APPLICATION AND IMPROVEMENT OF CONVENTIONAL STRESS-WAVE-BASED NON-DESTRUCTIVE TESTING METHODS FOR THE CONDITION ASSESSMENT OF IN-SERVICE TIMBER UTILITY POLES

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ABSTRACT

Timber utility poles represent a significant part of Australia's infrastructure for power distribution and communication networks. Due to their advanced age, significant efforts are undertaken to prevent utility lines from failure. However, the lack of reliable tools for assessing the condition of in-service poles seriously jeopardizes the maintenance and asset management. Non-destructive testing (NDT) methods based on stress wave propagation can potentially offer simple and cost-effective tools for the condition assessment of in-service timber poles. Based on the impact direction and location, mainly two wave types can be excited in a pole, i.e. longitudinal and bending waves. A conventional stress-wave-based method that analyses longitudinal waves is the Sonic Echo (SE) method; and a typical signal processing method for the analysis of bending waves (BW) is the Short Kernel Method (SKM). In this paper, firstly, the application of the conventional SE method and the BW method with SKM data analysis is investigated for the condition assessment of timber poles from a signal processing perspective. Secondly, to improve limitations of the current methods, the application of a multi-sensors array is proposed for more reliable and accurate results. The new method is validated on numerical data of a timber pole modelled with both isotropic and orthotropic material properties.

KEYWORDS

Non-Destructive Testing, Timber Pole, Signal Processing, Sonic Echo, Short Kernel Method.

INTRODUCTION

Timber utility poles play a significant role in power and telecommunication infrastructures all over the world (Crews 2000). As reported by Kent (2006), there are more than 5 million timber utility poles currently in-service throughout Australia's energy networks. According to the review of Australian Timber Pole Resources for energy networks conducted by Francis (2006), many of the currently installed timber poles need to be replaced or need remedial maintenance over the next decade. Based on the cost assumption of $500 for a new timber pole, 1.75 billion dollars would need to be invested to replace 3.5 million timber poles. Furthermore, new poles are required for new lines, costing 13.5 million dollars per annum with the assumption of constant demand at half of the total demand by utility networks in 2005 in the future years. In addition, Australian timber pole stakeholders are facing a critical pole supply shortage. The lack of reliable information regarding the in-service condition of timber poles, including the embedment length or the degree of deterioration or damage below ground level, makes it extremely difficult for asset managers to make decisions on the replacement/maintenance process with due consideration to economy, operational efficiency, risk/liability and public safety. Non-destructive testing (NDT) methods based on stress wave propagation can potentially offer simple and cost-effective tools for identifying the in-service condition of timber poles. Stress waves can be generated as a result of deformations caused by impact excitation. Based on the impact direction and location, mainly two wave types can be excited in a pole, i.e. longitudinal and bending waves. The propagation of the stress waves depends on the geometry of the structure as well as its material properties such as the modulus of elasticity, Poisson's ratio and density as shown by Davis (1998). In this regard, analysing captured impulse response signals from a timber pole can provide indications on the structure's soundness. A conventional stress-wave-based method that analyses longitudinal waves is the Sonic Echo (SE) method (Paquet 1968); and a conventional signal processing method for the analysis of bending waves (BW) is the Short Kernel Method (SKM) (Holt, et al. 1994). In this paper, firstly, the application of the conventional SE method and the BW method with SKM data analysis is investigated for the condition assessment of the timber poles with emphasis on signal processing. Secondly, to improve limitations of the current methods, the application of a multi-sensors array is proposed for more reliable results. The new method is only tested on numerical data of a timber pole modelled with both isotropic and orthotropic material properties. Experimental validation on in-service timber utility pole will be conducted in the future.

METHOD OF SOLUTION

Sonic-Echo method

The Sonic Echo (SE) method (also known as Seismic Echo, Pile Integrity Test, etc.), is the first surface stress-wave-based NDT method to become commercially available (Paquet 1968). In the SE method, first, an excitation impact is applied on top of a pile/pole structure causing longitudinal waves. Next, from sensor measurements, the signal is identified that is associated with the stress wave travelling from the impacted point, reflecting at the bottom surface of the pile and travelling back to the sensor. The reflected wave (echo) can be measured in terms of displacement, velocity or acceleration as a function of time by a sensor located near the impact location. Once the travelling time Δt of the echo is determined, the length L of the pile can be estimated with Eq. 1 (Huang and Ni 2012).

$$L = \frac{V_c \Delta t}{2} \tag{1}$$

where V_c is the longitudinal wave velocity in the pile. Larry, et al. (1998) investigated the benefits and the limitations of this method.

Short Kernel Method

The problem of the bending wave propagation in cylindrical structures was first investigated with elastic equations by Chree (1889). More information of the derivation can be found in Love (2013).

Bending Waves (BW) can be produced by applying a horizontal impact on a pile, and it is necessary to utilize at least two sensors to record the wave travel. In the case of length (or depth) estimation, dispersive analysis, in which wave data is extracted from a selected group of frequencies is required. These frequencies are analyzed for the individual time required to travel to the bottom of the structure and back. The Short Kernel Method (SKM) is a dispersive analysis technique that has been widely employed for the analysis of bending waves. The SKM is a mathematical procedure that is based on the cross-correlation procedure described by Bendat and Piersol (1993). It was developed for digital signal processing and determines the location and the velocity of selected frequencies inside dispersive time records. In the SKM, a single value of a specific frequency is indicated as follows:

$$SKM(j,k) = \sum_{i=1}^{N-1} g(\tau_i + j\Delta t) f[\tau_i, k]\Delta t \quad with \quad j = 1 \; to \; N2 - N1 \tag{2}$$

In Eq. 2, $SKM(j,k)$ is the jth term of the cross-correlation currently being performed at the kth frequency, g is the captured signal in one sensor, f is the kernel seed of the kth frequency used to perform the cross-correlation, $N1$ is the number of data points in the f, $N2$ is the number of data points in the g, and Δt is the time step at which the time record g is stored. Thus, Eq. 2 calculates each single SKM value as the cross-correlation of a given frequency with a discrete signal.

THE TEST STRUCTURE

For the presented study, numerical models of timber poles were created and analysed with the software ANSYS using transient analysis. The modelled poles were 11 m or 12 m long and had a diameter of 300 mm, which are typical dimensions of utility poles used in the field. For the isotropic modelling of the timber, the material properties are as follows: the density (ρ) was set to 950 kg/m^3, the elastic modulus (E) to 23,000 MPa, and the Poison's ratio (v) to 0.3. An impact force, generating stress waves, was applied to the surface of the pole based on the specific type of the test. The impact load was similar to a hammer impact typically executed in field testing. The following two timber pole cases were modelled and analysed for the investigations in this paper:

(a) Timber pole modelled with isotropic material properties embedded in soil.
(b) Timber pole modelled with orthotropic material properties embedded in soil.

For the orthotropic modelling, material properties in Tables 1 and 2 were used. The material properties of the soil were as follows: ρ = 1,520 kg/m^3, E = 100 MPa, and v = 0.3. The structural response was captured for a time duration of 0.025 s with a time step of 5 μs. The response was recorded as displacement and by double differentiation acceleration data was obtained and used for further signal analysis.

Table 1: Elastic modulus values of simulated orthotropic timber pole

	Radial direction	Transversal direction	Longitudinal direction
Elastic modulus (MPa)	1,955	850	23,000

Table 2: Shear modulus and Poison's ratio values of simulated orthotropic timber pole

	Radial transversal	Transversal longitudinal	Radial longitudinal
Shear Modulus (MPa)	357	1,037	1,513
Poison's ratio	0.682	0.023	0.044

RESULTS AND DISCUSSIONS

For the study of the SE method, the impact is applied at the top center of the modeled pole and eight measurement points (sensors), S1-S8, are placed along the pole with 0.2 m distance starting at 1.2 m (S8) and ending at 2.6 m (S1) from the bottom of the pole. For the BW method investigation, two groups of measurement points (each containing two sensor points) are positioned along the pole with 0.2 m distance starting at 1.6 m (S4) and ending at 2.4 m (S1) from the bottom of the pole. The impact is applied at the side of the pole, 1 m above the ground level. The estimated lengths and associated errors for all measurement points for both simulated timber pole cases, isotropic and orthotropic (after applying an Equiripple FIR filter with a 2 kHz cut-off frequency) are shown in Figure 1 and Table 3.

The velocity of the longitudinal wave is taken as 5000 m/s (more details about this assumption can be found in Subhani, et al. (2013)). As it can be seen in Figure 1, the errors of the estimated lengths differ from sensor to sensor. When assuming a constant value for the wave velocity, it has the effect of different estimation errors for sensors of different locations. This is because, firstly, the down-going and the reflection waves have different wave velocities, and secondly, the reflection peaks are not perfectly aligned on the time axis. In fact, in the conventional SE method, the embedded length is estimated using the time difference between the first arrival and the reflection peaks. However, the reflection wave is distorted as it travels through the pole, and hence, the peaks of different sensors are not perfectly in one line such as the peaks in the down-going wave (first arrivals). For these reasons, the estimation errors are different in sensors of different locations. It is also worth noting that sensor eight (S8) is located exactly at the soil level.
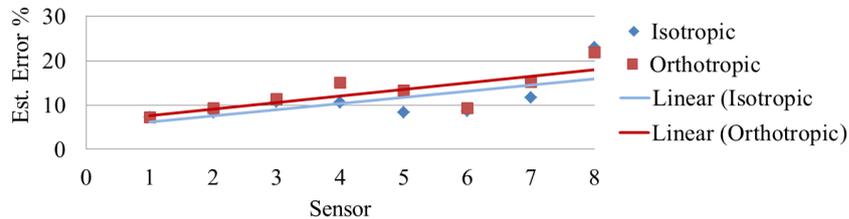

Figure 1: Length estimation errors (%) for all eight sensors for both simulated timber poles cases, isotropic and orthotropic, using the conventional SE method.

Table 3: Length estimation errors of all simulated cases using the SE method

Sensor	Real length (m)	Isotropic model	Orthotropic model
S1	2.6 m	7.21%	7.21%
S2	2.4 m	8.33%	9.37%
S3	2.2 m	10.79%	11.36%
S4	2.0 m	10.62%	15.00%
S5	1.8 m	8.33%	13.19%
S6	1.6 m	8.59%	9.37%
S7	1.4 m	11.60%	15.17%
S8	1.2 m	22.91%	21.87%

For the SKM, which utilizes the bending wave (BW), Figure 2 illustrates the Frequency Response Functions (FRFs) of all sensors for both simulated cases (isotropic and orthotropic).

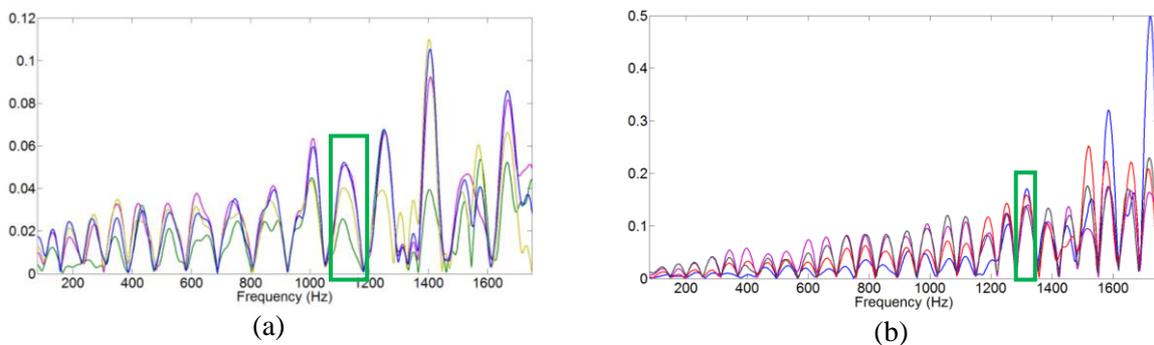(a)   (b)

Figure 2: FRFs of all sensors for (a) isotropic and (b) orthotropic model (the seed frequency is highlighted with a green rectangle)

The SKM procedures and length estimation results for the same simulated cases are shown in **Error! Reference source not found.** and Table 4 for signals from S1 and S2. It can be seen in Table 4 that the reflection peak could not be detected in S1 for the orthotropic case. In fact, the reflection peak detection (especially in the orthotropic case) is not an easy task and heavily depends on the experience

of the signal processor, and availability of prior knowledge of the pole (see **Error! Reference source not found.** (b)).

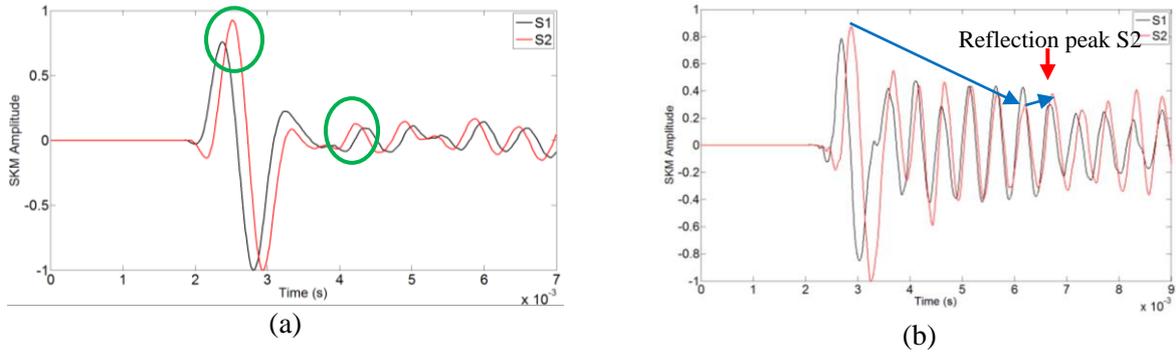(a)   (b)

Figure 3: Reflection peak detection of signals from S1 and S2 using the SKM.

Table 4 : Length estimation errors of all simulation cases for BW data using the SKM.

Sensor	Actual length	Est. length for the isotropic model	Errors	Est. length for the orthotropic model	Error
S1	2.4 m	1.70 m	-29%	…	…
S2	2.2 m	1.50 m	-31%	1.90 m	-13.63%
S3	1.8 m	1.23 m	-32%	1.64 m	-8.88%
S4	1.6 m	1.07 m	-33%	1.70 m	6.25

As shown above, the conventional SE method suffers from some limitations due to the distortions of the reflection wave. Therefore, in the following, a multi-sensors array is employed to overcome the shortcomings of the conventional SE method. Figure 4 shows the multi-sensors array analysis of the simulated orthotropic timber pole for the embedded condition.
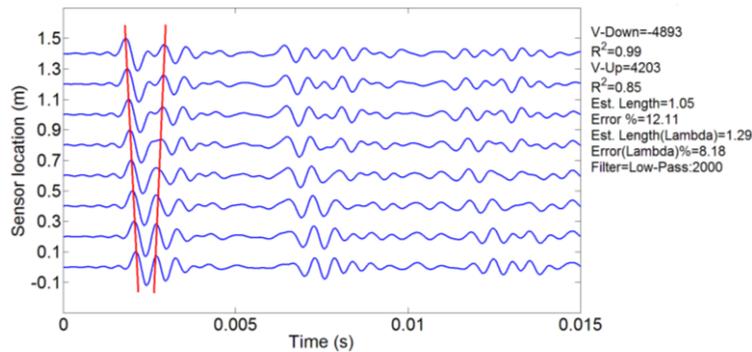

Figure 4: Multi-sensors array analysis for the orthotropic timber pole using the SE method.

To determine the length based on the multi-sensor array analysis, two methods have been employed. In the first method, the crossing of two lines is determined, which are related to the down-going and reflection waves (as shown by the red lines in Figure 4), and a decrement factor method. It is worth mentioning that crossing the two lines has the benefits of not directly utilizing the time differences between first wave arrivals and the reflection peaks. In fact, employing the curve fitting algorithm to both sets of the first arrivals and the reflection peaks makes the SE method less sensitive to the time differences in each sensor. In the second method, since the wave velocity under the soil decreases to about 90% of its value above the soil due to energy absorption by the soil, a decrement factor (λ) is introduced and the length is estimated using Eq. 3.

$$L_e = (t_8^2 - t_8^1) * \frac{V_u * V_d}{V_u + V_d} * \lambda$$

(3)

As it can be seen in Figure 4, the velocities of the down-going and the reflection waves are estimated with high fitting accuracies. Also, the length of the pole is estimated with higher accuracies, e.g.

8.18% using the decrement factor method, in contrast to 12.11% without the use of the decrement factor method.

CONCLUSIONS

The main contributions of this paper are: firstly, to demonstrate the shortcomings of the conventional Sonic-Echo (SE) method and the Short Kernel Methods (SKM) for the condition assessment of timber utility poles (i.e. embedment length estimation), and secondly, to propose a simple method to improve the SE method. For the SE method, it has been shown that the conventional method (in which a constant wave velocity value is assumed, and the length estimation relies on a single sensor) is reliant on the sensor location and its distance from the impact location. In other words, it heavily relies on the time difference between the first arrival and the reflection peak. Therefore, it is proposed to employ a multi-sensors array system to enable the calculation of the actual wave velocity, and to obtain more reliable length estimation results. In the method proposed in this paper, the length of the pole is estimated without directly utilizing the time difference between the first wave arrival and reflection peaks. The velocity analysis results showed that the down-going and the reflection waves do not have exactly the same velocities. Application of the SKM for bending wave data analysis showed that the reflection peak detection is not an easy task and heavily relies on the experience of the test performer and the signal processor, and availability of prior knowledge of the inspected timber pole. While the presented investigation was conducted on numerical data with impact on top of a pole, in future, it is intended to study the method for impact from the side of a pole, as well as an experimental validation on real in-service timber utility pole will be conducted.

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