

New Methodology for NDT Assessment of In-service Wood Poles

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Abstract

Wood poles are extensively used in North America to support electrical lines. To ensure the reliability of the electrical network, the condition of the poles is assessed usually through visual and sounding inspection. These methods have the disadvantage that they are subjective, they provide a local evaluation of the condition, and are unable of detecting early decay.

This paper summarizes the results of a research project that included the development of a new methodology to assess the condition of wood poles based on ultrasonic waves, the construction and calibration of the testing device, numerical modelling, and laboratory and field tests. The proposed methodology considers wood as an orthotropic material, takes into account the variability in the elastic and mechanical properties, and the effect of temperature and moisture content in these properties. Also provides a quantification of the damage and the remaining strength through statistical indexes. The method has the advantage that is nonintrusive, provides quantitative measurements of the internal condition of wood poles and allows detecting early decay in wood poles.

Keywords: ultrasonic testing, reliability, wood poles, maintenance, condition assessment

1. Introduction

Wood poles are usually used in both, transmission and distribution lines; and are preferred over other materials because of their lower price, high strength to weight ratio, low electrical conductivity, easiness of storage, handle and climb, wide availability and lower installation cost [1,3,5]. However, as wood is an organic material, environmental factors such as temperature, moisture conditions, bacteria or fungi may induce internal decay, which reduces the strength of the poles. In order to avoid sudden failures and to optimize the schedule of pole replacement and rehabilitation, the assessment of the actual condition of in-service poles is needed.

Design and safety specifications for electrical networks require that the poles should be replaced or rehabilitated when the strength of the pole had reduced to 60% of the required design strength [13]. To satisfy this requirement, the network owners implement periodic inspections using different testing methods to determine the actual condition of the poles. The most common methods are visual inspection, sounding inspection and evaluation using a resistograph. Visual inspection is an economical method, but it is limited to the external condition of the pole. The sounding inspection consists on the identification of void areas or defects by the sound perceived when the pole is hit with a hammer. Likewise to visual inspection, sounding has lower reliability because it is subjective, since it relies on the experience of the inspector and it is a qualitative evaluation. Another method of inspection consists of measuring the local penetration resistance with a resistograph, which is a patented instrument that correlates the drilling resistance to the density of the wood. This method has a lower statistical significance; given that the measurements are punctual and do not necessarily represent the general condition of the pole. Figure 1 shows two examples where the internal decay may not be detected by the conventional methods. If the poles were inspected through visual inspection the internal decay cannot be noticed because there are no signs of deterioration in the surface of the pole. If the assessment was based on resistograph



measurements, depending on the section and number of measurements done the decayed areas may not be identified.



Figure 1: Example of wood poles for which the traditional methods of inspection may not detect the internal deterioration

This paper presents the results of a research project which main objective was to develop an assessment method for in-service wood poles based on ultrasonic and statistical measurements. The proposed solution provides a quantitative estimation of the internal decay in the cross-section and an estimation of the remaining strength. The method gives a global assessment of the cross section and it is statistically significant. A new field testing device and software was developed and the proposed methodology also innovates in the consideration of the orthotropic nature of wood and the effect of moisture content and temperature on the mechanical properties.

2. Theoretical background

2.1 Nondestructive ultrasonic testing of wood

A method is considered nondestructive when the characteristics of the element being inspected are not affected by the tests. It is referred as ultrasonic testing the application of sound waves above human hearing (greater than 16 kHz) for material evaluation. The usual ultrasonic testing makes use of a transmitter and a receiver to measure the first arrival of compressional waves (P-waves) [2]. Generally, for ultrasonic testing are used piezoelectric transducers as transmitter and receiver. A piezoelectric transducer is a device that converts electrical energy in ultrasonic energy and vice versa [14]. These transducers need to be in contact with the object tested, and also require to be calibrated for the specific material under study. One of the improvements in the methodology presented herein is the use of an array of ultrasonic transducers, rather than one transmitter and one receiver. Arrays have the advantage that make possible to take different measurements from a single location and can be used to produce images for the visualization of internal structure of a component [10].

2.2 Wave propagation in wood

Wood is an orthotropic material, since its properties are different in three orthogonal directions: longitudinal, radial and transverse. To fully describe the wave propagation in wood under plain strain conditions are required eight parameters: mass density (ρ), three elastic moduli (the elastic modulus in the longitudinal direction E_l , elastic modulus in the radial direction E_r , elastic modulus in the tangential direction E_t), three Poisson's ratios (ν_{lr} , ν_{lt} , ν_{rt}).

and the shear modulus G_{rt} . These parameters vary between species, within the same wood species and depend on the temperature and moisture content [4]. Consequently, to obtain reliable ultrasonic measurements it is needed to take into account the intrinsic variability of these parameters and its influence on the wave velocity. For this, the velocity should be considered as a random variable and its probability distribution needs to be determined. A detailed explanation on how the probability distribution was determined may be found on [2, 4] where the methodology is demonstrated for red pine poles. For the purpose of this paper only a brief description of the methodology is presented.

The derivation of the probability distribution of wave velocity was based on laboratory tests, the consideration of uncertainty in the mechanical properties of wood and a simplified model of wave propagation in a cylindrical orthotropic material, validated with the results of 60,000 finite element numerical simulations [2]. The values of P-wave velocity (V_p) were estimated using the simplified method of analysis for wave propagation in wood given by the relationship between E_l (the elastic modulus in the longitudinal direction) and ρ is the mass density:

$$V_p = \sqrt{\frac{E_l}{\rho}} \quad (1)$$

Figure 2 shows the array of transducers and the receiver locations considered. Due to the anisotropy of wood, the ray paths between the transmitter and the receivers are curved, except for the receiver located at the opposite face of the transmitter. This relation is not linear because wood is not a homogeneous material, the cross-sections are not perfectly circular and the pith is not always located at the center [3].

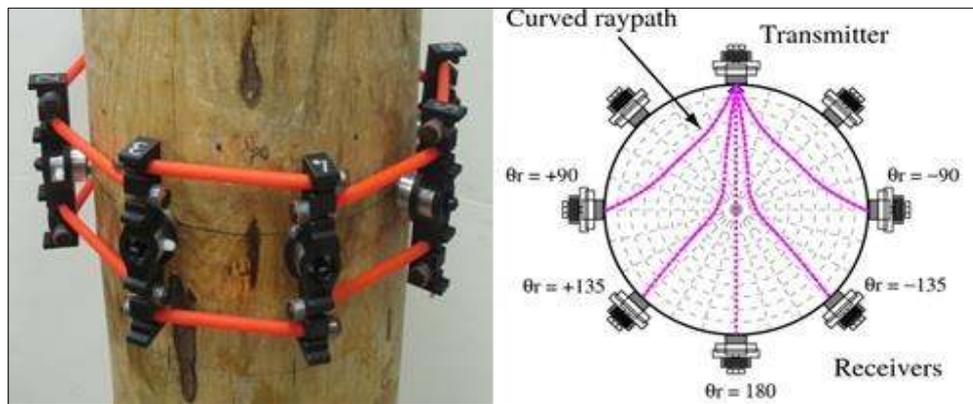


Figure 2: Ultrasonic transducer array used in the testing

Monte Carlo simulations (MCS) can be used to define the probability distribution. The wave velocity was studied with respect to the receiver location angle. For each receiver location, the probability distribution that describes better V_p was defined through the method of the Probability paper plots (PPP). The distributions studied were the normal, lognormal, gamma, Gumbel and Weibull distribution. Probability paper plots allow determining whether the data follows the assumed distribution. According to the results, the normal distribution provides the best-fitting of the data for wave velocity for the general case (all the variables are considered as random variables).

2.3 Consideration of effect of temperature and moisture content

The material parameters (elastic moduli, mass density, Poisson's ratios, shear modulus) depend on the temperature and moisture content, since water has an important effect on the mechanical properties of wood [4]. The proposed method includes a model to predict the moisture content based on the records of relative humidity and temperature.

The influence of the temperature and moisture content may be analyzed from their effect on the moduli of elasticity and mass density. Given that the square of the wave velocity is directly proportional to the modulus of elasticity and inversely proportional to mass density (equation (1)); the variations on the mass density induced by the changes in moisture content have an effect on wave velocity. The moisture content for the wood poles was studied during a full year to evaluate the effect of the moisture content and temperature on wave velocity. The poles were exposed to long-term (seasonal) and short-term (daily) variations in temperature and humidity. According to the results, the minimum values of moisture content occur between spring and summer, while the maximum values in winter. The variability in the moisture content and the temperature was considered using finite element numerical simulations. Monte Carlo simulations were done to evaluate the probability distribution of wave velocity when the mass density, the elastic moduli, Poisson's ratios and the moisture content are modeled as random variables. There were considered two situations: spring/summer and fall/winter. According to the results from 60,000 simulations and using the PPP method, the normal distribution gives the best fit of the data. From the simulations, a moisture-temperature factor to correct the velocity (R_{V_p}) for different moisture content (MC) and temperature (T) was derived and it is represented as:

$$R_{V_p}(MC, T) = (-0.000045T - 0.0111)MC - 0.0004T + 1.152 \quad (2)$$

The previous expression allows adapting the probability distributions of wave velocity for a given moisture content and temperature.

2.4 Definition of new statistical indices for condition assessment

One of the main disadvantages of the sounding and visual inspection is that they do not provide a quantification of the existing damage or an estimation of the remaining strength. The proposed method uses ultrasonic measurements (wave velocity, transmission factor, elastic moduli in the radial and tangential directions) to compute two statistical indexes: the Overall dissimilarity index (ODI) and the Condition rating index (CRI). These two parameters allow quantifying the damage existing in the cross section and estimate the remaining strength of the pole.

The ODI represents the number of standard deviations that the test results differ from the expected value for a new pole. Values of ODI in the range of [-2,-3] indicate that the pole has 98% probability of being decayed. The ODI is computed at each receiver location according to the next expressions:

$$ODI_{\theta_r} = DIV_{\theta_r} \cdot W + DIA_{\theta_r} \cdot (1 - W) \quad (3)$$

where DIV_{θ_r} is the dissimilarity index for the wave velocity (equation (4)), DIA_{θ_r} the dissimilarity index for the transmission factor (equation (5)) and W is a weight factor calculated from equation (6).

$$\text{DIV}_{\theta_r} = \frac{V_p - \mu_{V_p}}{\sigma_{V_p}} \quad (4)$$

In the previous equation V_p is the wave velocity computed, μ_{V_p} is the expected value and σ_{V_p} the standard deviation for the wave velocity for a sound pole of the same wood species at the same receiver location.

Considering A_f the measured transmission factor (reciprocal of the attenuation factor) computed in the frequency domain, μ_{A_f} the expected value and σ_{A_f} the standard deviation for a sound pole, the dissimilarity index for the transmission factor is defined as:

$$\text{DIA}_{\theta_r} = \frac{A_f - \mu_{A_f}}{\sigma_{A_f}} \quad (5)$$

The weight factor is defined as a function of CV_V (the coefficient of variation for the wave velocity) and CV_A (coefficient of variation for the transmission factor).

$$W = \frac{1}{1 + \frac{CV_V}{CV_A}} \quad (6)$$

The condition rating index CRI represents the strength relation of the expected modulus of elasticity in the radial direction of the inspected pole, and the expected modulus of elasticity of a sound pole. A value of CRI equal to one indicates that the pole has a similar strength to that of a new one. This parameter allows verifying the requirement for the strength for wood poles indicated in the specifications [13, 15], since CRI equal to 0.60 corresponds to the end of the service life of a pole. More detailed information about the determination of the index may be found in [8].

3. Methodology for the field testing

As indicated before, the condition assessment is based on three ultrasonic parameters: wave velocity, wave attenuation and the elastic moduli in the radial and tangential direction. These parameters are determined from the measurements of the first arrival of the compression waves propagating through the pole and the full waveform recorded at each receiver. The field testing is performed using a calibrated array of eight ultrasonic transducers evenly spaced around the pole cross section (Figure 2). The array is a customized belt that can be adjusted to test poles of different diameters and improves the coupling between the transducers and the surface. In each test, one of the transducers functions as a transmitter and the other seven as receivers. The test is repeated until each transducer has been used as a transmitter. The information registered is processed using a software developed specifically for the testing device. The program performs the required signal processing, computes the arrival times, and evaluates the correlation function between moisture content of the pole, and the in-situ relative humidity and temperature. Finally, the software generates an assessment report for each cross section tested and includes the information of the test in a data base. The assessment report summarizes the main information that may be used for maintenance decisions, such as ODI, CRI and a tomographic image of the cross section. The tomographic image shows the comparison of the measured wave velocity with the expected value of a sound pole, and allows identifying visually the decayed areas of the cross section. This tomographic image is generated by discretizing the cross section in the 25 regions and the 28

ray paths shown in Figure 3. For each region it is computed the wave velocity solving the inverse problem from the travel time measurements of the compression waves using the Least squares method.

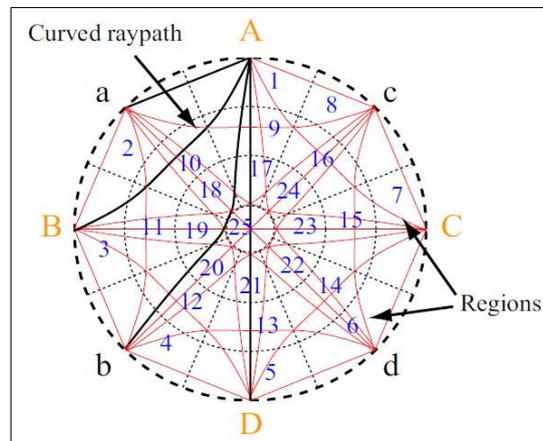


Figure 3: Discretization and ray paths considered for the tomographic method

The proposed methodology has been applied in the laboratory to thirty three new and aged red pine poles collected from Perth and Guelph in Ontario. There had also been tested five in-service wood poles at the Kleinburg Hydro One training centre. The results obtained in the laboratory and in the field demonstrate that the proposed methodology is able of detecting early decay and to provide a quantification of the internal condition of the poles and its remaining strength. Figure 4 shows an example of the tomographic image and the actual damage observed in the pole.

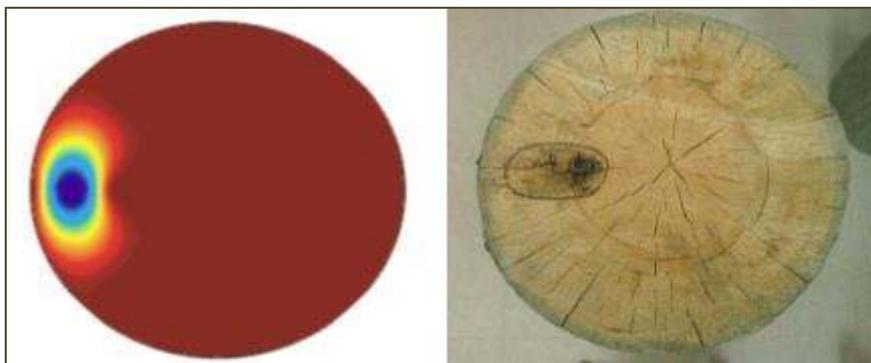


Figure 4: Example of the results from the tomographic image and the actual damage

Currently, a field testing prototype consisting of the transducers array and the portable electronic equipment built is being tested. The field testing program includes the assessment of 400 in-service wood poles in the Waterloo region. The sample includes poles of different ages (from newly installed to more than 60 years in service), of two species (red pine and cedar), located in urban and rural areas. The testing program includes measurements during winter and spring; and also the comparison of the results for cross sections located above the ground line and sections tested after excavating the soil surrounding the poles.

4. Conclusions

The main objective of this research project was to develop a new methodology for the condition assessment of in-service wood poles based on ultrasonic and statistical testing. The

project included theoretical, experimental and field work, which demonstrated the applicability and the advantages of the methodology.

Ultrasonic waves have been used before for the assessment of wood poles, but it has not been taken into account the orthotropic nature of wood and the variability in the mechanical properties that affect the propagation of sound waves. The neglect of these inherent characteristics of the wood affects the reliability of the testing, and it impedes the detection of early decay. In this project the anisotropic nature of wood was considered by using an orthotropic model for wave propagation, and the variability of the parameters that affect wave propagation was studied and included through the probability distribution of wave velocity (V_p). This probability distribution was determined for each receiver location, and it was also taken into account the effect of the temperature and the moisture content in the velocity. The assumed wave propagation model and the derived probability distribution were verified through numerical simulations and laboratory testing. According to the results, more accurate results are obtained for the general case, where the parameters needed to study the wave propagation in wood (ρ , E_l , E_r , E_t , v_{lr} , v_{tl} , v_{rl} and G_{rt}) are considered as random variables characterized by a probability distribution. Also from the study of the variation of the moisture content and temperature in one year, it is suggested to consider two scenarios: spring/summer and fall/winter.

An important limitation of the traditional methods of condition assessment of wood poles is their inability to quantify the damage. The proposed methodology overcomes this limitation by using two statistical indexes, the Overall dissimilarity index ODI and the Condition rating index CRI. These indexes quantify the extent of the decayed areas and the remaining strength of the pole. ODI is employed to construct a tomographic image of the cross section being tested, which can be used to identify visually the location and extent of the damaged areas. The CRI provides a quantification of the remaining strength and may be used to verify the strength requirements established in the specifications for overhead systems.

The novel features of the proposed methodology include also the use of an array of transducers and the development of a simple and efficient tool for nondestructive testing in the field. In addition, it was also developed software to process the inspection information and to generate a data base that may be used for management decisions.

The proposed NDT ultrasonic method has the advantage that is nonintrusive and provides quantitative measurements of the internal condition of wood poles. Also it is able of detecting early decay, which is an important improvement, given that the typical methods of inspection of in-service poles are not capable of detecting early stages of decay [3]. As indicated in [12] wood poles that are decayed, weathered or present significant checking may present shear failures that are undesirable failures because they occur suddenly. For the network owners it is essential to identify damage in due time to implement the pertinent actions and prevent unexpected failures. The proposed methodology substantially reduces the time required to perform the inspections, which may reduce the cost of maintenance of the electrical network by contributing to optimize the pole replacement and rehabilitation schedule.

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