

NONDESTRUCTIVE TESTING OF WOOD PRODUCTS AND STRUCTURES: STATE-OF-THE-ART AND RESEARCH NEEDS

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INTRODUCTION

Though much of the research on nondestructive testing and evaluation has focused on manufactured materials such as metals, polymers, ceramics, and concrete, many applications have been found for the use of non-destructive testing techniques in the inspection and evaluation of wood products and structures. In the case of existing wood structures, these techniques are used for in-place material property determination and detection of decay. In the case of new wood products, nondestructive methods are often used for process control, quality assurance measurements, and grade classification (during and after processing).

Nondestructive techniques have also found application in the evaluation of existing wood buildings and built-up components and in the periodic inspection of other essential facilities and structures such as wood utility poles, cooling towers, dock piling and piers, scaffold planks, and mine timbers.

This paper overviews nondestructive testing research as it is applied to wood products and structures and discusses areas of research needed to more fully utilize this technology. Specifically, the discussion includes acoustic techniques such as sonically and ultrasonically induced stress waves, acoustic emissions, and acousto-ultrasonics. Other methods, including optical scanning, electrical resistance, and those relying on the ability of wood to transmit waves in the form of x rays or microwaves, are discussed. Methods incorporating mechanical vibration characteristics, such as transverse vibrations, are also included.

BACKGROUND

Wood has been used for thousands of years as a construction material for dwellings, ships, and bridges. While availability and ease of workability have historically made wood a logical choice for construction, more recent uses are inspired by its low cost and high strength to weight ratio compared with metals and cementitious materials.

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Because the material properties of wood are not tightly controlled by its natural manufacturing process, these properties exhibit inherent variability. The presence of natural defects such as knots, splits, and checks, and the wide diversity of species available for various end uses, add to this variability.

Wood is a material with orthotropic material properties. The structural properties of a wood member depend not only on its orientation when cut from a log, but also on the distribution, size, and shape of the strength-reducing characteristics within the piece and the cellular makeup of the clear wood, which varies between species. The environmental conditions in which wood is used are very important because moisture content of the wood dramatically affects its mechanical properties and its susceptibility to degradation by decay. As a result of these factors, users of wood have long recognized the need to grade or assess quality of wood building materials before they are used in construction.

Nondestructive evaluation (NDE) of wood has been performed for generations. Visual inspection for strength-influencing characteristics has been traditionally used to grade wood into end-use categories. This assessment of wood quality is based only on the size and distribution of anomalies that can be seen on the surface of the lumber. Using this technique, strength-reducing characteristics and species are empirically related to member tensile, bending, or compression performance.

Machine stress rating (MSR) has evolved as a means of measuring and evaluating mechanical properties (strength and stiffness) of lumber (Hoyle 1968, Logan 1978). This nondestructive technique is based on the fact that a beam in bending will deflect in proportion to its average modulus of elasticity (MOE) when subjected to a known load. Lumber bending strength and other properties are then empirically related to MOE by species class. Visual grading and MSR have received considerable research attention and are well established in the solid wood products industry.

In addition to solid wood products, many flake, particle, fiber, and veneer products have been developed that are a combination of wood and adhesive. Following the development of these products there has been a growing need for NDE methods for grading and quality assurance. These methods usually involve identifying internal voids undetectable by visual means, such as "blows" in particleboard. These methods are also used for sorting veneers in the manufacture of parallel laminated veneer lumber.

The concept of "sound" wood has been used for generations to describe another basic form of NDE--aural assessment. Often used to assess the condition of wood utility poles, this method relies on the ability of an inspector to recognize sound patterns, produced by hammer blows, that

are indicative of the presence of decay. Besides being rather subjective, this method is limited by the rather limited frequency range perceptible by the human ear. The upper limit of which is about 20 kHz. In response to this limitation, research has incorporated the use of electronic sensors.

Electronic sensors containing piezoelectric crystals are sensitive to much higher frequencies of sound vibration, and mechanical accelerometers are available for detecting lower frequency sound vibrations. These sensors replace the human ear and serve as the basis of most acoustic techniques used for NDE of new wood products for quality assurance and for the in-place evaluation of wood structures.

NONDESTRUCTIVE EVALUATION METHODS BASED UPON ACOUSTIC MEASUREMENTS

Differences in terminology exist in the literature on acoustic methods applied to the nondestructive testing of wood. Though referred to by several names, such as sonic stress waves, ultrasonic stress waves, ultrasonics, and ultrasonic pulse methods, these methods rely on the theory of acoustic wave propagation and usually differ only in the mode and frequency of excitation. Typically, these methods incorporate two sensors to determine wave speed, the first at one location on the member used to start a timer and the second at another location on the member used to stop the timer. Some devices include signal processing hardware for time and frequency domain analysis.

The basic theory of acoustic wave propagation in a solid material incorporates the fact that energy storage (wave speed) and energy dissipation (damping or attenuation of the wave) characteristics are controlled by the same mechanisms that determine the mechanical properties of the material (Jayne 1959).

Sound Velocity Techniques

The determination of wood material properties using acoustic wave propagation has attracted considerable research effort. Bertholf (1965) described the use of elementary stress wave theory for the prediction of dynamic strain in wood. Galligan and Courteau (1965) applied this theory for the measurement of MOE in structural lumber by inducing stress waves and measuring wave passage time. This work led to the use of sonic stress wave velocity as a predictor of MOE, modulus of rupture (MOR, ultimate bending load capacity), and other material parameters (Kaiserlik and Pellerin 1977, Pellerin 1965, Ross and Pellerin 1988, Vogt 1985).

A high correlation (correlation coefficient of about 0.90) has been observed between stress wave velocity predictions of MOE and bending MOE from bending tests. It is more difficult to predict MOR using stress wave velocity because the presence (and location) of defects (such as knots) and the slope of grain have a significant effect on MOR but much less of an effect on longitudinal stress wave velocity over the length of a typical piece of structural lumber. Because the defects in wood affect the straightness of the grain (fiber direction) in the wood, any method that is sensitive to the slope of grain has high potential for assessing the strength of wood. Gerhards (1980) investigated the

effects of crossgrain on stress wave velocity and found that wave speed varied by as much as 1% per degree of grain angle up to about 30°. This study concentrated on local measurements with respect to grain deviations.

Using stress wave velocity measurements, Bucur and Archer (1984) determined the elastic compliance matrix for various species of wood. Shear moduli, Young's moduli, and Poisson's ratios for the longitudinal, radial, and tangential directions of the wood correspond to various coefficients of this matrix.

The relative change in moisture content of wood as it dries is reported to be well correlated with the speed of ultrasonic pulses (James et al. 1982). This fact has potential as a means to monitor and affect control of the drying process of wood.

Stress wave velocity measurements have been used to predict material properties in a variety of wood products including structural composite lumber, particleboard, roof and floor sheathing, floor underlayment, and medium density fiberboard (Ross and Pellerin 1988). Jung (1979) suggested stress wave grading techniques for use on veneer sheets used in the manufacture of parallel laminated veneer (PVL). Increases of 30% in allowable bending stress are being realized by sorting PLV strips using stress wave measures of MOE.

Stress wave velocity measurements have also been used to locate the presence and extent of decay in wood members. Hoyle and Pellerin (1978) used a sonic stress wave device to identify areas of decay in two school buildings constructed with glued-laminated timber arches. Areas of decay were successfully mapped out in the wooden arches by comparing stress wave velocity measurements from nondecayed portions of the arches to those from decayed portions. This correlation between perpendicular-to-grain (radial and tangential) stress wave velocities and levels of decay has been further investigated by Rutherford (1987), who found that stress wave velocity measurements could be used to predict about 80% of the variability in MOE for decayed and nondecayed portions of the wood.

Nondestructive tests on a wood barn by Lanius et al. (1981) compared two methods, sonic stress wave velocity measurements and visual grading. Visual-grading estimates of strength and stiffness and those based upon stress wave measurements were compared statistically. It was found that the stress wave method yielded mean material property estimates comparable to the visual grading technique. Additionally, the authors noted the importance of the stress wave measurements in detecting low-strength members.

Acoustically based NDE devices have found widespread use in the electric power industry and are used to monitor the structural condition of wood utility poles subject to the degradative effects of decay and insect attack (Hiller et al. 1965, Shaw 1978, Arita and Kuratani 1984). Bulleit and Falk (1985) worked with the power industry to investigate the use of stress wave velocity measurements to distinguish between strength-reducing decay and non-strength-reducing growth ring separations (ringshake). Using the results of field test measurements and finite element model analysis, they concluded that stress wave velocity measurements alone were not sufficient to confidently differentiate between ringshake and decay.

These acoustic NDE devices have also been useful in the inspection of marine pilings subjected to marine borer attack and decay (Walden and Trussel 1963, Pellerin 1978, Agi 1978, Aggour et al. 1984). Using a procedure similar to wood utility pole inspection, increases in wave passage time attributable to damaged wood are compared with a baseline time measurement for undamaged wood.

An ultrasonic stress wave device has been investigated for use in the detection of straight-grained wood in lumber to provide information for cutting decisions (McDonald 1978). Utilizing a pulsed, 500 kHz transducer and a 1 MHz receiver to propagate sound through wood, this patented (McDonald and Cox 1972) through-transmission technique locates all internal and surface defects that are associated with local grain-angle changes and includes location of decay or rotted wood. Using water as a couplant between the wood and the sensor, the device has been shown to function adequately for hardwood and softwood species, rough-sawn or planed, and green or dry lumber of thicknesses up to 4 in.

Application of sound velocity techniques for in-place wood structures has seen limited implementation because of the important coupling requirements necessary for proper signal transmission. Improvements in transducer construction and the development of self-coupling transducers may improve the utility of these techniques.

Acoustic Emission Techniques

Most of the failure modes that occur in wood are fracture-type mechanisms that emit high-frequency sound energy. Each release of sound energy is typically referred to as a burst of acoustic emission (AE). These brittle-type failure processes begin with microscopic fractures, particularly at stress concentrations around naturally occurring defects or those resulting from the manufacturing process. Acoustic emission techniques have been used extensively as NDE tools for materials other than wood. Typically, the material being evaluated is subjected to a proof load while the quantity and location of AEs are measured.

Although most of the research in utilizing AEs from wood has focused on damage occurring during destructive testing, recent research by Groom and Polensek (1987) shows that bending strength, proportional limit load, and ultimate bending deflection of lumber could be predicted with some accuracy through AE measurements below the proportional limit. Porter et al. (1972) evaluated use of AEs to assess quality of finger joints in wood products. It was concluded that the rate of AEs generated just beyond the proportional limit of the material was a reasonable predictor of finger joint strength.

Wood decay within a structural member causes significant loss of strength before one can visually detect the presence of decay. Beall and Wilcox (1987) used AE techniques to quantify the level of incipient decay in wood members by monitoring AEs during a compression test of small blocks of wood loaded in the radial direction. The specimens with early decay were found to begin emitting sound energy at a much lower load than the nondecayed control specimens.

As research progresses toward understanding the mechanisms that generate AEs during destructive tests of wood products, the technology will

become more useful for NDE of in-place wood members. For example, many types of chemicals are applied to wood to enhance its behavior for a particular end use. Some chemical treatments, such as those used for fire retardancy, are suspected to have a degrading effect on wood strength if subjected to temperatures in the range of 150 to 180°F. Monitoring AEs while testing the treated wood may provide a useful index of damage resulting from these treatments.

Waveform Analysis Techniques

There is considerably more information available in the acoustic waveform received through a material than is contained in the velocity measurements previously described. High-frequency sound waves (20 to 300 kHz) that pass through a material are influenced by the properties of the material. Acousto-ultrasonics is a technology that combines the AE analysis of the received waveform with ultrasonic pulsing technology. A typical system uses resonant sensors. Acousto-ultrasonics can be used in either a through-transmission or a one-sided mode. Both the time and the frequency domains of the received waveform are evaluated in a relative sense, using measurements such as waveform ringdown counts, measures of average signal level (root mean square, RMS), peak amplitude, and frequency content.

Patton-Mallory et al. (1987) used multiple waveform characteristics to distinguish decayed wood from nondecayed wood under controlled conditions in the laboratory. Dunlop (1983) analyzed the velocity and damping characteristics of longitudinal compression waves to evaluate deterioration in wood utility poles. The technique indicated that wood decay influences attenuation to a greater degree than it influences wave velocity.

Beall (1987) evaluated waveform RMS to successfully monitor glue-line curing of a wood adhesive connection and found RMS to increase proportionally with the curing of the adhesive. Lemaster and Dornfeld (1987) used acousto-ultrasonics in an effort to detect knots in lumber, decayed wood, grain orientation, and wood moisture content. They concluded that the laboratory technique looked promising for detecting knots, decayed wood, and a range of grain orientations. The results were inconclusive for detecting moisture content changes. The acousto-ultrasonic technique is still evolving and may have an important role in future evaluation of wood structures after additional research is undertaken.

NONDESTRUCTIVE EVALUATION METHODS BASED ON VIBRATIONAL MEASUREMENTS

While transverse vibrational techniques have been used to assess the material properties of wood members in bending (Pellerin 1965) and have led to the development of commercially available grading devices, recent efforts have been directed towards a better understanding of the time and frequency domain characteristics of longitudinally induced acoustic signals. Sound wood of a particular geometry has characteristic damping properties that influence the propagation of different frequencies of sound or vibration. The measurement of energy storage or energy loss can be made in the time or frequency domain. Depending on

the method used, lower frequency (0 to 20 kHz) or higher frequency (20 to 350 kHz) ranges are analyzed.

Wang (1980) investigated the change in the fundamental mode of frequency for wood specimens exposed to decay fungi by measuring their vibrational characteristics. Increasing levels of decay exposure dramatically reduced the stiffness of the specimens and hence lowered the fundamental mode of frequency.

Modal analysis techniques have also been used for the determination of in-place wood utility pole stiffness and strength (Murphy et al. 1987). This technique monitors the frequency content of the pole and utilizes the fact that stronger and stiffer poles vibrate at higher frequencies than do poles degraded by wood decay. Frequency content can be related to pole condition and hence to expected remaining life.

Additional research is needed in this area to correlate the vibrational characteristics (energy storage and energy dissipation) of the wood member with its stiffness and strength while accounting for the presence of knots, splits, grain deviations, incipient decay, and other defects.

OTHER NONDESTRUCTIVE EVALUATION METHODS APPLIED TO WOOD

In addition to acoustically based NDE methods, a number of other techniques have been applied to the evaluation of wood and wood structures. Many NDE systems have been developed and implemented for the NDE of wood products in a myriad of applications before, during, and after processing from logs to finished wood products. Included are the use of microwaves, x rays, lasers, optics, and digital images. A brief summary of these applications follows.

Microwaves have been used to detect defects in wood products based on wave sensitivity to density changes and grain direction. Using a rotating microwave transmitter, the grain angle at the surface of wood has been measured under laboratory conditions (James et al. 1985). Application of the technique, however, will require additional research to account for the interaction between density and moisture content effects.

The surface grain angle of wood can be measured by two other methods. One uses an electrical capacitance technique to obtain the grain angle based on the dielectric constant of wood, which is about 1.5 times greater along the grain than across the grain (McDonald and Bendtsen 1985). The other is an optical measurement using a laser light source and detectors to measure the variations in the intensity of light, reflected from the wood surface to sense grain direction and other defects (Soest 1987).

X-ray tomography, also known as computerized axial tomography (CAT), uses a photon source and an array of receivers to measure the absorption of gamma rays. This technique is capable of determining internal damage in wood (Ellinger et al. 1979, Funt and Bryant 1987) and has found application mainly in the detection and location of internal defects in round wood material, such as logs, poles, and pilings. Defects located include knots, cracks, worm holes, and decay.

Nuclear magnetic resonance (NMR) imaging of logs has been explored (Chang et al. 1987, Hailey and Swanson 1987), with positive results that are predicted to have an impact on future NDE applications of assessing the internal quality of wood. Digital images of slices of logs have shown the internal wood structure and defects in detail. Pattern recognition techniques will be necessary to automate the interpretation of such images for future application. Practical application of these commonly used medical devices for wood evaluation is limited by high cost and by the lack of portability necessary to test in-place structures.

Several optic systems have been developed for sensing and locating surface defects on lumber surfaces for grading processing decisions (Connors et al. 1987, Godinez 1987, Wallis 1987). These systems collect reflected light from the board surface or process analog or digital images from which pattern recognition algorithms obtain the defect information. Surface quality and acceptable blemishes are variables that must be given serious attention with these systems when transferring the technology to the production line.

RESEARCH NEEDS

This discussion indicates there are several nondestructive test methods that are being used for the evaluation of wood products and structures. However, many of these techniques cannot be fully utilized until more information is available to help interpret NDE measurements.

Specific areas of need are in relating NDE parameters to wood material properties and estimates of remaining life. This is especially important in the case of degraded wood. When estimating or predicting the strength of a piece of wood, it is known that flaws often cause failure. Techniques that can reliably and economically detect the presence of flaws will be considered useful in evaluating the strength of members. Research is also needed to bridge the gap between the known presence of a flaw, or decayed area, and the calculated strength or lifetime prediction.

Quality assurance and quality control procedures are emerging areas requiring research. Particularly for wood composite products and built-up wood members, reliable methods are needed to determine adhesive-to-wood bond strength and to assess mechanical properties for chemically treated wood materials. The challenge of NDE of wood products is enhanced by the natural variation found in this unique building material that is manufactured by nature.

LITERATURE CITED

Aggour, M. S., Ragab, A. M., White Jr., E. J., Determination of In-Place Timber Piling Strength, Transportation Research Record 962, Univ. of Maryland, College Park, pp. 69-77, 1984.

Agi, J. J. Nondestructive Testing and Structural Analysis of In-Place Wood Marine Piling, Proceedings of the Fourth Nondestructive Testing of Wood Symposium, Washington State University, Pullman, WA, 1978.

- Arita, K., and Kuratani, K., Wooden Pole Tester: For Determining the Strength of Decayed Poles, Japan Telecommunications Review, Nippon Telegraph and Telephone Public Corp., Tokyo, Japan, pp. 167-173. July 1984.
- Beall, F. C., Wilcox, W. W., Relationship of Acoustic Emission during Radial Compression to Mass Loss from decay, Forest Prod. J. 37(4): 38-42, 1987.
- Beall, F. C., Acousto-Ultrasonic Monitoring of Glueline Curing, Wood Fiber Sci. 19(2): 204-214, 1987.
- Bertholf, L. D., Use of Elementary Stress Wave Theory for Prediction of Dynamic Strain in Wood, Bulletin 291, Technical Extension Service, Washington State University, Pullman, WA, 1965.
- Bucur, V. and Archer, R. R., Elastic Constants for Wood by an Ultrasonic Method, Wood Sci. Technol. 18: 255-265 (1984).
- Bulleit, W. M., and Falk, R. H., Modeling Stress Wave Passage Times in Wood Utility Poles, Wood Sci. Technol. 19: 1983-191, 1985.
- Chang, S. J., Wang, P. C., and Olson, J. R., Nuclear Magnetic Resonance Imaging of Hardwood Logs. Proceedings 2nd International Conference on Scanning Technology in Sawmilling, Oakland/Berkeley Hills, CA, IX-1-IX-8, Oct. 1987.
- Connors, R. W., Klinkhachorn, P., McMillin, C. W., Franklin, J. P., Ng, C., A Computer Vision System for Grading Hardwood Lumber, Proceedings 2nd International Conference on Scanning Technology in Sawmilling. Oakland/Berkeley Hills, CA, XV-1-XV-7, Oct. 1987.
- Dunlop, J. I., Testing of Poles by Acoustic Resonance, Wood Sci. Technol. 17: 31-38. 1983.
- Ellinger, H., Morgan, I. L., Klinksiek, R., Hopkins, F., and Thompson, J. N., Imaging Applications for Automated Industrial Inspection and Assembly. Proceedings of the Society of Photo-Optical Instrumentation Engineers, Washington, DC, Apr. 1979.
- Funt, B. V., and Bryant, E. C., Detection of Internal Log Defects by Automatic Interpretation of Computer Tomography Images. Forest Prod. J. 37(1): 56-62, 1987.
- Galligan, W. C., and Courteau, R. W., Measurement of Elasticity of Lumber With Longitudinal Stress Waves and the Piezoelectric Effect of Wood, Proceedings of the Second Symposium on the Nondestructive Testing of Wood. Washington State University, Pullman, WA. 1965.
- Gerhards, C. C., Effect of Cross Grain on Stress Waves in Lumber, Forest Products Laboratory Research Paper FPL 386, U.S. Department of Agriculture, Forest Service, Madison, WI, May 1980.
- Groom, L., and Polensek, A., Nondestructive Prediction of Load-Deflection Relations for Lumber, Wood Fiber Sci. 19(3): 298-312, 1987.

- Godinez, P. A., Automated Optical Inspection of Wood Grain Patterns and Defects, Proceedings 2nd International Conference on Scanning Technology in Sawmilling, Oakland/Berkeley Hills, CA, XVI-1-XVI-5, Oct. 1987.
- Hailey, J. R. T., and Swanson, J. S., Imaging Wood Using Magnetic Resonance, Proceedings 2nd International Conference on Scanning Technology in Sawmilling, Oakland/Berkeley Hills, CA, VII-1-VII-12, Oct. 1987.
- Hoyle, R. J., Background to Machine Stress Rating, Forest Prod. J. 18(4):87-97, 1968.
- Hoyle, R. J., and Pellerin, R. F., Stress Wave Inspection of a Wood Structure, Proceedings of the Fourth Nondestructive Testing of Wood Symposium, Washington State University, Pullman, WA, 1978.
- James, W. L., Boone, R. S., and Galligan, W. L., Using Speed of Sound to Monitor Drying in a Kiln, Forest Prod. J. 32(9): 27-34. 1982.
- James, W. L., Yen, Y., and King, R. J., A Microwave Method for Measuring Moisture Content, Density, and Grain Angle of Wood, Forest Products Laboratory Research Note FPL-0250, U.S. Department of Agriculture, Forest Service, Madison, WI, 1985.
- Jayne, B. A., Vibrational Properties of Wood as Indices of Quality. Forest Prod. J. 9(11): 413-416, 1959.
- Jung, J., Stress-Wave Grading Techniques on Veneer Sheets, Forest Products Laboratory Research Paper FPL 27, U.S. Department of Agriculture, Forest Service, Madison, WI, 1979.
- Kaiserlik, J. H., and Pellerin, R. F., Stress Wave Attenuation as an Indicator of Lumber Strength. Forest Prod. J. 27(6) : 39-43. 1977.
- Lanius, R. M., Tichy, R., and Bulleit, W. M., Strength of Old Wood Joists, J. Struct. Div. ASCE 107(ST12), 1981.
- Lemaster, R. L., and Dornfeld, D. A., Preliminary Investigation of the Feasibility of Using Acousto-Ultrasonics to Measure Defects in Lumber, J. Acoust. Emiss. 6(3): 157-165, 1987
- Logan, J. D., Machine Stress Rating. Proceedings of the Fourth Nondestructive Testing of Wood Symposium. Washington State University, Pullman, WA. 1978.
- McDonald, K. A., Lumber Defect Detection by Ultrasonics, Forest Products Laboratory Research Paper FPL 311, U.S. Department of Agriculture, Forest Service, Madison, WI, 1978.
- McDonald, K. A., and Bendtsen, B. A., Localized Slope-of-Grain--Its Importance and Measurement, Proceedings of the Fifth Nondestructive Testing of Wood Symposium, Washington State University, Pullman, WA. pp. 477-489, 1985.
- McDonald, K. A., and Cox, R. G., Ultrasonic Detection of Lumber Defects, U.S. Patent No. 3,664,180, 1972.

- Miller, E. D., Taylor, F. L., and Popeck, R. A., A Sonic Method for Detecting Decay in Wood Poles, American Wood Preserves Association, Form No. 1351, 1965.
- Murphy, M. W., Franklin D. E., and Palylyk, R. A., A Nondestructive Testing Technique for Wood Poles, B.C. Hydro Research and Development, Surrey, BC, 1987.
- Patton-Mallory, M., Anderson, K. D, and DeGroot, R. C.. An Acousto-Ultrasonic Method for Evaluating Decayed Wood, Proceedings of Sixth Nondestructive Testing of Wood Symposium, Washington State University, Pullman, WA, pp. 167-189, 1987.
- Pellerin, R. F., Vibrational Approach to Nondestructive Testing of Structural Lumber, Forest Prod. J. 15(3): 93-101, 1965.
- Pellerin, R. F., Nondestructive Testing of Wood--A Possible Method for Timber Piling, Proceedings of the Fourth Nondestructive Testing of Wood Symposium, Washington State University, Pullman, WA, 1978.
- Porter, A. W., El-Osta, M. L., and Kusec, D. J., Prediction of Failure of Finger Joints Using Acoustic Emissions, Forest Prod. J. 22(9): 74-82, 1972.
- Ross, R. J., and Pellerin, R. F., NDE of Wood-Based Composites With Longitudinal Stress Waves, Forest Prod. J. 38(5): 39-45, 1988.
- Rutherford, P. S.. Nondestructive Stress Wave Measurement of Incipient Decay in Douglas Fir, M.S. Thesis, Department of Civil and Environmental Engineering, Washington State University, Pullman, WA. 1987.
- Shaw, D. A., Bandpass Filter Comparator for Confirming the Absence of Serious Internal Voids in Wood Poles, IEEE Trans. Instrum. Meas. IM-27 (31), 1978.
- Soest, J. F., Applications of Optical Measurements of Slope of Grain, Proceedings 2nd International Conference on Scanning Technology in Sawmilling, Oakland/Berkeley Hills, CA, XII-1-XII-10, Oct. 1987.
- Vogt, J. J., Evaluation of the Tensile and Flexural Properties and Internal Bond of Medium Density Fiberboard Using Stress Wave Speed and Attenuation, M.S. Thesis, Washington State University, Pullman, WA, 1985.
- Walden, C. C., and Trussell, P. C., Sonic Inspection of Marine Piles. Wood Pres. News, Jan. 1963.
- Wallis, H., Defect Detection for Wood Classification, Proceedings 2nd International Conference on Scanning Technology in Sawmilling, Oakland/Berkeley Hills, CA. XVIII-1-XVIII-8, Oct. 1987
- Wang, S., Suchsland, O., and Hart, J. H., Dynamic Test for Evaluating Decay in Wood. Forest Prod. J. 30(7): 35-37, 1980.