TECHNIQUES FOR HIGH RESOLUTION IMAGING OF WOOD STRUCTURE

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Abstract: High resolution imaging of wood requires the development of measurement techniques for nondestructive characterisation of this material. The techniques ranging from ionizing radiation to thermal techniques, microwaves, ultrasonics and nuclear magnetic resonance, provide excellent means of obtaining information about the internal structure of wood. The most relevant technique for the imaging of wood depends upon the particular application.

Keywords: wood , nondestructive characterisation, structure imaging, ionising radiation technique, thermal technique, microwaves, ultrasonics, NMR imaging

Introduction: The development of measurement techniques for nondestructive evaluation of the physical properties of wood has its origin in the necessity of solving practical problems without destruction of the integrity of the object under inspection.

The earliest nondestructive evaluation of wood was visual inspection, largely used even today for the grading of wood products (lumber, poles, etc) The development of scientific nondestructive methods was possible in the 20th century with the development of the theory of elasticity and of the corresponding instrumentation for the measuring of wood properties. Given the hierarchical structure of wood (annual rings at cm. scale, cells at mm scale, cell walls at µm scale, fibrils at nm scale and cellobiose molecules at Å scale), it is obvious that one should seek multiscale characterization tools.

The characterization of wood properties is critical for the understanding of material behavior and performance under operating conditions (Ross and Pellerin 1991). The large number of potential methods for nondestructive evaluation of wood requires a synergism of many scientific and engineering disciplines. Comprehensive monitoring of the quality of the products implies multiple sensing methods to determine the fuller spectrum of parameters that could be part of an in-process technology (Beall 1996).

The nondestructive methods can be classified in terms of the physical property of interest (Sobue 1993) and the particular application (for example the determination of moisture content, density, detection of defects in timber as knots, etc.).

Another criterion of classification of nondestructive techniques is the characteristic wavelength (Bucur 2003) of the radiation that interacts with wood specimen (X-ray, infrared, microwave, ultrasonic, nuclear magnetic resonance).

The general understanding of the interaction between the electromagnetic waves and the wood material under inspection must be based on an accurate description of the phenomena, with an increasing degree of sophistication of the theoretical models.

The technological progress achieved with nondestructive characterization techniques in the second half of the 20th century permitted the development of computed tomography for imaging of internal structure of wood from a complete set of projections of relevant physical parameters of this material. The resolution of different techniques covers a very large spectrum ranging from 10^{-9} m for X-rays, to 10^{-2} m for ultrasonic waves or 10^{-1} for microwaves. The NMR (Nuclear Magnetic Resonance) is totally nondestructive and noninvasive for wood. The availability in the future of low-cost devices will contribute to the widespread use of these methods.

In that follows, we analyze five representative techniques for high resolution imaging of wood structure: ionizing radiation techniques, thermal techniques, microwave techniques, ultrasonic techniques and NMR techniques. The images obtained are those of natural structural elements of solid wood such as: annual ring path, earlywood, latewood in annual ring, grain orientation, curly fibers, pith, core, bark, as well as natural defects like knots, decayed zones, resin pockets, cracks, zone with high moisture content, wet core, etc. For wood-based composites the voids, blisters, delaminations, and other adhesion defects are the main technological defects. The scale of these defects is between 10^{-1} and 10^{-3} m . All methods described in this article can be used *in situ* and *in vivo.*

Ionizing radiation (X-ray, gamma ray) techniques : The tomographic images produced with ionizing radiation are called tomograms or slices and are obtained from the translation and rotation of the source and detectors around the specimen, which is a log, a plank or a board. The parameter measured is the attenuation coefficient of X-rays or gamma rays.

In an inhomogeneous medium like wood, the attenuation coefficient depends on both the quantum energy of the ionizing radiation and the chemical composition of the object under inspection. The slices produce spatial information, in 3D, that makes it possible to discern zones of low attenuation contrast. The density variation observed on tomographic images is due to the distribution of various anatomic structural elements of the specimen under inspection and to the water content in the cell walls and in lumina. The tomograms are obtained by calculation, using a sophisticated computer program that involves a complex technology (Kak and Slaney 1988) .

First generation tomograms of wood structure have been obtained with one source and detector acting in parallel, by translation. The sample was rotated by a 1° step angle and the whole image was obtained for 180° of collected data. The second generation tomograms were also obtained by translation, using an array of detectors that made simultaneous measurements through different angles during a single, transverse inspection. The sample was rotated by the array beam angle. The third generation tomograms are produced by a fanning movement, with a scanner provided with many detectors located on an arc focused at the radiation source. The fourth generation of scanners has also a fan system of detection, and the detection array is located on a circle that surrounds the source and the sample. (Schmoldt 1996, Schmoldt et al. 1999; 2000)

The advantages of ionizing computed tomography are numerous when compared with conventional radiography such as : no film and optical densitometry, data in real time, improvement of calibration procedure, large volume of the material inspected, etc.

The scanning parameters are influenced by different factors such as : wood species, size of the specimen, level of contrast in density for different defects, end use of scan information, with large scale or fine details, speed of scanning required for the production context. (Grönlund et al. 1994; Wagner et al. 1985; 1989).

Portable and fixed equipment has been used for different purposes.

The portable equipment was designed to be used in situ inspection of trees (Habermehl and Ridder 1992) , poles and building elements. Gamma rays, which are mono energetic, were used in this case. Fixed equipment is represented by the industrial scanners in saw mills (Bucur 2003).

Applications of this technique are relevant for the inspection of logs and lumber (Asplund and Jahansonn 1984), determination of stability of wooden construction elements (Niemz et al. 1997), preservation of monuments and fine arts objects, trees, arboriculture, growth rate assessment, pollution effects on trees, dendrochronology, dendroarcheology (Unger et al. 1988), wood biology, wood drying, defect detection in wood-based composites, etc. .

Thermal techniques: Thermography is a generic term for a variety of techniques used to visualize in plane on a map view, the temperature at the surface of objects.

The physical parameter under investigation is the temperature. The thermal image is the result of a very complex interaction between heating source, the material and the defects. Active or passive heating procedures can be used. In wood science, thermography is a relatively new field of study. (Luong 1996; Tanaka and Divos 2000). Thermal imaging of sub-surface temperature distribution on wood-based composites to ascertain the integrity of sub-surface structure was developed at Stuttgart University, in Germany (Busse 2001; Wu and Busse 1995, 1996). Fig. 3 shows the presence of a defect (knot) under several veneer sheets of different thicknesses.

The active heating procedure, or stress-generated thermal field under cycling loading , was used to show the influence of defects on mechanical properties of wood. With lock-in thermography, a large sample depth range can be observed. Lock-in thermography can provide three types of image : thermographic, phase and magnitude images. The development of lock-in thermography allows the visualization of temperature distribution of oscillating components.

The passive heating method has a large field of applications for knot detection, slope of grain, imaging of moisture content distribution, wood rupture phenomena and imaging of cavities in trees. An advantage of passive heating over the active heating procedure is its ability to produce temperature distributions without resorting to mechanical loading of the material. The thermal stress is relatively low and does not damage the material. The disadvantage of the passive method is that the thermal images are transient and require a fast recording system to capture the most interesting images during the test. The most widely used for in situ detection is with an infrared camera, which produces an image of an object through electronic detection of infrared emitted from the object. The development of infrared video cameras has extended the wavelength range of visible light video cameras to a thermal infrared range between 3 and 12 µm. This procedure is very appropriate for the detection of cavities on trees in parks and public gardens. (Catena and Catena 2000).

Microwave Techniques: The imaging of wood structure using microwave techniques is based on the determination of its dielectric properties . For the correct interpretation of microwave imaging it is necessary to know the response of the material to the electrical and magnetic fields, and also to understand the mechanism of the interaction between the sample and the probe.

The industrial applications were originally oriented primarily toward improving of drying and gluing technology. Today, the industrial applications of the microwave imaging techniques are related to the detection of internal defects such as knots, spiral grain, slope of grain, structural discontinuities of logs, lumber and wood-based composites.

There are two basic microwave techniques, the transmission and the reflection technique. Signal analysis of probes is relatively simple and is related to the measurement of amplitude, phase and the polarization of the waves. These parameters are used for image reconstruction of wood structure.

Today the areas that may benefit from microwave imaging techniques are related to the internal defect detection of logs, lumber and wood-based composites, and also to the imaging of vegetation including leaves, stalks and stems under various moisture and temperature conditions over a wide range of frequencies (Choffel 1999; Ulaby and Jedlicka 1984).

The imaging of wood structure can be accomplished by scanning in the proximity of the sample with a resolution given by the aperture size. The images can be obtained in the far field or in the near field.

In the far field, the smallest detectable defect size is determined by the ratio $d / \lambda > 1$, where d is the length of the defect in the plane normal to the microwave vector and λ is the wavelength. The probes used to evaluate the properties of the medium can be either scatterometers or radars, which measure the scattering properties, or reflectometers, which measure the reflectivity of the medium due to its inhomogeneities and defects.

The probes can operate in the proximity of the medium as open-ended coaxial lines, cavity resonators or antennas. By moving the position of the transmitter, an image of the medium can be obtained. While microwave techniques have shown great potential for lumber inspection, their applicability seems to be limited by the difficulty of identifying the nature of the defects. To overcome this problem, a vision system has been coupled to microwave antennas.

Microwave imaging technique has several advantages such as: the non contact operating system and relatively small size of antennas (determined by the wavelength at microwave frequencies); the fine resolution of measurements which increases the ability of this technique to detect defects, and measurements of the wave parameters, such as amplitude, phase and polarization in real time.

The difficulties of applying microwave imaging to wood material arise from inherent material properties, such as the anisotropy, heterogeneity, and the presence of natural defects in wood.

The main disadvantage of the microwave system is that at a high rate of inspection, in a mill, the mechanical vibrations of logs or lumber disturb the measurements of polarization.

Ultrasonic Techniques : Ultrasonic tomography is a diffraction type tomography that is non-invasive and safe at low energy levels. As in X-ray computed tomography, ultrasonic tomography refers to the cross-sectional imaging of an object from either transmission or reflection data collected by illuminating the sample from different directions.

Different types of ultrasonic waves can be used for wood imaging, but the most common are bulk longitudinal waves. Ultrasonic images can be reconstructed from all characteristic parameters of the wave: time of flight, amplitude, frequency spectra of the waveform, the phase, etc. The energy distribution and energy flow are important parameters for enhancing the image contrast (Berndt et al. 1999).

There are three main types of algorithms that can be used to form tomographic images from ultrasonic data: transform techniques, iterative techniques and direct inversion techniques.

For the algebraic reconstruction algorithms (ART), each equation corresponds to a ray projection. The sums of the computed rays are a poor approximation of the measured ones, and the image suffers from significant noise.

The simultaneous iterative reconstruction technique (SIRT) reduces the noise of ART and produces better images. The factors that limit the accuracy of the images obtained with diffraction tomographic reconstruction are related firstly to the theoretical approach to the approximations in the derivation of the reconstruction process and secondly to the experimental limitations (Biagi et al. 1994). High resolution images have been obtained for small, clear specimens of different species, for standing trees, for lumber and for wood based-composites. 2D imaging requires advanced signal processing and modern digital computers (Socco et al. 2000; 2002)..

The equipment for ultrasonic imaging can operate in mode A, B and C in contact and non-contact (or air coupled) scanning, using frequencies ranging from 50 kHz to 5 MHz. As the frequency increases above 1 MHz, the image resolution increases as well as the signal attenuation (Bucur 1995) The resolution inherent in acoustic images is basically determined by the beam diameter and the pixel size.

The piezoelectric transducers used for ultrasonic tomographic imaging can operate in direct transmission mode, inducing bulk or surface waves. Conventional piezoelectric transducers in the range between 50 kHz and 1 MHz are commonly used for data acquisition. In practice, the air-coupled ultrasonic transducers are mainly used for inspection of wood based composites like veneer or low thickness fiberboard and particleboard .

Ultrasonic tomography has a very large field of applications in decay diagnosis (Martinis 2002) of standing trees in parks and public gardens, in the imaging of lumber structure (Neuenschwander et al. 1997) to reveal knots, grain deviation, cracks and compression wood, and in imaging of defects in wood composites, such as delaminations between layers and voids.

Nuclear magnetic imaging Techniques: NMR imaging is one of the most powerful and versatile techniques for characterization of materials.

The development of high speed computers and the introduction of high field superconducting magnets have increased the speed, sensitivity and flexibility of such characterizations. Only the cost of such equipment limits the utilization of NMR imaging in the fields of wood science and technology. Standard NMR parameters are the resonance frequency, the magnitude of the signal proportional to the density of the nuclei, the spin-lattice relaxation time T_1, the spin-spin relaxation time T_2, the diffusion coefficient, the flow velocity, and the spin-spin coupling time.

The values of these parameters depend on species, moisture content, physiological parameters of the wood, and on several instrumental and measurement factors including the Larmor precession frequency, temperature, etc.

On NMR imaging the pattern of annual rings is well defined as well as the presence of the pith and of the zone near the bark.

The NMR tomographic image depends on the scanning technique used, pulse sequence, and magnetic field intensity.

The NMR imaging technique relies on the interaction of nuclear magnetic moment (nuclei) in only a small, controlled zone of the sample under inspection and is achieved by placing the measured body in a spatially inhomogeneous magnetic field. Its nuclear resonance frequency is matched to the RF signal only in the corresponding zone of the object.

The NMR imaging technique can be used to investigate the spatial distribution of all parameters that can be determined by NMR, such as: densities, T_1 , T_2 , diffusion terms, etc. (Araujo et al. 1992 ; Chang et al. 1989 ; Hailey et al. 1985 ; Hall et al. 1986) Usually the nuclear spin density and relaxation time are mapped as a function of their spatial position. Using basic spatial encoding and slice selection principles, different techniques are available to form 1D, 2D or 3D images, using various spin-echo, stimulated echo and gradient echo pulse sequences. NMR signals inherently depend on the nuclear relaxation time constant, which in turn reflects the structural environment of the emitting nuclei.

There are several modalities for spatially encoding the signals. One is to apply a linear magnetic field to the original static field. In this way, nuclei on one side of the sample will feel a weaker total magnetic field than those on the other side. From such a set of data, the image of the sample is reconstructed with an appropriate algorithm.

Conventional NMR spectroscopy can be coupled with the corresponding imaging technique, and chemical structures of the specimen can be determined.

The main advantages of the NMR imaging technique are that the method is nondestructive, noncontact, relatively rapid, can be used *in situ* and *in vivo*, and does not induce any structural damage. In addition to providing a relative mapping of solid structural inhomogeneities, fluid (water, preservative solutions, etc) distributions can be observed (Pearce et al. 1997). The technique has the potential to provide an absolute measure of fluid absorption. A T_2 relaxation map can distinguish between free and bound water. The bound water is strongly bonded to the cellulose and has a much shorter T_2 than the free water. Because the NMR relaxation rates depend on the freedom of molecules to move, they are sensitive to indicators of the chemical and physical characteristics of the sample. For measurements in the presence of fluid-solid interfaces, the decay curve is a probe of the length scale of the structure. Applications such as measurement of the moisture content distribution in wood and in wood-based composites, continuos monitoring of lumber drying, adhesive curing and impregnation of wood with preservatives can be implemented in industry (Wang et al. 1986; 1990).

NMR imaging is one of the most powerful new techniques for wood science and technology and can be used to monitor industrial processes on a continuous basis in a production line.

Future availability of low-cost and easy-to-use devices will contribute to the more widespread use of this technique.

Discussion: The development of nondestructive techniques has as its principal purpose to reduce the uncertainty of wood products characteristics as influenced by the biological nature of this material.

Given the hierarchical structure of wood it is obvious that one should seek multiscale characterization tools. The problem of selecting the most relevant scale for the study of the properties of a product is a key problem for further industrial applications. For this reason a theoretical equivalent medium must be defined.

The mechanics of heterogeneous media require the definition of the representative elementary volume (Bourbié et al. 1987), which must be larger than the size of the elementary heterogeneity and, in case of wood, larger than the width of the annual ring, fiber length, etc. Under this assumption at different scales, the sample can be considered quasi-homogeneous. This approach can be applied to any physical property and the principle of physical analogies can be used. However, experimental studies as well as theoretical studies have confirmed the dependence of the properties of heterogeneous media on the scale of observation and size of the system.

Table 1 gives a comparison of the nondestructive methods discussed in this article, classified according to the wavelength of the radiation involved. The highest transmitted energy corresponding to the smallest wavelength is obtained with ionizing methods.

The interaction of X-rays with wood is accompanied by charges in the energy of the electrons.

The infrared, microwave and ultrasonic methods are related to molecular rotational and vibrational energy changes.

The NMR region is associated with transitions between energy levels corresponding to the magnetic states of atomic nuclear magnetic moment of ^{1}H, ^{13}C, ^{31}P etc.

It is generally accepted that wood is a natural composite that has a hierarchic structure, which is heterogeneous and anisotropic. Anisotropy and heterogeneity are not absolute characteristics, but are relative to a given physical property and to the scale length of the corresponding physical phenomenon, characterized by the wavelength. Having in mind the wood structure, the selection of the most relevant technique for structure imaging is directly related to the resolution required by the selected method.

Concluding Remarks: High resolution imaging obtained with computed tomography has been developed from a mathematical basis establishing that from a set of projections of relevant physical parameters it is possible to reconstruct the image of an object. The image is reconstructed by mapping of different measured parameters, using algorithms and advanced computational procedures for data collection, image reconstruction and display.

In the future, the challenge of the research activity in wood science and technology must be oriented to the development of noncontact, nondestructive techniques which can be used in situ and in vivo and not induce any structural damage in samples of various sizes ranging from laboratory small clear specimens to trees, structural elements, and industrial-size wood-based panels.

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Table 1 Comparison between different nondestructive techniques used for wood structure characterization and defect detection

Method	Parameter measured	Theoretical wavelength (m)	Sample	Structural features observed
Ionizing radiation (noncontact , invasive, in situ , in vivo for trees)	X or γ rays Attenuation	$10^{-12}\ldots10^{-9}$	Tree, logs, poles, lumber, wood-based composites	Density variation, growth rate, detection of metalic inclusions, knots, decay, influence of pollution, macrovoids in particleboards
Thermal (noncontact, noninvasive, in situ, in vivo for trees)	Temperature , phase magnitude	$10^{-5}\ldots10^{-4}$	Tree, forests, lumber, standard small clear specimens, wood based composites	Decay, knots, fiber direction, moisture distribution, effect of acid rains, rupture phenomena, subsurface integrity of composites,
Microwaves (noncontact, noninvasive, in situ)	Dielectric constants in three anisotropic directions, dielectric loss, amplitude, phase, polarisation	$10^{-3}\ldots10^{-2}$	Lumber, standard small clear specimens, wood based composites, forests	Slope of grain, knots, decay, cracks, moisture distribution, mechanical grading of lumber, lumber drying, voids in wood-based composites
Ultrasonic (contact, noninvasive, in situ, in vivo)	Velocity, time of flight, pulse length, amplitude, energy	$10^{-2}\ldots10^{3}$	Tree, lumber, structural elements, poles, wood based composites	Knots, decay, slope of grain, detection of fungal attack in wood, delaminations and voids in composites
N M R (noncontact, noninvasive, in situ, in vivo)	Relaxation times - (spin-lattice and spin-spin) , resonance frequency, magnitude	$10^{-2}\ldots10^{5}$	Tree, lumber, wood based composites, adhesion kinetics	Tree vitality, moisture distribution, knots, annual rings pattern, influence of climat, fungal induced diseases, preservative distribution, wood drying