United States
Department of
Agriculture

Forest Service

Forest
Products
Laboratory

General
Technical
Report
FPL–GTR–147

Assessment of Decay in Standing Timber Using Stress Wave Timing Nondestructive Evaluation Tools

A Guide for Use and Interpretation

Xiping Wang
Ferenc Divos
Crystal Pilon
Brian K. Brashaw
Robert J. Ross
Roy F. Pellerin

Abstract

This guide was prepared to assist field foresters in the use of stress wave timing instruments to locate and define areas of decay in standing timber. The first three sections provide background information, the principles of stress wave nondestructive testing, and measurement techniques for stress wave nondestructive testing. The last section is a detailed description of how to apply stress wave nondestructive testing methods to standing timber. A sample field data acquisition form is included.

Keywords: nondestructive evaluation, stress wave, decay, standing timber

Contents

Page

March 2004

Wang, Xiping; Divos, Ferenc; Pilon, Crystal; Brashaw, Brian K.; Ross, Robert J.; Pellerin, Roy F. 2004. Assessment of decay in standing timber using stress wave timing nondestructive evaluation tools—A guide for use and interpretation. Gen. Tech. Rep. FPL-GTR-147. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 12 p.

A limited number of free copies of this publication are available to the public from the Forest Products Laboratory, One Gifford Pinchot Drive, Madison, WI 53726–2398. This publication is also available online at www.fpl.fs.fed.us. Laboratory publications are sent to hundreds of libraries in the United States and elsewhere.

The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

Assessment of Decay in Standing Timber Using Stress Wave Timing Nondestructive Evaluation Tools

A Guide for Use and Interpretation

Xiping Wang, Research Associate
Natural Resources Research Institute, University of Minnesota, Duluth, Minnesota
Forest Products Laboratory, Madison, Wisconsin

Ferenc Divos, Associate Professor
Wood NDT Laboratory, University of Western Hungary, Sopron, Hungary

Crystal Pilon, General Engineer
Forest Products Laboratory, Madison, Wisconsin

Brian K. Brashaw, Program Director
Natural Resources Research Institute, University of Minnesota, Duluth, Minnesota

Robert J. Ross, Project Leader
Forest Products Laboratory, Madison, Wisconsin

Roy F. Pellerin, Emeritus Professor
Department of Civil & Environmental Engineering, Washington State University, Ocean Park, Washington

Introduction

Background

Our forests are an extremely valuable resource. In addition to their aesthetic and recreational value, forests serve as a renewable source of raw material for an ever-increasing list of wood and fiber products. The detection of deterioration in trees, particularly decay that does not have external indicators, is an interest of forest managers. An effective nondestructive evaluation (NDE) method for detecting decay in standing trees would help forest managers identify hazardous trees, prevent the spread of decay, and improve stand conditions.

Various techniques, based on different concepts, have been used to detect deterioration in trees. Sounding a tree by striking it with a tool can detect advanced decay or hollows inside the trunk, but this method is not effective on large thick-barked trees (Boyce 1948, McCracken 1985). X-ray and neutron radiography, computer tomography (CT), and magnetic resonance (MR) have been extensively investigated for imaging internal characteristics in logs and trees (Hailey and Morris 1987, Holoyen and Birkeland 1987, Oja and others 2000). These techniques can provide one- to three-dimensional spatial locations of various defects and internal wood characteristics, but their application to trees has been limited because of the high costs associated with their use.

Stress wave and ultrasonic techniques are simpler and less costly than imaging techniques. Because the propagation of stress waves is basically a mechanical phenomenon, it has been frequently used to detect internal defects in wood. Stress wave transmission time or attenuation in wood has been proven to be an effective parameter to detect and estimate deterioration in wood structural members (Hoyle and Pellerin 1978, Hoyle and others 1987, Pellerin and Ross 2002, Ross and Pellerin 1994, Wang and others 2002). Studies have also shown that the presence of deterioration in tree stems greatly affects stress wave transmission time and therefore can be properly identified using this technique (Lin and others 2000, Mattheck and Bethge 1993, Yamamoto and others 1998).

Purpose

The purpose of this manual is to provide guidelines on the application and use of the stress wave timing inspection method in locating and defining areas of decay in standing timber. A review of the basics of stress wave theory is provided, as well as a description of available equipment, practical procedures for field testing, workable forms for gathering data, and guidelines for interpretation of data. This information was derived from research performed to quantify the ability of stress wave timers to detect decay in wood, from laboratory and field studies of deteriorated wood, and, most importantly, from the experience of field inspection professionals familiar with the use of these devices.

Principles of Stress Wave Nondestructive Testing

Stress wave propagation in wood is a dynamic process that is directly related to the physical and mechanical properties of wood. In general, stress waves travel faster in sound and high quality wood than in deteriorated and low quality wood. By measuring wave transmission time through a tree stem in the radial direction, the internal condition of the tree can be fairly accurately evaluated.

As an introduction, a schematic of the stress wave concept for detecting decay in a tree is shown in Figure 1. A stress wave is induced by striking the tree with an impact device instrumented with an accelerometer that emits a start signal to a timer. A second accelerometer, held in contact with the other side of the tree, senses the leading edge of the propagating stress wave and sends a stop signal to the timer. The elapsed time for the stress wave to propagate between the accelerometers is displayed on the timer. This measured time, when converted to a transmission time on a per length basis (or wave propagation speed), can be used as a predictor of the physical conditions inside the tree stem.

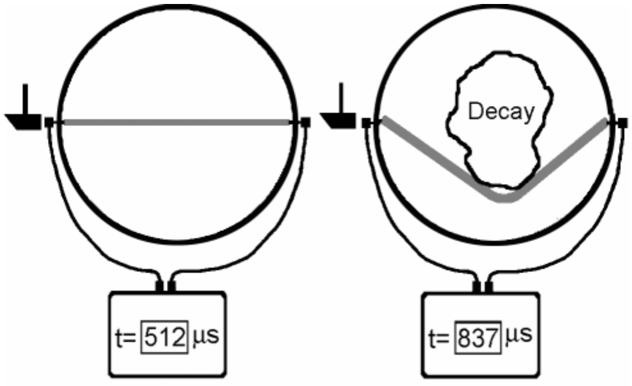


Figure 1—Concept of stress wave timing for detecting decay in a tree.

Because wood is an organic substance, the speed of wave propagation varies with grain direction. Hammering the side of a tree will cause a sound wave across or transverse to the wood cells (perpendicular to grain). The speed of sound across the grain is about one-fifth to one-third of the longitudinal value (Forest Products Laboratory 1999). Table 1

Table 1—Stress wave transmission times for various species of nondegraded wood

Reference	Species	Moisture content (% ovendry)	Stress wave transmission time (µs/m (µs/ft))	
			Parallel to grain	Perpendicular to grain
Armstrong and others 1991	Birch	4–6	213–174 (65–53)	715–676 (218–206)
	Black cherry	4–6	207–184 (63–56)	689–620 (210–189)
	Red oak	4–6	226–177 (69–54)	646–571 (197–174)
	Yellow-poplar	4–6	194–174 (59–53)	715–676 (218–206)
Elvery and Nwokoye 1970	Several	11	203–167 (62–51)	—
Gerhards 1978	Sitka spruce	10	170 (52)	—
	Southern Pine	9	197 (60)	—
Gerhards 1980	Douglas-fir	10	203 (62)	—
Gerhards 1982	Southern Pine	10	197–194 (60–59)	—
Hoyle and Pellerin 1978	Douglas-fir	—	—	1,073 (327)
Jung 1979	Red oak	12	302–226 (92–69)	—
Pellerin and others 1985	Southern Pine	9	200–170 (61–52)	—
Ross 1982	Douglas-fir	11	—	850–597 (259–182)
Rutherford 1987	Douglas-fir	12	—	1,092–623 (333–190)
Smulski 1991	Red oak	11	262–200 (80–61)	—
	Sugar maple	12	256–194 (78–59)	—
	White ash	12	252–197 (77–60)	—
	Yellow birch	11	230–180 (70–55)	—
Soltis and others 1992	Live oak	12	—	613–1,594 (187–486)

summarizes recent research on stress wave transmission times for various species of nondegraded wood. Note that stress wave transmission times are shortest along the grain (parallel to fiber) and longest across the grain (perpendicular to fiber). For Douglas-fir and Southern Pine at dry conditions, stress wave transmission time is approximately 200 µs/m (60 µs/ft) parallel to grain, but ranges from 850 to 1000 µs/m (259 to 305 µs/ft) in the perpendicular direction.

A stress wave can pass through a tree stem transversely in three different paths: perpendicular to the rings (radially), parallel to the rings (tangentially), and crossing the rings at an angle between 0° and 90° (perpendicular). Figure 2 shows the stress wave transmission time in relation to annual ring orientation (Ross and others 1999). The longest transverse-to-grain transmission time is found at a 45° orientation to the annual rings. The shortest is in the radial direction; stress wave speed is about 30% faster than that in the other directions. Tangential transit times are expected to be about halfway between radial and perpendicular.

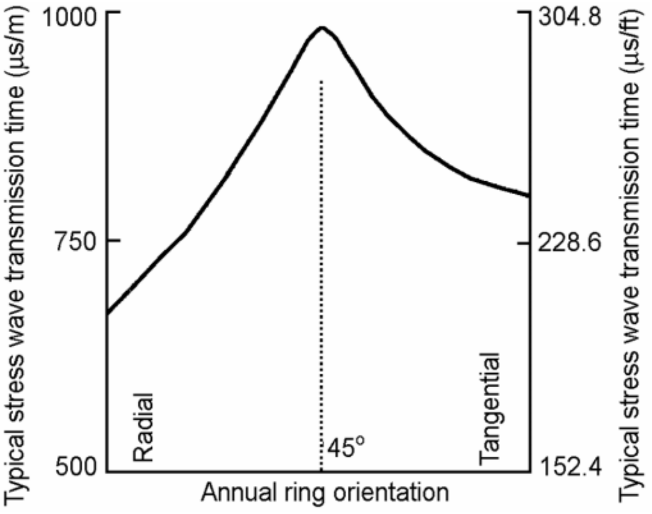


Figure 2—Stress wave transmission time in relation to annual ring orientation (Ross and others 1999).

The presence of deterioration from decay can greatly affect stress wave transmission time in wood. Transmission times for decayed wood are much greater than that for nondecayed wood. For example, transmission time for nondegraded Douglas-fir is approximately 800 µs/m (244 µs/ft), whereas severely degraded members exhibit values as high as 3,200 µs/m (975 µs/ft) or greater. A study conducted by Pellerin and others (1985) demonstrated that a 30% increase in stress wave transmission time implies a 50% loss in strength. A 50% increase indicates severely decayed wood (Fig. 3).

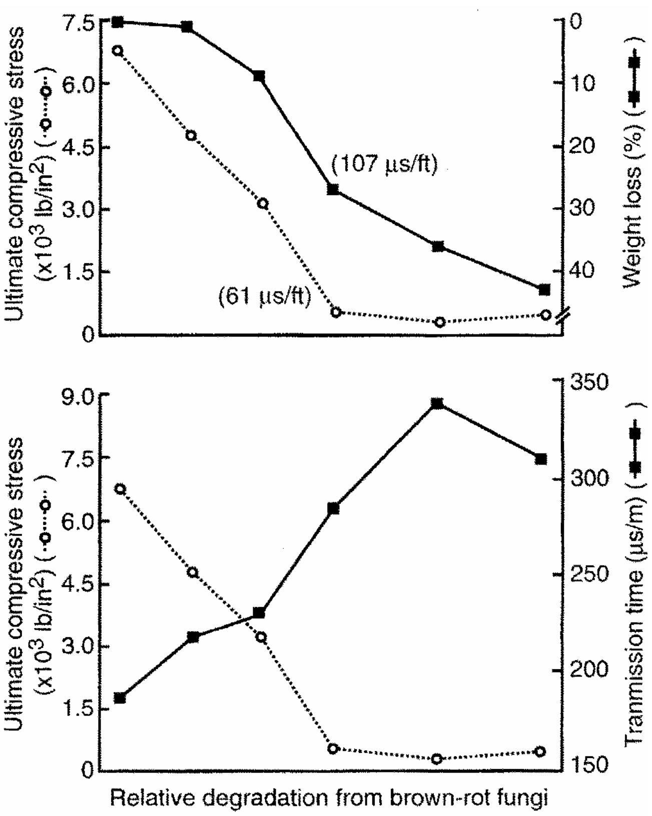


Figure 3—Relationship between stress wave transmission time and fungal degradation (Pellerin and others 1985).

The speed of sound propagating perpendicular to grain is also affected by tree species. Mattheck and Bethge (1993) measured speed of sound in different species of healthy trees using a commercially available stress wave timing unit. The speed was determined by dividing the transit distance (tree diameter) by the time measured. Table 2 shows both radial stress wave velocity and transmission time on a per length basis for 5 softwood species and 14 hardwood species. Generally, sound travels faster in hardwood species than in softwood species. To account for species difference, Divos and Szalai (2002) provided some baseline reference velocities for different species for tree evaluation (Table 3). This reference velocity can be used to evaluate the actual measured wave velocity and assess the internal condition of the tree inspected.

Measurement of Stress Wave Transmission Time

General Measurement

The most common technique used to measure stress wave transmission time utilizes simple time-of-flight-type measurement systems. Two systems that use this technique are

Table 2—Radial stress wave velocities and transmission times in healthy standing trees (from Mattheck and Bethge 1993)

	Radial stress wave velocity		Radial stress wave transmission time	
Species	m/s	ft/s	µs/m	µs/ft
Hardwoods				
Ash	1,162–1,379	3,810–4,520	725–861	221–262
Birch	967–1,150	3,170–3,770	870–1,034	265–315
Black locust	934–1,463	3,060–4,800	684–1,071	208–326
Black poplar	869–1,057	2,850–3,470	946–1,151	288–351
Horse chestnut	873–1,557	2,860–5,110	642–1,145	196–349
Lime	940–1,183	3,080–3,880	845–1,064	258–324
Maple	1,006–1,600	3,300–5,250	625–994	191–303
Oak	1,382–1,610	4,530–5,280	621–724	189–221
Pine poplar	967–1,144	3,170–3,750	874–1,034	266–315
Plane	950–1,033	3,120–3,390	968–1,053	295–321
Red beech	1,206–1,412	3,960–4,630	708–829	216–253
Silver poplar	821–1,108	2,690–3,640	903–1,218	275–371
Sweet chestnut	1,215–1,375	3,990–4,510	727–823	222–251
Willow	912–1,333	2,990–4,370	750–1,096	229–334
Softwoods				
Douglas-fir	905–1,323	2,970–4,340	756–1,105	230–337
Fir	910–1,166	2,990–3,830	858–1,099	261–335
Larch	1,023–1,338	3,360–4,390	747–978	228–298
Pine	1,066–1,146	3,500–3,760	873–938	266–286
Spruce	931–1,085	3,050–3,560	922–1,074	281–327

Table 3—Reference stress wave velocities and transmission times in radial direction (Divos and Szalai 2002)

Species	Radial stress wave velocity (m/s)	Radial stress wave transmission time (µs/ft)
Beech	1,670	183
Black fir	1,480	206
Larch	1,490	205
Linden	1,690	180
Maple	1,690	180
Oak	1,620	188
Poplar	1,140	267
Scotch fir	1,470	207
Silver fir	1,360	224
Spruce	1,410	216

illustrated in Figures 4 and 5. With these systems, a mechanical or ultrasonic impact is used to impart a wave into the member. Piezoelectric sensors are placed at two points on the member and used to detect passage of the wave. The time required for the wave to travel between the sensors is measured by detecting the leading edge of the stress wave pulses.

There are two key points to consider when using time-of-flight measurement systems:

1. The sensors must be in line with each other.
2. Many sensors are sensitive to the manner in which they are installed. For example, commonly used accelerometers yield waveforms that are strongly dependent on the direction in which they sense the pulse. The base of the accelerometer should directly face an approaching compressive wave (Fig. 6). Simply turning the accelerometer so that its base faces away from the approaching compressive wave changes the characteristics of the waveform.

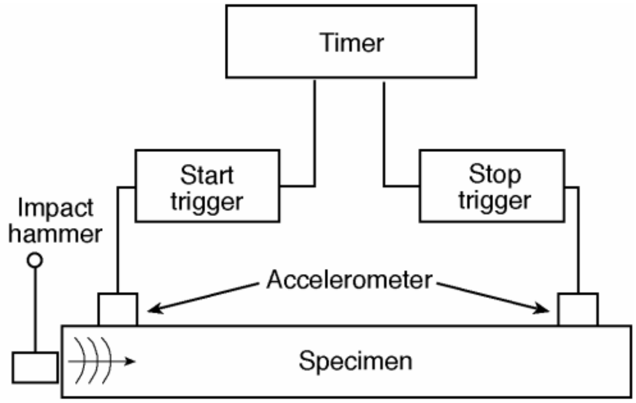


Figure 4—Technique used to measure impact-induced stress wave transmission time in wood products.

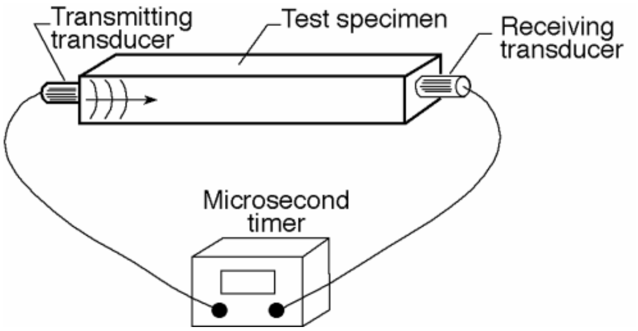


Figure 5—Ultrasonic measurement system used to measure stress wave transmission time in wood products.

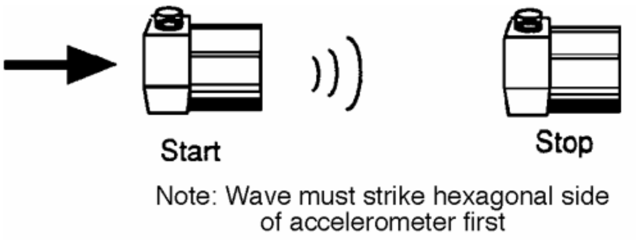


Figure 6—Orientation of accelerometer.

Commercial Equipment

The following types of commercial equipment are available to measure stress wave transmission times in trees. The manufacturer, method of operation, key considerations, and specifications for these equipments are also given.

- **Metriguard Model 239A Stress Wave Timer (Fig. 7)**

Manufacturer: Metriguard, Inc., P.O. Box 399, Pullman, WA 99163; telephone (509) 332–7526;
fax (509) 332–0485.

Figure 7—Metriguard Model 239A Stress Wave Timer.

Method of operation: A mechanical stress wave is induced in a member by a hammer or other means and is detected with accelerometers at two points along the propagation path. The timer starts when the wave front arrives at the first accelerometer and stops when the wave front arrives at the second accelerometer. The propagation time between accelerometers is displayed in microseconds.

Specifications

Power requirements: 9-V battery

Resolution: ±1 µs

Dimensions: 18 by 23 by 23 cm (7 by 9 by 9 in.)

Weight: 5.4 kg (12 lb) (including hammer and accelerometers)

- **James “V” Meter (Fig. 8)**

Manufacturer: James Instruments, Inc., 3727 North Kedzie Avenue, Chicago, IL 60618; telephone (800) 426–6500 or (312) 463–6565; fax (312) 463–0009.

Method of operation: The James “V” Meter utilizes an ultrasonic pulse generator to impart a stress wave into the member. As illustrated in Figure 8, two transducers are placed a fixed distance apart on a member. As the transmitting transducer imparts a wave into the member, the timer unit begins timing passage of the wave. When the wave reaches the receiving unit, the timer stops. Transit time is displayed in microseconds.

Key considerations: Coupling of the transducers is key to obtaining reliable results. The surface of the members should be free of debris, mud, or dirt. A coupling agent, provided by the manufacturer, is often used to facilitate measurements.

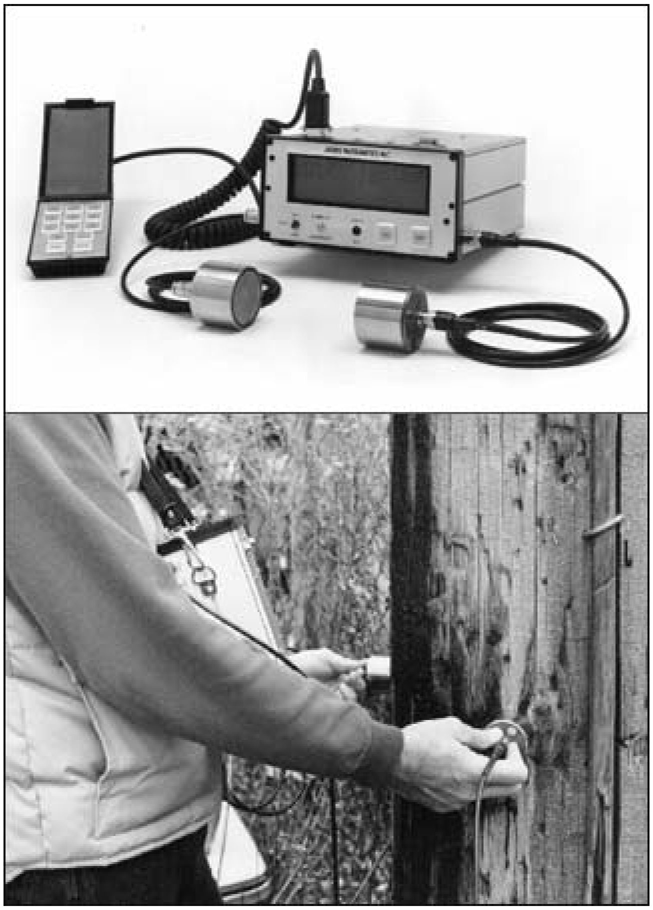


Figure 8—James V-Meter.

Specifications

Power requirements: rechargeable NI-CAD

Sylva Test (Fig. 9)

Manufacturer: Sandes SA, Zone industrielle, Case postale 25, CH–1614/Granges/Veveyse, Switzerland; telephone (021) 907 90 60; fax (021) 907 94 82.

Method of operation: The Sylva test unit utilizes an ultrasonic pulse generator to impart a stress wave into a member. Two transducers are placed a fixed distance apart on the member. A transmitting transducer imparts a wave into the member, and a receiving transmitter is triggered upon sensing of the wave. The time required for the wave to pass between the two transducers is then coupled with various additional information, such as wood species, path length, and geometry, to compute modulus of elasticity.

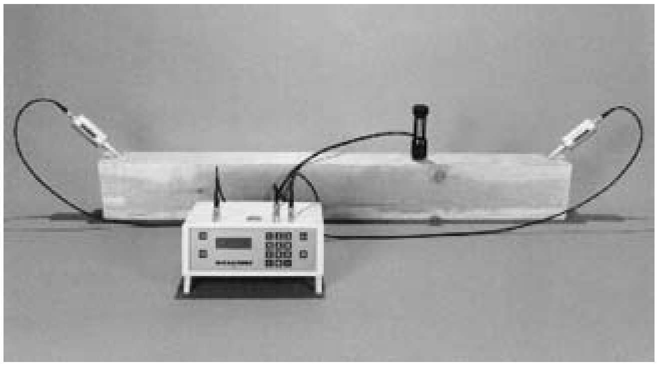


Figure 9—Sylva test.

Figure 10—FAKOPP Microsecond Timer.

Specifications

Power requirements: rechargeable batteries

Dimension: 29 by 20 by 12 cm (11.5 by 7.9 by 4.7 in.)

Weight: 2.3 kg (5.1 lb), instrument only; 5.7 kg (12.6 lb), instrument with carrying bag and accessories

- **FAKOPP Microsecond Timer (Fig. 10)**

Manufacturer: FAKOPP Enterprise, H–9423 Agfglva, Fenyo Str. 26, Hungary; telephone +36 99 510 996; fax +36 99 33 00 99; website: www.fakopp.com

Method of operation: FAKOPP is a microsecond timer for tree tests. The equipment is battery operated and designed for field applications. Needles attached to accelerometers are used as mediators that penetrate the bark and reach the sapwood of a tree. A hammer is used to tap the start sensor to generate a stress wave into the tree stem in the radial direction. The two sensors pick up the start and stop signal, and the wave transmission time is displayed on an LCD screen.

Specifications

Power requirements: 4 AA batteries

Dimension: 29 by 82 by 156 mm (1.1 by 3.2 by 6.1 in.)

Weight: 220 g (0.48 lb)

Resolution: ±1 µs

FAKOPP 2D Microsecond Timer (Fig. 11)

Manufacturer: FAKOPP Enterprise, H–9423 Agfglva, Fenyo Str. 26, Hungary; telephone +36 99 510 996; fax +36 99 33 00 99; website: www.fakopp.com

Method of operation: FAKOPP 2D is a multi-channel version of the original FAKOPP microsecond timer. It generates tomographic data through multiple transmission measurements at a cross section of a tree trunk. The system is self-calibrated based on near-tangential transmission measurements between neighboring sensors. The average of the tangential transmission data of the healthy section is used as the basic reference data.

Specifications

6 or 8 transducers equipped with 60-mm- (2.36-in.-) long nails

Dimension: 40 by 100 by 205 mm (1.6 by 3.9 by 8.1 in.)

Time base: 20 MHz quartz oscillator

Time resolution: ± 2 µs

RS 232 interface baud rate: 2400

Display: 32 character LCD

Microsoft Windows evaluation software

Two 9-V block batteries

Figure 11—FAKOPP 2D Microsecond Timer.

- **Impulse Hammer (Fig. 12)**

Manufacturer: IML, Instrumenta Emchnik Labor GmbH, GroBer Stadtacker 2, D–69168 Wiesloch, Germany; telephone (49) 06222–8021; fax (49) 06222–52552.

Method of operation: The impulse hammer is also known as the stress wave timer and electronic hammer. It measures the rate at which sound travels through wood. To take a measurement on a tree, two screws are fixed through the bark across the cross section under inspection. A sensor is mounted onto one screw. A special hammer is used to strike the opposing screw and create a sound pulse. Wiring transmits the signals back to the electronic device, and the results are displayed on a screen.

Specifications

Power requirements: 7.2-V rechargeable battery

Weight: 4 kg (8.8 lb)

Figure 12—IML Impulse Hammer.

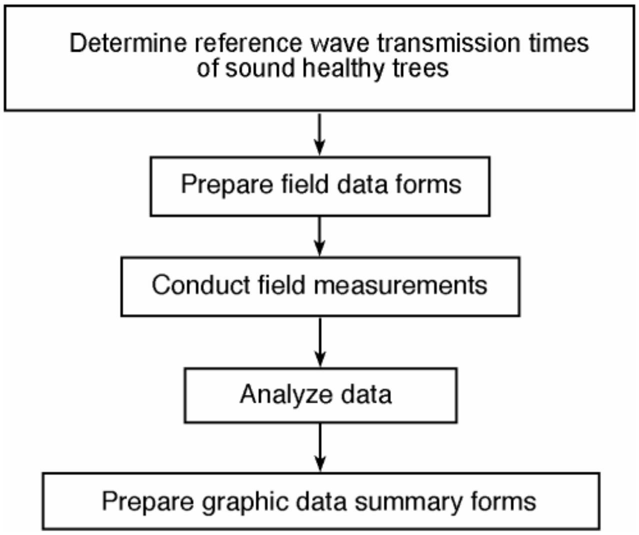


Figure 13—General procedures used to prepare and use stress wave timing methods for field work.

Field Considerations and Use of Stress Wave Methods

General Procedure

Figure 13 outlines the general procedures used to prepare and utilize stress wave NDE methods for field work. Stress wave transmission time may vary from species to species, even from tree to tree. Before venturing into the field, it is important to estimate the reference wave transmission time for the trees to be inspected.

The baseline data collected from healthy trees in previous research can be used as an initial evaluation standard. More precise reference data can be obtained in the field, prior to field tree evaluation, by testing a sample of healthy trees or the healthy part of the tree. To facilitate the tree evaluation process, it is also helpful to prepare a data acquisition form before field testing. An example of a typical field data acquisition form is shown in the Appendix. Key items to include on the form are tree species, tree ID number, location of inspection, test orientation, equipment used, name of inspector, and date of inspection.

Reference Wave Transmission Time

The stress wave transmission time of healthy trees is species dependent, as indicated by Tables 2 and 3. In general, the reference information can be summarized into two groups: softwoods and hardwoods. As a rule of thumb, the baseline transmission time is 1,000 μs/m (300 μs/ft) for softwoods and 670 μs/m (200 μs/ft) for hardwoods. Measured transmission time (per length basis) less than this would indicate a sound and healthy tree. Conversely, transmission time greater than this value would indicate a potentially decayed and unhealthy tree. Using this value, an inspector can estimate the transmission time for a sound tree by knowing its diameter and using the following formulas:

For softwoods,

$$T_0 = 1000D \quad (\mu\text{s/m})$$

$$T_0 = 300D \quad (\mu\text{s/ft})$$

For hardwoods,

$$T_0 = 670D \quad (\mu\text{s/m})$$

$$T_0 = 200D \quad (\mu\text{s/ft})$$

where T_0 is baseline transmission time (μs/m or μs/ft) and D is diameter of tree (m or ft). By knowing this value for various tree diameters, field work can proceed rapidly.

In practice, a more precise reference wave transmission time can also be determined in the field for the species inspected. This can be done by identifying several sound and healthy trees and measuring the transmission times across the tree stems at breast height. This pre-test data can then be used as a baseline to guide the inspection work.

Field Measurements

Field measurements should be conducted in accordance with the instructions provided by equipment manufacturers. In general, the following testing procedures should be adhered to regardless of what equipment is used:

1. Determine test locations in the tree under inspection.
2. Draw a schematic to show all test locations and sensor orientation and arrangement.
3. Measure diameter of tree at each location/orientation using a D-type measure (for round stems) or caliper (for irregular stems).
4. Mount start and stop sensors onto tree stem at each determined test location, with one sensor each arranged in radial and perpendicular to grain directions.
5. Measure transmission time by tapping the start sensor (impact-type equipment) or turning on the acoustic emitter (ultrasonic-type equipment).
6. Skip first stress wave reading and run test several times. Derive average value from at least three readings.
7. Convert stress wave readings to transmission times on a per length basis (μs/m or μs/ft).
8. Compare test results to reference transmission time value; make on-site decision if intensive measurements are needed at or near the same location.

Note that the baseline values provided serve as a starting point for tree evaluation. It is important to conduct measurements at several points at varying distances away from the suspect location. In a sound tree, the deviation in observed transmission times should be small. If a significant difference is observed in measured transmission times, the tree should be considered suspect and an intensive inspection (test at various orientations across the tree stem) should be followed.

To eliminate bark effect and obtain consistent readings of transmission time, two probes are usually required to attach both start and stop sensors to the tree by penetrating the bark and reaching the sapwood. Some manufacturers provide needles or sharp probes that are attached to or connected with the sensors to facilitate measurements. If probes are not provided, then nails and clamps can be used to mount sensors and similar results should be obtained.

Data Analysis and Interpretation

Stress wave readings from tree testing need to be converted into transmission times on a per length basis (or per time basis if preferred) to compare with the reference transmission time T_0. The following formula can be used to calculate measured transmission time on a per length basis:

$$T_{\mathrm{m}} = \frac{T_{\mathrm{reading}}}{D}$$

where T_{m} is measured transmission time on per length basis (μs/m or μs/ft), T_{reading} is stress wave reading (μs), and D is tree diameter in test direction (m or ft).

An effective way to evaluate the testing results is to determine the percentage of increase in transmission time in comparison to the reference value. This can be calculated by the following formula:

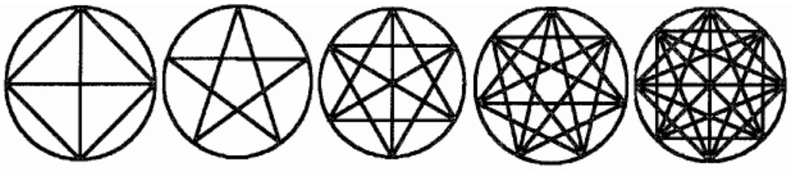
$$\Delta T = \frac{T_{\mathrm{m}} - T_0}{T_0} 100\%$$

Generally, if the increase of transmission time is higher than 10% of the reference value, the tree is suspected of having internal decay. For trees so identified, intensive stress wave measurements should be followed to confirm the condition and define the extent and precise location of decay.

Stress-Wave-Based Tomography

The sensitivity of the stress wave transmission technique is limited. A single pass stress wave measurement can only detect internal decay that is above 20% of the total cross-section area. To increase the reliability of the inspection and define the extent and location of any internal decay, it would be practical to conduct multiple measurements in different orientations at one cross section, especially for suspect trees. Tomographic inversion of stress wave data from multiple measurements could allow inspectors to obtain an image of the distribution of stress wave transmission times in the cross section and help define the extent of internal decay with accuracy.

Divos and Szalai (2002) proposed several possible measurement arrangements with four to eight test points, as shown in Figure 14. The minimum detectable size of a defect can be calculated, assuming that the defect approximates a circle. As indicated in Figure 14, the minimum detectable defect size is 8%, 6%, 4%, 3%, and 1% of the cross-sectional area for an arrangement with 4, 5, 6, 7, and 8 test points, respectively. Since reference transmission time depends on anatomical direction, two or more reference values may be needed, depending on the measurement arrangement.



No. of test points	4	5	6	7	8
No. of measurements	6	5	9	14	20
No. of reference velocity	2	1	2	2	3
Min. detectable defect (%)	8	6	3	4	1

Figure 14—Sensor arrangements for measuring stress wave transmission time (Divos and Szalai 2002).

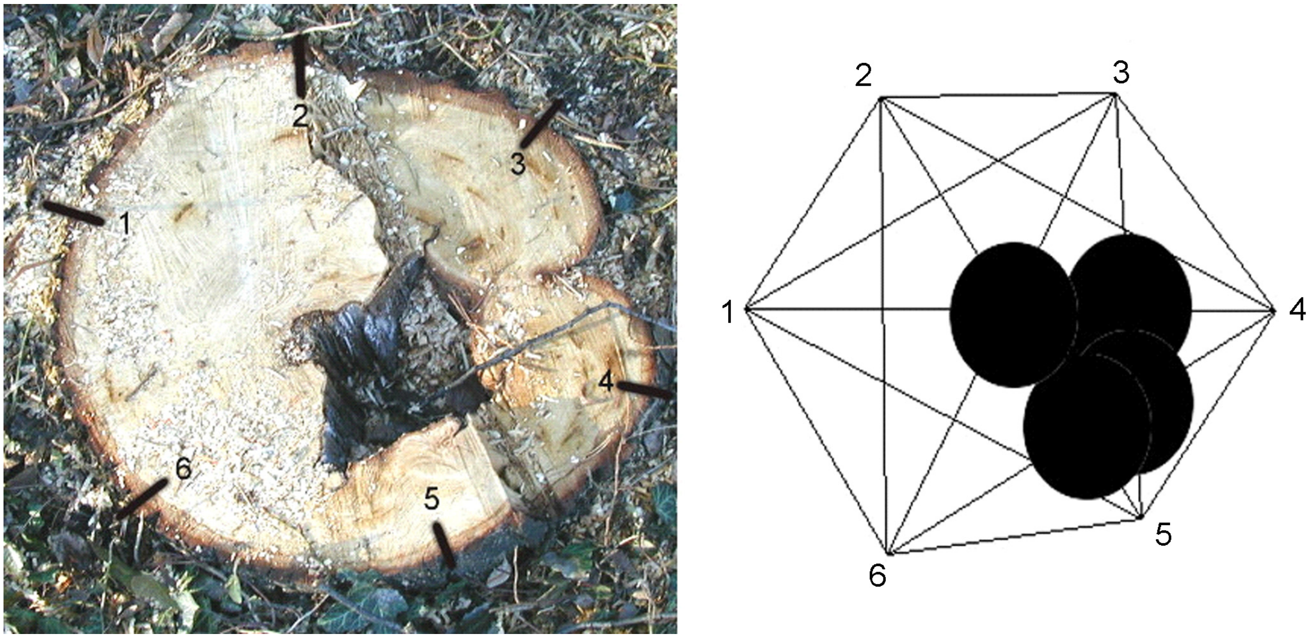


Figure 15—Tomographic inversion of stress wave data from multiple measurements in decayed tree (Divos and Szalai 2002).

Figure 15 demonstrates the application of this technique in evaluating a tree stem using the 6-point arrangement. The evaluation process is based on the comparison between measured transmission times and reference data. The line where the measured transmission time is 10% higher than the reference time is marked as the "defect line." The intersection of two defect lines designates the defect location, which is marked as a black area. Note that the measured and actual decay areas overlap with fair accuracy. The resolution of the tomographic image can be increased by increasing the number of transducers.

Literature Cited

Armstrong, J.P.; Patterson, D.W.; Sneckenberger, J.E. 1991. Comparison of three equations for predicting stress wave velocity as a function of grain angle. Wood and Fiber Science. 23(1): 32–43.

Boyce, J.S. 1948. Forest Pathology. 2nd ed. New York, NY: McGraw–Hill Book Co., Inc. 348 p.

Devos, F.; Szalai, L. 2002. Tree evaluation by acoustic tomography. In: Proceedings of the 13th International symposium on nondestructive testing of wood; 2002 August 19–21; Berkeley, CA. Madison, WI: Forest Products Society: 251–256.

Elvery, R.H.; Nwokoye, D.N. 1970. Strength assessment of timber for glued laminated beams. In: Proceedings, Paper II, Nondestructive testing of concrete and timber, organized by the Institution of Civil Engineering and the British Commission for Nondestructive Testing; 1969 June 11–12, London, BC: Institute of Civil Engineering: 105–110.

Forest Products Laboratory. 1999. Wood Handbook—Wood as an engineering material. Gen. Tech. Rep. FPL–GTR–113. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 463 p.

Gerhards, C.C. 1978. Effect of earlywood and latewood on stress-wave measurements parallel to the grain. Wood Science. 11(2): 69–72.

Gerhards, C.C. 1980. Effect of cross grain on stress waves in lumber. Res. Pap. FPL–RP–368. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Gerhards, C.C. 1982. Effect of knots on stress waves in lumber. Res. Pap. FPL–RP–384. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Hailey, J.R.; Morris, P.I. 1987. Application of scanning and imaging technology to assess decay and wood quality in logs and standing trees. Vancouver, BC: Forintek Canada Corporation.

Holoyen, S.; Birkeland, R. 1987. Industrial methods for internal scanning of log defects: A program report on an ongoing project in Norway. In: Proceedings, 2nd International conference on scanning technology in sawmilling. Pap. X1–X18. San Francisco, CA.

Hoyle, R.J.; Pellerin, R.F. 1978. Stress wave inspection of a wood structure. In: Proceedings, 4th Symposium on nondestructive testing of wood. Pullman, WA: Washington State University: 33–45.

Hoyle, R.J., Jr.; Rutherford, P.S. 1987. Stress wave inspection of bridge timbers and decking. Pullman, WA: Washington State University, Department of Civil and Environmental Engineering.

Ihlseng, M.C. 1878. The modulus of elasticity in some American woods, as determined by vibration. Van Nostrand Engineering Magazine. 19: 8–9.

Jung, J. 1979. Stress wave grading techniques on veneer sheets. Gen. Tech. Rep. FPL–GTR–27. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Lin, C–J; Chiu, C–M; Wang, S–Y. 2000. Application of ultrasound in detecting wood decay in squirrel-damaged standing trees of Luanta Chin fir. Taiwan Forest Science 15(2): 267–279.

Mattheck, C.G.; Bethge, K.A. 1993. Detection of decay in trees with the Metriguard Stress Wave Timer. Journal of Abroriculture. 19(6): 374–378.

McCracken, F.I. 1985. Using sound to detect decay in standing hardwood trees. In: Proceedings, 5th International symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 281–287.

McCracken, F.I.; Vann, S.R. 1983. Sound can detect decay in standing hardwood trees. Res. Pap. SO–195. New Orleans, Louisiana: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station.

Oja, J; Grundberg, S.; Gronlund, A. 2000. Predicting the strength of sawn products by x-ray scanning of logs: A preliminary study. Wood and Fiber Science. 32(2): 203–208.

Pellerin, R.F.; Ross, R.J.; eds. 2002. Nondestructive evaluation of wood. Madison, WI: Forest Products Society.

Pellerin, R.F.; DeGroot, R.C.; Esenther, G.R. 1985. Nondestructive stress wave measurements of decay and termite attack in experimental wood units. In: Proceedings, 5th Nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 319–353.

Ross R.J. 1982. Quality assessment of the wooden beams and columns of Bay C of the east end of Washington State University's football stadium. Unpublished research. Pullman, WA: Washington State University.

Ross, R.J.; Pellerin, R.F. 1994. Nondestructive testing for assessing wood members in structures. A review. Gen. Tech. Rep. FPL–GTR–70. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 40 p.

Ross, R.J.; Pellerin, R. F.; Volny, N.; Salsig, W.W.; Falk, R.H. 1999. Inspection of timber bridges using stress wave timing nondestructive evaluation tools—A guide for use and interpretation. Gen. Tech. Rep. FPL–GTR–114. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 15 p.

Rutherford, P.S. 1987. Nondestructive stress wave measurement of incipient decay in Douglas-fir. Pullman, WA: Washington State University. M.S. thesis.

Smulski, S.J. 1991. Relationship of stress wave and static bending determined properties of four northeastern hardwoods. Wood and Fiber Science. 23(1): 44–57.

Soltis, L.; Baker, A.; Ferge, L. [and others]. 1992. USS Constitution. Inspection and evaluation procedures for live and white oak members. Report submitted to U.S. Navy, Maintenance and Repair, USS Constitution, Boston Naval Shipyard, Charlestown, MA.

Volny, N.J. 1992. Timber bridge inspection case studies in use of stress wave velocity equipment. In: Proceedings, 8th International nondestructive testing of wood symposium; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 235–246.

Wang, X.; Ross, R.J. [and others]. 2002. Timber assessment at Quincy Mine blacksmith shop, Keweenaw National Historical Park. APT Bull. The Journal of Preservation Technology. 33(2–3): 70–3.

Yamamoto, K.; Sulaiman, O.; Hashim, R. 1998. Nondestructive detection of heart rot on *Acacia mangium* trees in Malaysia. Forest Products Journal. 48(3): 83–86.

Appendix—Data Acquisition Form

Page _______ of _______

Data Log – Stress Wave Transmission Times of Trees

Site ______________________________________

Stand/Plot ____________________________

Tree Species _______________________________

Reference Transmission Time ____________

Inspector __________________________________

Equipment ___________________________

Date _____________________________________

Tree no.	Location	Orientation	Tree diameter (cm or in.)	Equipment reading (µs)	Transmission time (µs/m or µs/ft)	Condition