

Stress Wave Propagation on Standing Trees -Part 2. Formation of 3D Stress Wave Contour Maps

Juan Su, Houjiang Zhang, and Xiping Wang

Abstract

Nondestructive evaluation (NDE) of wood quality in standing trees is an important procedure in the forest operational value chain worldwide. The goal of this paper is to investigate how a stress wave travel in a tree stem as it is introduced into the tree through a mechanical impact. Experimental stress wave data was obtained on freshly cut red pine logs in the laboratory. Three dimensional (3D) stress wave contour maps were generated using the MATLAB software. The 3D stress wave contour maps represent the wave fronts at a series of locations along the length, which can help to visualize the propagation of stress waves in a tree stem. The experimental simulation of wave fronts in the log specimens shows that stress waves travel as a three dimensional wave initially, then gradually transformed to a quasi one dimensional wave with a non-flat wave front.

Introduction

Stress wave method is a well-established technique for nondestructively evaluating the mechanical properties and characterizing natural defects of various wood products (Pellerin and Ross 2002). In the past, research and industrial application of this method have been focused on structural lumber, sawn timber, and in-situ wood structural members. Recent research development showed a very good potential for stress wave technique to be used to assess wood quality of living trees (Wang et al. 2007b). Some field studies have been completed on trees of different species and yielded good relationships between stress wave speed and wood mechanical properties (Wang 1999, Huang 2000, Wu 2002, Wang et al. 2003, 2007a). Comparing with nondestructive evaluation of structural lumber and sawn logs, there are still big challenges ahead in evaluating wood quality in 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 in trees. So far, the wave propagation mechanism for living trees is not fully understood. The goal of this study was to investigate how stress waves travel in a tree stem as a stress wave is introduced into the tree through a mechanical impact. Experimental stress wave data of red pine trees was obtained in a previous study (Zhang et al. 2009) and 2D stress wave contour maps were generated to visualize the wave propagation in the longitudinal-radial (L-R) plane of a tree stem. This paper was focused on constructing 3D stress wave contour maps with the experimental data using the MATLAB software. A three dimensional presentation of wave fronts in a tree stem would help researchers to better determine the nature of wave propagation in standing trees and see how tree diameter, species, and other factors affect stress wave measurements on trees.

Su:

Graduate student, School of Technology, Beijing Forestry University, Beijing, China

Zhang:

Associate Professor, School of Technology, Beijing Forestry University, Beijing, China

Wang:

Research Forest Products Technologist, USDA Forest Products Laboratory, Madison, Wisconsin, USA

Materials and Methods

Laboratory experiments were designed to obtain stress wave data needed for simulating stress wave propagation in standing trees. To facilitate experiments, stress wave measurements were conducted on log specimens in the laboratory instead of trees. Three 3-m long green logs were cut from red pine plantation 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 on the logs were conducted in the environmental room based on the schematic shown in **Figure 1**. The details of stress wave measurements on log sections are given by Zhang et al (2009).

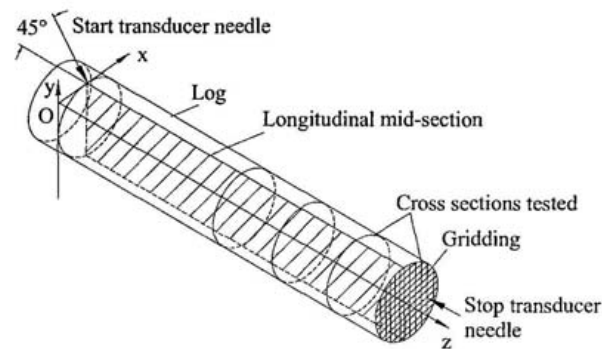


Figure 1. —Schematic of stress wave measurements on a log section.

Data Analysis

Procedure for data processing

MATLAB 7.0 (Math Works Cop., USA) was used to process the stress wave transmission data and develop stress wave contour maps for each log section. MATLAB is based on matrix, providing two program modes, command operation and M file. The main procedure was written by the first mode and the subprogram was written by the second one, for the purpose of easy modification and fast calling.

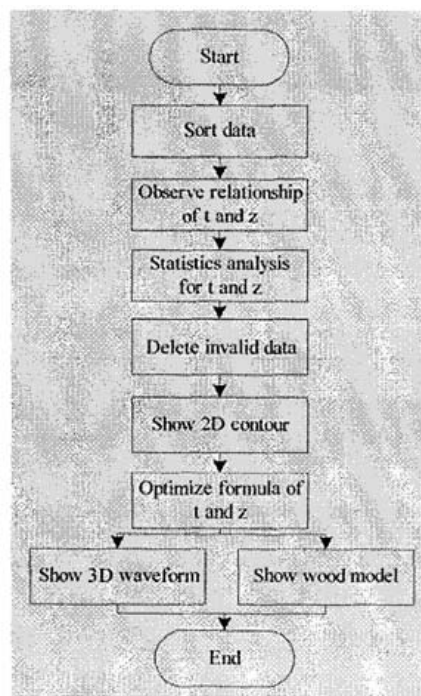


Figure 2. —Flow chart of main procedure

Figure 2 is a flow chart that outlines the data processing procedures. First, sort stress wave data according to equal x and equal y , through which we can get some pairs of data about the relationship of z and t . In each pair, z has a good correlation with t , so that they can be fitted by statistical method to get fitting formula. Secondly, the relevant z of t was calculated through fitting formula. Finally, lots of points coordinates including data of x , y and z in 3D stress wave contours were obtained to build 3D wave fronts for a various cross-sections. Using a MATLAB function “polyfit”, we obtained the fitting formula of t and z and further calculated the z , prior to deleting invalid data and optimizing the fitting formula oft and z .

A 3D waveform can be formed at a given t . Several waveforms can be mapped if a series oft values are given. The figure result as well as wood model can be observed by moving picture and also static single contour. In this way, we can visualize the transformation and propagation path of the stress wave within a tree trunk.

Algorithm for data sorting

The data set for each testing point includes four parameters: x , y , z and t . x , y and z are space coordinates of the point, and t is the transmission time between the start sensor and the stop sensor. For each testing location (x , y), a pair of data set (t , z) was obtained. The number of (t , z) data set was determined by the number of testing points in the largest cross section of a log. For Log No. 1, No. 2 and No. 3, we obtained 151, 110, and 64 pairs of data sets respectively using the MATLAB program.

For further data processing, the pairs of data were arranged in a 2D matrix. The testing data of a single log were arranged in a 3D matrix. The sorting data function was implemented by a sub-procedure, “sortxy.m”. Take Log No.1 as an example, the data before sorting was saved in an excel sheet with 1224 lines and 4 columns, while a 3D matrix with 9 lines, 4 columns and 151 pages after sorting. Data storage formats before and after sorting is shown in **Table 1**.

Table 1. - Comparison of data storage formats before and after sorting (Log No. 1)

a Data storage format before sorting				b Page 1 of data after sorting				c Page 86 of data after sorting			
x	y	z	t	x	y	z	t	x	y	z	t
20.3	-5.0	30.4	61	2.5	-12.7	91.4	260	20.3	-25.4	30.4	174
17.7	-2.5	30.4	62	2.5	-12.7	213.3	538	20.3	-25.4	60.9	216
12.7	-12.7	60.9	172	2.5	-12.7	274.3	691	20.3	-25.4	91.4	268
17.7	-5.0	91.4	201	0	0	0	0	20.3	-25.4	121.9	336
27.9	-30.4	121.9	346	0	0	0	0	20.3	-25.4	152.4	397
10.1	-33.0	182.8	499	0	0	0	0	20.3	-25.4	182.8	457
15.2	-7.6	213.3	504	0	0	0	0	20.3	-25.4	213.3	534
.....				0	0	0	0	20.3	-25.4	243.8	612
2.5	-25.4	274.3	709	0	0	0	0	20.3	-25.4	274.3	673

It should be noted that the sorting program just sorts the testing data according to the fixed x and y , and changes the storage formats to matrix. It doesn’t change any values of the data sets, and all the values are same as that of testing record.

Establishing z - t relationship

The wave propagation time in testing data are discrete, t and z of the same x and y in the testing data are supposed to transform mathematical expression of t and z . Fitting method and

interpolation method are used in this paper, as fitting method can get better result, only former method is introduced here.

Polynomial curve fitting method is one of the common fitting methods, based on least square principle and structured a polynomial with exponent number less than known point number, its theory is as below.

If there are some discrete points (t_i, z_i) , then a polynomial with exponent number m can be structured:

$$z(t) = a_1 t^m + a_2 t^{m-1} + \dots + a_m t + a_{m+1} \quad [1]$$

In this polynomial, the value of $\sum_{i=1}^n (z(t_i) - z_i)^2$ is least, and $a_1, a_2, \dots, a_m, a_{m+1}$ are coefficients of polynomial, and n is the number of points. The vector of polynomial coefficients P is defined as:

$$P = (a_1, a_2, \dots, a_m, a_{m+1}) \quad [2]$$

When using polynomial curve fitting method, the vector of polynomial coefficients P is computed actually. In this paper called MATLAB own function “polyfit” to get that P , the format is following.

$$P = \text{polyfit}(Z, T, m) \quad [3]$$

Therein, Z and T two vectors with the same size, $z(t)$ is polynomial formula of t and z which is finally needed

Constructing 3D contour map

The values of x , y and z with the same propagation time “ t ” are extracted to build 3D contour map for each log. This was completed through MATLAB’s “surf” function. A 3D contour map represents a series of wave fronts where stress wave propagation time is same at every point.

Proper gridding method is used to grid the known points, and further get more points in the same 3D contour. After that, the gridding in the 3D contour is smaller and wave front is smoother. There are two commands in MATLAB that can interpolate the data, namely “interp2” and “griddata”. The former command is used to interpolate regular data, while the later command is used to interpolate irregular data. Calling format is as follows:

$$z_i = \text{griddata}(X, Y, Z, x_i, y_i, \text{'method'}) \quad [4]$$

Where:

(X, Y, Z) are the coordinates of original points, (x_i, y_i, z_i) are the relevant coordinates after interpolation.

There are four methods in MATLAB to interpolate data. Here we used method ‘cubic’ and it can get better waveform comparing with other methods with respect to the data in this paper.

3D stress wave contour maps

The 3D stress wave contour maps developed using MATLAB are shown in **Figure 3**. **Figure 3 (a)** and **Figure 3 (b)** show the wave front in Log No.1 when stress wave propagation time is 142 μs and 603 μs respectively. While **Figure 3 (c)**, **Figure 3 (d)** and **Figure 3 (e)** showed a series of wave fronts in Logs No. 1, No. 2 and No. 3 respectively.

From **Figure 3**, we observed some unique features of stress wave propagation in logs. During initial period of stress wave propagation, the wave front is not perpendicular to log's longitudinal direction, but leading to the impact direction. The shape of the wave front is a curved surface with protuberance in the middle section. These are the indications that stress waves are traveling in the log as a three dimensional wave (dilatational wave). As the wave traveled further away from the impact point and moved forward, both shape and direction of the wave fronts changed, with a tendency to flat-out and turn to a position that is close to the longitudinal direction. In the later period of propagation, the wave fronts turned to an orientation similar to the cross-sections and almost perpendicular to the longitudinal direction of the log section, which indicated that stress wave propagation is close to one-dimensional situation. As the stress wave approached to the end of the log, the wave fronts changed to a concave form, with the wave leading in the outer wood of the log section.

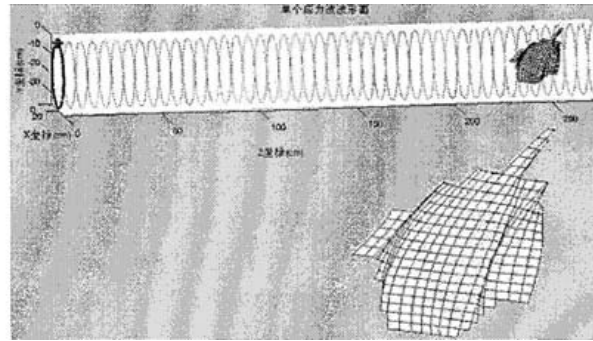
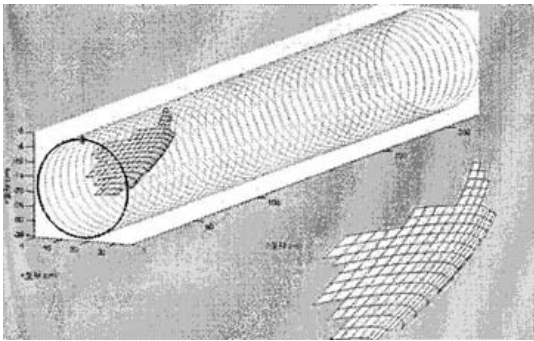


Figure 3. — (a) Wavefront at $t = 142 \mu s$ (Log No. 1) **Figure 3.** — (b) Wave front at $t = 603 \mu s$ (Log No. 1)

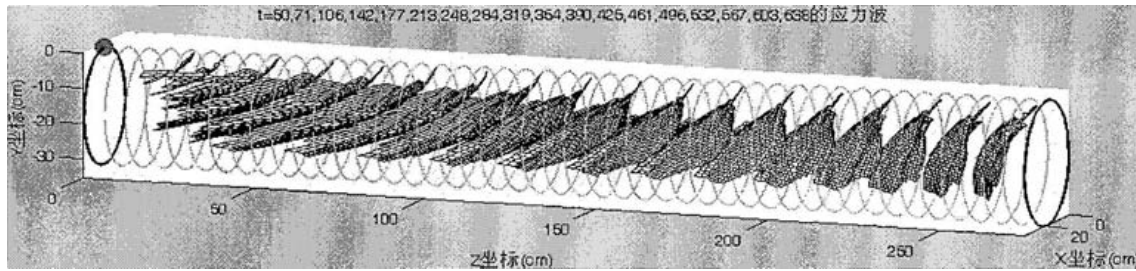


Figure 3. — (c) Wavefronts at $t = 50, 71, 106, 142, 177, 213, 248, 284, 319, 354, 390, 425, 461, 496, 532, 567, 603, 638 \mu s$ (Log No.1)

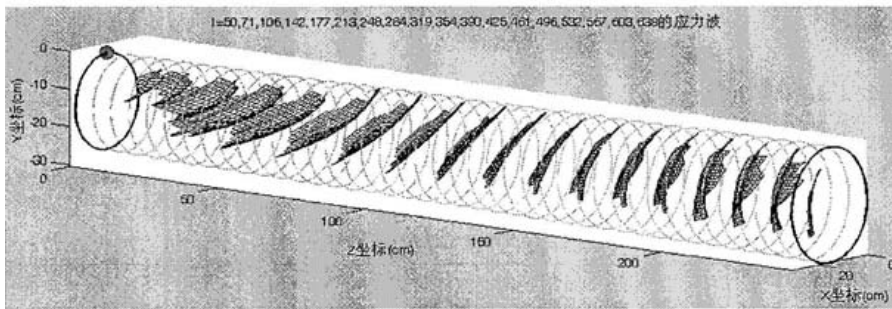


Figure 3. — (d) Wavefronts at $t = 50, 71, 106, 142, 177, 213, 248, 284, 319, 354, 390, 425, 461, 496, 532, 567, 603, 638 \mu s$ (Log No.2)

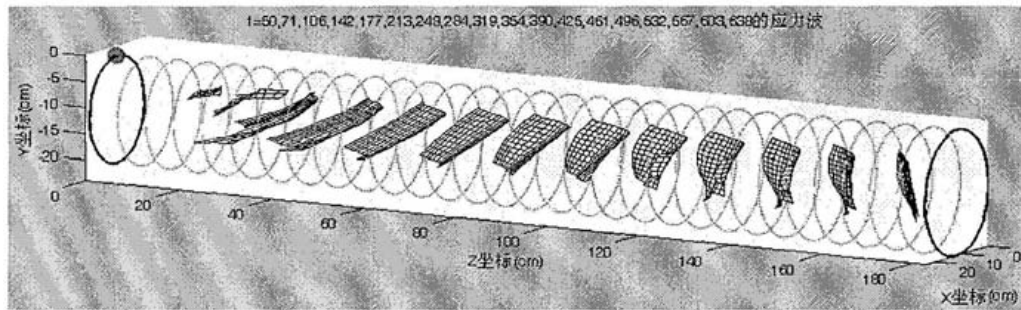


Figure 3. — (e) Wavefronts at $t = 50, 71, 106, 142, 177, 213, 248, 284, 319, 354, 390, 425, 461 \mu s$ (Log No.3)

Figure 3 3D stress wave contour map (wave fronts in a time sequence) of the red pine log sections (The dot on the upper left side of the log is the impact point).

Conclusion

Based on the experimental stress wave data collected from three freshly cut red pine log sections, we constructed 3D stress wave contour maps using the MATLAB program. The 3D contour map simulates a series of wave fronts as a stress wave travel through a tree stem, which help to visualize the process of wave propagation. The results indicated that stress waves in a tree stem, when generated through a mechanical impact, travel as a three dimensional wave (dilatational wave) initially, then gradually transformed to a quasi one dimensional wave with a changing wave front. This research provides some preliminary understandings of the wave propagation mechanism in standing trees.

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