Detection and Assessment of Decay in Wooden Utility Poles Using an Acoustic Approach

Adam Senalik¹, Megan McGovern², Frank C. Beall³, Henrique Reis^{*4}

^{1,2,4}Department of Industrial and Enterprise Systems Engineering, University of Illinois at Urbana-Champaign, 104 South Mathews, Urbana, Illinois, USA

³College of Natural Resources, University of California at Berkeley, Berkeley, CA 94720, USA

^{*1}csenalik@gmail.com; ²meg.e.mcg@gmail.com; ³fmbeall@gmail.com; ^{*4}h-reis@illinois.edu

Abstract- A plane strain, two-dimensional, finite-difference time domain model is used to simulate wave propagation through wooden utility poles cross-sections. Simulation results are then used to develop metrics capable of detecting and assessing the level of internal decay. Computer tomography scans of utility pole cross-sections are used to create simulations that accurately reflect the poles both in terms of wood density and geometry. The dependence of both the wave velocity and attenuation upon frequency and mass loss is included in the model. After model validation using analytical and experimental data, the developed metrics are then used to estimate the defect size and location within cross-sections of three different utility poles. Results indicate that detected regions of decay are within 2% of the wooden poles cross-sectional area.

Keywords- Wooden Utility Poles; Structural Lumber; Wood Decay; Mass Loss; Safety; Damage

I. INTRODUCTION

Wood is created by nature with solar energy. All over the world there exists about $4x10^9$ ha of forest, which represents about $384x10^9$ m³ of renewable biomass, out of which $0.4x10^9$ m³ saw wood is produced [1]. The use of wood as a construction material and the integration of wood residues into energy systems is an efficient way to reduce both greenhouse emissions and fossil fuel use. Continuous planting also increases wood carbon storage [2]. The low energy production costs makes wood and wood products, including wooden utility poles, competitive when compared with other construction materials such as steel and reinforced concrete [3, 4]. According to the Brazilian Association of Wood Preservation (ABPM) [4], a growing tree consumes between 18 kg and 35 kg of CO₂ per year. The production of 1 ton of dry wood sequesters 1.8 tonne of CO₂ and releases 1.2 tonne of O₂. In 12 years of growth a eucalyptus tree that produces 10 m of roundwood consumes 216 to 420 kg of CO₂; its mass reaches 250 kg; and it contributes to the sequestering of 450 kg of CO₂ and the releasing of 300 kg of O₂. Furthermore, according to the Brazilian Association of Wood Preservation (ABPM) [4], wood and wood products, including wooden utility poles, are very energy efficient. Table I shows a comparative consumption of energy to produce one tonne of several construction materials. Clearly, the ubiquity of wood and wood products is justified.

ABLE I COMPARATIVE CONSUMPSION OF ENERGY TO PRODUCE ONE TONNE OF SEVERAL MATERIALS [4]
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To produce one tonne of:	Exhausts (kg EC)			
Aluminum	4,200			
Plastic	1,800			
Steel	1,000			
Cement	260			
Simple concrete	26			
Wood	0.8			
kg EC—Equivalent kg of coal				

The two major forms of biodeterioration of wood and wood products are decay and insect attack. While many wood structures are routinely inspected for insect attack, such as termite inspection in real estate transactions, inspection for internal wood decay in wooden members is rarely performed mainly because of the lack of an effective testing method. The process of decay varies with species, but follows a sequential process of incipient, intermediate, and advanced decay. Incipient decay normally occurs with little visible change of the wood, although the dynamic strength properties can be greatly reduced. The other extreme, i.e., advanced decay, is characterized by wood with no intrinsic strength.

The economic impact of wood decay is significant. In a survey of 261 utilities across the United States that owned over 42 million poles, utilities reported purchasing approximately 252,000 poles of various species annually. This figure represented all purchases including upgrades, damage in accidents and failure from deterioration, representing a 0.6% annual replacement rate. A similar 2006 survey of utilities in the Pacific Northwest found similar results and further segregated the causes for replacement. Over half of the poles removed from service (i.e., 56%) were decayed. However, while some of these poles might have had reduced load capacity, they had not deteriorated to the point where their condition necessitated replacement. A recent Electric Power Research Institute study suggested that wooden poles last 50 years. Most utilities assume that their poles provide 30 to 40 years of service life. Others assume that wooden utility poles will last 80 years or more, far in excess of the 30

or 40 years assumed by most utilities; in most utility systems there are many lines installed in the 1950's where the vast majority of poles still remain in service. Although many utility poles still have a useful life, they are often removed from service on a precautionary basis. The replacement costs per pole depend upon size and location and typically vary from \$2,500 for small poles to about \$10,000 for larger ones.

II. RESEARCH NEEDS AND CURRENT METHODOLOGY

Clearly, there is a need to develop a nondestructive evaluation method that can reliably detect and assess the level of decay in wooden utility poles. The method should lead to a portable device capable of being used in the field. Beyond the direct cost savings provided by the use of a reliable nondestructive evaluation technique, the reduction of risk to line workers is an even greater benefit. A good literature review on methods to detect and assess wood decay can be found in Senalik et al [5], Beall et al [6], and Titta et al [7].

Several acoustic tomography (CT) studies of trees and wood poles [8-17] have been conducted. These studies have demonstrated the feasibility of using acoustic inspection as a means of locating and evaluating internal decay. However, the approaches described are infeasible for field use because (1) the equipment is expensive, (2) the methodology is computationally intensive, and (3) over one hundred measurements were required to evaluate a single cross section. The pole assessment method presented here only uses four measurements and light computational requirements, which can leads a portable instrument. These advantages greatly increase the potential for the method to be adopted for field use.

In this analysis, only four independent surface acceleration measurements were used to determine the size and general location of a decayed region within a pole cross-section. Impact wave propagation through wooden utility poles was simulated using a two-dimensional, plane-strain, finite-difference time domain (FDTD) model. The simulation results were validated using results from a simplified theoretical model and from experimental tests performed upon utility pole specimens. The validated model was used to simulate wave motion through several pole cross-sections with internal decay regions varying in diameter from zero (a pole free of defect) to half the radius of the utility pole. Simulation outputs were used to identify several metrics, i.e., rules-of-thumb, which correlated the size of the internal defect with signal characteristics. The developed metrics in identifying and assessing internal decay were then validated using experimental data collected from utility pole specimens retired from the field. These rules-of-thumb have the potential to lead to the development of a portable, easy-to-use instrument, that an operator can be used in the field to detect and assess levels of decay in wooden utility poles.

III. X-RAY COMPUTER TOMOGRAPHY OF WOODEN POLES AND MASS-LOSS FROM WOOD DECAY

Three 1.5 m long sections of Douglas-Fir poles with a cross-section diameter of approximately 380 mm were salvaged from the field. X-ray tomographic inspection was carried out every 25 mm along the length of each 1.5 m long wooden pole. This permitted characterization of the pole cross-sections and showed where the poles had decay. It also permitted an estimation of wood density at each point in a pole cross-section using the same approach described by Senalik et al [5]. Several cross-sections had areas of lower wood density, corresponding to decayed areas. Fig. 1 shows three X-ray tomographical cross-sectional views of three different poles, where the decayed regions are hatched to increase visibility. Fig. 2 shows the wood density of the cross-section of pole 966, which was computed from the X-ray computer tomography as described by Senalik et al [5]. The variation in wood density provided by the CT density images was used in the numerical simulation model presented in this paper.



Fig. 1 Computer tomography cross-sections of three Douglas Fir poles labled: (a) Pole 966, (b) Pole 491, and (c) Pole 477. The decayed regions are hatched to increase visibility, and white squares indicate positions of the transducers during experimental testing. Note checks around the poles and the bright area at the center of pole 996 as the location where a branch sprouted of the tree.



Fig. 2 Wood density values extracted from the computer tomography view of pole 966 showing a region of decay (see Fig. 1)

Following ASTM standard D1413-99, the authors recently studied the change in energy velocity and attenuation values of acoustic waves along the material principal directions in laboratory-prepared wood samples with increased amounts of decay, i.e., mass loss [18-20]. The velocity and attenuation values of the two (polarized) shear waves along each of the material principal directions were also measured. The authors have shown that wood decay leads to a continuous variation, i.e., gradation, of material properties from sound to decayed wood and not to the creation of an acoustic reflective surface separating sound wood from decayed wood. This lack of a reflective surface caused by wood decay explains some of the difficulties encountered in detecting and assessing decay using traditional ultrasonics. Note the high natural variability of wood (i.e., dependence upon moisture content, different growth ring thickness and orientation, presence of knots, splits etc.), which can mask the presence of decay. The authors [18-20] show the mass loss as a function of time exposed to decay (to 12 weeks), and the velocities and corresponding attenuations along the three material principal axes as a function of levels of decay and frequency. Data is provided for frequencies ranging from 4.5 to 200 kHz and decay exposure ranging from no decay to 40% mass loss.

IV. NUMERICAL SIMULATION OF THE WAVE FIELD EVOLUTION IN A POLE CROSS-SECTION FROM IMPACT

The structure of wood has many aspects making analytical modeling difficult. Sound wood is anisotropic, heterogeneous, has high attenuation, and it is fibrous, porous, and hygroscopic. These characteristics complicate attempts to model wave motion through wood. The work of Ting [21, 22] provided rigorous analysis of the behavior of anisotropic solids. Martin [23] provided additional analysis regarding anisotropic solids in cylindrical coordinates. Building upon the works of Ting and Martin, Payton [24] wrote a computationally series of publications in which he derived the equation of motion for a unit impulse in a semi-infinite, two-dimensional, anisotropic solid in cylindrical coordinates. While Payton's analytic solution provides great insight into wave motion, it is limited in its applicability in wood analysis as it does not allow for: (a) material attenuation, (2) inclusion of local defects such as checks and voids, and (3) changes to material properties based upon the location within the solid. The scope of Payton's work, however, does provide a means of validation for any potential wood simulation models, including this one.

Yee's staggered grid [25, 26] provides the basis of the numerical simulation model. In the model, the following two distinct locations are addressed: the center point and the impact location, i.e., source. The calculation of the center point displacement involves finding the mean displacement of the surrounding medium. The source is modeled as a Gaussian impulse and implemented through the use of a transparent source as described by Schneider [27]. There are also three regions that need to be addressed. Following Gsell [28] and Schubert [29], the wood is assumed to be both elastic and anisotropic. Adjacent to the wood is a region of air. Between the region of air and the outer extents of the model there is a reflectionless boundary. The reflectionless boundary is implemented through the use of perfectly matched layer (PML) as described by Berenger [30] with refinements provided by Liu [30, 32]. Chew [33], Chen [33], and Gedney [35]. Chew adapted the techniques for elastodynamic equations in an inhomogeneous medium [33], and Liu extended Chew's work for acoustic waves in Cartesian, cylindrical, and spherical coordinates [36, 37].

Plain strain conditions ($\varepsilon_z = \varepsilon_{z\theta} = \varepsilon_{zr} = 0$) are assumed; therefore the stiffness matrix is condensed to the following form where its terms are constructed from nominal elastic modulus values. Elastic modulus values for several species of wood are available from references [3, 38, 39].

$$\begin{bmatrix} \sigma_r \\ \sigma_{\theta} \\ \tau_{r\theta} \end{bmatrix} = \begin{bmatrix} C_{rr} & C_{r\theta} & 0 \\ & C_{\theta\theta} & 0 \\ \text{Sym} & 2G_{r\theta} \end{bmatrix} \begin{bmatrix} \varepsilon_r \\ \varepsilon_{\theta} \\ \varepsilon_{r\theta} \end{bmatrix}$$
(1)

Assuming plain strain conditions, the equilibrium equations written in terms of displacements are as follows, see Equations 2, which are numerically integrated using a finite difference scheme:

$$\rho \frac{\partial^2 u_r}{\partial t^2} = C_{rr} \frac{\partial^2 u_r}{\partial r^2} + \frac{C_{rr}}{r} \frac{\partial u_r}{\partial r} - \frac{C_{\theta\theta}}{r^2} u_r - \left(\frac{G_{r\theta} + C_{\theta\theta}}{r^2}\right) \frac{\partial u_{\theta}}{\partial \theta} + \left(\frac{G_{r\theta} + C_{r\theta}}{r^2}\right) \frac{\partial^2 u_r}{\partial \theta^2} \right)$$

$$+ \left(\frac{G_{r\theta} + C_{r\theta}}{r}\right) \frac{\partial^2 u_{\theta}}{\partial r \partial \theta} + \left(\frac{G_{r\theta}}{r^2}\right) \frac{\partial^2 u_r}{\partial \theta^2} + \rho \frac{\partial^2 u_{\theta}}{\partial r^2} + G_{r\theta} \frac{\partial^2 u_{\theta}}{\partial r^2} + \left(\frac{G_{r\theta} + C_{r\theta}}{r}\right) \frac{\partial^2 u_r}{\partial r \partial \theta} + \frac{G_{r\theta}}{\partial r \partial \theta} \frac{\partial^2 u_r}{\partial r \partial \theta} + \left(\frac{G_{r\theta} + C_{r\theta}}{r^2}\right) \frac{\partial^2 u_r}{\partial r \partial \theta} + \frac{G_{r\theta}}{\partial r \partial \theta} + \frac{G_{r\theta}}{r^2} \frac{\partial u_{\theta}}{\partial r} + \left(\frac{G_{r\theta} + C_{\theta\theta}}{r^2}\right) \frac{\partial u_r}{\partial \theta} - \frac{G_{r\theta}}{r^2} u_{\theta}$$
(2)

McGovern related the velocity and material attenuation to frequency and mass loss, i.e., density, from decay [19, 20]. The density is determined from the CT scans. The stiffness values used in the FDTD model equations are derived from the velocity values. The stiffness matrix is made up of four unique values: the radial stiffness, C_{rr} , the tangential stiffness, $C_{\theta\theta}$, the shear modulus, $G_{r\theta}$, and the radial/tangential coupling stiffness, $C_{r\theta}$. Three of these terms, C_{rr} , $C_{\theta\theta}$, and $G_{r\theta}$, are determined directly from the density and values for the radial dilatational, tangential dilatational, and shear velocities as shown in the radial/tangential coupling term is calculated using the radial stiffness term and the Poisson's ratio for Douglas-fir [3].

$$C_{rr}^{k,i} = \rho^{k,i} c_r^2 \qquad C_{r\theta}^{k,i} = \mu_{r\theta} \rho^{k,i} c_r^2 C_{\theta\theta}^{k,i} = \rho^{k,i} c_{\theta}^2 \qquad G_{r\theta}^{k,i} = \rho^{k,i} c_{r\theta}^2$$
(3)

Where:

 $\rho^{k,i} \quad \text{-- density of sound wood at location, } k=r, \, i=\theta.$

C_{il}^{k,i} -- stiffness matrix value in Pascals

 $G_{il}^{k,i}$ -- shear modulus in Pascals at a location, $k = r, i = \theta$.

c_r -- radial wave velocity

 c_{θ} -- tangential wave velocity

 $c_{r\theta}$ -- shear wave velocity

 $\mu_{r\theta}$ -- Poisson's ratio for Douglas-fir relating radial and tangential strains. It has a value of 0.382 [3].

The simulated cross-section is surrounded with a layer of air and the edge of the simulation space is surrounded by a perfectly matched layer PML [30] (see Fig. 3).



Fig. 3 Schematic diagram of model to study wave propagation in wooden utility poles

A. Time Step and Grid for the Finite Difference Time Domain Model

Chen [34] gives an empirically strict time step criterion for cylindrical coordinates that insures stability. Following Chen, the time step is given by Equation 4, where the radial velocity, c_r , is chosen because it is the maximum wave velocity.

$$\Delta t \le \frac{\Delta r \Delta \theta}{c_r \sqrt{1 + (\Delta \theta)^2}} \tag{4}$$

Fig. 4 shows the coordinate system, grid layout, and nomenclature used in the model. The points at the intersections of the gridlines shown in Fig. 4 represent locations where displacements are calculated. Choosing node spacing is a balancing act between accuracy of the simulation and minimizing calculation time. One of the goals of the simulation was to allow density information obtained from CT scan images to be used. The CT scan images have square pixels, where each pixel has a scaled edge length of 0.97 mm. The maximum distance between nodes is chosen such that it does not exceed the edge length of a pixel. The radial distance, Δr , is set equal to the edge length of a pixel. However, because the circumferential distance increases with the radius, when the circumferential distance between nodes exceeds the edge length of a pixel, a new nodal region is created (Fig. 4). The grid enhancement scheme was based upon the sub-gridding method demonstrated by Zivanovic [26] and was chosen as it is numerically stable and does not entail additional numerical error. The newly created region has an

angle between the nodes equal to one half the angle of the previous region. The half angle causes the tangential distance between nodes to be halved and doubles the number of tangential nodes. The minimum distance between nodes for each region other than the first region (which surrounds the center point) is $\frac{1}{2}\Delta r$.



Fig. 4 Model with grid enhancement scheme

Where:

Nr -- is the total integer number of radial divisions.

 $N_{\theta}\mbox{--}$ is the total integer number of circumferential divisions.

Note r₀ represents the center point

 θ_i -- is the circumferential coordinate.

 Δr -- is the radial spacing in meters between adjacent grid points.

 $\Delta \theta$ -- is the circumferential angle in units of radians.

B. Material Attenuation

Following Chew [33] material attenuation is applied to the system by use of coordinate stretching into an imaginary dimension. At each time step the displacements are solved using the finite difference scheme, and the results modified to include the attenuation resulting from stretched coordinates as shown in Equation 5, where α is the material attenuation [19, 20].

$$u_{\eta}^{n+1} \approx -u_{\eta}^{n-1} e^{-2\alpha\omega\Delta t} + \left(2u_{\eta}^{n} + \left(\frac{C_{\eta,\eta_{2}} (\Delta t)^{2}}{\rho} \right) \frac{\partial^{2} u}{\partial \eta^{2}} \right) e^{-\alpha\omega\Delta t}$$
(5)

In Equation 5, the attenuation coefficients were experimentally determined [19, 20]. They are dependent on mass loss from decay and frequency. The authors [19, 20] provide polynomials from which velocity and attenuation values can be easily calculated as a function of mass loss (up to 40%) and for a frequency range of 4.5 to 200 kHz.

V. MODEL VALIDATION

To validate the results of the proposed FDTD model, a comparison was made between the wavefront behavior as predicted by the FDTD simulation and the analytic model of a wavefront traveling through a cylindrically orthotropic medium developed by Patyon [24]. Furthermore, the numerical results were also compared with those obtained from testing real wooden utility poles in the laboratory.

A. Model Validation Using the Payton's Theoretical Results

In Payton's model plane strain is assumed and a unit impulse is assumed as the system input. For the FDTD model, an ideal defect-free circular cross-section was subjected to a narrow Gaussian pulse of six microseconds. The narrow Gaussian pulse was chosen as the input rather than a unit impulse as it produced distinct dilatational and shear waves without causing significant noise.

Furthermore, the poles are assumed to be Douglas-fir with a circular cross-section diameter of 380 mm, and individual ring thickness of 6 mm (3 mm earlywood, 3 mm latewood). These dimensions were selected as they are approximately the same as the corresponding dimensions of the physical specimens obtained for the experimental testing.

Table II shows the behavior of the predicted wavefronts. Table II is broken into two sections: dilatational and shear waves. Each section is broken into four columns: "Time", "Simulation", "Analytical", and "Overlay". The times are given in microseconds after the unit impulse for the analytical model and in microseconds after the peak of the Gaussian impulse for the

simulation. The "Simulation" column contains the simulated results shown in grayscale where white indicates peaks and black indicates troughs. The "Analytical" column contains the analytical model results as a black and white line. The "Overlay" column contains both wavefront predictions overlayed. There is excellent agreement between the model numerical simulation results and the results obtained via Payton's analytical model. Table II indicates excellent agreement between current model numerical results and Payton's analytical results.



TABLE II VALIDATION OF SIMULATED LONGITUDINAL AND SHEAR WAVE PROPAGATION WITH PAYTON'S ANALYTICAL RESULTS

B. Model Validation Using Experimental Testing of a Wooden Pole Cross-Section in the Laboratory

A simulation was then carried out using the utility pole cross-section shown in Fig.1 (pole 966), extracted from the CT images. This cross-section was also tested experimentally, and Fig. 5 shows a schematic diagram of the experimental data acquisition system. The input impact location for all tests was at the 0° location. A steel, cylindrical impact plate of 13 mm diameter and 6 mm thick was affixed at the 0° location using heavy vacuum grease to prevent the input impact from marring the pole surface. The input impact was caused by a 0.50 g, 6 mm lead pellet fired from an air gun. The air gun was positioned 150 mm from the impact plate. The air gun provided a consistent and repeatable input pulse. At each of the four monitored

locations, the magnitude of signals was recorded using accelerometers with a resonant frequency of 120 kHz. Heavy vacuum grease was used as couplant.



Fig. 5 Schematic diagram of wooden pole data acquisition system. The system excitation is an air gun shooting lead pellets. Data is recorded by accelerometers at 0°, 90°, 180°, and 270°

The accelerometer affixed adjacent to the impact plate is referred to as the source accelerometer. The space between the impact plate and the source accelerometer never exceeded 3 mm. The three remaining accelerometers, i.e., receiving accelerometers, were affixed at the following three locations: 90°, 180°, and 270° as shown in Fig. 5. Data was monitored continuously from both the source and receiving accelerometers; however, data collection began only after the voltage from source accelerometer surpassed a defined threshold of 19 mV. During each test, each accelerometer collected 4096 data points at a sampling rate of 500 kHz. Five independent tests were conducted, and the five signals were averaged to obtain a representative experimental signal at each location.

The output signals collected from the utility pole experimental tests and the signals obtained from simulations are presented in Fig. 6 for comparison. In the frequency domain, the excited bandwidths of the two groups conformed for 82% or more of the expected range. The peaks in the frequency domain of the simulation results were approximately two kilohertz lower than those observed in the pole tests. This discrepancy is mainly from differences between the nominal wave velocities assumed in the simulation space and the actual wave velocity values in the wooden test pole. For the 90° location, the magnitude of simulated signal is 250% higher than that of the pole test. This discrepancy is caused by the presence of a large region of compression wood around the 90° location in the utility pole cross-section.



Fig. 6 Experimentally recorded time domain and corresponding frequency domain records from pellet impact compared to the corresponding simulation responses at 0°, 90°, 180°, and 270° locations, respectively

The presence of compression wood is not included in the simulation model. Compression wood has several distinctive characteristics including greater density and lower wave velocity than normal wood [8, 17, 40, 41]. Wielandt [41] described a phenomenon in which ray paths of transverse waves through a cross-section avoid regions in which the wave velocities are lower. Several other researchers have encountered the same phenomenon [42-45]. Wave energy that would normally travel toward the 90° location was redirected towards other regions of the cross-section. Based upon the size of the compression wood region, and the percentage decrease in signal magnitude from the simulated signal, it would be expected that the rest of the cross-section would see an increase in signal magnitude of approximately 33%. The magnitude of the pole test signals recorded at 180° and 270° was higher than that of the simulated signals by 24 and 36%, respectively.

Clearly, the presence of a large region of compression wood explains the observed differences between the experimentally obtained results and the simulation results. Therefore, the FDTD model is considered validated. A more detailed explanation of the validation study is provided by Senalik [44].

VI. METRICS AS RULES-OF-THUMB

Using the validated model, a series of simulations were carried out with the goal of developing metrics, i.e., rules-of-thumb, useful in determining the presence of internal decay. The annual rings were assumed to be 3 mm wide. The ratio of the density of earlywood to latewood was assumed to be 0.318:1, to be representative of the ratios seen in the CT scans of the utility poles. The simulation input was modeled from an impact of a lead pellet onto a cylindrical, steel impact plate with 13 mm diameter and 6 mm thickness. The simulated cross-sections had defects, i.e., areas of decayed wood at their centers. The defect diameters were varied in proportion to the pole radii with fractional values of: 0.000 (control, free of defects), 0.133, 0.267, 0.400, 0.533, 0.667, 0.800, and 0.933. For a 380 mm pole, the fractional values correspond to a center defect diameters ranging from 25 to 175 mm in 25 mm increments. To more closely model the type of defects seen in the utility pole cross-sections, the simulated defect was assumed to be a void surrounded by 25 mm of decay using a sawtooth boundary (see Fig.7). A continuous variation of material properties from sound to decayed wood was made by assuming the properties of decayed wood to follow a half cosine law (see Fig. 7).



Fig. 7 Plane view of decayed region showing transition from sound to decayed wood with sawtooth boundary, **i**. sound wood, **ii**. Transition region is functionally graded according to a half cosine from sound wood at 100% mass to severely decayed wood at 70% mass loss, **iii**. decayed region comprised of severely decayed wood (70% mass loss) or a void.

Acceleration signals were obtained from each simulation at each of the four fixed locations around the circumference of the poles. The first was next to the source and is referred to as the 0° location. The other three locations were +90°, 180°, and -90° (270°).

In previous studies by Tiitta [45, 46] and Beall [47], it was noted that no single metric reliably detects the presence of decay in every pole cross-section; thus, three metrics were developed using the simulated data. These metrics were then validated against experimental data from utility pole cross-sections. The three metrics described here were chosen from their robustness in accurately estimating defect size across a variety of cross-sectional geometries. To normalize the metrics each of the three metrics is defined as the ratio of values obtained at the 180° location to the corresponding values obtained either at the 90° or at 270° location. The three metrics are: wave area (WA), time centroid (TC), and time-of-flight (ToF) as discussed below. For additional discussion of these three metrics, the reader refer to [44].

A. Wave Area Metric

Wave area metric (WA) is the ratio of the rectified areas of the radially traveling dilatational wave to the tangentially traveling dilatational wave, respectively. To minimize the dependence of this metric upon the interference phenomena between the radially and the tangentially traveling waves, the WA is based upon points taken early within the recorded signals.

Fig. 8 shows the shape of the radially and tangentially dilatational wavefronts traveling across a cylindrically orthotropic solid cross-section, i.e., idealised pole cross-section, as predicted by Payton's [24] analytical model. The input source is located at 0°, as shown in Fig. 8. First, the radial dilatational wave travels from the source towards the center of the cross-section (Fig. 8b and 8c). At the center, a radial wave is excited in all directions (Fig. 8d through 8f). The first arriving wave at the 180° location is the excited radial wave, as shown in Fig. 8f. The excited radial wave arrives at all locations around the circumference simultaneously; the arrival time of the radial wave is designated as τ_{180} . The tangential dilatational wave travels from the source circumferentially around the cross-section (Fig. 8b through 8d) and, for both loblolly pine and Douglas-fir, is the first wave to arrive at the 90° and 270° locations; the arrival time of the tangential wave is designated τ_{90} . Comparing characteristics of the first arriving wave at either the 90° (or 270°) location to the first arriving wave at the 180° location, is equivalent to comparing the tangentially and radially traveling dilatational waves.



Fig. 8 Wavefront traveling through a wooden pole at differing times with a source at 0°, **a.** prior to input, **b.** after input, **c.** wavefront arrives at the center of the pole, **d.** wavefront crossing the center of the pole excites a radial wave in all directions, **e.** the wavefront traveling in the tangential direction reaches the receiver locations at 90° and 270°, **f.** the radial wavefront reaches the 180° location and arrives prior to the tangentially traveling wavefront

The earliest arriving portions of the acceleration signals recorded at the 90° and 180° locations are shown in Fig. 9. By examining a portion of the 90° location acceleration signal between the time of the source input at time t = 0 and the arrival of the radial wave at time $t = \tau_{180}$, the tangential wave, arriving at time $t = \tau_{90}$, can be examined without influence from the radial wave. Fig. 9c shows the time partition used to isolate the tangential wave within the 90° location acceleration signal. The time partition used is t = 0 to $0.95*\tau_{180}$. The tangential wave continues to travel circumferentially around the cross-section and arrives at the 180° location at time $t = 2*\tau_{90}$. By examining a portion of the 180° location acceleration signal between time t = 0 and the arrival of the tangential wave, $t = 2*\tau_{90}$, the radial wave can be examined without influence from tangential wave. Fig. 9d shows the time partition used to isolate the radial wave within the 180° location acceleration signal. The time t = 0 and the arrival of the tangential wave, $t = 2*\tau_{90}$, the radial wave can be examined without influence from tangential wave. Fig. 9d shows the time partition used to isolate the radial wave within the 180° location acceleration signal. The time partition used is t = 0 to $1.9*\tau_{90}$.



Fig. 9 Time partitions for the radial and tangential waves. **a.** The tangential wave arrives at the 90° location at time $t = \tau_{90}$. **b.** The radial wave arrives at the 180° location at time $t = \tau_{180}$. **c.** The time partition used to examine the arriving tangential wave at the 90° location is t = 0 to $t = 0.95*\tau_{180}$. **d.** The time partition used to examine the arriving radial wave at the 180° location is t = 0 to $t = 1.9*\tau_{90}$

The area under the rectified, time partitioned, acceleration signals was calculated and normalized by the root mean square of the time partition. The area of 180° location signal is normalized by the area of the 90° location signal. This ratio gives an indication of the relative rate of displacement between the 180° and the 90° locations. The time partitioned regions shown in Fig. 9c and 9d show the areas examined. The wave area metric (WA) is expressed by Equation 6.

$$WA = \frac{\frac{1}{\mathsf{RMS}_{180}^{1.9^{*}\tau_{90}}} \sum_{t=0}^{t=1.9^{*}\tau_{90}} |\mathsf{A}_{180}(t)|}{\frac{1}{\mathsf{RMS}_{90}^{0.95^{*}\tau_{180}}} \sum_{t=0}^{t=0.95^{*}\tau_{180}} |\mathsf{A}_{90}(t)|}$$
(6)

Where:

WA -- wave area metric of the time partition

RMS-- root mean square

A-- acceleration amplitude

Fig. 10 shows the diameter of the center defect, expressed as a fraction of the pole radius (d/R), vs simulated values of the wave area metric (WA) for eight values of (d/R). The value of WA decreases as the diameter of the defect increases. The rate of change of the WA was higher for smaller defects than larger defects, indicating that this metric may be effective in identifying small internal defects. The trend of simulated values shown in Fig. 10 was fitted to a third order polynomial (see Polynomial in Table III).



Fig. 10 Defect size estimated from wave area metric defined by Equation 22 and is plotted against the defect diameter, d, expressed as a fraction of the pole radius, R. Trend line fitted to simulation data (see Table III).

d/R = a3x3 + a2x2 + a1x + a0								
Metric	a ₃	\mathbf{a}_2	\mathbf{a}_1	\mathbf{a}_0	r ²			
Wave Area	-0.0959	0.7666	-2.2205	2.3580	0.9982			
Time Centroid	-9.2417	172.634	-12.9509	34871	0.9982			
Time of Flight	-3.4122	14.4954	-185289	7.4246	0.9996			
d/R= defect diameter as a function of the pole radius								
x=value of metric								

B. Time Centroid Metric

The time centroid metric (TC) is the percentage difference between the area time centroid and the energy time centroid. This metric is based upon a large number of points taken from the recorded signals and is sensitive to interference phenomena.

There are two different time centroids examined in this section, the area time centroid, T_A , and the energy time centroid, T_E . The defect size is estimated through the use of fractional differences of time centroids. The area time centroid represents the time at which most of the signal content has arrived at the receiver. The area moment is the first moment of the rectified acceleration signal with respect to time divided by zeroth moment with respect to time. The energy time centroid is the first moment of the square of the acceleration signal with respect to time divided by the zeroth moment with respect to time. The energy time centroid represents the time at which most of the signal energy has arrived at the receiver. It is similar to the area time centroid, but gives greater emphasis to large peaks within the signal. The area and energy time centroids are given by Equation 7.

$$T_{A} = \frac{\sum_{i=1}^{N} |A_{i}| t_{i}}{\sum_{i=1}^{N} |A_{i}|} \qquad T_{E} = \frac{\sum_{i=1}^{N} A_{i}^{2} t_{i}}{\sum_{i=1}^{N} A_{i}^{2}}$$
(7)

Where:

 T_A - area time centroid

 T_E -- energy time centroid

A_i -- amplitude of the acceleration signal at time t_i.

The normalized difference between the area time centroid and the energy time centroid are then divided by the area time centroid to reduce the effect of velocity variations between different pieces of wood as shown in Equation 8. The value, m, called "centroid fraction" is the fractional difference between centroids. The ratio of the 180° to the 90° centroid fractions values is the time centroid metric (TC). Fig. 11 shows the diameter of the center defect expressed as a fraction of the pole radius versus simulated values of the wave area metric (TC) for eight values of (d/R). The trend of simulated values shown in Fig. 11 was fitted to a third order polynomial (Polynomial in Table III).

(8)



Fig. 11 Time centroid metric versus the defect diameter, d, expressed as a fraction of the pole radius, R. The time centroid metric is the ratio of the centroid fractions, m, defined in Equation 24. Trend line fitted to simulation data (see Table III).

C. Time-of-Flight Metric

The time-of-flight (ToF) metric compares the time-of-flight of the radial and tangential dilatational waves. The ToF is defined as the time necessary for the first wavefront to travel from the source to the receiver. This metric is based upon a single value early in the recorded signals and is not affected by interference phenomenon.

ToF is also used to identify the general location defects in the cross-section. The predicted wave motion across a wood pole cross-section permits an observer to make conclusions regarding the location of a defect by comparing the ToF values around the circumference of the utility pole. The ToF of the waves at 90°, 270° and the 180° locations is used to approximate the tangential and radial dilatational wave velocities, respectively. It is assumed that the relationship between velocity, density, and stiffness obeys Equation 3. The ratios of those velocities should approach a nominal ratio that can be obtained from published sources [3]. Note that in idealized cross-sections, by virtue of symmetry, the ToF ratio of 90° to 270° requires no additional calculations since both wavefronts would be traveling at the tangential velocity and traveling the same (assumed) distance.

Assuming a circular cross-section of diameter D, Equation 9 provides the velocity ratio between the tangential and radial velocities, R_v , as a function of the radial and tangential time-of-flight values, τ_r and τ_t , respectively. If the calculation was performed on an actual pole, then the radial travel distance, D_r , and the tangential travel distance, D_t , can be approximated independently of each other. As a result of taking the ratio of the velocities, the metric becomes independent of the pole diameter.

$$R_{v} = \frac{V_{t}}{V_{r}} = \frac{D_{t}}{D_{r}} = \frac{\pi D}{4\tau_{t}} = \frac{\tau_{r}}{T_{r}} = \frac{\tau_{r}}{\tau_{t}} \frac{\pi}{4}$$
⁽⁹⁾

Where:

R_v -- ratio of tangential velocity to radial velocity

vt , vr -- tangential and radial velocities, respectively

Dt, Dr -- tangential and radial travel distances, respectively

 τ_t , τ_r -- tangential and radial times-of-flight, respectively

D -- cross-section diameter

Equation 10 shows the calculation of the nominal velocity ratio based upon published values of the radial and tangential stiffnesses, E_r and E_t , respectively. Reference [3] provides ratios between the longitudinal stiffness, E_l , and E_r and E_t .

$$R_{vo} = \left[\frac{V_{t}}{V_{r}}\right]_{N} = \sqrt{\frac{\rho V_{t}^{2}}{\rho V_{r}^{2}}} = \sqrt{\frac{E_{t}}{E_{r}}} = \sqrt{\left[\frac{E_{t}}{E_{r}}\right]_{N}} \left[\frac{E_{t}}{E_{r}}\right]_{N}$$
(10)

Where:

R_{vo}-- nominal velocity ratio calculated using nominal values from published sources.

ρ-- average cross-sectional density.

Et, Er, El -- tangential, radial, and longitudinal elastic moduli, respectively [3].

Equation (11) is the ratio formed by the radial and tangential times-of-flight normalized by the nominal ratio calculated using published stiffness values [3]. In this form, the value of R_{ToF} approaches the value of 1.0 for a sound wooden pole, i.e., a pole free of decay. The value of R_{ToF} depends only upon different times-of-flight and is referred to as the time-of-flight metric. The values of k_v for loblolly pine and Douglas-fir are 0.946 and 0.916, respectively. Fig. 12 shows the diameter of the center defect expressed as a fraction of the pole radius vs simulated values of the ToF metric for eight values of (d/R). The trend of simulated values shown in Fig. 12 was fitted to a third order polynomial (Polynomial in Table III).



Fig. 12 Time of flight metric vs defect diameter, d, expressed as a fraction of the pole radius, R. The time of flights metric is the ratio of times of flights of arriving radial and tangential dilatational waves multiplied by the factor k_v. Trend line fitted to simulation data (see Table III).

The ToF metric is also usable to estimate the location of the internal defect, i.e., decayed area. The speed of waves traveling through decayed wood is lower than the wave speed when traveling through sound wood. By comparing the time-of-flight metric between the three receiver locations, the general region of the defect within the cross-section is identified. Fig. 13 shows a schematic of the defect regions based upon a 76 mm defect. Table IV gives the combination of velocity ratios that indicate a defect in a particular defect region (see Fig. 13).



Fig. 13 Defect regions identified by a letter A through J using the time of flight metric in accordance with Table V. The figure assumes a 76 mm diameter defect, an input source at 0°, and 25 mm surface checks (region J)

Defect	Time of Flight Metric					
Regions	$\frac{V_{+90}}{\tau_{\pm 180}} = \frac{\tau_{\pm 180}}{\kappa}$	$V_{-90} = \frac{\tau_{\pm 180}}{k}$	$V_{+90} = \tau_{-90}$			
C	$V_{\pm 180} = \tau_{\pm 90}$	$\frac{1}{V_{\pm 180}} - \frac{1}{\tau_{-90}} K_{v}$	$\frac{1}{V_{-90}} - \frac{1}{\tau_{+90}}$			
А	>1	>1	≈1			
В	<k<sub>V</k<sub>	≈1	<1			
С	≈Kv	≈1	≈Kv			
D	Unspecified	≈1	<1			
Ε	Unspecified	Unspecified	Unspecified			
F	>1	Unspecified	>1			
G	≈1	≈ K _V	≈1/ K _V			
Н	≈1	$< K_V$	>1			
I or no	≈1	≈1	≈1			
decay						
I*						

TABLE IV TIME OF FLIGHT METRIC SETS IDENTIFYING DEFECT REGIONS IN FIG. 13

*Region J assumes no surface checks. Defects in region J are the least likely to be identified using this technique.

 $V_{+90},\ V_{-90},\ and\ V_{+180}$ are wave velocities between the source and $+90^\circ,\ -90^\circ,\ and\ +-180^\circ$ from the source.

Pole Test	Defect Region from CT Scan	$\frac{\tau_{\pm 180}}{\tau_{\pm 90}}k_{v}$	$\frac{\tau_{\pm 180}}{\tau_{-90}}k_{v}$	$\frac{\tau_{\text{-90}}}{\tau_{\text{+90}}}$	Predicted Defect Region
966Z	A or F	1.357	0.965	1.405	F
966N	Α	1.380	1.312	1.052	Α
966R	А	1.199	1.172	1.024	А
491Z	А	1.319	1.221	1.080	А
491N	D or B	1.108	1.439	0.770	D
477Z	A or H	1.020	0.684	1.491	Н
477N	Α	1.227	1.277	1.000	А

TABLE V TIME OF FLIGHT METRICS FROM UTILITY POLES AND PREDICTED DEFECT REGIONS

The idealized configuration of the defect regions as shown in Fig. 13 assumes an input source at 0° . If the source were located at 90°, then the figure would need to be rotated counterclockwise by 90°, i.e., the figure must be rotated such that region E is at the source location. The general location of the defect is determined by the relationship between the ToF metrics (see Table IV). Fig. 13 can only provide a general indication of the decayed area. For further information on the use of Fig. 13 and Table IV, the readers refer to Senalik [43].

Defects in region I produce no changes in the velocity ratio, since the defect would not interrupt the direct path of travel between source and receivers. All the ratios would approach a value of 1.0. In a defect-free cross-section, the ratios would approach values of one as well. Whereas this metric alone would be unable to identify defects in region I, the presence of the defects should still be identified using the other metrics described here. Also, conducting a second set of tests, where the source is placed at the 90°, 180°, or 270° location would eliminate one or more I regions.

The concern regarding the low probability of sensing defects in region J is mitigated by the fact that region J is composed of the portion of the utility pole that is both most resistant to fungal decay and easiest to inspect with current inspection methods. From CT scans, it was apparent that preservative penetration usually exceeded the length of the majority of the surface checks, i.e., 25 mm. The proximity of region J to the surface made it ideal for defect identification using traditional inspection techniques.

VII. EXPERIMENTAL VALIDATION

For validation of the proposed approach, seven experimental tests were conducted on three wooden pole specimens in the Laboratory. Fig. 1 shows X-ray computer tomography views of the cross-sections examined and the corresponding transducer locations. Each cross-section was tested twice with the source placed at the 0° location for one test and 90° for the other. Pole 966 was tested a third time with the source at the 180° location on the pole. Tests were designated by pole number and a letter representing the source location. The suffix letters Z, N, and R represented sources located at 0°, 90°, and 180°, respectively. The receiver locations are defined as +90°, $\pm 180^\circ$, and -90° relative to the source; therefore, if the source was placed at the 90° location, the +90° receiver would be at the 180° location, the $\pm 180^\circ$ receiver would be at the 0° location. For each pole test, each metric was calculated for the ratios $\pm 180^\circ/+90^\circ$ and $\pm 180^\circ/-90^\circ$.

Using the time-of-flight metrics sets shown in Table IV and the regions as defined in Fig. 13, the location of the defect can be estimated. Pole test 966Z has a region of decay that would normally be predicted to be in region A; however, the deep check at approximately 330° may compact the internal regions and place the defect in region F. In pole test 966N, the defect region diagram in Fig. 13 must be rotated counterclockwise such that region E is placed at the source location of 90°. As a result of the relocated source, the decay is predicted to be located in region A. The defect is also predicted to be in region A when the source was placed at 180° for pole test 966R. In pole test 491Z, the defect is clearly predicted to be in region A; however, for pole test 491N, the defect is predicted to be in either region D or B. In pole test 477Z the defect is predicted to be in region A or H. In pole test 477N, the defect region is predicted to be in region A. Table V contains the times of flight obtained from each pole and the associated time-of-flight metric sets and predicted defect regions. In general, the defect locations predicted using the time-of-flight metric agreed with the locations of the defect regions identified in the utility pole CT scans (see Fig. 1 and 13). With the general location of the defects known, all three developed metrics are then used to estimate the size of the defect (see Fig. 10-12 and Table III).

The developed metrics are made non-dimensional by taking ratios. Fig. 14 represents a three-dimensional space where the dimensions correspond to the three developed metrics, i.e., the coordinates of each data point (i.e., pole test) in this three-dimensional metric space correspond to the defect size estimates from the three metrics associated with that particular pole test. A value located at or near the origin corresponds to a pole test in which all three metrics indicate a small or non-existent defect. A value located at coordinate (1,1,1) would correspond to a pole test in which all three metrics indicate a defect diameter the size of the radius of the pole is present. Each of the three poles was tested several times: Pole 966 was tested six times, while Pole 491 and pole 477 were each tested four times. Table VI provides a key for the different tests regarding the corresponding placement of the source relative to the pole geometry and regarding to the normalization of the three used metrics. The colors red, blue, and green represent values from Poles 966, 491, and 477, respectively.



Fig. 14 All defect estimates plotted in three dimensional space. The defect diameter, d, is expressed as a fraction of the pole radius, R. Pole Test suffixes Z, N, and R, indicate the source is at the 0°, 90°, 180° locations of the pole, respectively. Ratio angles are relative to the source location (i.e. ±180° from a 90° source location is the 270° location on the pole). Colors red, blue, and green designate values from poles 966, 491, and 477, respectively (see Table VI).

Pole Test	966Z	966N	966R	491Z	491N	477Z	477N
$\pm 180^{\circ} / +90^{\circ}$					•		*
±180° / -90°	V	∇	Δ		\diamond	0	\$

In Fig. 15, the estimated defect size (d/R) is plotted against the distance of each data point from the origin in the threedimensional space, where the estimate of the defect size is the root mean square of the defect size estimates from the three metrics. The dashed line shown in Fig. 15 represents the mean estimate of the defect size using the corresponding number of test samples for that particular pole. The shaded region in each plot is the range of the defect sizes observable from the CT scan. The defect regions are roughly elliptical in shape. The high and low values of the shaded regions represent the approximate major and minor axes of the defect region observed in the CT scan when fitted to an elliptic shape. The major and minor axes of the defect regions, normalized by the cross-sectional radius of the respective poles, are given in Table VI. The values obtained from for Pole 966 are shown in Fig. 15a. The mean of the estimated values, 0.439, falls within the range defect sizes observed from the CT scans (0.295 to 0.461). The values for pole 491 are shown in Fig. 15b. The mean of 0.600 underestimates the lower range of the observed defect values (0.625 to 0.700) by 4.0%. The values for Pole 477 are shown in Fig. 15c. The mean, 0.342, underestimates the lower range of the observed defect values (0.364 to 0.521) by 6.0%. For each of the three utility pole specimens, the combined estimate of the defect size accurately predicts the true size of the internal defect, i.e., decayed area, to within 6% or less.



Fig. 15 Distance from the origin versus estimate of defect size for the poles 966, 491, and 477. The mean of the defect size estimates for each pole are shown as colored dashed lines. The colored regions the range of defect values obtained from the CT Scans. **a.** Pole 966, **b.** Pole 491, **c.** Pole 477.

For each pole Table VII shows the estimated decayed cross-sectional area as well as the decayed cross-sectional area measured from the CT scans. The estimation of the decayed cross-sectional area is based on the three metrics, and the measured scan-based decayed cross-sectional area assumes the area to be approximately elliptical in shape with major and minor axes (see Table VII). For Pole 966 the measured and estimated fractional areas are 0.034 and 0.048, respectively, with a difference of 0.014 (1.4% of the cross-sectional area). For Pole 491, the measured and estimated fractional areas are 0.110 and

TABLE VI RATIO SYMBOLS

0.090, respectively, with a difference of 0.020 (2.0% of the cross-sectional area). For Pole 477, the measured and estimated fractional areas are 0.047 and 0.029, respectively, with a difference of 0.018 (1.8% of the cross-sectional area).

POLES	Experimental	Exp. estimation of	Decayed area sizes from CT scans		Decayed fraction cross-section area	Difference in fraction cross-
	estimation of (u/K)	fraction decayed area	Minor axis	Major axis	from CT scan	section decayed area
966	0.439	0.048	0.295	0.461	0.034	0.014
491	0.600	0.090	0.625	0.700	0.110	0.020
477	0.342	0.029	0.364	0.521	0.047	0.018
Defects are assumed to have a generally elliptical shape with major and minor axes						

TABLE VII COMPARISON OF ESTIMATED AND ACTUAL DEFECT SIZES IN POLES

VIII. CONCLUSIONS

A plane strain, two-dimensional finite difference time domain simulation is presented to study wave propagation through the cross-section of a wooden pole. The model is capable of using the density and geometry information extracted from CT images of a utility pole specimen. The model was validated against analytical and experimental data. Based upon this model, three metrics were developed that are capable of determining the size of the internal defects, i.e., decay, within wooden pole cross-sections using four measurements collected around the pole circumference. Using these metrics three different wooden pole cross-sections were tested. In all cross-sections, the general location of the defect location was accurately located. The size of the defect area, i.e., decay, was also determined to within 2% of the pole cross-sectional area.

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REFERENCES

- [1] "State of the World's Forests," Technical Report, FAO, Food and Agriculture Organization of the United Nations, Rome, Italy, 2011.
- [2] L. Gustavsson, and R. Sathre, "Variability in Energy and Carbon Dioxide Balances of Wood and Concrete Building Materials," *Building and Environment*, vol. 41, iss. 7, pp. 940-951, 2006.
- [3] "Wood Handbook—Wood as an Engineering Material," Technical Report FPL-GTR-190, Forest Products Laboratory, US Department of Agriculture, Forest Service, Madison, WI, USA, 2010.
- [4] F. M. Gravito, and N. S. Filho, "Inspection and Maintenance of Wooden Poles structures," *IEEE Symposium*, Orlando Florida, March 17-21, pp. 151-155, 2003.
- [5] A. Senalik, F. C. Beall, and H. Reis, "Detection and assessment of wood decay in glulam beams using a modified impulse-echo approach," *INSIGHT*, vol. 52, iss. 10, pp. 553-560, 2010.
- [6] F. C. Beall, J. M. Biernacki, and R. L. Lemaster, "The Use of Acousto-Ultrasonic to Detect Biodeterioration in Utility Poles," Journal of Acoustic Emission, vol.12, iss. ½, pp. 55-64, 1994.
- [7] M. Tiitta, F.C. Beall, and J.B. Biernacki, J.M., "Acousto-Ultrasonic Assessment of Internal Decay in Glulam Beams," Wood and Fiber Science, vol. 30, iss. 3, pp. 259-272, 1998.
- [8] L. Socco, L. Sambuelli, R. Marinis, E. Comino, and G. Nicolotti, "Feasibility of ultrasonic tomography for nondestructive testing of decay on living trees," American Society for Nondestructive Testing, Research in Nondestructive Evaluation, vol. 15, pp. 31-54, 2004.
- [9] K. Kim, J. Lee, S. Lee, and H. Yo, "Improvement of wood CT images by consideration of skewing of ultrasound caused by grown ring angle," Wood and Fiber Science, vol. 40, iss. 4, pp. 572-579, 2008.
- [10] K. Kim, S. Lee, and J. Lee, "Cross-sectional image reconstruction of wooden members by considering variation of wave velocities," Mokchae Konghak, Vol. 35, iss. 5, pp. 16-23, 2007.
- [11] K. Kim, and J. Lee, "CT image reconstruction of wood using ultrasonic velocities I," Mokchae Konghak, vol. 33, iss. 5, pp. 21-28, 2005.
- [12] K. Kim, and J. Lee, "NDE of decayed wood with ultrasonic CT," Key Engineering Materials, vol. 321-323, pp. 1182-1185, 2006.
- [13] S. Lee, K. Kim, and J. Lee, "Improvement of ultrasonic and X-ray CT techniques for field application," 9th World Conference on Timber Engineering, Portland, Oregon, USA, August 6-10, 2006.
- [14] H. Yanagida, Y. Tamura, K. Kim, and J. Lee, "Development of ultrasonic time-of-flight computed tomography for hard wood with anisotropic acoustic property," Japanese Journal of Applied Physics, vol. 46, iss. 8A, pp. 5321-5325, 2007.
- [15] S. Hagrey, "Geophysical imaging of root-zone, trunk, and moisture heterogeneity," Journal of Experimental Botany, vol. 58, iss. 4, pp 839-854, 2007.
- [16] S. Liang, X. Wang, J. Wiedenbeck, Z. Cai, and F. Fu, "Evaluation of acoustic tomography for tree decay detection," Proceedings of the 15th International Symposium on Nondestructive Testing of Wood, Duluth Minnesota, USA, Sept. 10-12, 2007.
- [17] G. Nicolotti, L. Socco, R. Martinis, A. Godio, and L. Sambuelli, "Application and comparison of three tomographic techniques for detection of decay in trees," Journal of Arboriculture, vol. 29, iss. 2, pp. 66-78, March 2003.
- [18] American Society for Testing and Materials, "Standard test method for wood preservatives by laboratory soil-block cultures." D-1413-99. Annual Book of ASTM Standards 4.10, 2003.

- [19] M. McGovern, "Assessment of brown rot decay using X-ray computer tomography and ultrasonic measurements," MS Thesis, University of Illinois at Urbana-Champaign, Urbana, Illinois, 2011.
- [20] M. McGovern, A. Senalik, G. Chen, F. C. Beall, and H. Reis, "Detection and assessment of wood decay using X-ray computer tomography," SPIE Smart Structures Conference, Paper 7647-152, San Diego, CA, 2010.
- [21] T.C. Ting, "Pressuring, shearing, torsion and extension of a cylindrical tube or bar of cylindrically anisotropic material," The Royal Society, Proc. of Math., Physical and Eng. Sciences 452, iss. 1954, pp. 2397-2421, 1996.
- [22] T.C. Ting, Anisotropic Elasticity: Theory and Applications, Oxford Science Publications, New York, 1996.
- [23] P. A. Martin, and J.R. Berger, "Waves in wood: Free vibrations of a wooden pole," Journal of Mechanics and Physics of Solids, vol. 49, pp. 1155-1178, 2001.
- [24] R. G. Payton, "Wave fronts in wood," The Quarterly J. of Mechanics and Applied Math., vol. 56, iss. 4, pp. 527-546, 2003.
- [25] K.S. Yee, "Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media," IEEE Transactions on Antennas and Propagation, vol. 14, iss. 3, pp. 302-307, 1966.
- [26] S. S. Zivanovic, K. S. Yee, K. K. Mei, "A Subgridding Method for the Time-Domain Finite-Difference Method to Solve Maxwell's Equations," IEEE Transactions on Microwave Theory and Techniques, vol. 39, iss. 3, pp. 471-479, March 1991.
- [27] J. B. Schneider, C.L. Wagner, and S.L. Broschat, "Implementation of transparent sources embedded in acoustic finite-difference timedomain grids," Journal of the Acoustical Society of America, vol. 103, pp. 136-142, 1998.
- [28] D. Gsell, T. Leuteneggar, and J. Dual, "Modeling three-dimensional elastic wave propagation in circular cylindrical structures using a finite difference approach," Journal of the Acoustical Society of America, vol. 116, pp. 3284-3293, 2004.
- [29] S. Schubert, D. Gsell, M. Motavalli, J. Dual, and P. Niemz, "Non-destructive testing of trunks: Studying elastic wave propagation by numerical simulation," Wood Research, vol. 51, iss. 3, pp. 11-24, 2006.
- [30] J. Berenger, "A perfectly matched layer for absorption of electromagnetic waves," Journal of Computational Physics, vol. 114, pp.185-200, 1994.
- [31] Q. H. Liu, and J. Tao, "The perfectly matched layer for acoustic waves in absorptive media," Journal of the Acoustical Society of America, vol. 102, pp. 2072-2082 1997.
- [32] Q. H. Liu, "Perfectly matched layers for elastic waves in cylindrical and spherical coordinates," Journal of the Acoustical Society of America, vol. 105, pp. 2075-2084, 1999.
- [33] W. C. Chew, and Q.H. Liu, "Perfectly matched layers for elastodynamics: A new absorbing boundary condition," Journal of Computational Acoustics, vol. 4, pp. 341-359, 1996.
- [34] Y.H. Chen, W.C. Chew, and Q.H. Liu, "A three-dimensional finite difference code for modeling sonic logging tools," Journal of the Acoustical Society of America, vol. 103, pp. 702-712, 1998.
- [35] Gedney, S., "An Anisotropic Perfectly Matched Layer-Absorbing Medium for the Truncation of FDTD Lattices," IEEE Transactions on Antennas and Propagation, vol. 44, No. 12, pp. 1630-1639, December 1996.
- [36] Q. H. Liu, "Perfectly matched layers for elastic waves in cylindrical and spherical coordinates," Journal of the Acoustical Society of America, vol. 105, pp. 2075-2084, 1999.
- [37] F. Hu, "A Stable, Perfectly Matched Layer for Linearized Euler Equations in Unsplit Physical Variable," Journal of Computational Physics, vol. 173, pp. 455-480, 2001.
- [38] J. Haygreen and J. Bowyer, Forest Products and Wood Science: An Introduction Third Edition, Iowa State University Press, Ames, Iowa, 1996.
- [39] V. Bucur, Acoustics of Wood, Institute National de la Recherche Agronomique Centre de Recherches Forestieres. Nancy, France. CRC Press, Inc. Boca Rotan, Florida, 1995.
- [40] W. Gindl, "Comparing Mechanical Properties of Normal and Compression Wood in Norway Spruce: The Role of Lignin in Compression Parallel to the Grain," Holzforschung, vol. 56, pp. 395-401, 2002.
- [41] E. Wielandt, "On the validity of the ray approximation for interpreting delay times," Seismic Tomography, ed. G. Nolet, and D. Reidel, pp. 85-98, 1987.
- [42] S. Schwarze, C. Rabe, D. Ferner, and S. Fink, "Detection of decay in trees with stress waves and interpretation of acoustic tomograms," Journal of Arboriculture. J. vol. 28, pp. 3-19, 2004.
- [43] H. Maurer, S. Schubert, F. Bächle, S. Clauss, D. Gsell, J. Dual, and P. Niemz, "A simple anisotropy correction procedure for acoustic wood tomography," Holzforschung, vol. 60, pp. 567-573, 2006.
- [44] A. C. Senalik, "Detection and Assessment of Wood Decay Glulam Beams and Wooden Utility Poles," Ph.D. Thesis, University of Illinois at Urbana-Champaign, Urbana, IL, 2012.
- [45] M. Tiitta, F. Beall, and J. Biernacki, "Acousto-ultrasonic assessment of internal decay in glulam beams," Wood and Fiber Science, vol. 30, iss. 3, pp. 259-272, 1998.
- [46] M. Tiitta, "Non-destructive methods for characterization of Wood Materials," Doctoral Dissertation, University of Kuopio, Department of Physics, Finland, November, 2006.
- [47] F. C. Beall, "Overview of the use of ultrasonic technologies in research on wood properties," Wood Science and Technology, vol. 36, pp. 197-212, 2002.