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Experimental investigation of stress wave propagation in standing trees

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Abstract

The objective of this study was to investigate how a stress wave travels in a standing tree as it is introduced into the tree trunk through a mechanical impact. A series of stress wave time-of-flight (TOF) data were obtained from three freshly-cut red pine *(Pinus resinosa* Ait.) logs by means of a two-probe stress wave timer. Two-dimensional (2D) and three-dimensional (3D) stress wave contour maps were constructed based on the experimental data using a commercial software. These stress wave contour maps represent the wave fronts in a time sequence, illustrating the flow of stress wave energy within a log. The analysis of TOF data and wave fronts indicates that stress wave propagation in standing trees is affected by tree diameter, travel distance, and internal wood conditions (wood properties and structural defects). When a stress wave is introduced into a tree trunk from a point source, it initially propagates in the impact direction as a 3D wave. Then the flow of the stress wave energy gradually changes towards the longitudinal directions. As the diameter-to-distance ration reaches 0.1 or below, the wave begins to travel as a quasi 1D wave.

Keywords: logs; standing trees; stress wave contour map; stress wave propagation; time-of-flight; wave front.

Introduction

Non-destructuve assessment of raw wood materials is of high practical relevance to forestry and wood processing industry. A significant effort has been devoted toward developing robust non-destructive evaluation technologies capable of predicting wood properties in standing trees before harvesting and detecting internal defects before logs are processed. Recent research included evaluation of wood and fiber properties in standing trees based on stress wave propagation measurements (Wang et al. 2007a,b). Moreover, internal log features were evaluated by means of computed tomography (Wei et al. 2009), resin defects in slash pine logs were detected by means of microwave radar (Hislop et al. 2009), and green density and moisture condition in plantation-grown radiata pine were estimated by increment core measurements (Chan et al. 2010).

Stress wave technologies have been well-established as material evaluation tools in the past several decades, and their use has become widely accepted in the forest products industry for on-Iine quality control and products grading (Jung 1979; Gerhards 1982; Ross and Pellerin 1988; Pellerin and Ross 2002; Wang et al. 2004). Recent research developments on stress wave sensing technology offer further opportunities for forest managers and wood manufacturers to evaluate raw wood materials (standing trees, stems, and logs) for general wood quality and intrinsic wood properties (Wang et al. 2007b). The applicability of the wave propagation method concerning the estimation of wood stiffness in standing trees has been validated by many research works (Nanami et al. 1993; Wang 1999; Huang 2000; Addis et al. 2000; Wang et al. 2001, 2001a; Lindstrom et al. 2002). A typical approach for measuring wave propagation velocity in standing trees involves inserting two sensor probes (transmit probe and receiver probe) into the sapwood and introducing stress wave energy into the tree trunk from a point source through a hammer impact. Wave propagation velocity in a standing tree is determined by measuring time-of-flight (TOF) for a single pulse wave to pass through the tree trunk from the transmit probe to the receive probe.

Comparing with nondestructive evaluation of structural lumber and sawn logs, there are still technical challenges in evaluating wood quality of standing trees with the wave propagation method. One of the key issues is to fully understand the stress wave behavior in standing trees so that measured stress wave parameters can be correctly interpreted and wood properties of the trees can be predicted with a high accuracy. The objective of this study was to investigate how a stress wave propagates in a standing tree as it is introduced into the tree trunk through a mechanical impact. Specifically, an adapted experimental approach was used to obtain stress wave data needed for simulating stress wave propagation in standing trees. This paper focuses on physical determination of wave fronts in longitudinal-radial plane, cross-section plane, and three dimensionsin a tree trunk, wave propagation path with respect to tree stem length, and influence of knots on wave propagation.

Material and methods

Log specimens

Laboratory experiments were deigned to obtain stress wave TOF data needed for simulating stress wave propagation on standing

Table 1 Dimensions of the freshly-cut red pine log specimens.

Log specimen	Length (m)	Large end Ø (mm)	Small end Ø (mm)	Average Ø (mm)
Log no. 1	3.0	355	330	343
Log no. 2	3.0	305	240	273
Log no. 3	3.0	240	178	209

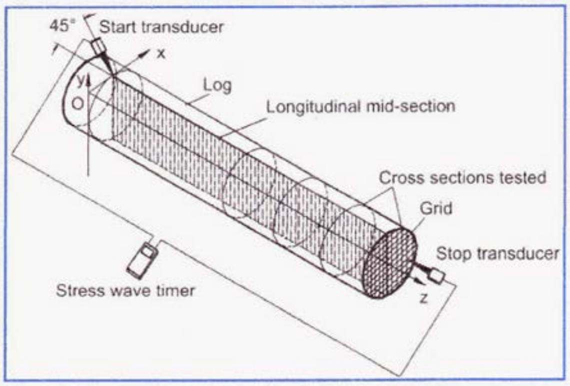

Figure 1 Schematic of TOF stress wave measurement on a log specimen.

trees. For simplicity, the measurements were conducted on log specimens in laboratory instead of trees in forest. Three 3 m long green logs were cut from *two* 45-year-old red pine (*Pinus resinosa* Ait.) plantation trees at an experimental forest stand in Arena, Wisconsin, USA. The freshly cut logs (dimensions shown in Table 1) were immediately transported to the laboratory and kept in an environmental room [23°C, 65% relative humidity (RH)]. The measurements were conducted in the same room within two days. All three logs were straight and had a regular (round) diameter. The position and size of the knots visible on the surfaces were recorded.

Time-of-flight stress wave measurements

The scheme of TOF stress wave measurement is shown in Figure 1. The laboratory testing setup consisted of a battery-operated stress wave timer (FAKOPP Microsecond Timer, Fakopp Interprise, Hungary), two spike-type transducers with long cables, and a pendulum device. The start transducer was mounted by inserting the spike 1 cm deep close to the small end of the log – with an angle of 45" with respect to the surface – and the stop transducer at the large end gain, also about 1 cm deep. A constant impact on the start transducer was generated by a special pendulum device mounted onto the upside surface of the log. The stop transducer received stress wave signals, and the TOF of the stress wave was displayed on an LCD screen of the stress wave timer. The testing setup was calibrated with a standard bar provided by the manufacturer. A series of stress wave measurements were conducted by moving the stop transducer to different locations at the end cross-section to map the wave fronts traveling through a log. Figure 1 shows the 25 mm X 25 mm grids for guiding the stop transducer in the course of the measurements.

Once the TOF stress wave measurements were completed at one end cross-section, a 300-mm long section was cut off from the large end, and the same procedure was repeated on the new cross-section. By this way, TOF data were obtained on consecutive cross-sections: nine in the case of log no. 1, four for log no. 2, and three for log no. 3. Logs no. 2 and no. 3 had many hots on the surface through the length and some were quite large. To avoid inserting the sensors directly into the knotty areas, a portion of the log was selected as a testing subject and less cross-sections were tested (Table 2).

Results and discussion

Stress wave contour maps in longitudinal-radial plane

For each log cross-section tested, a series of stress wave TOF data were obtained indicating the stress wave propagation time from the impact point to a specific point on the end cross-section. Figure 2 shows an example of TOF data matrix from log no. 1, illustrating the stress wave propagation time distribution on the cross-section no. 1–4.

A 2D stress wave contour map was developed for each log specimen by means of the 3D FieldPro software (Vladimir Galouchko, Moscow, Russia) (Figure 3) based on the data obtained on the vertical centerline of each cross-section. This 2D contour map is a cluster of TOF lines where the travel time is same at any point of the line (iso-travel times); they represent therefore the wave fronts in a time sequence on the longitudinal-radial plane (shaded area as shown in Figure 1). It essentially demonstrates the flow of stress wave energy in two dimensions after it was initiated from the start transducer by a mechanical impact.

It can be observed from Figure 3 that the contour maps of all three logs have similar patterns: the stress wave initially traveled within the logs in the impact direction, which had an approximately 45" angle with the longitudinal axis of the log; then the travel direction gradually changed towards the longitudinal directions as the wave moved away from the initiating source and propagated through the logs. This is evidenced by the changing shape of the wave fronts.

Table 2 Red pine log specimens and the cross-sections tested.

Log specimen	Distance of the cross-sections from the impact position (mm) and number of cross-sections (no.) tested								
	300 no.	600 no.	900 no.	1200 no.	1500 no.	1800 no.	2100 no.	2400 no.	2700 no.
Log no. 1	1–1	1–2	1–3	1-4	1–5	1–6	1–7	1–8	1–9
Log no. 2		2–2		2-4		2-6		2–8	
Log no. 3		3–2		3-4		3–6			

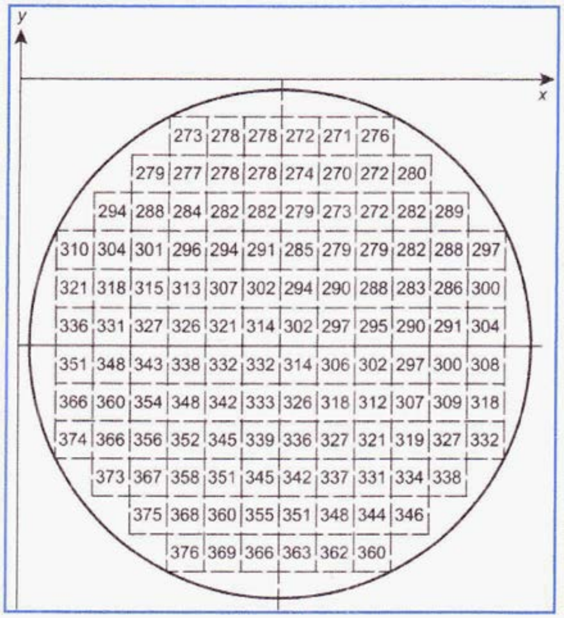

Figure 2 Stress wave TOF data obtained on red pine log cross-section no. 1-4 (unit: μs).

Wave front in relation to log diameter and travel distance

The shape of the wave front is apparently related to the log diameter (0) and travel distance (L). Wave front is more uniform (smooth lines) in small diameter logs (log no. 2 and no. 3) than in large diameter log (log no. 1). The wave front

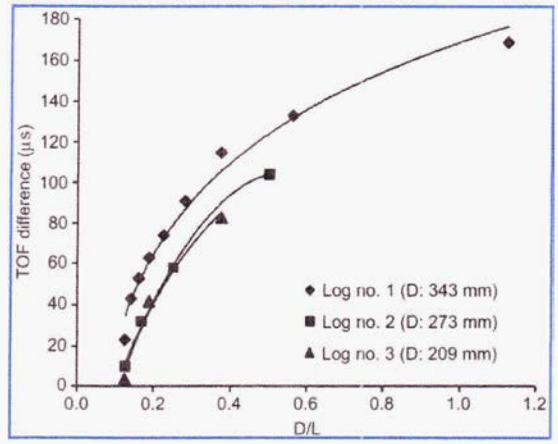

Figure 4 TOF difference in relation to diameter to distance ratio (DL).

in the longitudinal-radial plane approached to a vertical line more quickly in a smal1 diameter log than in a large diameter log.

The characteristics of wave fronts in a log can be measured by the TOF difference $[TOF_{max}$-$TOF_{min})$ in a log cross-section. A TOF difference of "0" means a wave front having a vertical line. The larger TOF difference corresponds to a wave front with bigger slope. The maximum TOF point was always located on the downside of the cross-section due to the longer travel distance. Figure 4 shows the relationships between the TOF differernc in a cross-section and the diameter to distance ratio (*D/L*). This figure reveals that log diam-

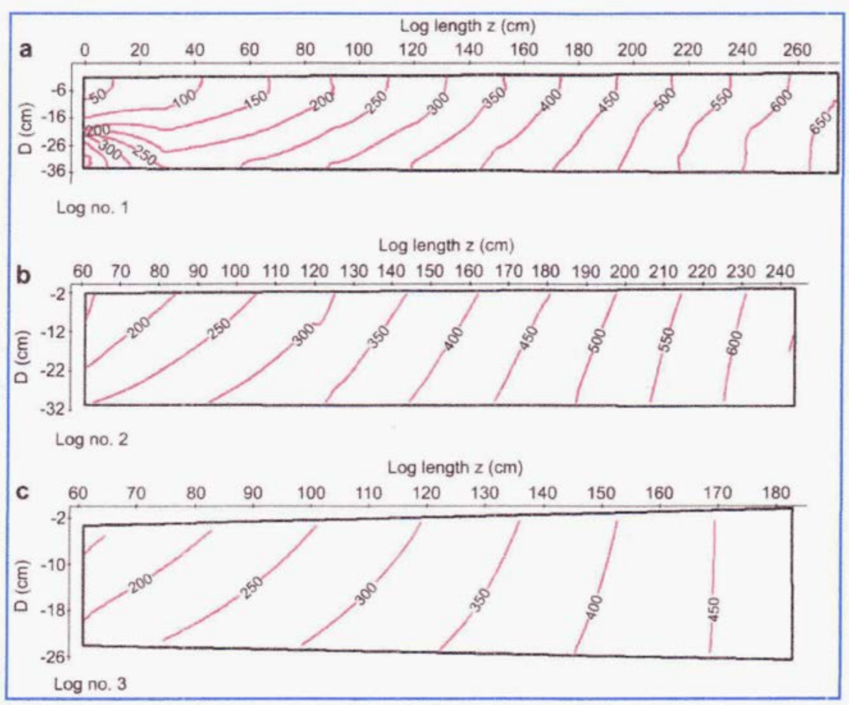

Figure 3 Stress wave contour maps in longitudinal-radial plane of rerl pine logs (Impacting point: z = 0. Contour unit: μs).

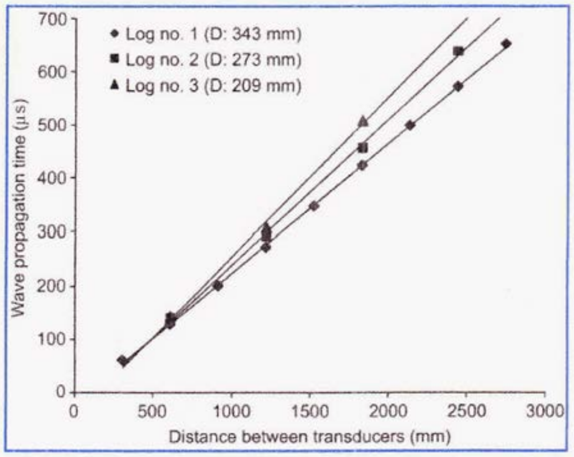

Figure 5 Relationship between wave propagation time and distance between two transducers.

eter and travel distance are two key factors that determine the characteristics of the wave fronts. As *D/L* approached to 0.1, the wave front in logs no. 2 and no. 3 almost approached to a vertical line (note that these two logs were from the same tree). The TOF difference in a cross-section was greater in log no. 1 than that in logs no. 2 and no. 3. This might be due to property differences between the two sampled trees.

Stress wave propagation time measured on the log surface

Another observation from the 2D stress wave contour maps is that the leading point of the wave front is in the upside of a log's cross-section. The TOF of the leading point corresponds to the field TOF stress wave measurement on a standing tree where both start and stop transducers are aligned in a vertical line on the same side of a tree trunk. Therefore, the wave propagation time measured on the upside of the log in this experiment is equivalent to a standing tree measurement. Figure 5 shows the stress wave propagation time measured on the upside of the log in relation to the distance between two transducers, which is essentially the wave propagation distance. The regression analysis indicates an excellent linear relationship between wave propagation time and the distance between the transducers. The coefficients of determination (R^2) of the relationships are 0.999, 0.998, and 0.997 for logs no. 1, no. 2, and log no. 3, respectively. The

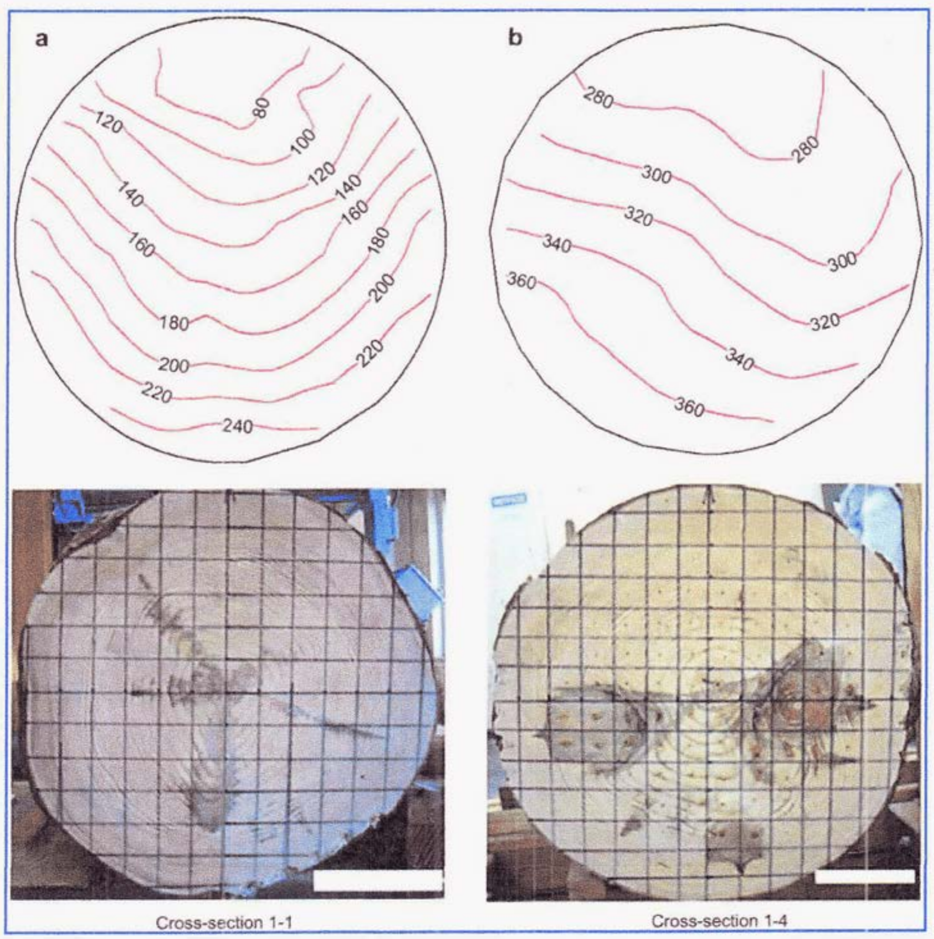

Figure 6 Stress wave contour maps in cross-section plane of red pine log no. 1 (Contour unit: μs).

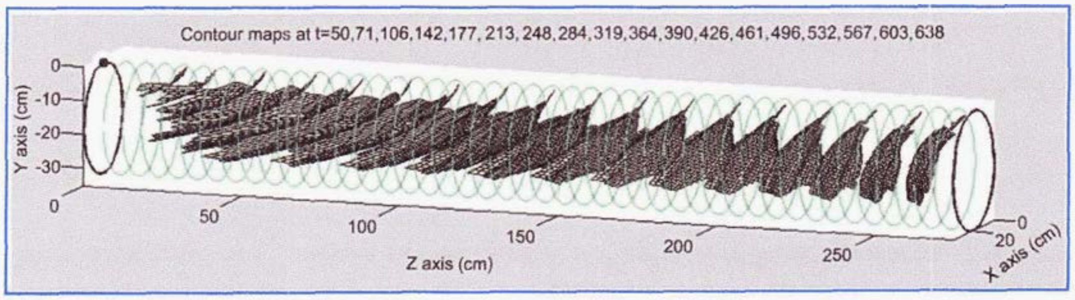

Figure 7 3D stress wave contour map of red pine log no. 1 (The dot on the upper left of the log is the impact point)

different slopes of the regression lines simply represent different wave propagation velocities in three log specimens (4134 m s^{-1} in log no. 1, 3683 m s^{-1} in log no. 2, and 3351 m s^{-1} in log no. 3).

In standing tree TOF measurements, for the convenience of the operation, the distance between two transducers is typically set to 1.2 m (Wang et al. 2007a). This distance can vary between measurements from one tree to another or vary for differrent operators. Our laboratory results indicated that the distance between the transducers (equivalent to the testing span in tree TOF measurements) had no significant effect on TOF stress wave measurements. Small changes of the testing span in tree TOF measurements will not affect the testing results.

Stress wave contour maps in cross-section plane

The stress wave contour maps in Figure 3 only represent wave fronts in the longitudinal-radial plane. To understand how stress waves propagate in a cross-section plane, similar stress wave contour maps were constructed at two log cross-sections (cross-sections no. 1-1 and no. 1-4 in log no. 1) (Figure 6). The time interval between two neighboring contour curves is 20 µs. The wave fronts in the cross-section are affected by the internal wood condition and wood properties. In the log sections tested, sound knots and grain distortion associated with the knots were the main structural defects that affected the shape of the wave fronts in the cross-sections. Stress wave propagated fastest in radial direction as in the case of cross-section no 1-1. The wave fronts were distorted by the prescence of two big knots in cross-section no. 1-4. It should be noted that these contour curves reflect the third dimension of the same wave fronts as shown in Figure 3.

3D stress wave countour maps

To visualise the flow of stress wave energy in three dimensions as a stress wave propagates through a log, a 3D stress wave contour map was developed for log no. 1 by means of the MATLAB software (Figure 7). From this 3D contour map, some unique features of stress wave propagation in logs were observed. During the early period of wave propagation, the wave traveled in the impact direction and the shape of the wave front was a curved surface with protuberance in the middle section. These are the indications that stress waves were traveling in the log as a three-dimensional wave (dilatational wave). As the wave propagated further away from the impact point and moved forward, both shape and direction of the wave fronts gradually changed, with a tendency to flat-out and turn to a position that is close to the longitudinal diection. In the later period of propagation, the wave fronts turned to an orientation similar to the cross-sections and almost perpendicular to the logitudinal direction of the log section, indicating that stress wave propagation was close to one-dimensional situation.

Conclusions

The analysis of stress wave TOF data and wave fronts indicates that stress wave propagation in standing trees is affected by tree diameter, travel distance, and internal wood conditions (wood properties and structural defects). When a stress wave is introduced into a tree trunk from a point source through a mechanical impace, it initially propagates in the impact direction as a three-dimensional (dilatational) wave. Then the flow of the stress wave energy gradually changes towards the longitudinal directions. As the diameter-to-distance ratio reaches 0.1 or below, the wave begins to propagate as a quasi one-dimensional wave.

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