Stress Wave Propagation on Standing Trees–Part 1. Time-of-Flight Measurement and 2D Stress Wave Contour Maps

Houjiang Zhang, Xiping Wang and Robert J. Ross

Abstract

The objective of this paper is to investigate how a stress wave travel in a standing tree as it is introduced into the tree trunk through a mechanical impact. A series of stress wave time-of-flight data were obtained on three freshly cut red pine logs using a two-probe stress wave timer (Fakopp Microsecond Timer). Two dimensional (2D) stress wave contour maps in both cross-section plane and longitudinal-radial plane of the logs were constructed using a 3DFieldPro software. These 2D stress wave contour maps represent the wave fronts in a time sequence, which show stress waves propagating through a tree stem in radial and longitudinal directions. The experimental results indicate that stress wave propagation on standing trees are affected by tree diameter and localized defects such as knots.

Introduction

Stress wave technology is a well-established technique in wood industry for nondestructively evaluating the mechanical properties of various wood and wood composite materials (Jung 1979; Gerhards 1982; Ross et al. 1992; Pellerin and Ross 2002; Wang et al. 2004). In the past, the industrial use of this technology has been on sorting and grading structural lumber and sawn timber, and assessing the condition of wood structural members in service (Pellerin and Ross 2002). Recent research development showed a very good potential for stress wave technique to be used to assess wood quality of standing trees (Wang et al. 2000, 2004, 2007). Some field studies have been completed on trees of different species and yielded good relationships between stress wave speed and wood mechanical properties. Comparing with nondestructive evaluation of structural lumber and sawn logs, there are still big challenges ahead in evaluating wood quality of standing trees with the stress wave method. Instrumentation for stress wave measurement on trees is involving and improvements are expected in the near future. Interpretation of stress wave properties of standing trees is another aspect that is related to stress wave behavior of standing trees. So far, the wave propagation mechanism for standing trees is not fully understood (Wang et al. 2000, 2004). The objective of this study was to investigate how stress waves travel in a standing tree as a stress wave is introduced into the tree trunk through a mechanical impact. Specifically, we used an experimental approach to obtain stress wave data needed for simulating stress wave propagation on standing trees This paper focuses on physical determination of wave fronts, wave propagation path with respect to tree stem length, and influence of knots on wave propagation.

Materials and Method

Log Specimens

Laboratory experiments were designed to obtain stress wave time-of-flight (TOF) data needed

Zhang:
Associate Professor, School of Technology, Beijing Forestry University, Beijing, China
Wang:
Research Forest Products Technologist, USDA Forest Products Laboratory, Madison, Wisconsin, USA
Ross:
Project Leader, USDA Forest Products Laboratory, Madison, Wisconsin, USA

for simulating stress wave propagation on standing trees. To facilate experiments, stress wave measurements were conducted on log specimens at the laboratory instead of trees. Three 3-m long green logs were cut from red pine (Pinus resinosa Ait.) plantations trees at an experimental forest stand in Arena, Wisconsin, USA. The freshly cut log specimens were immediately brought back to the laboratory and put into an environmental room (23°C, 65% RH). Stress wave measurements were conducted on the logs in the environmental room within 2 days. **Table 1** shows dimension parameters of the log specimens. All three log specimens were straight and in a perfect round form. The position and size of the knots visible on the log surfaces were recorded.

Table 1. - *Physical parameters of the red pine log specimens.*

Log specimen	Length (cm)	Large end diameter (cm)	Small end diameter (cm)	Average diameter (cm)
Log No. 1	305	35.5	33.0	34.3
Log No.2	305	30.5	24.0	27.3
Log No.3	305	24.0	17.8	20.9

Table 2. - *Log sections and cross sections tested*

Log Specimen	Distance of the cross section from the impact position (cm)									
	0	30.5	61	91.5	122	152.5	183	213.5	244	274.5
	Cross section no.									
Log No. 1	1-0	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			

Time-of-Flight Measurements

Stress wave measurements were conducted on three log specimens using a stress wave timer (FAKOPP Microsecond Timer, Fakopp Interprise, Hungary). **Figure 1** shows the experimental setup for the time-of-flight stress wave measurement in a log specimen. The testing equipment consisted of a battery operated meter and two spike-type transducers with long cables. Spikes were mounted on the logs by penetrating the bark and reaching the sapwood of the logs. A special pendulum device was built and mounted onto the log specimens and used to generate constant impacts on the start transducer throughout the measurement process. The stop transducer picked up stress wave signal, and the stress wave transmission time was displayed on an LCD screen of the timer.

In order to physically map the wave fronts as a wave travels through a log, we conducted stress wave measurement at a series of locations and paths for each log specimen. **Figure 2** illustrates the measurement locations and stress wave paths on a log specimen. The start transducer was fixed at one location throughout the test and inserted into the log at a 45° angle with respect to the log surface. The location of the impact point (start transducer position) was as follows: 2.7 m from the large end for Log No. 1; 2.4 m from the large end for Log No. 2; 1.8 m from the large end for Log No. 3. The stop transducer was directly inserted into the end grain in the large end cross section as shown in **Figure 1** and **Figure 2.** Time-of-flight was measured as the stop transducer moved to a series locations at the end cross section. **Figure 3** shows the schematic of 2.5 cm × 2.5 cm grids on the end cross section for mounting the stop transducer and making a series of stress wave measurements.

Once the stress wave measurements were completed at one end cross section, a 30-cm-long section was cut off from the large end and the same procedure was used to conduct stress wave measurements on the new end cross section. Stress wave data were obtained on 10 sections for Log No. 1, 4 sections for Log No. 2, and 3 sections for Log No. 3. The log sections and positions of the cross sections tested are summarized in **Table 2.**

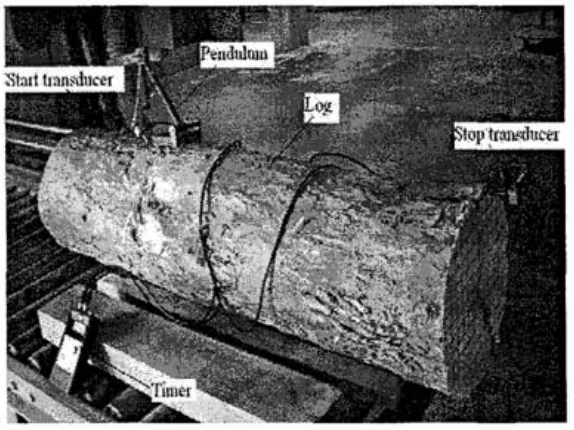


Figure 1 . — *Experimental setup for time-of-flight measurement on a log specimen.*

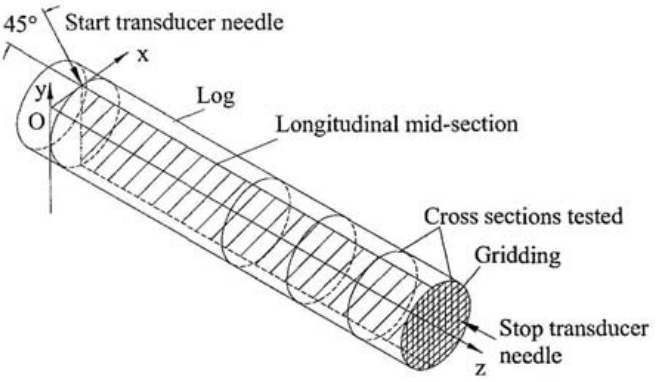


Figure 2. — *Schematic of measurement locations and transducer arrangement.*

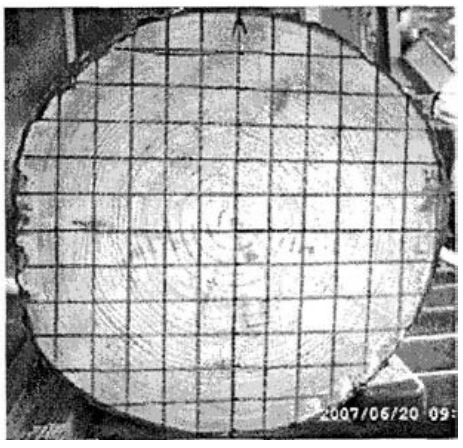


Figure 3. — *2.5 cm × 2.5 cm grid on the end cross section of a log.*

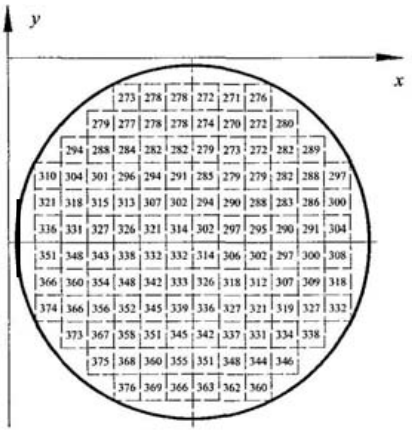


Figure 4. — *Stress wave TOF data measured on the log cross section no. 1-4 (unit: μs)*

Results and Discussion

Stress Wave Contour Maps in Longitudinal-Radial Plane

For each log cross section tested, we obtained a series of stress wave TOF data which indicated stress wave propagation time for an impact stress wave to travel from the impact point (start transducer position) to a specific point on the cross section. **Figure 4** shows a typical stress wave propagation time distribution on a cross section.

With the stress wave propagation time obtained on the Y-axis of each cross section, we developed a 2D stress wave contour map for each log specimen using a 3DFieldPro software (Vladimir Galouchko, Russia) **(Fig.5).** This contour map represents the wave fronts in a time sequence on the longitudinal-radial plane (longitudinal mid-section of a log), which is the vertical mid-section of the logs (shaded area in **Fig.2**). It was observed that the contour maps of all three logs have similar patterns: the stress wave initially traveled within the logs at the impact direction, which had an approximately 45° angle with the longitudinal axis of the log; the travel direction gradually changed towards the longitudinal directions as the waves propagated through the logs, which is evidenced by the changing shape of the wave fronts. The shape of wave fronts was apparently related to the log diameter and travel distance. Wave fronts were more uniform (smooth lines) in small diameter log specimens (Log No. 2 and No. 3) than large diameter log specimen (Log No. 1). The wave front approached to a vertical line more quickly in a small diameter log than in a large diameter log.

The characteristics of wave fronts in a log can also be measured by the stress wave time difference (T_{max} - T_{min}) at a log cross section. A time difference of "0" represents the wave front in a vertical line. Figure 6 shows the relationships between the stress wave time difference at a cross section and travel distance. This figure indicated that log diameter and travel distance are two key factors that determine the characteristics of the wave fronts. The smaller the log diameter, the smaller the stress wave time difference. The wave front approached to vertical line in a much shorter travel distance in a small diameter log than that in a large diameter log.

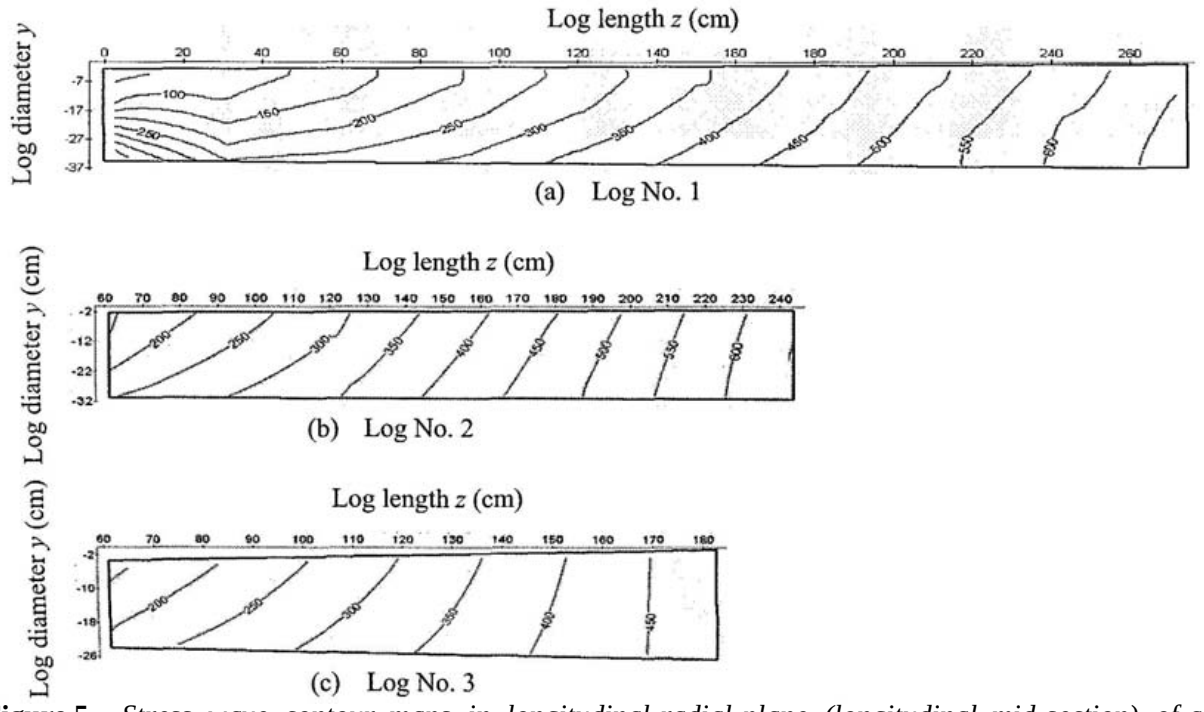


Figure 5. *Stress wave contour maps in longitudinal-radial plane (longitudinal mid-section) of a log. (Impacting point: z = 0. Unit ofthe time on the contours: µs)*

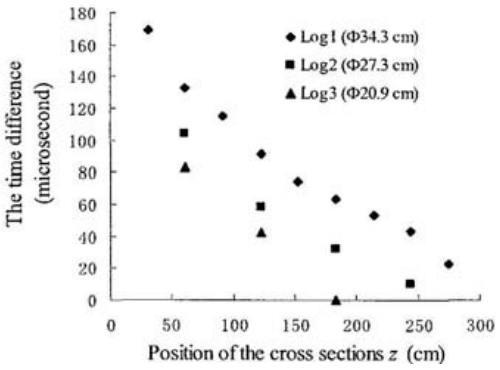


Figure 6. *–Relationship between the time differences in a cross section and travel distance.*

Stress Wave Propagation Time Measured on the Log Surface

Another important observation from the stress wave contour maps is that the leading point of the wave front is in the upper side surface of the log. This corresponds to the field stress wave testing on a standing tree where both start and stop transducers are aligned in a vertical line on one side of the tree trunk. The wave propagation time measured on the upper side of the log in this experiment is equivalent to a standing tree measurement. Figure 7 shows the stress wave propagation time measured on the upper side of the log in relation to the distance between two transducers (test span) on Log No. 1. The regression analysis indicated an excellent linear relationship (R^2 = 0.998). For Log No.2 and Log No.3, similar relationships existed between the stress wave propagation time and the test span (R^2 = 0.996 and 0.993 respectively).

In field tree measurements, for the convenience of the operation, the distance between the two transducers is usually set to 122 cm (4 feet) (Wang et al. 2000). Our laboratory results indicated that the test span had no significant effect on stress wave measurement. From practical stand point, small changes on a testing span will not affect the testing results.

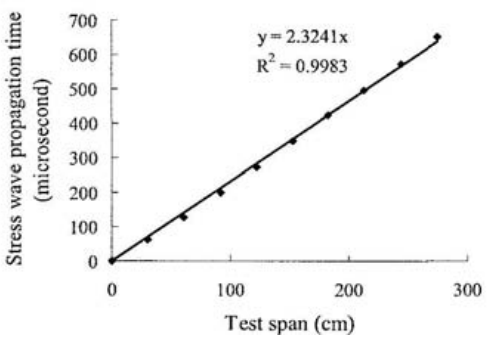
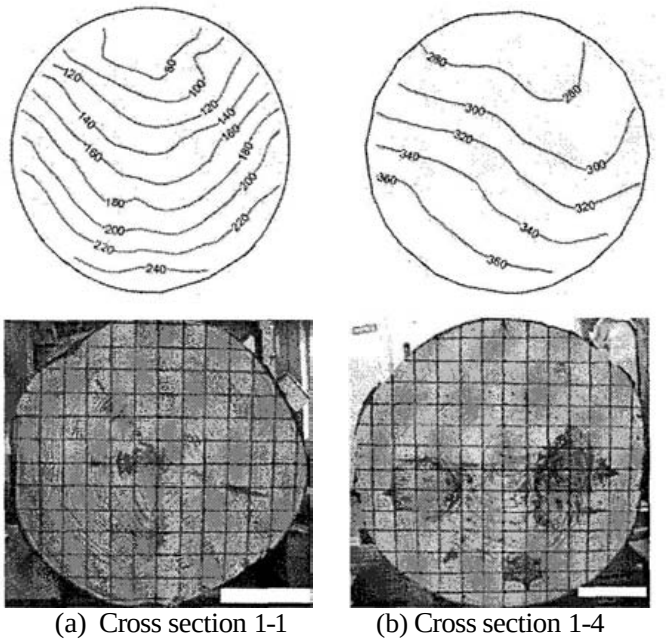


Figure 7. *–Relationship between stress wave propagation time and test span (Log No. I)*

Stress Wave Contour Maps in Cross Section Plane

The stress wave contour maps in **Figure** 5 only represent wave fronts in the longitudinal-radial plane. To understand how stress waves propagate in the cross-sectional plane, we constructed similar stress wave contour maps at two log sections (Log No. 1, section 1-1 and section 1-4) **(Fig. 8).** 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 we 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 section. Stress waves propagated fastest in radial direction as in the case of section 1-1. The wave fronts were distorted by the existence of two big knots in section 1-4. It should be noted that these contour curves reflect the third dimension of the same wave fronts as shown in **Figure 5.**



(a) Cross section 1-1 (b) Cross section 1-4

Figure 8. *Stress wave contour maps in cross section plane (Log No. 1)*

Conclusions

This paper investigated how a stress wave travel in a tree stem as it is introduced into the tree through a mechanical impact. A series of time-of-flight data were obtained on three freshly cut red pine logs using a two-probe stress wave timer. Two dimensional (2D) stress wave contour maps in both longitudinal-radial plane and cross-section plane of red pine logs were constructed to represent the wave fronts in a time sequence. The experimental results indicate that stress wave propagation in standing trees are affected by tree diameter, test span, and internal wood conditions (wood properties, structural defects). Stress waves travel in the impact direction initially, and then gradually change towards the longitudinal directions as the waves propagate through the tree trunk. The wave front approaches to a vertical line (in vertical mid-section plane) more quickly in a small diameter log than in a large diameter log.

References

Gerhards, C.C. 1982. Effect of knots on stress waves in lumber. USDA Forest Products Laboratory, FPL-384.

Jung Joseph. 1979. Stress-wave grading techniques on veneer sheets. USDA Forest Products Laboratory, FPL-27.

Pellerin, R.F. and R.J. Ross. 2002. Nondestructive Evaluation of Wood. Forest Products Society, Madison, Wisconsin, USA.

Ross, R.J., J.C. Ward, A. Tenwolde. 1992. Identifying bacterially infected oak by stress wave nondestructive evaluation. USDA Forest Products Laboratory, FPL-RP-512.

Wang, X., R.J. Ross, M. McClellan, etc. 2000. Strength and stiffness assessment of standing trees using a nondestructive stress wave technique. USDA Forest Products Laboratory, FPL-RP-585.

Wang, X. F. Divos, C. Pilon, etc. 2004. Assessment of decay in standing timber using stress wave timing nondestructive evaluation tools. USDA Forest Products Laboratory, FPL-GTR-147.

Wang X., R.J. Ross, B.K. Brashaw, etc. 2004. Diameter effect on stress-wave evaluation of modulus of elasticity of logs. Wood and Fiber Science 36(3): 368-377.

Wang, X., P. Carter, R.J. Ross, B.K. Brashaw. 2007. Acoustic assessment of wood quality of raw forest materials – Apath to increase profitability. Forest Products Journal 57(5): 6-14.

Zhang, Houjiang; Wang, Xiping; Ross, Robert 2009. Stress wave propagation on standing trees--Part 1. Time-of -flight measurement and 2D stress wave contour maps. In: Proceedings of the 16th nondestructive evaluation of wood symposium. 2009 October 12-14. Beijing, china: Beijing Forestry University, Beijing, China. Dr. Houjian Zhang and Dr. Xiping Wang, Des. p. 53--58. 2009