A NUMERICAL INVESTIGATION ON THE DAMAGE IDENTIFICATION OF TIMBER UTILITY POLES BASED ON WAVELET PACKET ENERGY

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ABSTRACT

Timber utility poles are traditionally used for electricity and telecommunication distribution. Due to the old age of many distribution networks, the health condition of these timber poles needs to be assessed. Non-destructive testing (NDT) methods based on stress wave propagation have successfully been used in practice for the condition assessment of timber poles. However, for the successful application of these methods for damage identification, some limitations exist. To overcome these limitations, this paper proposes the use of wavelet packet energy (WPE) for the stress wave data analysis and damage identification. WPE is a sensitive indicator for structural damage and has been used for damage detection in various types of structures. This paper presents a comprehensive investigation on the novel use of WPE for the damage identification in timber utility poles using finite element (FE) models. The research study comprises of the following investigations: i) a comparative study between 2D and 3D models, ii) a sensitivity study of mesh density for 2D models, and iii) a study of the novel WPE-based technique for damage detection in timber poles. The results of the new method clearly show the effectiveness of the proposed damage identification technique based on WPE.

KEYWORDS

Wavelet packet energy, stress waves, finite element analysis, damage detection, timber pole.

INTRODUCTION

Timber utility poles represent a significant part of infrastructure for electricity distribution and communication networks in Australia. Nearly 7 million timber poles are in service and about $40-$50 million are spent annually on their maintenance and asset management. To prevent the ageing poles from collapse, about 300,000 electricity poles are replaced in the Eastern States of Australia every year. However, up to 80% of the replaced poles are still in a very good condition (Nguyen et al., 2004). Therefore, huge natural resources and money is wasted.

Non-destructive testing (NDT) methods based on stress wave propagation are one of promising candidates for pole/pile assessment and can be used in practice to address the needs of the utility pole asset management industry. However, current methods are often based on over-simplified assumptions and thus fail to deliver reliable results. In the presented study, in order to gain an in-depth understanding of the propagation of stress waves in damaged poles and to develop an effective damage detection method, a solid numerical study of wave behaviour is undertaken and a new WPE method is investigated for damage identification. Wavelet-packet-based damage detection is an effective method to identify damage in structure health monitoring. As such, Ren et al. (2005) and Sun et al. (2002) proposed damage detection methods using changes of WPE before and after damage. However, the application of these methods has the limitation that sensors/measurement points have to cover the entire area where damage has to be assessed. For embedded utility poles, however, the part that is buried in soil, which is indeed most prone to damage, cannot be covered with sensors. Therefore, a novel WPE damage detection method is investigated for application to timber utility poles.

GENERATION OF EFFECTIVE FINITE ELEMENT MODEL

Comparison between two-dimensional (2D) and three-dimensional (3D) FE models

Finite element (FE) analysis is based on a system of nodes that form a mesh and thereby create a number of elements. These elements are associated with material and structural properties, which determine the behaviour of the structure. In general, more accurate results are obtained from a finer mesh density. While 3D models deliver more accurate results compared to 2D models, they require more computational time and resources. For the modelling of timber poles for stress-wave-based damage detection, at least 30 elements must be created per wave length (depending on the excitation frequency) in order to capture the wave front accurately. Hence, a large number of elements is required, which results in a very long computation time. To overcome this problem, a 2D axisymmetric numerical model can be considered (see Figure 1).

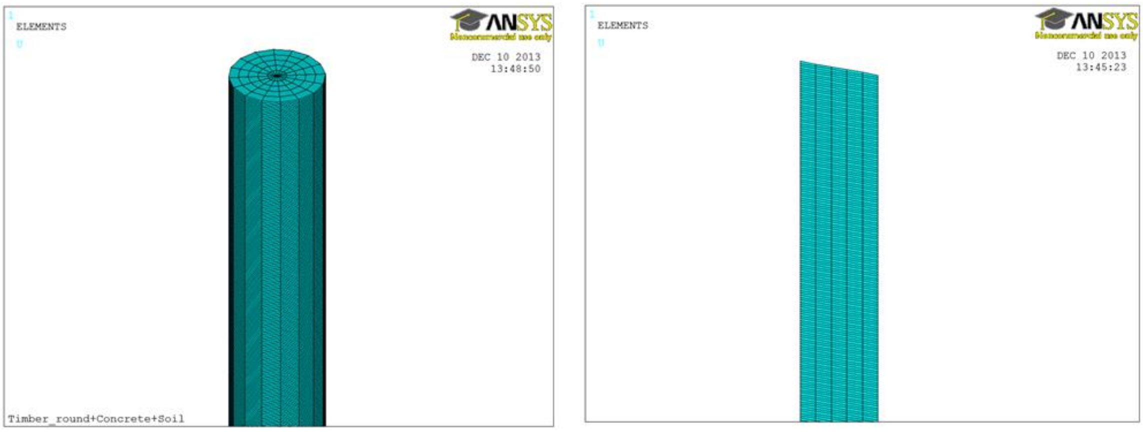


Figure 1 3D and 2D axisymmetric models created with ANSYS

To justify whether a 2D model is reasonable to represent a 3D model, a comparative study between 2D and 3D models was undertaken. Therefore, a 5 m free standing timber pole was simulated with the FE software ANSYS and an excitation force with Gaussian distribution (see Eq. 1) with a central frequency of 20 kHz was applied on the top centre of both models to generate longitudinal waves.

$$P(t) = \frac{A}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2} \sin(2\pi t f) \qquad (1)$$

where σ is standard deviation, μ is mean (where Gauss distribution is a maximum), A is amplitude and f is central frequency. Figure 2 shows the recorded acceleration results from a measurement point located at a distance of 1 m from the bottom of the pole under the same excitation. The solid line is the result of the 2D model and the dotted line is the result of the 3D model. From Figure 2, it can be seen that even though the amplitudes are slightly different, the wave patterns of the two models are consistent. Based on these results, it was concluded that a 2D model can be used for the further study.

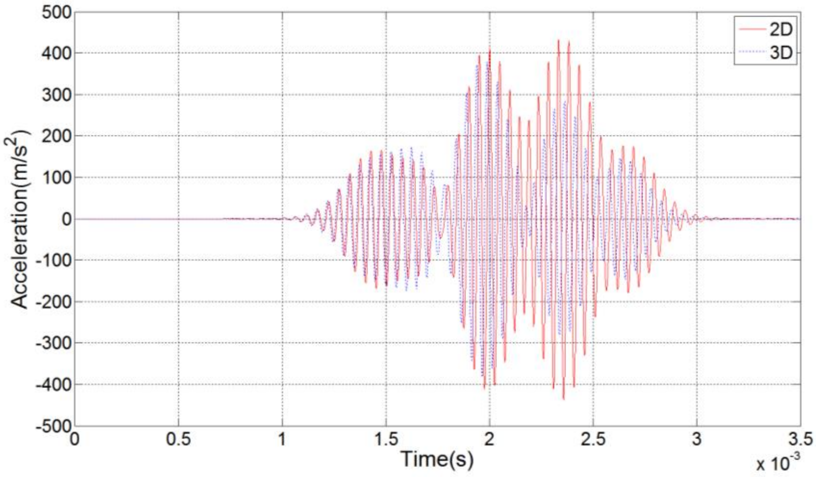


Figure 2 Result comparisons between 2D and 3D models of 5 m long pole

It is noted that the research work in this paper is based on an isotropic model without soil influence. According to a dispersion study by Subhani et al. (2013) on the wave propagation in timber poles, the influence of the surrounding soil on the wave velocity is negligible. Hence, only a free standing pole model is considered in this study. For further information, a thorough study on the boundary modelling of timber poles under soil influence was previously published by the authors (Yan et al., 2012). Considerations of electrical conductors at the pole top are not considered at this research stage.

Sensitivity study of mesh density for 2D models

In FE analysis, the mesh density significantly influences the numerical results. Therefore, several different mesh densities were studied under different excitation frequencies. A fine mesh of 40 elements per wavelength (depending on the input frequency) was set as a standard (Fischer et al., 2010). The results from signals from different measurement points under different mesh density conditions were compared to the results from the standard mesh condition. To evaluate the results, the cross-correlation coefficient was used, which is a similarity measurement of two signals or waveforms. If two signals are exactly the same, the coefficient will be 1; if the signals do not match at all, the coefficient will be 0. In this study, this methodology was used to identify the differences between signals that were obtained from two mesh conditions with the same measurement point. Table 1 shows the cross-correlation coefficients between the standard mesh condition (fine mesh) and different medium and coarse mesh conditions. In the table, λ represents the wavelength; w and h indicate the width and the height of an element, respectively. The measurement points were selected at 1.7 m to 2.7 m from the bottom of the pole with a distance between each point of 200 mm.

Table 1 Comparison of cross-correlation coefficients under different mesh densities

Excitation frequency: 25 kHz, λ = 0.12 m			Measurement points					
Mesh	Mesh density	Element size [w/h]	2.7 m	2.5 m	2.3 m	2.1 m	1.9 m	1.7 m
Fine	60x2000	0.0025 m/0.0025 m	-	-	-	-	-	-
Medium	40x1000	0.00375 m/0.005 m	0.988	0.929	0.986	0.947	0.955	0.983
	24x1000	0.00625 m/0.005 m	0.980	0.895	0.985	0.938	0.936	0.979
	20x1000	0.0075 m/0.005 m	0.970	0.850	0.983	0.925	0.917	0.975
Coarse	20x800	0.0125 m/0.00625 m	0.958	0.766	0.971	0.874	0.866	0.965
	4x2000	0.0375 m/0.0025 m	0.829	0.622	0.876	0.680	0.496	0.608
Excitation frequency: 12 kHz, λ = 0.25 m			Measurement points					
Mesh	Mesh density	Element size [w/h]	2.7 m	2.5 m	2.3 m	2.1 m	1.9 m	1.7 m
Fine	60x2000	0.0025 m/0.0025 m	-	-	-	-	-	-
Medium	20x800	0.0075 m/0.00625 m	0.976	0.986	0.977	0.978	0.956	0.951
Coarse	12x800	0.0125 m/0.00625 m	0.964	0.980	0.973	0.971	0.943	0.939
	12x500	0.0125 m/0.001 m	0.953	0.976	0.962	0.968	0.926	0.927
	4x2000	0.0375 m/0.0025 m	0.830	0.937	0.911	0.953	0.818	0.870

Excitation frequency: 8 kHz, λ = 0.5 m			Measurement points					
Mesh	Mesh density	Element size [w/h]	2.7 m	2.5 m	2.3 m	2.1 m	1.9 m	1.7 m
Fine	60x2000	0.0025 m/0.0025 m	-	-	-	-	-	-
Medium	20x500	0.0075 m/0.01 m	0.976	0.973	0.973	0.970	0.971	0.961
Coarse	8x1000	0.02 m/0.001 m	0.973	0.973	0.973	0.966	0.962	0.957
	4x2000	0.0375 m/0.0025 m	0.971	0.965	0.954	0.951	0.950	0.943
	8x200	0.02 m/0.025 m	0.955	0.954	0.955	0.947	0.939	0.944

In Table 1, the cross-correlation coefficients of four excitation frequencies are listed. Waves of a higher frequency have a smaller wavelength. While an excitation of 8 kHz generates waves with a wavelength of 0.5 m, the excitation of 25 kHz generate waves of a wavelength of 0.12 m. For the 2D model, the mesh density can be increased or decreased in radial and longitudinal direction. For example, the standard mesh condition model with an excitation frequency of 8 kHz has 60 elements in radial direction and 2000 elements in longitudinal direction, and the element size is 0.0025 m in width and 0.0025 m in height. A coarse mesh has 8 elements in radial direction and 200 elements in longitudinal direction, and the element size is 0.02 m in width and 0.025 m in height.

The cross-correlation coefficient study of different mesh densities lead to the following findings.

1. From the coefficients, it can be seen that for high frequency excitations, such as 25 kHz, the coarse mesh generates larger errors compared to the fine mesh condition. For the low frequency excitation, such as 8 kHz, the coarse mesh is still quite accurate. This indicates that to capture the wave front accurately, the mesh density plays a crucial role.

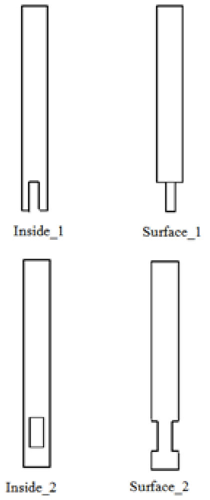
2. An optimised mesh density in all directions is more important than the total number of elements. The results of the model with an excitation frequency of 12 kHz supports this phenomenon. When comparing the two coarse mesh conditions, it is found that the mesh dimension of 12×500 contains a much smaller number of elements than the dimension of 4x2000, but the results are more accurate.

Hence, from the cross-correlation coefficient results, it is concluded that a medium mesh delivers a good balance between computation time and result accuracy and is therefore used in further studies.

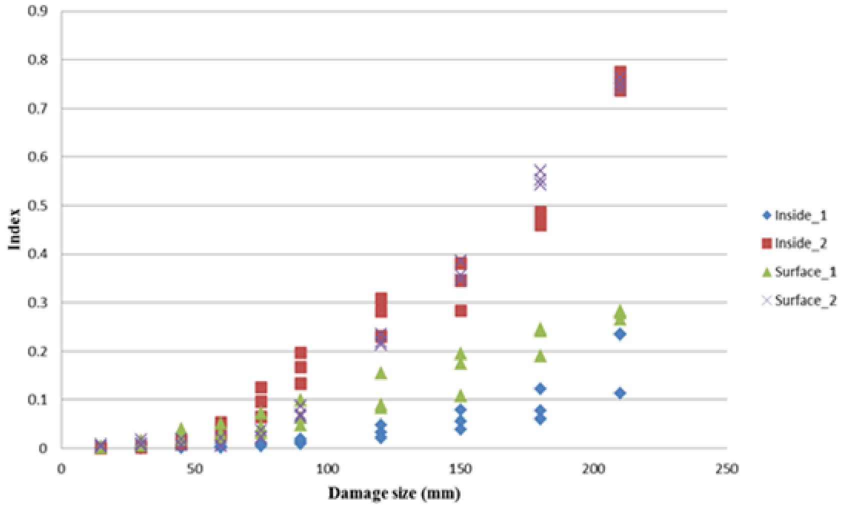
DAMAGE DETECTION BASED ON WAVELET PACKET FREQUENCY BAND ENERGY

The wavelet packet (WP) transform is a mathematical method that decomposes a signal into low and high frequency components at random time-frequency resolutions. WPs consist of a series of linearly combined wavelet functions. Wavelet packet energy (WPE) methods are traditionally used with vibration-based methods to identify damage in a structure. Thereby, sensors are placed at different locations of a structure covering the entire area that needs to be assessed. Significant energy changes indicate the occurrence of damage in the proximity of the measurement point. For the assessment of embedded timber poles, however, sensors cannot be placed at the vulnerable underground section of the pole. Therefore, WP-based damage detection of embedded timber poles can only rely on WPEs from reflected wave signals. Using reflection waves, however, can lead to uncertainties in the damage identification due to interferences between the incident wave and reflected wave causing energy changes not only from damage but also from other sources.

To overcome this issue, the use of a sensor network is proposed to minimise the effect of the interferences between the incident wave and reflected wave. In the numerical model of this study, seven sensors (measurement point) are placed from 1.7 m to 2.9 m from the bottom of the pole with a distance between each measurement point of 200 mm. Damage is simulated by removing specific elements. Different damage types with varying sizes are simulated with a damage width of 15 mm, 30 mm, 45 mm, 60 mm, 75 mm, 90 mm, 120 mm, 150 mm, 180 mm and 210 mm, respectively, and a constant damage height of 200 mm. The four investigated damage types are illustrated in Figure 3 (a).



(a)



(b)

Figure 3 (a) Damage types and (b) damage indicator

The wave signals are generated with a continuous sine wave of 8 KHz that is applied at the top centre of the pole. The wave measurements are captured by the seven sensors and the WP component energies of each sensor are calculated. The BiorSplines 6.8 wavelet is selected due to its features of good orthogonality and high vanishing moments. The sampling rate is set to 5 MHz and the decomposing scale to 10. After the WP decomposition, 1024 frequency bands are obtained for each sensor, e.g. 1024 energy components.

The difference of each component energy (*DEC*) between any two sensors under the same condition are calculated using Eq. 2. For the seven sensors, this will generate 21 combinations of *DECs*. The comparison of each combination of *DECs* between the intact and the damaged conditions will then indicate the damage severity. The cross-correlation coefficient is considered as a comparison parameter and defined by Eq. 3

$$DEC = E_{c,i} - E_{c,j} \qquad (i,j = 1,2,\dots 7) \tag{2}$$

$$R(\tau) = \max\left|\sum_{n=1}^{N-1} DEC_{ci}(n) DEC_{cd}(n+\tau)\right| \tag{3}$$

where E_c are the component energies, *R* is cross-correlation coefficients of two signals, and indicates the similarity of *DECs* under intact and different damage conditions, DEC_{ci} presents the results from the intact condition and DEC_{cd} is obtained from the damaged condition. A damage severity index based on a set of *R* is calculated by Eq. 4

$$Index = \sqrt{\frac{\sum(1-R)^2}{Ns}} \tag{4}$$

Where *Ns* is the total number of *R for all combinations*. The rationale of the presented method is that the comparison of *DECs* between the intact and damaged condition will indicate the presence of damage, and the larger the damage size the larger the difference of *DECs*. In this method, the interferences between the incident wave and reflected wave will not affect the results since the interference phenomenon also occurs in the intact condition, e.g. the *DEC* between any two sensors of the intact condition also includes the energy changes caused by the interference of waves. As a result, comparing the *DEC* between the intact and the damage condition will indicate the size of the damage. The proposed method can be summarised in the following steps:

1. Apply 10 level WP decomposition to wave signals and obtain 1024 energy components for each sensor for the intact and damage conditions;

2. Calculate *DECs* between any two sensors for the intact and different damage conditions (21 combinations for each condition if seven sensors are placed)

3. Calculate the cross-correlation coefficients for each combination of DEC between the intact and damage conditions (21 coefficients are obtained if seven sensors are placed)

4. Calculate the damage index based on the obtained cross-correlation coefficients for each damage condition.

The calculated indexes according to different damage conditions under four damage types were plotted in Figure 3 (b). The x-axis indicates different damage size and the y-axis shows the calculated index value. The different signs demonstrate the four investigated damage types. From the figure, it can be seen that the index value increases with an increase of the damage size. To verify the consistency of these results, in an additional study, 13 and 25 sensors were recorded, respectively, with measurement locations from 1.7 m to 2.9 m with equal spacing between the sensors. After calculating the index of the two additional sensor arrangements, the results showed consistency with the previous study using only seven sensors. The presented results indicate that the proposed damage detection method can be used for damage identification of embedded pole/pile structures with inaccessible damage regions.

CONCLUSIONS

This paper presented a novel damage detection method based on WP energies. The method was validated on numerical timber pole models identifying damage severities of structures where measurement sensors cannot be placed in the damage region, such as the studied embedded timber poles. The results of the study showed a clear trend of the proposed damage index, however, some obtained indices were outliers. Hence, a more refined damage classification method will be developed in the future so that the damage severity indicator will be more effective. In such study, an orthotropic model and advanced signal processing method will be considered. Also, in the future the method will be validated on in-situ timber pole structures.

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