Nondestructive Testing and Evaluation of Wood: A Worldwide Research Update

Brian K. Brashaw, Voichita Bucur, Ferenc Divos, Raquel Gonçalves, Jianxiong Lu, Roger Meder, Roy F. Pellerin, Simon Potter, Robert J. Ross, Xiping Wang, and Yafang Yin

Introduction

The field of nondestructive testing (NDT) and nondestructive evaluation (NDE) of materials is constantly evolving. This is especially true in the area of wood and fiber-based materials. For example, early research on NDT/NDE technologies for wood products focused on methods for assessing the performance characteristics of structural lumber in North America. The NDT techniques, equipment, and evaluation procedures that resulted from those efforts are now in widespread use. Currently, worldwide research and development efforts are underway to examine the potential use of a wide range of NDT technologies for evaluating wood and wood-based materials—from the assessment of standing trees to in-place structures.

The original impetus for research in NDT/NDE of wood was the need to provide methodologies for assessing wood-based materials and products so that more accurate decisions could be made about proper use. This remains the major driving force for NDT/NDE wood research, with two significant additional challenges. First, there is an increased emphasis around the world to address forest and ecosystem health issues. Utilization of woody biomass from widely varying growing conditions will play a key role in providing economical options for managing the health of these forests and ecosystems. Second, the marketplace has become increasingly global in nature. Shipments of raw materials and products between countries on different continents is now commonplace. Both of these challenges will require accurate, cost-effective NDT/NDE technologies.

The international forest products research community is responding to these driving forces by conducting NDT/NDE research to provide the technologies needed to address these challenges. This article presents a sample of the on-going NDT/NDE research efforts being conducted in several areas of the world.

International Nondestructive Testing and Evaluation of Wood Symposium Series

In an effort to provide a forum for researchers, the international NDT/NDE research community sponsors a series of technical symposia for the exchange of technical information. These symposia are scheduled on a biannual basis at locations throughout the world.

The International Nondestructive Testing and Evaluation of Wood Symposium Series was initiated by Washington State University and the USDA Forest Products Laboratory (FPL). The first symposium was held at FPL in the fall of 1963, with proceedings produced and distributed in 1964. At the meeting nearly 100 scientists, engineers, and industry leaders discussed the possibilities of a wide range of scientific means for testing wood nondestructively.

The original goals of this series of symposia were to:

1. provide a technical and scientific forum for researchers to present and exchange results from their latest research endeavors, and
2. bring researchers and industry together in an attempt to bridge the gap between the results of the researchers' efforts and the utilization of those results by the wood industry.

Published proceedings from each symposia summarize the research and development efforts presented (**Fig. 1**). Fifteen symposia have been held to date, and the sixteenth is scheduled for May 11-13, 2009, in Beijing, PR China (**Table 1**).

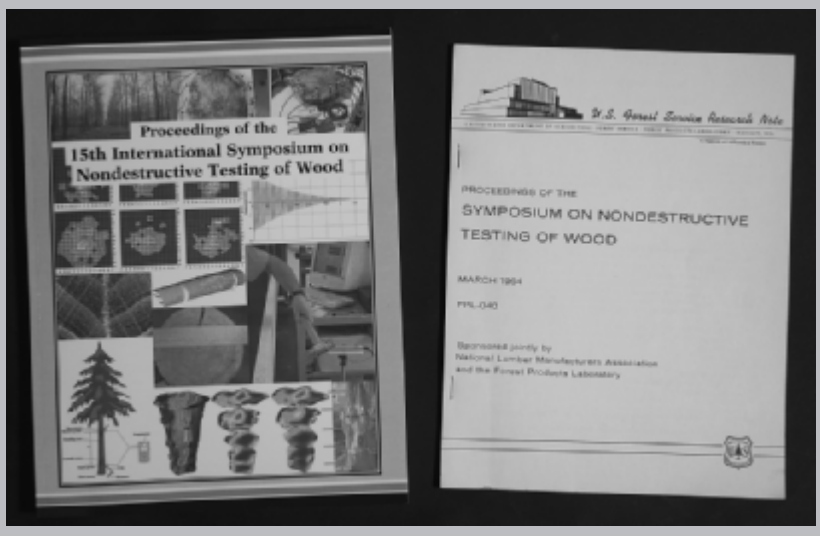
While the early symposia focused on basic NDE principles and lumber assessment procedures, the symposia now attracts researchers and industry representatives from throughout the world and represents the full spectrum of technical interests, from basic and applied science

to the use of various methods in industrial and field applications. Recently, papers have been presented on the latest NDT techniques including those that focus on tomography, near infrared scanning, acousto-ultrasonics, and innovative combinations of stress wave, laser, and ultrasound techniques. A significant number of papers have been presented on assessment of trees and logs, with most of the work on lumber focusing on the use of well-established techniques for evaluating species in Asia, Europe, and South America.

North America

Recently, near infrared (NIR) technologies have received considerable attention for their use in the quality control and sorting programs that are used with wood-based products in North America. NIR spectroscopy evaluates the interaction of electromagnetic radiation with materials. Infrared radiation is just beyond what the human eye can see, and NIR is the infrared region closest to the visible region. The use of NIR to evaluate the chemical, mechanical, and anatomical properties of wood has been investigated extensively. Studies designed to examine the value of this method to quantitatively measure the chemical composition, mechanical properties (strength and stiffness), and some anatomical properties (microfibril angle and fiber diameter) have provided positive indication of the usefulness of these techniques for evaluating wood. In addition, processed biomass and wood composites can be characterized and monitored on-line by NIR spectroscopy. An excellent technical review of the technology and its potential applications in the wood products industry is summarized in a publication prepared by So et al. (2004).

Figure 1. — Published proceedings have helped disseminate the information presented during the International Nondestructive Testing and Evaluation of Wood Symposia.



The assessment of the quality of raw wood materials has become a crucial issue in the operational value chain as forestry and the wood processing industry are increasingly under economic pressure to maximize extracted value. A significant effort has been devoted toward developing robust NDE technologies capable of predicting the intrinsic wood properties of individual trees and stems and assessing the value of stands and forests. In North America, initial research on tree quality assessment focused on proving the fundamental concepts of NDE theory and developing portable field testing tools (Wang et al. 2007). A typical approach for assessing wood quality of standing trees is to measure acoustic velocity on the lower part of a tree stem. The testing procedure involves inserting two sensor probes into the sapwood and introducing

Table 1. — Dates and locations for the International Nondestructive Testing and Evaluation of Wood Symposiums.

Symposium	Dates Held	Host Institution and Location
1	October 7–9, 1963	U.S. Forest Products Laboratory, Madison, WI, USA
2	April, 1964	Washington State University, Spokane, WA, USA
3	April – May, 1970	Washington State University, Vancouver, WA, USA
4	August 28–30, 1978	Washington State University, Vancouver, WA, USA
5	September 9–11, 1985	Washington State University, Pullman, WA, USA
6	September 14–16, 1987	Washington State University, Pullman, WA, USA
7	September 27–29, 1989	U.S. Forest Products Laboratory, Madison, WI, USA
8	September 23–25, 1991	Washington State University, Vancouver, WA, USA
9	September 22–24, 1993	U.S. Forest Products Laboratory, Madison, WI, USA
10	August 26–28, 1996	IBOIS-Chair of Timber Construction of the Swiss Federal Institute of Technology, Lausanne, Switzerland
11	September 9–11, 1998	U.S. Forest Products Laboratory, Madison, WI, USA
12	September 13–15, 2000	University of Western Hungary, Sopron, Hungary
13	August 19–21, 2002	University of California, Berkeley Campus, CA, USA
14	May 2–4, 2005	University of Applied Sciences Ebenwalde, Hanover, Germany
15	September 10–12, 2007	University of Minnesota Duluth, Duluth, MN, USA
16	May 11–13, 2009	Beijing Forestry University, Beijing, P.R. China

acoustic energy into the tree through a hammer impact. The standing tree acoustic tool measures time-of-flight (TOF) for a single pulse wave to pass through the tree trunk from the transmit probe to the receive probe (**Fig. 2**).

For tree quality assessment, going from velocity measurement to wood property prediction is a critical step. Until recently, post-harvest NDE methods such as E-rating, machine stress rating (MSR), and ultrasound veneer grading have been the standard procedures for evaluating wood stiffness and strength. The timber owner does not have a reliable way to assess the value of the final products prior to harvest. Recent wood quality research has shown that a range of wood and fiber properties can be predicted through a simple acoustic measurement in standing trees (Wang et al. 2007). This will facilitate the use of acoustic NDT technology at a number of stages in the operational value chain, from timberlands through to the processing site.

NDE technologies are not only critical in the forest operational value chain, they also play an important role ensuring public safety by detecting internal decay and defects in urban trees. Within an urban community, trees are valuable assets providing ecological, aesthetic, social, and economic benefits. At the same time, they pose a potential risk to people and property when they become structurally unstable. The science of tree stability analysis uses NDE and biological and engineering principles in attempting to rate a tree's structural soundness and make reasonable predictions of potential for failure. Concerns related to public safety and urban forest conservation efforts support the development and application of rapid and precise diagnostic technologies to detect decay and other types of structural defects in trees, particularly in the lower portion of the trunks. Early research on tree decay detection in North America involved drilling and measuring electronic resistance (Shigo and Shigo 1974) and conducting single-path sonic wave measurement across the stem (McCracken and Vann 1983). Recent studies have focused on investigating the applicability of various tomography techniques (X-ray, acoustic, and georadar) in urban trees. A tree inspection procedure that uses a combination of visual inspection, acoustic testing (single-path and tomography), and resistance microdrilling has been found successful for evaluation of urban trees (Wang and Allison 2008) (**Fig. 3**). It has been noted that visual inspection and single-path stress wave tests can identify a general problem; acoustic tomography reveals the general location and magnitude of a defect within the cross section tested; and resistance microdrilling precisely locates defects and differentiates between decay and crack-induced acoustic shadows.

The application of various NDT concepts in on-site structure inspection and evaluation has been on the rise in North America. While the traditional methods

Figure 2. — Measuring the acoustic velocity in a standing tree.

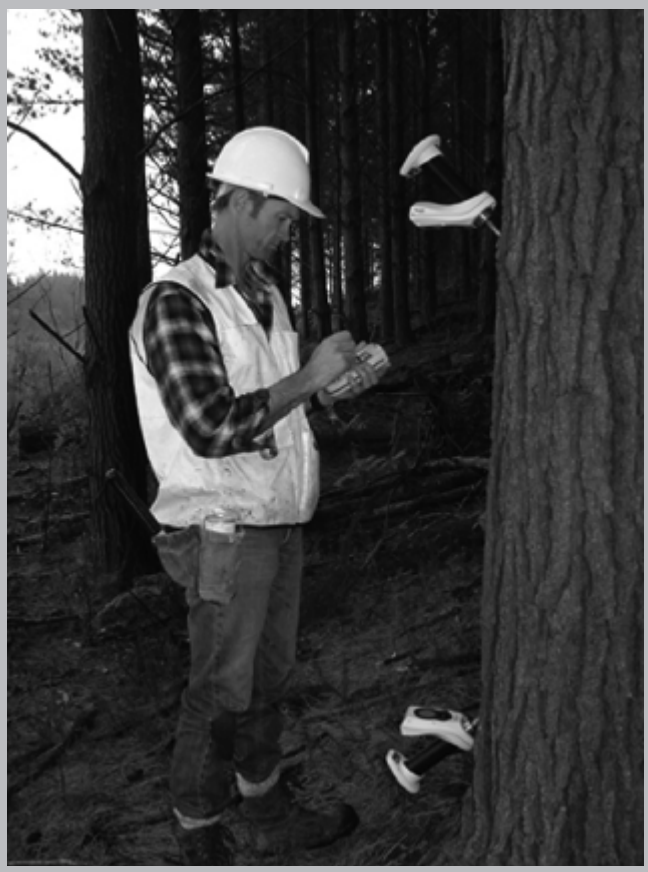


Figure 3. — Application of acoustic tomography in tree decay detection in an urban environment.

used to assess the condition of wood structures are based on evaluating individual members or small areas within a member, an extensive experimentation program has been conducted to examine the feasibility of testing entire structural wood systems. The results to date have shown that it may be possible to assess the in-place stiffness of several types of structural systems, in particular short span bridges and floor systems, using forced and free vibration techniques (Soltis et al. 2002, Morison et al. 2002).

Central and South America

The forests of Central and South America comprise the most significant volumes of tropical species in the world. Their diverse ecosystems and many species of trees mean that there are widely varying material property characteristics and significantly different properties from wood grown in more temperate climates. Recently, both Central and South American countries have been investing heavily in plantation-based reforestation programs that focus on *Pinus* spp., *Eucalyptus* spp., and teak (*Tectona grandis*). Currently, plantations account for only 2 percent of the forested area, but supply more than 27 percent of the world's industrial roundwood. In Chile, with its highly advanced plantation industry, the plantations reached 85 percent of its forested land. In Costa Rica, a country which has traditionally harvested its wood from natural forests, an estimated 62 percent of roundwood now comes from plantations. Over 11 million hectares of plantation have been established in the last several years. Seventy percent of these are found in Brazil (5.4 million ha). Other leading countries include Chile (2.7 million ha), Argentina (1.2 million ha), Uruguay (0.8 million ha), and Venezuela (0.8 million ha) (FAO 2001, 2005).

NDT research is being conducted at various universities in South America, and significant advances have been made in the establishment of fundamental property information and the relationship between nondestructive test parameters and wood quality. For example, the relationship between NIR parameters and various properties (specific gravity, shrinkage coefficients, deterioration from fungal attack) have yielded excellent results. The relationship between information obtained from several penetration/probing techniques, including micro-resistance drilling, and wood specific gravity, has been investigated. Efforts aimed at identifying and locating growth defects, such as knots and biological infestation, with microwave, laser, X-ray, and gamma radiation technologies have shown positive results with numerous potential applications, especially when coupled with advanced data analysis methods. Research with ultrasound techniques has resulted in excellent basic information relating wave velocities and anisotropic material properties. These results have excellent potential application, especially in defining material properties that can be used in software simulations designed to examine the impact of silvicultural practices on wood quality. Similar to studies in other parts of the world, researchers are investigating the potential of assessing the quality of wood in trees and logs.

Figure 4. — a) In-service testing of a utility pole using ultrasonics; and b) static testing of a utility pole.

Research efforts have resulted in significant technological advances. In Brazil, as a result of research conducted during the last decade, the first standard for mechanical classification of hardwood lumber using ultrasonic NDT techniques was approved in November 2007 (NBR 15521) (Brazilian Standards Association 2007). Efforts are on-going to develop a similar standard or approve this standard for use with softwood species, which are in great demand by the wood export industry. Another important successful transfer of NDT technology in Brazil was the adaptation of ultrasound technology to classify new and inspect in-service electric power transmission poles (**Fig. 4**). The team responsible for this accomplishment is working on the development of field equipment for classification and inspection of poles.

Driven by global markets, forest products companies are investigating technologies that can more accurately grade or classify materials. In Chile, a team of research scientists has formed to study, develop, and apply NDT/NDE technologies for characterizing wood and wood products. A significant component of this team's work is developing innovative partnerships between researchers and the wood products industry to accelerate the adaptation and use of NDE technologies in Chile's forest products industry.

Asia — People's Republic of China and Japan

In 1998, the Chinese government established the Natural Forest Conservation Program (NFCP). As a result

Figure 5. — A larch plantation forest in the northeastern region of China.

of the implementation of this national forestry policy, China's main source of wood fiber has shifted significantly toward the use of plantation-grown materials (**Fig. 5**). The most recent national forestry data indicates that about 53.3 million hectares of land are currently devoted to plantation stock, while the area of naturally grown forests is more than 115.8 million hectares (Lei 2005). This emphasis on plantation forests demands a change in the forest industry's strategy on how best to utilize this resource. Clearly, research and development that supports efficient and effective utilization of plantation timber is essential to the successful implementation of the NFCP.

China currently has the largest area of fast-grown plantation forests in the world. To better understand the potential for plantation forests to provide fiber for use in value-added products, the impact of growth characteristics on wood properties such as strength and dimensional stability must be assessed. Application of NDE techniques to plantation-grown materials is an important step in understanding and learning how to improve the quality of plantation-grown material and identifying the optimal use by the forest products industry. Recent research has focused on developing portable, cost-effective field assessment techniques capable of evaluating wood quality, from rugged field tools for evaluation of trees to automated quality control systems for monitoring the quality of final products. A wide range of NDE techniques, including low frequency vibration, stress waves, ultrasound, near infrared, X-ray, and mechanical probing technologies, have been investigated and are being adopted by industry.

In 2003, the Chinese Research Institute of Wood Industry (CRIWI) of the Chinese Academy of Forestry (CAF) initiated a series of studies to develop methods for assessing the quality of wood in trees. The research is focused on several major tree species, including *Cunninghamia lanceolata*, *Populus* spp., *Eucalyptus* spp., and *Larix* spp, that are widely planted in many large plantations. The studies have identified useful correlations between acoustics-based measurement of the modulus of elasticity of trees and logs and the static bending properties of lumber cut from them (Yin et al. 2004). Techniques such as mechanical probing and strain gauges combined with resistance micro-drill were also found to provide a relatively low cost way of assessing the quality of wood in trees.

With the recent introduction of modern timber construction practices in China, the use of imported structural lumber in local building construction has increased rapidly. While domestic wood species have been used in traditional post and beam construction, they have not been viewed as able to meet the increased market demands for structural lumber. To counter that trend, efforts are underway to produce high-value structural lumber from plantation-grown trees to increase the use of domestic wood. This includes a nationwide initiative that focuses on developing and demonstrating the necessary science and technology to enhance the utilization of domestic species in Chinese building construction. In particular, machine grading systems for lumber are being developed and demonstrated. This effort includes the establishment of appropriate grading criteria, based on established machine grading principles, for lumber products that will be used in a range of engineering applications. A key component of this effort will be the development of standardized material evaluation processes.

NDE techniques can also be useful in assessing historic wood structures. China, Japan, and other Asian countries have an exceptionally long history of using timber as a construction material (**Fig. 6**). While a variety of techniques are available for evaluating the condition of in-service members, it is virtually impossible to use them in many ancient structures because their use damages the decorative wood finishes on the surface of the wood member. Maintaining the integrity of the surface is critical in the preservation of historically significant structures. Research is currently being conducted at the CRIWI to explore suitable NDE techniques for assessing historic wood structures and improving preservation practices.

The rapid progress attained in research and use of NDE methods in China has been aided by strong international partnerships. The number of active research scientists and engineers involved in this area has increased steadily, beginning with participation at the Thirteenth International Nondestructive Testing and Evaluation of Wood Symposium and continuing with involvement in subsequent symposia. In addition, two seminars, one sponsored by CRIWI and the International Union of Forestry Research Organizations (IUFRO) that focused on NDT of wood and an international seminar that examined wood quality and utilization issues for domestic species (sponsored and hosted by CRIWI), were held in Beijing in 2006.

These symposia and seminars provided excellent forums for interaction and exchange of the latest information on NDE of wood and challenges facing the manufacturers and users of wood products.

Researchers in Japan have contributed significantly toward quality assessment of logs and standing trees in terms of structural performance and understanding the effect that moisture has on the dynamic properties of wood (Aratake et al. 1992, Nanami et al. 1993, Mishiro 1995). They also developed models that can be used to adjust dynamic values of modulus of elasticity obtained from acoustic wave measurements at moisture contents above the fiber saturation point (Sobue 1993). The ability to adjust these values will become more important as industrial equipment and its use becomes more widespread.

Australia and New Zealand

In recent years, the focus of efforts in the area of NDE in wood and wood products in Australia and New Zealand has been three-fold:

1. the determination of solid wood properties for end-use segregation,
2. the assessment of pulp yield for hardwoods, and
3. more recently, the rapid phenotyping of softwoods (Radiata pine) and hardwoods (*Eucalyptus* spp.) to assist in genetic breeding programs.

Considerable effort was expended in New Zealand to develop rapid densitometry techniques for use with increment cores to extensively map density variation within Radiata pine. This provides information that is used in processing optimization. Formalized sampling strategies have been developed for hardwood and softwood properties.

Australian researchers have also been at the forefront of employing NIR spectroscopy for the prediction of Kraft pulp yield in hardwoods (Schimleck et al. 2005). Early work used wood meal obtained from whole-tree chip samples. Later developments used increment cores and thereby provided a non-destructive measure of pulp yield. While the Australian interest in NIR application has focused on pulp, New Zealand researchers have assumed a solid wood focus, particularly the prediction of stiffness on everything from small, clear wood samples to veneer and profiling the stiffness distribution in cants prior to secondary breakdown (Meder et al. 2002, 2003).

While NIR prediction of wood properties is used for the assessment of wood performance in service, the next evolution in the utilization of NIR is to use NIR-predicted values to provide rapid phenotyping of key traits of genetic interest which can then be used to provide input into genetic selection and associated genetics studies.

Similar to other regions in the world, considerable effort has been expended on exploring acoustics for sorting trees, logs, and lumber (Tsehaye et al. 2000, Lindström et al. 2002, Grabianowski et al. 2006). Fibre-Gen developed a series of acoustic-based tools (HITMAN series) that has made a considerable impact in the ability to segregate standing trees and logs according to wood quality. The soon-to-be-released integrated harvester head acoustic tool, also developed by Fibre-Gen, will be the first of its kind to offer acoustic segregation at the time of harvest. The hardwood processing industry must deal with materials which contain small internal checks which form during drying. Measuring only a few millimeters or less, the checks are difficult to detect and yet are responsible for the majority of degrade when lumber is machined for appearance-grade products. Following research conducted by CSIRO, the processing division of ITC Timber Ltd. has installed an air-coupled ultrasonic system (Airstar Inc., CA) at its Heyfield (Victoria, Australia) plant to locate internal checks in hardwood lumber. Similarly, pulsed ultrasonic systems have been used successfully to image the surface of lumber to locate knots.

The tracheid effect (tracheid laser scatter to follow the surface grain angle on lumber or logs) has been exploited by the New Zealand consortium, WQI Ltd., which funded the Industrial Research Limited design and subsequent Scion modification of the Spiralometer™, a tool for the rapid radial profiling of grain angle in 10-mm increment cores. This instrument provides a measure of relative grain angle at 1 mm radial resolution along the length of the core by mapping the intensity of laser transmission through the core with respect to angular rotation of the core (the maximum transmission occurs when the laser axis and tracheid are aligned).

The recent formation of the National Plant Phenomics Facility in Australia will offer exciting new NDE opportunities for wood scientists and geneticists. One node of the facility is designed for high throughput phenotyping via foliar imaging and will be applied to Eucalypt and Acacia species. The second node provides rapid spectroscopic phenotyping via fluorescence, infra red, nuclear magnetic resonance, and NIR spectroscopy. This will provide phenomic data for large populations thereby providing statistically significant input into breeding and molecular genetic programs.

Figure 6. — Timber has a long history of being used as a construction material in China.

Europe

NDT/NDE of wood research in Europe dates back over 50 years with some of the first reported work on the establishment of fundamental relationships between various nondestructive test parameters and mechanical properties.

Currently, the European Union's policy is to promote harmonization of research efforts across Europe, with much of the work being conducted at universities and research institutes.

Significant research and equipment development activities are being devoted to the in-place assessment of historic structures. Thermography, radar, ultrasound, and shear wave propagation techniques are being investigated for evaluating in-place timbers, glulam, and other structural components.

Strength grading and sorting technologies for a range of materials, including logs and lumber, are being rigorously evaluated. NDT techniques that utilize bending stiffness, X-rays, and various sound propagation and vibration techniques are being studied for use either individually or in combination.

NDT of trees has received considerable attention in Europe. A variety of techniques, including resistance drilling, electrical impedance, ground penetrating radar, sound transmission, and mechanical tests are being utilized.

The scientific community in Europe has been actively involved in technology transfer efforts as well. After an initial symposium in Sopron, Hungary in 1994 focused on the European NDT/NDE research community, the European community has served as host for several International Nondestructive Testing and Evaluation of Wood Symposia. They have also taken a lead role in standardization efforts. Currently, a formal training course on NDT/NDE of wood is conducted annually at the University of Western Hungary. In addition, private firms have worked closely with universities and research institutes to develop, manufacture, and market precision NDT tools for a variety of end uses (**Table 2**).

Closing Remarks

A significant effort has been devoted toward the discovery and development of NDT/NDE technologies for use with wood-based products. Today, research and technology transfer efforts are underway throughout the world to further the development and use of nondestructive methods to address the many challenges that arise with using forest resources. Efforts are underway that span a broad spectrum of utilization and technology issues; from those that focus on use of previously developed techniques for solving utilization issues with plantation wood to the use of NDT/NDE techniques in the assessment of historic artifacts and structures.

Table 2. — Available NDT tools.

Company	Instrument	Principle used	Home page
Argus	Picus tree tomography	acoustic tomography	www.picus-info.com
Brookhuis Micro Electronics	Timber-Lumber Grader	resonance	www.brookhuis.com
CBS-CBT	Sylvatest Triomatic Pollux	ultrasonic ultrasonic + mechanical mechanical test	www.cbs-cbt.com
CNS Farnell	Pundit	ultrasonic	www.cnsfarnell.com
Dimter GmbH	Dimter 403 Grademaster	mechanical	http://greenteamkft.hu/gepek0404.htm
Dynalyse AB	Dynagrade Precigrader	resonance tool	www.dynagrade.com
FAKOPP Bt.	Microsecond timer, 2D timer, Ultrasonic timer, TreeSonic portable lumber grader Screw withdrawal resistance meter	acoustic tools resonance tool mechanical test	www.fakopp.com
GreCon	UPU3000	ultrasonic	www.grecon.de
IML	Resi Impuls hammer Fractometer	drilling stress wave mechanical test	www.iml.de/
John Ersson Engineering AB	Ersson ESG 240	mechanical test	www.foeretag-sverige.se/foeretag/ersson-engineering-ab-9677194.html
Lemmens N.V	Grindosonic	resonance	www.grindosonic.com/en/
Microtec	GoldenEye ViSCAN	multisensor resonance tool	www.microtec.eu
Rinntech	Resistograph Arbotom	drilling acoustic tomography	www.rinntech.com

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About the Authors

Brian K. Brashaw is Program Director, Natural Resources Research Institute, University of Minnesota Duluth, Duluth, MN, bbrashaw@nrri.umn.edu. Voichita Bucur is Visiting Research Fellow, CSIRO, Materials Science and Engineering, Clayton, Australia, voichita.bucur@csiro.au. Ferenc Divos is Professor, Faculty of Wood Sciences, University of West Hungary, Sopron, Hungary, divos@fmk.nyme.hu. Raquel Gonçalves is Associate Professor and Coordinator of Laboratory of Nondestructive Testing, University of Campinas, Campinas, Brazil, raquel@feagri.unicamp.br. Jianxiong Lu is Deputy Director, Research Institute of Wood Industry, Chinese Academy of Forestry, Beijing, China, jianxiong@caf.ac.cn. Roger Meder is Stream Leader, CSIRO Plant Industry, St. Lucia, Australia, roger.meder@csiro.au. Roy F. Pellerin is Professor Emeritus, Washington State University, Ocean Park, Washington, rf-pa-pellerin@hotmail.com. Simon Potter is Theme Leader, CSIRO Materials Science and Engineering, Clayton, Australia, simon.potter@csiro.au. Robert J. Ross is Project Leader, USDA Forest Products Laboratory, Madison, WI, rjross@fs.fed.us. Xiping Wang is Senior Research Associate, Natural Resources Research Institute, University of Minnesota Duluth, Duluth, MN, xwang@fs.fed.us. Yafang Yin is Associate Professor, Research Institute of Wood Industry, Chinese Academy of Forestry, Beijing, China, yafang@caf.ac.cn.