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A novel methodology for condition assessment of wood poles using ultrasonic testing

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ABSTRACT

This paper presents a new methodology based on theoretical, numerical, and experimental studies for condition assessment of wood poles using ultrasonic tests. Conventional ultrasonic testing of wood poles is based only on wave velocity measurements. Whereas in the new methodology, the condition assessment of a wood pole is represented by statistical quantities called dissimilarity indices; which are computed from ultrasonic measurements. These measurements include compressional wave velocities, transmission factors, and elastic moduli in the radial and tangential directions. The dissimilarity index is computed by comparing the measured parameters in a given pole section with the corresponding expected values and standard deviations for a sound pole. Four ultrasonic transmitters, with nominal frequency of 50 kHz, are evenly spaced around the circumference of the cross-section of the pole. For each transmitter location, an array of five receivers at different angles from the transmitter is used to measure the response of the wood pole to the ultrasonic excitation. Thus, a total of 14 independent raypaths across the section are defined for each test. Laboratory results show that for an area of decay of 30% of the cross-section, the wave velocity and the transmission factor decrease by 51% and 96%, respectively. Whereas the average elastic moduli in the radial and tangential directions are 80% and 43% smaller than the expected values for a sound pole. The observed deterioration pattern in a blind test is in perfect agreement with the predicted condition using the new methodology.

1. Introduction

Since the beginning of electrification in North America, wood poles have been used to support electric transmission and distribution lines. In general, wood poles are preferred instead of steel and concrete poles because of their lower price and installation cost; expected service life; easiness to handle, store, and climb; low electrical conductivity; environmental compatibility; and wide availability in North America [1,2].

Wood poles are exposed to severe environmental conditions, which can lead to deterioration in the form of decay, insect attack, and weathering. The average service life of wood poles varies from 35 to 50 years depending on wood species, preservative treatments, service conditions, and maintenance practices [3–5]. The province of Ontario has over 2 million distribution poles, and approximately 50% of them have been in-service for more than 35 years [5]. To ensure high reliability of an electrical distribution network, a large number of aging wood poles must be inspected every year to verify that they are in adequate condition to remain in-service.

Wood pole inspection is a critical part of maintenance programs for the detection of hazardous poles and early stages of decay. Visual inspection is the easiest and lowest cost method for in situ pole inspection. It is commonly complemented with other methods such as impacting the pole with a hammer (sounding method) and measuring the penetration resistance with a pointed tool (resistograph method). However, visual inspection and sounding methods are subjective and consequently prone to errors; whereas the resistograph method is invasive, point-measurement, and unable to detect early stages of decay (micro-drills). More reliable inspection methods are therefore needed for condition assessment of in-service wood poles.

Ultrasonic testing is a nondestructive test (NDT) which has been used for inspection of wood poles [6]. However, the condition assessment is commonly based on the comparison of the measured wave velocity (V_p) with a reference value depending on the wood species. This simple method cannot be used for the detection of early stages of decay because of the high variation involved in the calculation of the wave velocity V_p. A better understanding of wave propagation in an orthotropic medium and the consideration of uncertainties in elastic and mechanical properties are essential for condition assessment of wood poles using ultrasonic testing.

A new methodology for condition assessment of wood poles using ultrasonic testing is presented. It is based on the

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propagation of ultrasonic waves in a cylindrical orthotropic medium including uncertainties in the elastic and mechanical properties. The effects of moisture content and temperature on the elastic modulus are also studied using previous results from the literature.

The mechanical properties of red pine wood are presented first, followed by the methodology, the experimental setup, exploratory results and analysis, and finalizing with the conclusions.

2. Mechanical properties of red pine

Water has an important effect on the mechanical properties of wood. It may be present as bound water and as free water. Bound water is within the cell walls and affects volume changes associated with changes in moisture content (MC); whereas free water is in the cell cavities. The fiber saturation point (FSP) is the value of MC at which there is no free water in the wood cavities, but the cell walls are still 100% saturated. The FSP varies depending on the wood species; in average, FSP=28%.

Air-dry condition corresponds to $\mathrm{MC}=12\%$ whereas green condition corresponds to $\mathrm{MC} \geq \mathrm{FSP}$. Moisture contents higher than the FSP have practically no effect on the mechanical properties. The specific gravities for air-dry (S_n) and green (S_b) conditions are computed using the oven-dry weight and the corresponding volumes in air-dry and green conditions. For $\mathrm{MC} < \mathrm{FSP}$, wood swells as MC increases and shrinks when MC decreases; thus, $S_b < S_n$. The mass density as a function of MC can be estimated by [7]

$$\rho_{(\mathrm{MC})} = \frac{1000 S_b \left(1 + \frac{\mathrm{MC}}{100}\right)}{1 - \left(\frac{30 - \mathrm{MC}}{30}\right) 0.265 S_b} \quad (1)$$

The elastic modulus in the longitudinal direction or parallel to the wood fiber depends on the state of stresses (compression, E_l, or bending, MOE) and the type of loading (static or dynamic). In general, E_l is 10–20% greater than MOE [8–11]; and the elastic modulus measured from dynamic tests is 5–15% greater than the measured value from static methods [12–14,10]. On the other hand, E_l is greater than the elastic moduli in the radial (E_r) and tangential (E_t) directions, and $E_r > E_t$ [15,9]; thus, $E_l > \mathrm{MOE} > E_r > E_t$ (in average, $E_l/E_r \approx 12$ and $E_r/E_t \approx 1.4$). Typical specific gravities (S_n, S_b) and elastic moduli in bending (MOE) for red pine wood in air-dry and green conditions are [8]: S_n=0.46, MOE = 11.2 GPa and S_b=0.41, MOE = 8.8 GPa. Even though experimental values for the elastic moduli E_r and E_t are not available in the literature for most wood species, estimated values are given as fractions of E_l. For red pine wood in air-dry condition, $E_r/E_l = 0.088$ and $E_t/E_l = 0.044$ [8]; therefore, $E_r/E_t = 2$.

Isotropic materials are characterized by a single value of Poisson's ratio; however, the characterization of orthotropic materials require six Poisson's ratios. Only three of them are independent when the symmetry of the stiffness matrix is considered. Average values of Poisson's ratios for red pine obtained from static tests are $\nu_{lr} = 0.347$, $\nu_{lt} = 0.315$, and $\nu_{rt} = 0.408$ [8]; where the value of ν_{lr} is given by the ratio of the radial (r) strain to the longitudinal (l) strain, ν_{lt} is the ratio of the tangential (t) strain to the longitudinal (l) strain, and ν_{rt} is the ratio of the tangential (t) strain to the radial (r) strain.

The elastic modulus for $\mathrm{MC} < \mathrm{FSP}$ can be computed as [16]

$$E_{(\mathrm{MC})} = E_n \left(\frac{E_n}{E_b}\right)^{(12-\mathrm{MC})/(\mathrm{MP}-12)} \quad (2)$$

where E_n and E_b are the elastic moduli in air-dry and green conditions, respectively. The apparent fiber saturation point (MP) is determined by the interception of the curves representing the variation of the elastic modulus with MC above and below the FSP; in general, a value of MP=25% can be assumed [8].

Temperature also affects the elastic moduli in wood poles. The elastic moduli decrease when the temperature increases and vice versa [15]. Moisture content plays an important role in the relationship between temperature and the elastic modulus. For a MC=0%, the relationship between elastic modulus and temperature is linear. This linearity is lost as the MC increases [17]. The following relationship has been proposed to evaluate the effect of the temperature on the elastic modulus within the range of 20–65 °C.

$$E_{(t_2)} = E_{(t_1)}[1 - (t_2 - t_1)\alpha_m] \quad (3)$$

where $E_{(t_2)}$ and $E_{(t_1)}$ are the elastic moduli at the temperatures $T = t_2$ and $T = t_1$, respectively; α_m is a coefficient that varies with MC from $\alpha_m = 0.0004$ for $\mathrm{MC} = 0\%$ to $\alpha_m = 0.0035$ for $\mathrm{MC} = 24\%$ [18].

Finite elements numerical simulations of wave propagation in a cross-section of red pine poles are used to compute the wave velocity V_p for different values of temperature and moisture content [19]. The elastic modulus for a given moisture content and temperature is estimated from Eqs. (2) and (3). The moisture–temperature factor for wave velocity is defined as $R_{V_p(\mathrm{MC},T)} = \mu_{V_p}(\mathrm{MC},T)/\mu_{V_p}(12,20)$, where $\mu_{V_p}(12,20)$ is the mean value of the wave velocity V_p for $\mathrm{MC} = 12\%$ and $T = 20$ °C. The moisture–temperature factor for wave velocity decreases linearly with moisture content and temperature and is represented by the following equation:

$$R_{V_p}(\mathrm{MC},T) = (-0.000045T - 0.0111)\mathrm{MC} - 0.0004T + 1.152 \quad (4)$$

Thus $R_{V_p}(\mathrm{MC},T)$ varies between 1.09 and 0.81 for a change in MC from 5% to 28% ($T = 20$ °C), and between 1.02 and 0.98 for a change in temperature from 0 °C to 40 °C ($\mathrm{MC} = 12\%$).

3. Methodology

3.1. Location of ultrasonic transducers

The location of ultrasonic transducers in a cross-section of wood poles is shown in Fig. 1. The transmitter is located at four positions even spaced around the wood pole surface (points A, B, C, and D in Fig. 1). For each transmitter position, five receivers are set at the receiver angles $\theta_r = \pm 90°$, $\theta_r = \pm 135°$, and $\theta_r = 180°$. The receiver angle θ_r is the angle between the transmitter and the receiver and is positive in the counterclockwise direction. An array of five receivers for each transmitter position is chosen for characterization of wave velocity in a cross-section of wood poles as an orthotropic material.

3.2. Ultrasonic parameters

The condition assessment of wood poles is based on four parameters: wave velocity, transmission factor (reciprocal of the wave attenuation), and the elastic moduli in the radial and tangential directions. These parameters are defined for $\mathrm{MC} = 12\%$ and $T = 22$ °C.

3.3. Wave velocity

The probability density functions of the wave velocity V_p for different receiver locations are computed using a simplified method of plane wave propagation in an infinite cylindrical orthotropic material. The simplified method of analysis is validated using wave propagation results from 62 finite element numerical simulations. The maximum difference between the results obtained using the simplified method of analysis and finite elements is smaller than 3%.