Ultrasonic detection of knots, cross grain and bark pockets in wooden pallet parts

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ABSTRACT

This study investigates defect detection in wooden pallet parts using ultrasonic scanning. Yellow-poplar (*Liriodendron tulipifera*, L.) deckboards were scanned using two rolling transducers in a pitch-catch arrangement to detect unsound and sound knots, bark pockets and cross grain. Data were collected, stored, and processed using LabView™ software. Six ultrasonic parameters—three involving time-of-flight, two involving ultrasound pulse energy, and one using ultrasound pulse duration—were measured for each defect type. Four of the six parameters were affected by transmission through unsound knot regions. Sound knots also showed decreased values forthe energy-related parameters. All ultrasonic parameters changed sharply for bark pockets. Cross grain also affected ultrasound energy transmission. Small coefficients of variation for repeated measurements indicates that this scanning arrangement is stable and scanning rate has little effect on the measurements. Results indicate that on-line detection of these defects is possible by ultrasonic scanning.

INTRODUCTION

Wooden pallets are the largest single use of sawn hardwood logs, consuming around 40% of all US hardwood lumber produced. Every year, over 400 million wooden pallets are manufactured using 4.5 billion board feet of hardwood lumber. Pallets are integral to the US transportation infrastructure, and wood is the primary raw material used in pallets. Most wooden pallets consist of two parts, stringers—the structural center members that carry the product load—and deckboards—the top and the bottom members that provide dimensional stability and product placement. There are many types of pallet designs—depending on the size, number, and position of stringers and deckboards—but most are produced from solid wood, lumber, or from the center cant material of logs. Most solid wood material, that is manufactured into pallet parts, is low quality (having a high percentage of defects) and therefore has less market value for other solid wood products.

The most common defects in pallet parts are knots, cross grain, reaction wood, bark pockets, insect holes, splits, decay, shake, and wane. For quality pallet production, it is necessary to detect defects during manufacturing and then grade and sort parts prior to pallet assembly. An economic analysis by Schmoldt et al. (1993) indicated that improved pallet durability and performance imparts much greater value to carefully manufactured pallets. Current pallet manufacturing operations, however, do lend themselves to manual grading and sorting of parts. Therefore, this research program aims to develop automated techniques that include scanning, defect detection, and grading.

Previous work has investigated a variety of ultrasonic waveform parameters to detect defects in wood (McDonald 1980, Lemaster and Dornfeld 1987, Patton-Mallory and DeGroot 1990, Ross et al. 1992, Schmoldt et al. 1994, Fuller et al. 1995, Kabir et al. 1997). Most of these studies were conducted using laboratory samples or surfaced lumber, whereas in practice, conditions may be quite different. This is especially the case in the pallet industry where low quality, unsurfaced wood must be scanned. Furthermore, simple ultrasonic propagation velocity alone may not be sufficient to detect most defects. Other ultrasonic parameters, e.g. peak amplitude, time to peak amplitude, centroid time, root mean square of the time domain, pulse length, energy, frequency domain modes, frequency domain energy, etc., may be required. Recently, Halabe et al. (1993, 1994, 1996) conducted a study using ultrasonic frequency analysis for decay detection in wooden

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timbers. They reported that frequency domain analysis can significantly increase prediction sensitivity for modulus of elasticity and strength of clear and defective wood under controlled laboratory conditions.

More research needs to be done comparing different ultrasonic parameters' sensitivities to defects. The final goal of this study is to develop an automated ultrasonic scanning system for defect detection in pallet parts. This initial experiment was carried out to determine which ultrasonic parameters respond well to particular defects and also to observe the reliability and repeatability of data collection using pressure-contact rolling transducers.

MATERIALS AND METHODS

Scanning equipment

A materials handling system was designed by the Forest Products Division of Perceptron and purchased by the USDA Forest Service. It consists of in-feed and out-feed roll-beds and an ultrasonic scanning ring where rolling transducers are mounted. Perceptron provided the necessary electronics and software to control material movement, signal generation, and waveform capture and analysis. Pallet parts move through the system lying on a face and pitch-catch ultrasonic transmission propagates through the part's thickness. The transducers can be operated using a range of frequencies in 90-180 kHz. A single scan line of data is collected during each pass of the part through the scanner. The desire resolution of this scan line (number of waveforms per inch) can be achieved by controlling roller speed and number of pulses/sec. Data were processed to create six ultrasonic parameters—time of flight-centroid (TOF-centroid), time of flight-energy (TOF-energy), time of flight-amplitude (TOF-amplitude), pulse length (PL), energy value (EV), and energy/pulse value (EPV), to be discussed further below.

Definition of the ultrasonic parameters[4]

The most important parameters relate to the energy in the received signal. Wave energy is expressed as the time integral of the voltage squared:

$$E = \int v^2(t)dt \tag{1}$$

Because of the wide variation in transmitted energy levels between sound wood and defects, it is more convenient to express the energy on a logarithmic basis. The energy value (EV) is derived from the energy *E*, and is expressed in decibels (dB). By convention, this is a negative number, with lower signals (containing less energy) being more negative.

The pulse length parameter (in units of microseconds) is simply the time for which the pulse is "on", and depends upon the transmitted ultrasound frequency. These two parameters, energy value and pulse length, can be combined to provide a single parameter, which is known as energy/pulse value (EPV). Again, because of the wide range of energy levels, EPV is also expressed on a logarithmic scale (in dB).

TOF-energy is calculated as the time at which the energy integral (Equation 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, for instance, 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. No frequency domain parameters were calculated in this study.

Data collection

Twelve, fresh-cut yellow-poplar boards 40 inches in length and approximately 1/2 inch thickness were collected from a pallet manufacturer. The boards were kept in cold storage to reduce their drying rate. A line was drawn on each board through a defect of interest and scanning was performed along this line. All parameters were calculated for each scan. Three boards were scanned for each defect type. The boards were scanned with two scanning rates—10 waveforms/inch (70 ft/m roller speed) and 4 waveforms/inch (220 ft/m roller speed). Each board scan line was repeated ten times for each defect type and scanning rate. All measurements were made at 120 kHz transmitting frequency and 500 kHz sampling frequency.

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[4] For proprietary reasons, full details regarding the ultrasonic parameters and their measurement cannot be released at this time.

RESULTS AND DISCUSSION

Fig. 1 depicts graphs of ultrasonic parameters plotted against board length for a scan line that includes an unsound knot. These data are taken from one of the sample boards; other boards behaved in a similar manner. Data collected at 10 waveforms/inch and 4 waveforms/inch are also shown. The graphs show that PL and TOF-centroid increase sharply with the unsound knot. TOF-amplitude and TOF-energy seem relatively unaffected, however. On the other hand, the presence of an unsound knot causes a dramatic decrease in EV and EPV. Scanning rate does not appear to affect parameter measurements (Figs. 1c & 1d); both, EV and EPV have nearly identical values at scanning rates of 10 waveforms/inch and 4 waveforms/inch. In addition to a dramatic loss in transmitted energy, unsound knots also tend to spread out the received waveform, increasing the pulse length and centroid value.

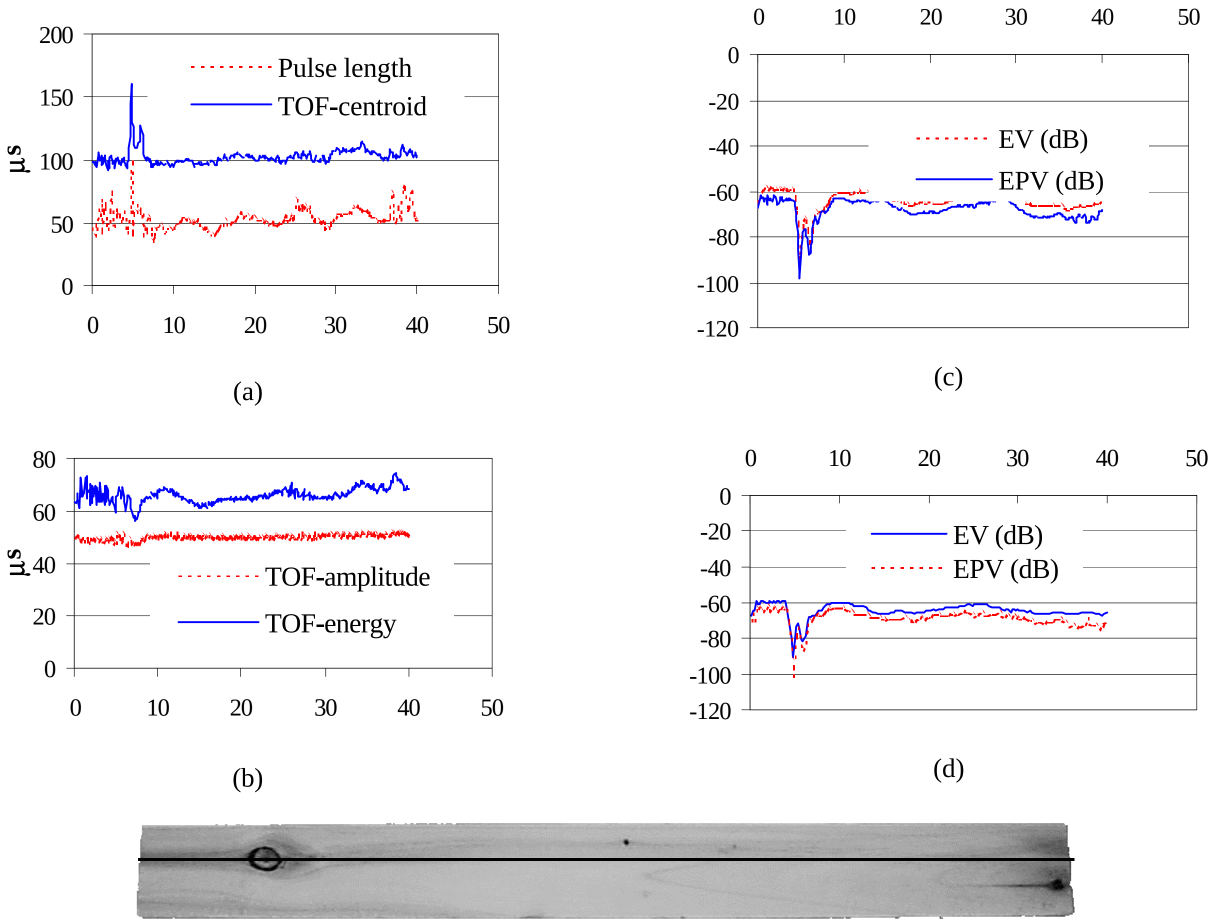
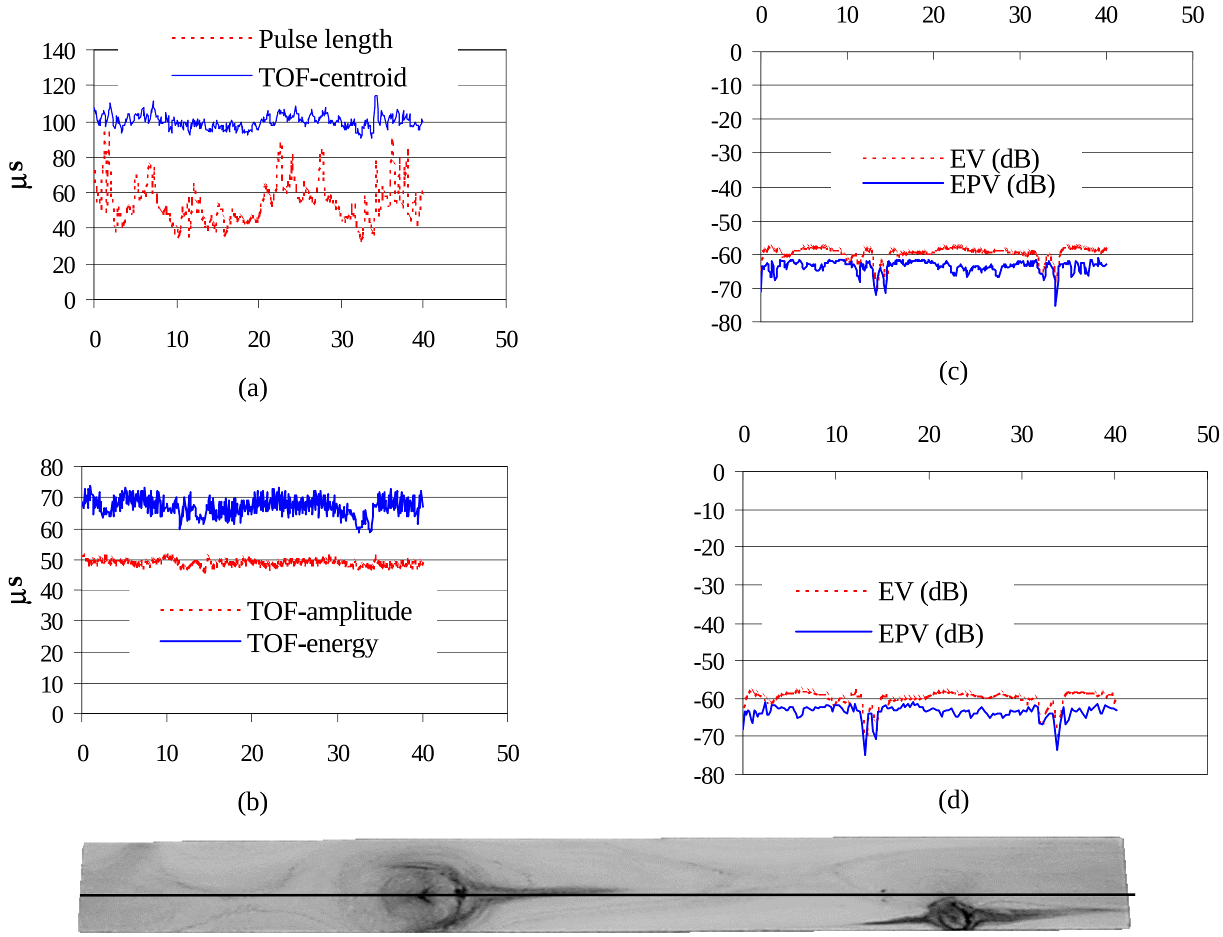


Figure 1. Ultrasonic measurements taken at 10 waveforms/inch along the length of a scan line (x-axis) are shown for all six parameters (a, b, c). An unsound knot is present between the 5- and 10-inch locations. For comparison, the last graph (d) shows measurements made at 4 waveforms/inch for EV and EPV.

The effects of sound knots on ultrasonic parameters appear in Fig. 2. PL, TOF-centroid, TOF-amplitude, and TOF-energy seem unaffected by the sound knots, but EV and EPV exhibit a sharp decrease around the regions of sound knots. While unsound knots contain incipient or advanced decay or have a complete separation of knot from surrounding wood (loose), sound knots influence wood properties by interrupting the longitudinal direction of wood fibers (Anon 1987). Wood fibers around a sound knot are distorted, developing localized cross grain which may have substantial impact on ultrasonic measurements. While it is well established that TOF measurements can detect the presence of sound knots (e.g., McDonald 1980, Kodama and Akishika 1993, Schmoldt et al. 1996; Kabir et al. 1997), it appears, from this study, that energy losses (Figs. 2c & 2d) are more sensitive than TOF measurements (Figs. 2a & 2b). Like unsound knots, sound knots do not have any noticeable effect on measurements at different scanning rates (Figs. 2c & 2d).

Bark pockets contain some bark in place of wood, so one would expect them to have a significant effect on ultrasonic measurements. Fig. 3 illustrates how the ultrasonic parameters vary with bark pockets. PL, TOF-centroid, and TOF-energy increase sharply with bark pockets whereas EV and EPV decrease. The tremendous increase or decrease of the parameters may be associated with the presence of a small split and decay in the bark pocket of this sample board.



(a) (c) (b) (d)

Figure 2. Ultrasonic measurements taken at 10 waveforms/inch along the length of a scan line (x-axis) are shown for all six parameters (a, b, c). Sound knots are present between the 12- and 18-inch locations and also between the 32- and 38-inch locations. For comparison, the last graph (d) shows measurements made at 4 waveforms/inch for EV and EPV.

Cross grain represents a generalized slope of grain; it is often measured as a ratio of perpendicular deviation versus longitudinal reach, e.g. 1:10 or 1:6. Deviations from longitudinal (*X* direction) are measured in both the *Y* (d_y) and *Z* (d_z) directions, with the resultant cross grain *d* calculated as in (2). Ultrasound propagation is known to differ with grain direction (anisotropy), so one would expect several measured parameters to be affected. PL shows high variability in the cross grain region (Fig. 4a). There are also some decreases in EV and EPV measurements, but not as dramatic as bark pockets or knots. Again scanning rate showed no effect on data collection.

$$d = \sqrt{d_y^2 + d_z^2} \tag{2}$$

To test the repeatability of measurements and the reliability of the data, boards were scanned ten times with coefficients of variation calculated. These are presented in Fig. 5 for a bark pocket scan line using the board appearing in Fig. 3. The low CV% values suggest that the repeatability of data collection using pressure-contact rolling transducers is very good. Some inflation of CV values likely occurs because of errors in data point registration between repeated scans.

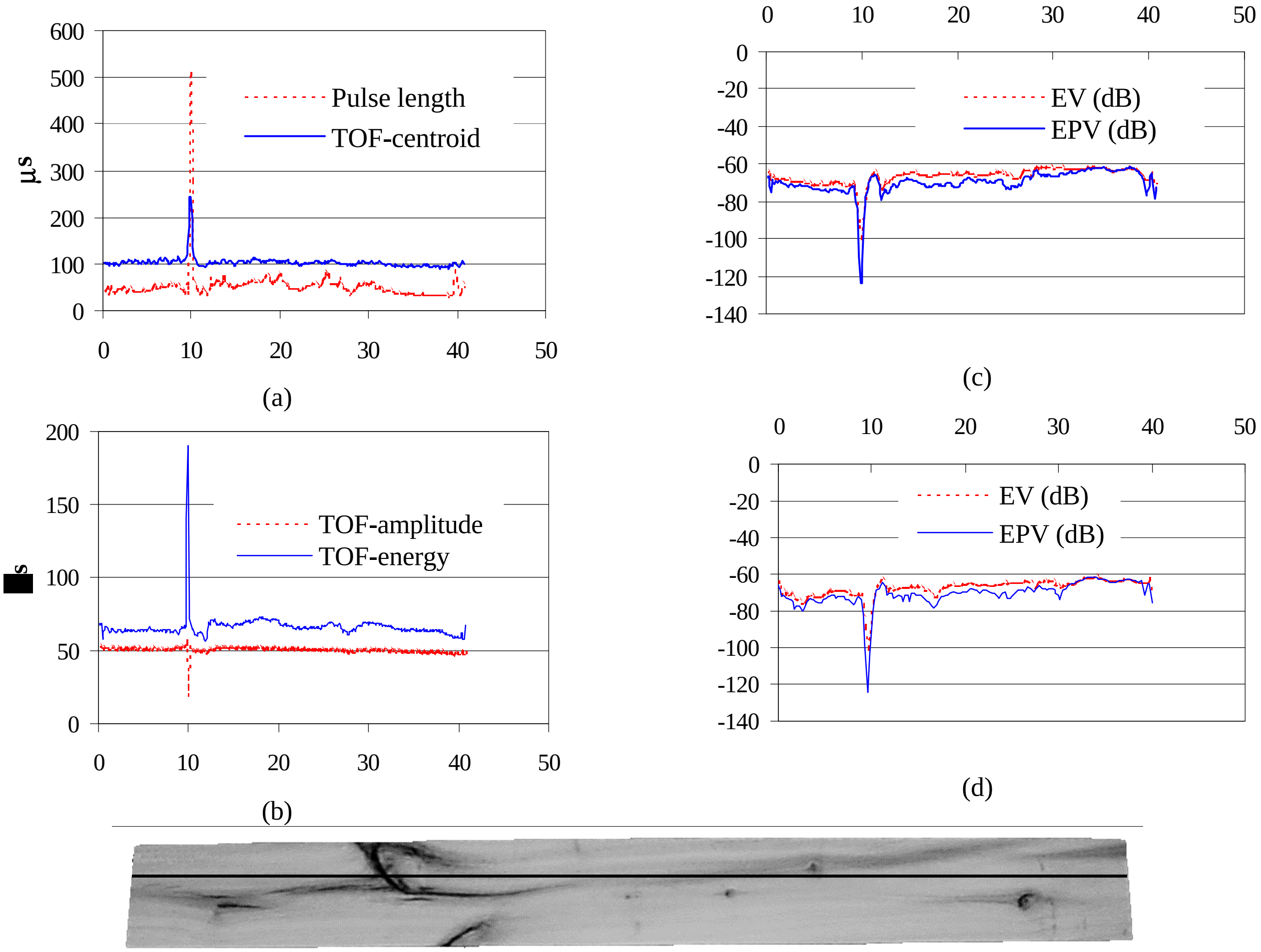
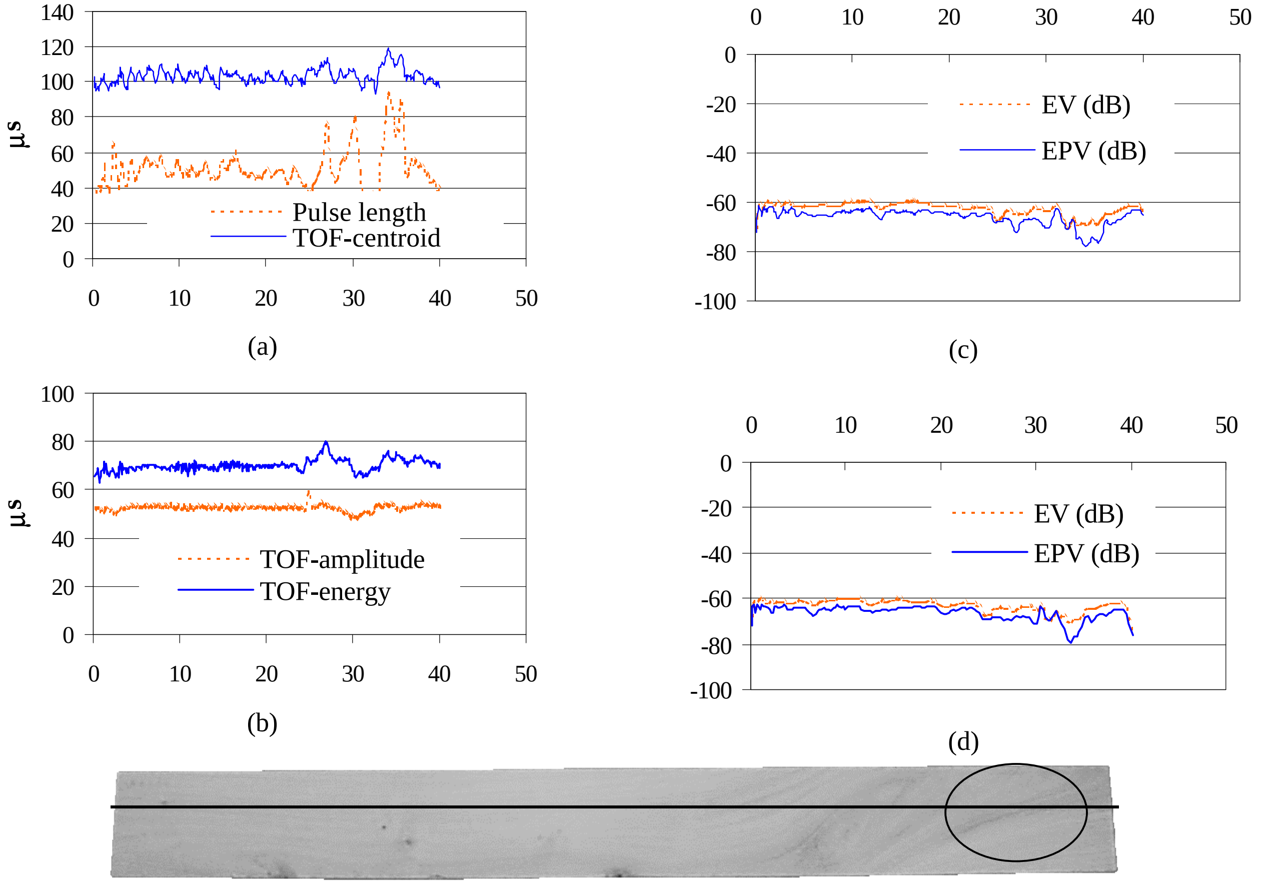


Figure 3. Ultrasonic measurements taken at 10 waveforms/inch along the length of a scan line (x-axis) are shown for all six parameters (a, b, c). A bark pocket is present at approximately the 10-inch location. For comparison, the last graph (d) shows measurements made at 4 waveforms/inch for EV and EPV.

CONCLUSIONS

There appear to be significant, defect-specific differences in several ultrasonic parameters for yellow-poplar deckboards. Most of the ultrasonic parameters examined here change rapidly in the region of defects, which can be used for on-line inspection of defects. Because species and individual pallet parts will vary in the magnitude of various ultrasonic parameters, *relative* changes may prove to be the most informative and diagnostic characteristic of ultrasonic signal propagation. Energy value and energy/pulse value were found to be the most sensitive ultrasonic parameters for the defects examined in this study. Bark pockets and unsound knots are more easily detected compared to sound knots and cross grain. Small values for coefficients of variation indicate that repeatability and reliability are acceptable. Scanning rate has little effect on data collection, which means that it should be possible to scan at relatively high industrial speeds.

Continued work in this project will expand data collection further. Other wood species will be tested to determine if significant inter-specific differences exist with respect to the ability of ultrasonic parameters to distinguish defect types. We also plan to examine still other ultrasonic parameters, e.g., in the frequency domain, that have been shown to discriminate between certain defect types. Eventually, multiple scan lines will be collected for each board to enable us to create ultrasonic 2-D maps (images). Such maps will actually be 3-D (multi-dimensional), as the 2-D maps will have values at each scan point for a variety of useful ultrasonic parameters. The contribution of several parameters should produce fairly accurate defect characterization at each scan point on the pallet part.



(a)

(b)

(c)

(d)

Figure 4. Ultrasonic measurements taken at 10 waveforms/inch along the length of a scan line (x-axis) are shown for all six parameters (a, b, c). A region of cross grain is delineated by the tilted oval. For comparison, the last graph (d) shows measurements made at 4 waveforms/inch for EV and EPV.

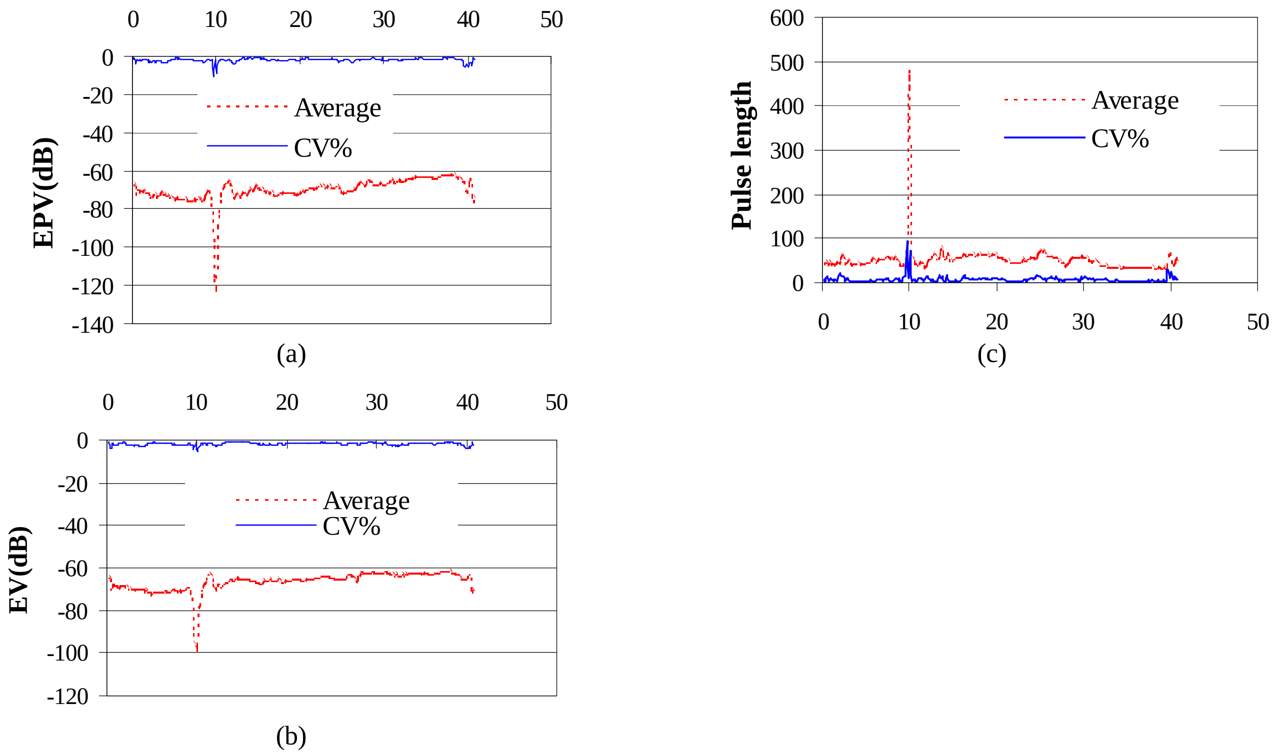


Figure 5. Average values and coefficients of variation (%) are shown for 10 repeated measurements of three ultrasonic parameters taken at 10 waveforms/inch along the length of a scan line (x-axis). The board and scan line appearing in Fig. 3 are the source of the data.

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