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

A DISSERTATION

SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS

for the degree of

DOCTOR OF PHILOSOPHY

in the field of

Civil and Structural Engineering

by

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March 2014
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.

________________________________________
Mahbube Subhani

Date:
To my loving younger sister Ummul Afia Shammi
Acknowledgements

I would like to express my deepest appreciation to my supervisors Prof. Bijan Samali and A/Prof Jianchun Li over the last four years as the completion of my research and the dissertation would have never been possible without their guidance. From the very beginning of the postgraduate study till now, I have been receiving advice from them not only on the planning for the research study and analysing the test results but also on my future career. As an international student, it was not so easy for me to adapt to a totally new environment initially, but Prof. Samali always helped me to make a right decision and to cope with challenge. I still recall most of the meetings I had with Prof. Bijan, where I always felt very comfortable to express my opinion regarding the research and discuss my personal issues. The kindness and co-operation of him would always be memorable throughout my life. I was very lucky that A/Prof Jianchun Li’s office was on the same floor as mine, which allowed me to meet him any time I required to. Specially, in the case of any new observations related to my research, I could freely discuss them with him which certainly helped me in explaining the findings. Prof Li’s door was always open for discussion about technical and even for any personal issues. His constant inspiration and critical reasoning about my work gave me the enthusiasm to pursue for the better.

I would also like to give special thanks to Dr Hamid Reza Valipour who was the panel member for my Master’s assessment, for his inspirations which made it possible to upgrade my course of study from Masters by research to PhD. I am also very thankful to Dr. Ali Saleh, Dr. Emre Erkmen and Prof. Keith Crews because of the time they spent with me for strengthening some of my fundamental concepts on Structural Analysis, Numerical Modelling and properties of timber materials.

I am also grateful to all the members of the timber pole project. Mr. Amir Zad always helped me to learn about all the experimental work in the laboratory and in the field. And the other members, Mr. Roman Elsener, Mr. Bahram Jozi, Ms. Ning Yan, Dr. Ulrike Dackermann, and the capstone student Mr. Andrew Tang, who always helped me to develop a holistic view of the project, and I was always comfortable to work as a
team with them. I cannot thank enough the laboratory staff, especially Mr. Peter Brown for his patient and cordial support and teaching me about the instrumentation and different equipment. Also, Mr. Rami Haddad and Mr. David Dicker always came forward to help me for conducting any kind of test under the best possible circumstances.

My parents and siblings certainly have made an invaluable contribution to the completion of my research as I would have never been able to come overseas for postgraduate studies without their support and encouragement. Many times during my PhD, I felt it was impossible to take it to the next stage; however, I was always motivated by my family to complete my research study.

I cannot but mention about some of my colleagues and friends who have contributions to the successful completion of my dissertation. Firstly, I would like to thank Mr. Aslan Hokmabadi and Mr. Mohsen Askari with whom I discussed about many technical details of my work and they helped me with their best as a friend to overcome my difficulties. Secondly, I am very thankful to Mr Chij Shrestha, Mr. Ikramul Kabir, Dr. Yancheng Li and Ms. Yukari Aoki who were not only my fellow researchers but also very good friends.

Finally, I would like to acknowledge the financial supports provided by the ARC linkage project in conjunction with Ausgrid for conducting my research. Also, the IRS scholarship offered by UTS provided me extensive support to accomplish my PhD goal.

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Mahbube Subhani

March 2014
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Journal Publications


Conference Publications


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<tr>
<td>1D</td>
<td>One dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>Three dimensional</td>
</tr>
<tr>
<td>BEM</td>
<td>Boundary element method</td>
</tr>
<tr>
<td>CRF</td>
<td>Converted flexural mode reflection</td>
</tr>
<tr>
<td>CRS</td>
<td>Converted shear mode reflection</td>
</tr>
<tr>
<td>CWT</td>
<td>Continuous wavelet transform</td>
</tr>
<tr>
<td>DFT</td>
<td>Discrete Fourier transforms</td>
</tr>
<tr>
<td>EBT</td>
<td>Euler-Bernoulli beam theory</td>
</tr>
<tr>
<td>FDM</td>
<td>Finite difference method</td>
</tr>
<tr>
<td>FE</td>
<td>Finite element</td>
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<tr>
<td>FEM</td>
<td>Finite element method</td>
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<tr>
<td>FFT</td>
<td>Fast Fourier transforms</td>
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<tr>
<td>FRF</td>
<td>Frequency response function</td>
</tr>
<tr>
<td>FSDT</td>
<td>First order shear deformation theory</td>
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<tr>
<td>FT</td>
<td>Fourier transforms</td>
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<tr>
<td>GW</td>
<td>Guided wave</td>
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<tr>
<td>HSDT</td>
<td>Higher order shear deformation theory</td>
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<tr>
<td>IF</td>
<td>Incoming flexural mode</td>
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<td>IFFT</td>
<td>Inverse fast Fourier transforms</td>
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<td>IR</td>
<td>Impulse response</td>
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<tr>
<td>IS</td>
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<td>KED</td>
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<tr>
<td>LISA</td>
<td>Local interaction simulation approach</td>
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<td>MC</td>
<td>Moisture content</td>
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<td>MRA</td>
<td>Multi resolution analysis</td>
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<tr>
<td>MSLM</td>
<td>Mass spring lattice model</td>
</tr>
<tr>
<td>NA</td>
<td>Neutral axis</td>
</tr>
<tr>
<td>NDE</td>
<td>Non-destructive evaluation</td>
</tr>
<tr>
<td>NDT</td>
<td>Non-destructive testing</td>
</tr>
<tr>
<td>ODE</td>
<td>Ordinary differential equation</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>PDE</td>
<td>Partial differential equation</td>
</tr>
<tr>
<td>PEP</td>
<td>Polynomial eigenvalue problem</td>
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<tr>
<td>PWR</td>
<td>Power flow density</td>
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<tr>
<td>PWVD</td>
<td>Pseudo Wigner – Ville Distribution</td>
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<tr>
<td>RF</td>
<td>Reflected flexural mode</td>
</tr>
<tr>
<td>RS</td>
<td>Reflected shear mode</td>
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<tr>
<td>SAFE</td>
<td>Semi analytical finite element method</td>
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<tr>
<td>SBFEM</td>
<td>Scaled boundary finite element method</td>
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<tr>
<td>SE</td>
<td>Sonic echo</td>
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<tr>
<td>SED</td>
<td>Strain energy density</td>
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<tr>
<td>SFEM</td>
<td>Spectral finite element method</td>
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<tr>
<td>SHPB</td>
<td>Split Hopkinson pressure bar</td>
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<tr>
<td>SKM</td>
<td>Short kernel method</td>
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<tr>
<td>STFT</td>
<td>Short time Fourier transforms</td>
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<tr>
<td>SVD</td>
<td>Singular value decomposition</td>
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<tr>
<td>WT</td>
<td>Wavelet transforms</td>
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<tr>
<td>WVD</td>
<td>Wigner – Ville Distribution</td>
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</tbody>
</table>

\[ E_r \] Modulus of elasticity in the radial direction
\[ E_z \] Modulus of elasticity in the longitudinal direction
\[ E_\theta \] 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
\[ \tilde{M} \] Moment in the frequency domain
\[ \tilde{N} \] Axial force in the frequency domain
\[ \tilde{V} \] Shear force in the frequency domain
\[ f_{Nyquist} \] Nyquist frequency
\[ \tilde{u}(x,t) \] Axial displacement in the frequency domain
\[ \tilde{v}(x,t) \] Transverse displacement in the frequency domain
\[ \nu_{rz} \] Poisson’s ratio corresponding to a contraction in longitudinal direction when an extension is applied in radial direction
Poisson’s ratio corresponding to a contraction in tangential direction when an extension is applied in radial direction

Poisson’s ratio corresponding to a contraction in radial direction when an extension is applied in longitudinal direction

Poisson’s ratio corresponding to a contraction in tangential direction when an extension is applied in longitudinal direction

Poisson’s ratio corresponding to a contraction in radial direction when an extension is applied in tangential direction

Poisson’s ratio corresponding to a contraction in longitudinal direction when an extension is applied in tangential direction

Shear contraction

Lateral contraction in the frequency domain

Mother wavelet in the frequency domain

Stiffness matrix

Compliance matrix

Divergence operator

Cross sectional area

Radius of cylinder

Unknown coefficients

Wave velocity

Unknown coefficients

Flexural wave velocity

Bulk longitudinal wave velocity

Bulk shear wave velocity

Diameter

Dynamic stiffness matrix

Modulus of elasticity or Young’s modulus

Longitudinal modulus of elasticity \((E_L)\) at zero \(MC\)

\(E_L\) at temperature \(T\)

Longitudinal modulus of elasticity

Frequency

Shear modulus

Translation of a window of a given length

Moment of inertia

Bessel’s function of first kind

Hankel function
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$j$</td>
<td>Imaginary number</td>
</tr>
<tr>
<td>$K$</td>
<td>Spring constant</td>
</tr>
<tr>
<td>$K_1, K_2, \ldots, K_4$</td>
<td>Adjustable parameters</td>
</tr>
<tr>
<td>$L$</td>
<td>Length/reflection depth</td>
</tr>
<tr>
<td>$l_1$</td>
<td>Distance between the sensor and ground level</td>
</tr>
<tr>
<td>$L_s$</td>
<td>The distance between sensors</td>
</tr>
<tr>
<td>$L_T$</td>
<td>The distance between sensor and the bottom of the pole</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of sampling points</td>
</tr>
<tr>
<td>NRG</td>
<td>Total energy</td>
</tr>
<tr>
<td>$p$</td>
<td>Circumferential order of cylinder</td>
</tr>
<tr>
<td>$P_m$</td>
<td>Power flow of a mode</td>
</tr>
<tr>
<td>$PWR_z$</td>
<td>Component of poynting vector in the direction of propagation</td>
</tr>
<tr>
<td>$q(x,t)$</td>
<td>Externally applied load</td>
</tr>
<tr>
<td>$r$</td>
<td>Any distance from the centre of the circular cross section along the radius</td>
</tr>
<tr>
<td>$R_i$</td>
<td>Amplitude ratio</td>
</tr>
<tr>
<td>$S$</td>
<td>Cross section of the cylinder</td>
</tr>
<tr>
<td>$s$</td>
<td>Scaling parameter</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
</tr>
<tr>
<td>$t$</td>
<td>Time</td>
</tr>
<tr>
<td>$u$</td>
<td>Displacement</td>
</tr>
<tr>
<td>$u_r$</td>
<td>Displacement component along radial direction</td>
</tr>
<tr>
<td>$u_z$</td>
<td>Displacement component axial/longitudinal direction</td>
</tr>
<tr>
<td>$u_\theta$</td>
<td>Displacement component along tangential/angular direction</td>
</tr>
<tr>
<td>$V_{gr}$</td>
<td>Group velocity</td>
</tr>
<tr>
<td>$V_{ph}$</td>
<td>Phase velocity</td>
</tr>
<tr>
<td>$V_{soil}$</td>
<td>Bulk wave velocity of soil</td>
</tr>
<tr>
<td>$V_z$</td>
<td>Energy velocity</td>
</tr>
<tr>
<td>$w$</td>
<td>Rotation vector</td>
</tr>
<tr>
<td>$x(t)$</td>
<td>Any arbitrary signal</td>
</tr>
<tr>
<td>$Z$</td>
<td>Ordinary and modified Bessel function of first kind</td>
</tr>
<tr>
<td>$\alpha_{\text{leak}}$</td>
<td>Leakage angle</td>
</tr>
<tr>
<td>$\Delta f$</td>
<td>Distance between the two peaks in velocity versus frequency function</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>Time difference between the arrival and reflected peaks</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>Rotation vector</td>
</tr>
</tbody>
</table>
\( u(x, t) \) | Axial displacement in the time domain
\( v(x, t) \) | Transverse displacement in the time domain
\( \alpha \) | Wavenumber for longitudinal waves
\( \beta \) | Wavenumber for shear waves
\( \gamma \) | Shearing strain
\( \varepsilon \) | Normal strain
\( \eta \) | Viscous damping
\( \lambda \) | Lam\text{\textae} constant
\( \mu \) | Lam\text{\textae} constant or shear modulus
\( \nu \) | Poisson’s ratio
\( \xi \) | Wavenumber
\( \rho \) | Mass density
\( \sigma \) | Normal stress
\( \tau \) | 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
\( \omega \) | Angular frequency
\( \phi \) | Slope