University of Technology Sydney
Faculty of Engineering and Information Technology

A Study on the Behaviour of Guided Wave Propagation in Utility Timber Poles

A DISSERTATION

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by
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Abstract

Timber is a widely used engineering material because of its availability and good engineering properties. The round timber is suitable for electricity poles, wharfs, piles, bridge piers, etc. There are nearly 7 million utility poles in the current network in Australia, in which around 5 million timber poles are used for distribution of power and communications. The utility pole industry in Australia spends about \$40~\$50 million annually on maintenance and asset management to avoid failure of the utility lines. Each year about 30,000 electricity poles are replaced in the eastern states of Australia, despite the fact that up to 80% of these poles are still in a very good serviceable condition. In addition, with discovery of scour problems in bridge foundations in the past 30 years, a study on the USA's national bridge stock showed that out of approximately 580,000 highway timber bridges in the National bridge inventory, about 104,000 of these bridges had unknown foundations depth. Therefore, a reliable non-destructive evaluation technique is essential for the condition assessment of timber poles/piles to ensure public safety, operational efficiency and to reduce the maintenance cost.

Different types of non-destructive tests (NDT) were developed during the last decades to evaluate the embedment depth and the quality of materials of embedded structures. Some of these methods have also been utilised for timber piles or poles. However, the extent of knowledge developed on non-destructive tests for timber piles is far from adequate and the effectiveness and reliability of current NDTs are questionable due to uncertainty on materials, structures and environment. In addition, one dimensional assumption is usually considered while dealing with timber poles/piles which is insufficient to reflect the actual behaviour of stress wave propagation in the columnar structures. Also, the anisotropic behaviour of timber and the effects of environment are not taken into account in numerous conventional non-destructive evaluations (NDE) that leads to errors regarding the condition assessment of timber poles.

Waves propagating along a pile/pole include different clusters of waves, called guided waves (GWs). In GW, the velocities of a wave (such as phase velocity, group velocity, energy velocity) become a function of frequencies (i.e. wave dispersion behaviour) and displacement magnitude varies when waves propagate along the pole. Besides, GWs that have the same frequencies possess shorter wavelengths than their counterpart of conventional surface wave. Hence, it is possible to detect smaller sized defects with a guided wave technique than a surface wave technique. Hence, it is essential to model the actual three dimensional behaviour of wave propagation inside the timber pole instead of one dimensional assumption, and the environmental factors in conjunction with the actual timber pole situation is necessary to be addressed before suggesting an experimental set up and verification.

This thesis investigates the GW propagation inside the timber pole using an analytical, one semi analytical and one numerical method. The actual GW equations are solved analytically considering the timber as both isotropic and transversely isotropic material to emphasize the importance of modelling timber as an anisotropic material. Some parametric studies are also carried out to show the effect of the diversity in material properties of timber on the stress wave propagation. Also, the dispersion curves, mode shapes, contribution of different branches of longitudinal and flexural waves in a signal are presented in order to propose a suitable input frequency and number of cycles, the distances among the sensors, the location and orientation of sensors, etc. Although the analytical GW solution can offer a number of suggestions for the experimental set up, the time domain results cannot represent the actual boundary conditions due to the complexity involved in solving the partial embedment of soil that reflects the actual field behaviour. Besides, the impact location and orientation cannot be implemented in the analytical GW solution. Accordingly, a semi analytical method, namely, Spectral finite element method (SFEM) is employed to model the timber pole with the actual boundary conditions together with the impact location and orientation to illustrate the propagation of different kind of waves and branches. Even though SFEM can explain both the dispersion curves and time domain reconstruction, the dispersion curves are only accurate up to a certain frequency. Further, the three dimensional behaviour is unavailable in SFEM as this method cannot present the wave propagation in the circumferential direction. To overcome this issue, a numerical technique is implemented using the Finite Element method, and based on the signal obtained from this method, the three dimensional behaviour is explained which is then utilized to separate different kind of waves. Beyond that, two popular advanced signal processing techniques are applied to the numerical signals to compare the efficiency of these two approaches leading to determining the wave velocity and the embedment length of the timber pole.

Certificate of authorship/originality

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Mahbube Subhani

Date:

To my loving younger sister Ummul Afia Shammi

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List of Publications based on this research

Journal Publications

1. **Subhani, M.**, Li, J., Gravenkamp H. & Samali, B. (2013), 'Effect of Elastic Modulus and Poisson's Ratio on Guided Wave Dispersion Using Transversely Isotropic Material Modelling', *Advanced Material Research*, vol. 778, pp. 303-311.*

2. **Subhani, M.,** Li, J., Samali, B. & Yan N. (2013), 'Determination of the embedded lengths of electricity timber poles utilising flexural wave generated from impacts', *Australian Journal of Structural Engineering, vol. 14, no. 1, pp. 85.**

3. **Subhani, M.**, Li, J. & Samali, B. (2013), 'A comparative study of guided wave propagation in timber poles with isotropic and transversely isotropic material models', *Journal of Civil Structural Health Monitoring, vol. 3, no. 2, pp. 65-79.**

4. Li, J., **Subhani, M.** & Samali, B. (2012), 'Determination of Embedment Depth of Timber Poles and Piles Using Wavelet Transform', *Advances in Structural Engineering*, vol. 15, no. 5, pp. 759-770.*

Conference Publications

1. **Subhani, M.**, Li, J., Gravenkamp H. & Samali, B. (2013), 'Effect of Elastic Modulus and Poisson's Ratio on Guided Wave Dispersion Using Transversely Isotropic Material Modelling', *Proceedings of the International Conference on Structural Health Assessment of Timber Structures (SHATIS 13)*, 4-6 September 2013, Trento, Italy.

2. **Subhani, M.**, Samali, B. & Li, J. (2012), 'Behaviour of stress wave propagation in utility timber pole', *Proceedings of the 22nd Australasian Conference on the Mechanics of Structures and Materials (ACMSM 22)*, 11-14 December 2012, University of Technology, Sydney, Australia.*

3. Li, J., Dackermann, U. & **Subhani, M.** (2012), 'R&D of NDTs for Timber Utility Poles in Service - Challenges and Applications (Extension for Bridge Sub-Structures and Wharf Structures)', *Proceedings of the Workshop on Civil Structural Health*

Monitoring (CSHM-4), 6-8 November 2012, Bundesanstaltfür Materialforschung und -prüfung (BAM), Berlin, Germany, Lecture 13, (published on CD).*

4. **Subhani, M.,** Li, J. & Samali, B. (2012), 'A comparative study of guided wave propagation in timber poles with isotropic and orthotropic material models', *Proceedings of the First International Conference on Performance-based and Life-cycle Structural Engineering (PLSE)*, 5-7 December 2012, The Hong Kong Polytechnic University, Hong Kong, (published on CD).*

5. **Subhani, M.**, Li, J., Samali, B. & Dackermann, U. (2011), 'Determinations of stress wave velocity in a timber pole using wavelet transform', Dynamics for Sustainable Engineering, *Proceeding of the 14th Asia Pacific Vibration Conference*, 5-8 December 2011, The Hong Kong Polytechnic University, Hong Kong, pp. 222-231.*

6. Li, J., Crews, K., Samali, B., **Subhani, M.** & Zad A. (2011), 'Determination of Embedment Depth of Timber Poles and Piles using wavelet transform', *Proceedings of the International Conference on Structural Health Assessment of Timber Structures (SHATIS 11)*, 16-17 June 2011, Lisbon, Portugal, (published on CD).*

(* indicated peer-reviewed publications)

Table of contents

List of Tables

List of Figures

List of Abbreviations and Notations

1D	One dimensional
3D	Three dimensional
BEM	Boundary element method
CRF	Converted flexural mode reflection
CRS	Converted shear mode reflection
CWT	Continuous wavelet transform
DFT	Discrete Fourier transforms
EBT	Euler-Bernoulli beam theory
FDM	Finite difference method
FE	Finite element
FEM	Finite element method
FFT	Fast Fourier transforms
FRF	Frequency response function
FSDT	First order shear deformation theory
FT	Fourier transforms
GW	Guided wave
HSDT	Higher order shear deformation theory
IF	Incoming flexural mode
IFFT	Inverse fast Fourier transforms
IR	Impulse response
IS	Incoming shear mode
KED	Kinetic energy density
LISA	Local interaction simulation approach
MC	Moisture content
MRA	Multi resolution analysis
MSLM	Mass spring lattice model
NA	Neutral axis
NDE	Non-destructive evaluation
NDT	Non-destructive testing
ODE	Ordinary differential equation

PDE	Partial differential equation
PEP	Polynomial eigenvalue problem
PWR	Power flow density
PWVD	Pseudo Wigner – Ville Distribution
RF	Reflected flexural mode
RS	Reflected shear mode
SAFE	Semi analytical finite element method
SBFEM	Scaled boundary finite element method
SE	Sonic echo
SED	Strain energy density
SFEM	Spectral finite element method
SHPB	Split Hopkinson pressure bar
SKM	Short kernel method
STFT	Short time Fourier transforms
SVD	Singular value decomposition
WT	Wavelet transforms
WVD	Wigner – Ville Distribution

E_r	Modulus of elasticity in the radial direction
E_z	Modulus of elasticity in the longitudinal direction
E_θ	Modulus of elasticity in the tangential direction
G_{rz}	Shear modulus on the radial – longitudinal plane
$G_{r\theta}$	Shear modulus on the radial – tangential plane
$G_{\theta z}$	Shear modulus on the tangential – longitudinal plane
L_{emb}	Embedment length of the timber pole
$\widehat{M}$	Moment in the frequency domain
$\widehat{N}$	Axial force in the frequency domain
$\hat{V}$	Shear force in the frequency domain
$f_{Nyquist}$	Nyquist frequency
$\hat{u}(x,t)$	Axial displacement in the frequency domain
$\hat{v}(x,t)$	Transverse displacement in the frequency domain
ν_{rz}	Poisson's ratio corresponding to a contraction in longitudinal direction when an extension is applied in radial direction

$\nu_{r\theta}$	Poisson's ratio corresponding to a contraction in tangential direction when an extension is applied in radial direction
ν_{zr}	Poisson's ratio corresponding to a contraction in radial direction when an extension is applied in longitudinal direction
$\nu_{z\theta}$	Poisson's ratio corresponding to a contraction in tangential direction when an extension is applied in longitudinal direction
$\nu_{\theta r}$	Poisson's ratio corresponding to a contraction in radial direction when an extension is applied in tangential direction
$\nu_{\theta z}$	Poisson's ratio corresponding to a contraction in longitudinal direction when an extension is applied in tangential direction
$\hat{\varphi}(x,t)$	Shear contraction
$\hat{\psi}(x,t)$	Lateral contraction in the frequency domain
$\breve{\psi}(\omega)$	Mother wavelet in the frequency domain
$[C]$	Stiffness matrix
$[S]$	Compliance matrix
∇	Divergence operator
A	Cross sectional area
a	Radius of cylinder
A, B….F	Unknown coefficients
C	Wave velocity
C_1, C_2 … C_4	Unknown coefficients
C_f	Flexural wave velocity
C_l	Bulk longitudinal wave velocity
Cs	Bulk shear wave velocity
D	Diameter
D_{SFEM}	Dynamic stiffness matrix
E	Modulus of elasticity or Young's modulus
E_0	Longitudinal modulus of elasticity (E_L) at zero MC
E_g	E_L at temperature T
E_L	Longitudinal modulus of elasticity
f	Frequency
G	Shear modulus
$h(t)$	Translation of a window of a given length
I	Moment of inertia
J	Bessel's function of first kind
H	Hankel function

j	Imaginary number
K	Spring constant
K_1, K_2... K_4	Adjustable parameters
L	Length/reflection depth
l_1	Distance between the sensor and ground level
L_s	The distance between sensors
L_T	The distance between sensor and the bottom of the pole
N	Number of sampling points
NRG	Total energy
p	circumferential order of cylinder
P_m	Power flow of a mode
PWR_z	Component of poynting vector in the direction of propagation
$q(x,t)$	Externally applied load
r	Any distance from the centre of the circular cross section along the radius
R_i	Amplitude ratio
S	Cross section of the cylinder
s	Scaling parameter
T	Temperature
t	Time
u	Displacement
u_r	Displacement component along radial direction
u_z	Displacement component axial/longitudinal direction
u_θ	Displacement component along tangential/angular direction
V_{gr}	Group velocity
V_{ph}	Phase velocity
V_{soil}	Bulk wave velocity of soil
V_z	Energy velocity
w	Rotation vector
$x(t)$	Any arbitrary signal
Z	Ordinary and modified Bessel function of first kind
α_{leak}	Leakage angle
Δf	Distance between the two peaks in velocity versus frequency function
Δt	Time difference between the arrival and reflected peaks
I	Rotation vector

$u(x,t)$	Axial displacement in the time domain
$v(x,t)$	Transverse displacement in the time domain
α	Wavenumber for longitudinal waves
β	Wavenumber for shear waves
γ	Shearing strain
ε	Normal strain
η	Viscous damping
λ	Lamě constant
μ	Lamě constant or shear modulus
ν	Poisson's ratio
ξ	Wavenumber
ρ	Mass density
σ	Normal stress
τ	Shearing stress
$\varphi(x,t)$	Shear contraction in the time domain
$\psi(t)$	Mother wavelet in the time domain
$\psi(x,t)$	Lateral contraction in the time domain
ω	Angular frequency
ϕ	Slope