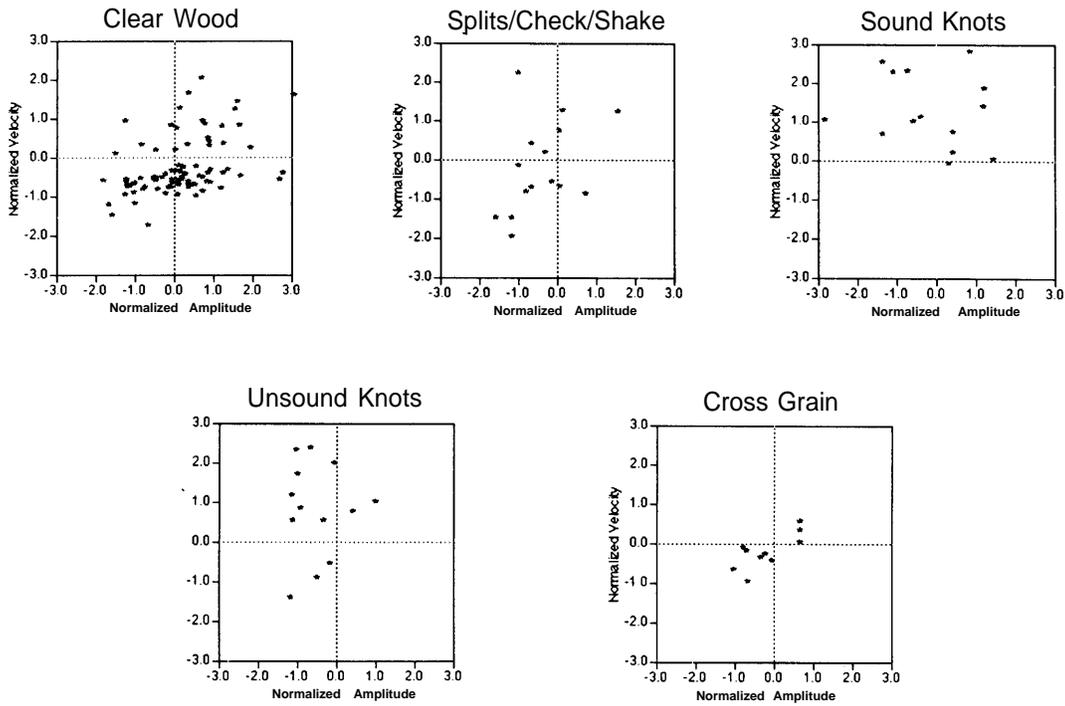


Figure 5. — Five plots relate normalized velocity to normalized peak amplitude for clear wood, splits/checks/shake, sound knots, unsound knots, and cross grain. These results were produced by edge-to-edge through transmission of nine oak deckboards. Values are multiples of the standard deviation for $N(0,1)$.

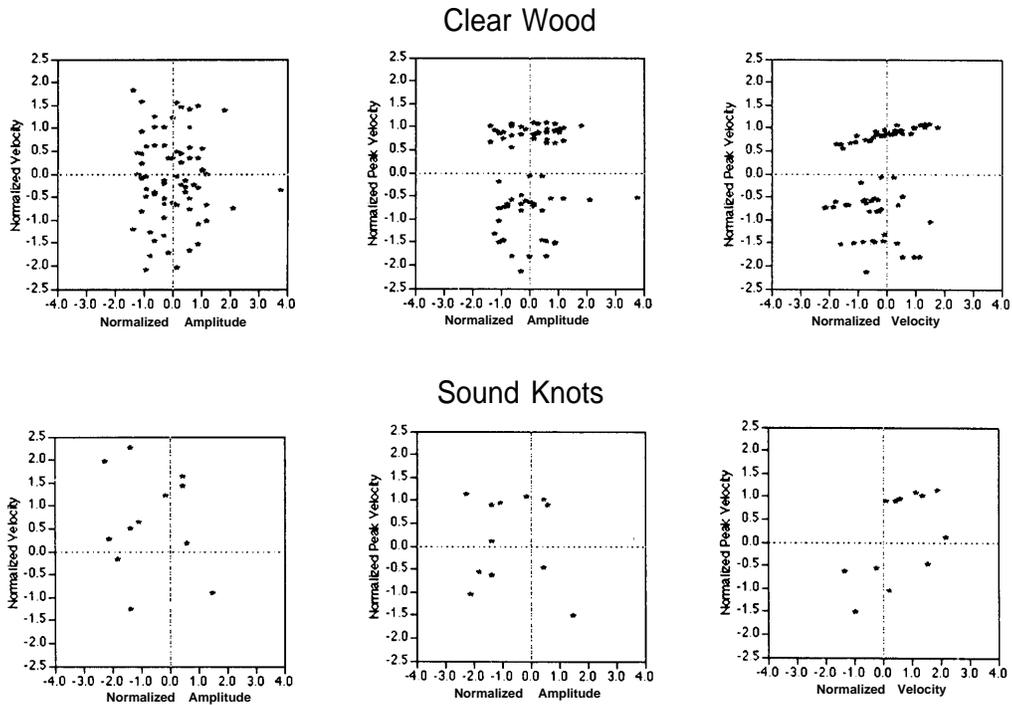
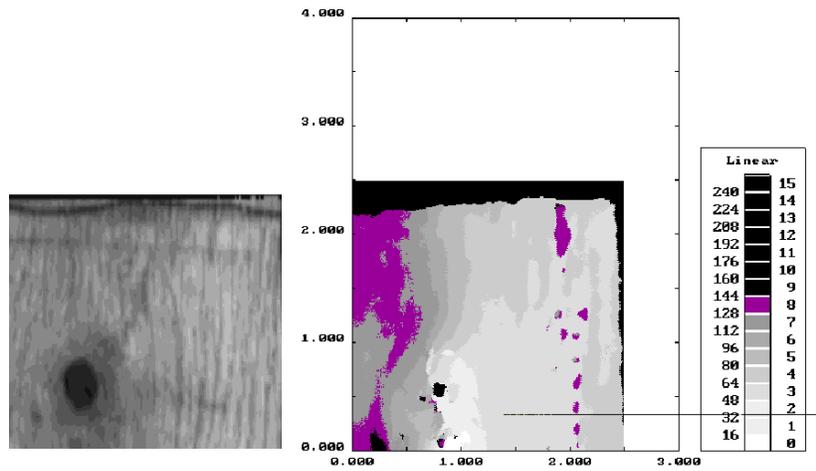
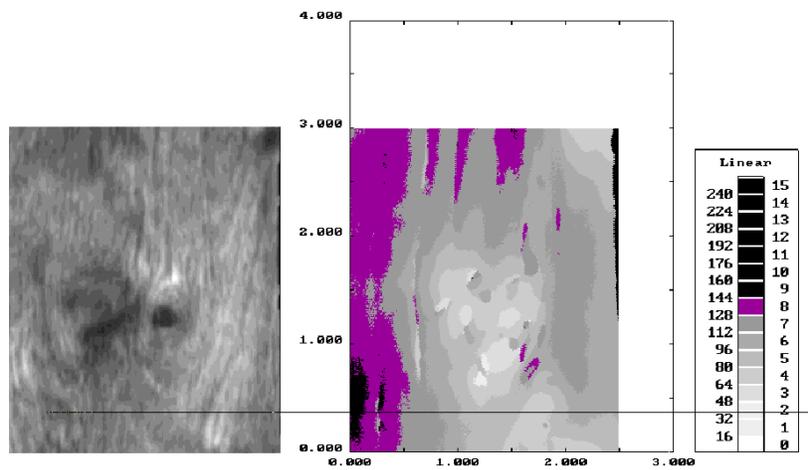


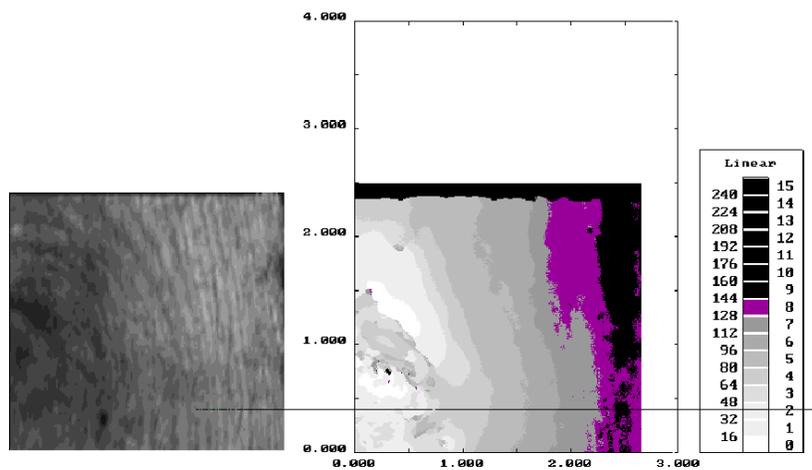
Figure 6. — Pairwise plots of normalized peak amplitude, normalized velocity, and normalized velocity-to-peak amplitude illustrate the impact of knots versus clear wood for face-to-face through-transmission of a single oak deckboard. Values are multiples of the standard deviation for $N(0,1)$.



(a)



(b)



(c)

Figure 7. — *Time-of-flight images (right) show variable ultrasound velocity in relation to the line-scan camera images (left). The black portions (top and right edge) of (a) and (c) correspond to the edge of the sample and, therefore, transmission through water.*

Figure 8. Some preliminary analyses of these images indicates that knot regions correspond to TOF values less than one standard deviation from the mean.

Conclusions

Clear wood areas and defect areas exhibit different response trends for both velocity and peak amplitude. Velocity is either below the mean (Figure 5) or unaffected (Figure 6) by clear wood, whereas sound and unsound knots have velocities above the mean. Differences in Figures 5 and 6 for clear wood may be due to the nature of ultrasound propagation through the different radial/tangential orientations. Unsound knots tend to have peak amplitudes below the mean value, and similarly for split/check/shake areas. Velocity-to-peak values in Figure 6 do not exhibit any recognizable pattern for either clear wood or sound knots. There does seem to be, however, a two-cluster pattern in the latter two clear wood plots; this result remains unexplained at this time.

Structural lumber and appearance lumber are cut from the outside portions of logs. Con-

sequently, they have orthogonal characteristics similar to those in Figure 2 that are consistent throughout a single piece of material. Pallet parts, however, are cut from the centers of logs. In this case, the orthogonal geometry can vary throughout the piece. For example, face-to-face scans across a stringer cut from the center of a log can have both entirely radial and entirely tangential ultrasound transmission as one moves the transducers along a face from one edge to the other. Because the radial axis tends to have higher ultrasound velocity (5), this may limit the use of velocity measurements for defect detection. Although our results indicate that knots have a much lower TOF than wood with a radial geometry, one cannot definitely say that a knot is present by examining the TOF histogram alone.

A number of continuing research efforts are indicated by these results. First, based on our success using higher frequency ultrasound, we will investigate other transducers in the range 0.25 MHz to 5 MHz. Second, we plan to continue water-bath experiments on other defect types as well as on clear wood specimens. It appears from

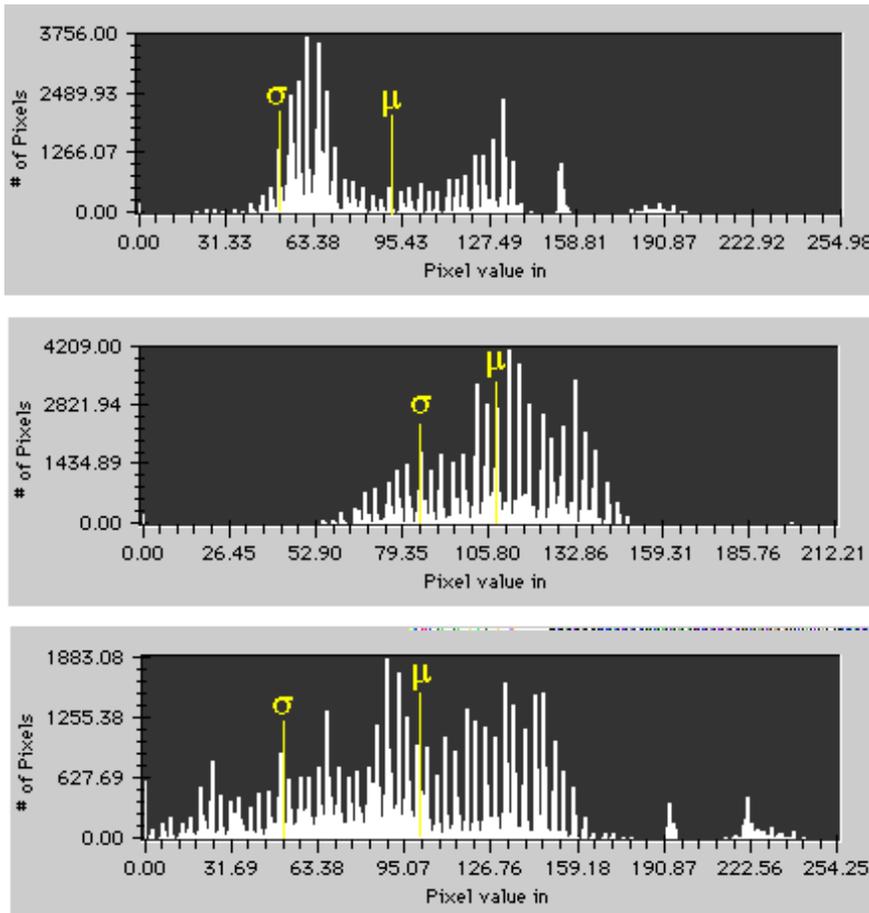


Figure 8. — Three histograms correspond to the time-of-flight images in Figure 7. Mean μ and standard deviation σ are labeled.

the first experiment that peak amplitude is sensitive to splits/checks/shake areas. Third, we are examining the effect of reducing the resolution from 100 points per inch to 50,25, and 10. Fourth, we expect that velocity alone will not allow us to distinguish all types of defects, so we are obtaining the equipment necessary to automatically calculate and record RMS amplitude and signal waveforms.

Even with highly diagnostic response signals, however, it is unlikely that point-by-point labeling of defect areas will be reliable. We fully expect the need to development machine vision software to accompany these nondestructive evaluation results. That software will take into account defect geometry and spatial arrangement to make reliable defect classifications and to grade pallet parts.

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Proceedings of the

**9th International Symposium on
Nondestructive Testing of Wood**

September *22-24, 1993*

Inn on the Park, Madison, Wisconsin, U.S.A.

Published
by
Conferences & Institutes
Washington State University

1994

Printed and Distributed by

Forest Products Society
2801 Marshall Court
Madison, WI 53705
Phone: 608-231-1361
Fax: 608-231-2152