A Method for Compensation of Changing Environmental
and Operational Conditions for Structural Health
Monitoring Using Guided Waves

By

Pouria Aryan

School of Mechanical Engineering

Faculty of Engineering, Computer and Mathematical
Science

This thesis is submitted for the degree of
Doctor of Philosophy

July 2016
Summary

Structural health monitoring (SHM) systems using guided waves permit the detection of structural damage via a network of permanently attached or embedded sensors. The benefits of such systems in terms of the reduction of maintenance and operation costs across many industries are now widely recognised. To identify the presence of damage, the amplitude of residual wave signals remaining after the subtraction of the reference data is often utilised in damage diagnostics. However, even in the absence of structural damage, these residual signals are usually not non-zero because of changing environmental or operational conditions (EOCs). Therefore, some form of compensation for variable EOCs is absolutely essential for guided wave based SHM methods reliant on baseline subtraction, to work accurately in real-world applications.

Many studies have demonstrated that the effect of changing EOCs can mask damage to such a degree that a critical defect might not be detected. Several effective strategies, based on signal processing, have been developed in recent years, specifically in order to compensate for ambient temperature variations. Nevertheless, many other factors and conditions, such as a progressive failure of the actuator and the adhesive bonding layer, changing humidity and boundary conditions or degradation of material properties, cannot be identified or compensated for with the existing strategies and techniques.

This research describes a conceptually new method, which is capable of reconstructing the baseline time traces corresponding to the current state of the structure and EOCs. Thus, there is no need for any other compensation for EOCs when using this method for damage diagnosis. The method is based on 3D surface measurements of the velocity field near the actuator, using laser vibrometry in
conjunction with high-fidelity finite element simulations of guided wave propagations in the defect-free structures. To demonstrate the feasibility and efficiency of the proposed method, the thesis provides several examples of the reconstruction of named baseline time traces and damage detection in isotropic and composite structural components.

It is recognised that the utilisation of 3D laser measurement systems and transient FE simulations can significantly increase the cost of the damage detection if this method is to be employed in practice. However, it is believed that with the advances in computer and laser technologies the cost-efficiency can be significantly improved and, in the future, the method will be applied in a wide range of engineering applications. It should be highlighted that for the current thesis the concept and idea have been verified through comprehensive numerical and experimental studies and this is a fundamental step in the development of this innovative method. As a result, this thesis is largely focused on the feasibility, quantifiable proof of the conceptualisations underpinning the thesis and demonstrations of the potential of this new development in engineering applications.
Acknowledgement

I would have not been able to complete this journey without the aid, support and contribution of many people. Foremost, I would like to express my sincere gratitude to my advisors; Associate Professor Andrei Kotousov, Dr Ching Tai-Ng (Alex) and Professor Benjamin Cazzolato for the continuous support of my study and supervising my research using both their valuable knowledge and experience.

I truly thank Andrei for his support, patience, motivation, enthusiasm, and immense knowledge through my studies. His guidance helped me a lot in all the time of the research and writing of this thesis. I have been extremely lucky to have a supervisor like Andrei.

I am highly indebted to Alex for his support and valuable assistance. There is no doubt that this progress would have not been possible without his kind support, attention and advice in particular regarding numerical simulations.

I would like to express my sincere gratitude to Benjamin for his brilliant ideas on this research in particular his suggestions regarding the experimental setup, results and the manuscripts. Special thanks for his detailed, precise and very helpful comments. It is impossible for me to show my sincere gratitude in few sentences.

I am also very thankful to Dr Stuart Wildy for his valuable assistance regarding access to Flinders University facilities and 3D SLV.

I would like to acknowledge Australian Postgraduate Award (APA) for their financial support. I would also like to thank the current and former staffs of the School of Mechanical Engineering (MECHENG) for their support and help through the time of this research.

Finally yet importantly, in memory of my passed away parents Homa and Daryoush who gave me deep love forever, I would like to thank my dearest sister and
brother Mehrnaz and Abtin who stood by me through every moment. I truly thank them for their dedication, deep love and support during my life and in particular for my studies.
Declaration by Author

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

I give consent to this copy of my thesis when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968.

I also give permission for the digital version of my thesis to be made available on the web, via the University’s digital research repository, the Library Search and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

Pouria Aryan                    Date

__________________________    ________________________
# Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Latin Alphabet</strong></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Amplitude of sinusoidal tone burst</td>
</tr>
<tr>
<td>$A_0$</td>
<td>Fundamental anti-symmetric mode of Lamb waves</td>
</tr>
<tr>
<td>$C_g$</td>
<td>Group velocity</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Phase velocity</td>
</tr>
<tr>
<td>$C_L$</td>
<td>Longitudinal bulk wave velocity</td>
</tr>
<tr>
<td>$C_T$</td>
<td>Transverse bulk wave velocity</td>
</tr>
<tr>
<td>$d$</td>
<td>Distance from actuator</td>
</tr>
<tr>
<td>$E$</td>
<td>Young’s modulus</td>
</tr>
<tr>
<td>$f$</td>
<td>Frequency</td>
</tr>
<tr>
<td>$h$</td>
<td>Half of plate thickness</td>
</tr>
<tr>
<td>$G$</td>
<td>Shear modulus</td>
</tr>
<tr>
<td>$k$</td>
<td>Wavenumber</td>
</tr>
<tr>
<td>$k_p$</td>
<td>The coefficient relating changes Phase velocity</td>
</tr>
<tr>
<td>$L$</td>
<td>Length of scanning area</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of cycles</td>
</tr>
<tr>
<td>$P$</td>
<td>Remote point</td>
</tr>
<tr>
<td>$S_0$</td>
<td>Fundamental symmetric mode of Lamb waves</td>
</tr>
<tr>
<td>$t$</td>
<td>Time</td>
</tr>
<tr>
<td>$U$</td>
<td>Displacement</td>
</tr>
<tr>
<td>$V$</td>
<td>Velocity</td>
</tr>
<tr>
<td>$w(t)$</td>
<td>Hanning window function</td>
</tr>
</tbody>
</table>

| **Greek Alphabet** | |
| $\alpha$ | Coefficient of thermal expansion |
\( \lambda \)  
Wavelength

\( v \)  
Passion’s ratio

\( \rho \)  
Density

\( \mu \)  
Shear modulus of elasticity

\( \omega \)  
Angular frequency

\( \phi \)  
Displacement potential

\( \psi \)  
Displacement potential

**Acronyms**

1D  
One-dimensional

2D  
Two-dimensional

3D  
Three-dimensional

AE  
Acoustic emission

BSS  
Baseline signal stretch

CFRP  
Carbon fiber reinforced polymer

DDT  
Damage detection technique

DOF  
Degree of freedom

EC  
Eddy current

EOC  
Environmental and operational condition

FBG  
Fiber Bragg Grating

FE  
Finite element

GW  
Guided wave

NDT  
Non-destructive testing

OBS  
Optimal baseline selection

PZT  
Lead Zirconate Titanate Transducer

RMS  
Root mean square

SHM  
Structural health monitoring

SLV  
Scanning laser vibrometer

TOF  
Time of flight
# Table of Content

Summary .................................................................................................................. iii

Acknowledgment ..................................................................................................... v

Declaration by Author ............................................................................................ vii

Nomenclature .......................................................................................................... viii

1. Introduction ......................................................................................................... 1
   1.1 Background and Motivation .............................................................................. 2
   1.2 Thesis objectives ............................................................................................... 8
   1.3 Thesis outline .................................................................................................. 10
   1.4 Publications .................................................................................................. 12
   1.5 Thesis format ................................................................................................. 14

References .............................................................................................................. 15

2. Literature Review .............................................................................................. 21
   2.1 Introduction .................................................................................................. 22
   2.2 Brief Overview of Common Damage Detection Techniques ....................... 23
       2.2.1 Eddy Current ......................................................................................... 24
       2.2.2 Conventional Ultrasonic ................................................................. 26
       2.2.3 Acoustic Emission ................................................................. 28
       2.2.4 Vibration Based Techniques .................................................. 30
       2.2.5 Other Common Methods .......................................................... 30
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2.6 Structural Health Monitoring</td>
<td>31</td>
</tr>
<tr>
<td>2.3 Fundamentals of GW Propagation</td>
<td>33</td>
</tr>
<tr>
<td>2.4 SHM using Lamb Waves</td>
<td>40</td>
</tr>
<tr>
<td>2.5 Sensor Technology for Lamb Waves</td>
<td>44</td>
</tr>
<tr>
<td>2.5.1 Ultrasonic Probe</td>
<td>44</td>
</tr>
<tr>
<td>Piezoelectric, Piezoceramic and Piezocomposite Transducers (PZT)</td>
<td>46</td>
</tr>
<tr>
<td>2.5.3 Fiber Optics</td>
<td>47</td>
</tr>
<tr>
<td>2.5.4 Laser Vibrometry</td>
<td>48</td>
</tr>
<tr>
<td>2.6 The Effect of Changing EOC on Damage Diagnostics</td>
<td>51</td>
</tr>
<tr>
<td>2.6.1 Effect of Changing Temperature</td>
<td>54</td>
</tr>
<tr>
<td>2.6.2 Quantitative Assessment of the Signal to Noise Ratio due to Temperature Variations</td>
<td>56</td>
</tr>
<tr>
<td>2.6.3 Effects of Variation of Thickness and Mechanical Properties of Adhesive Bonding on GW</td>
<td>58</td>
</tr>
<tr>
<td>2.7 Previous Strategies for EOC Compensation</td>
<td>60</td>
</tr>
<tr>
<td>2.8 Summary</td>
<td>62</td>
</tr>
<tr>
<td>References</td>
<td>64</td>
</tr>
</tbody>
</table>

3. Lamb wave Characterisation and Damage Imaging with 3D Scanning Laser Vibrometry ......................................................... 85

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 Introduction</td>
<td>86</td>
</tr>
<tr>
<td>3.2 Lamb wave characterisation and damage imaging with 3D SLV</td>
<td>87</td>
</tr>
<tr>
<td>3.2.1 Experimental approach</td>
<td>91</td>
</tr>
</tbody>
</table>
3.2.2 Experimental set-up ................................................................. 93
3.3 Results and Discussion .............................................................. 95
  3.3.1 Wave Scattering at a Blind Hole ............................................ 97
  3.3.2 Wave Scattering at a Crack-Like Defect ............................. 101
  3.3.3 Wave Scattering at Dents ..................................................... 103
  3.3.4 Wave Scattering at a Delamination .................................... 107
3.4 Summary .................................................................................. 111
References ..................................................................................... 115

4. A Method for Compensation of Changing Environmental and Operational
   Conditions .................................................................................. 119
  4.1 Introduction ............................................................................. 120
  4.2 Conceptual Idea ................................................................. 121
  4.3 Determination of Material Properties ................................. 124
  4.4 Details of Numerical Approach and Validation ................... 127
  4.5 Feasibility Study ............................................................ 132
  4.6 Summary ........................................................................... 140
References ..................................................................................... 142

5. Reconstruction of Baseline Time Trace and Damage Detection in Isotropic
   Plates and Beams ....................................................................... 145
  5.1 Introduction ........................................................................... 146
  5.2 Details of Experimental Set up and Specimens ..................... 147
  5.3 Reconstruction of Baseline Time Trace for A Beam .............. 150
5.4 Example of Damage Detection in Beams ........................................... 154
5.5 Reconstruction of Baseline Time Trace under Changing Temperature .... 156
5.6 Damage Detection in Isotropic plates .................................................. 165
5.7 Effect of Plate Boundaries on the Reconstruction of Baseline Time Traces ... 168
5.8 Summary .................................................................................................. 172

6. Detection of Delamination Damage in Composites ................................. 175
6.1 Introduction ............................................................................................ 176
6.2 The Details of the Experimental Set-up for Composites......................... 177
6.3 The Effect of Temperature Variations on the Baseline Time Trace for
Composites ..................................................................................................... 179
6.4 Identification of Material Properties ....................................................... 181
6.5 Reconstruction of Baseline Time Trace for CFRP Composites ............... 189
6.6 Detection of Delamination at Changing Temperature Conditions .......... 193
6.7 Summary .................................................................................................. 198
   References .................................................................................................. 200

7. Thesis Summary and Future Work............................................................ 203
7.1 Overall Outcomes of the Thesis.............................................................. 204
7.2 Chapter-by-Chapter Summary ................................................................ 206
7.3 Discussions and Future Work ................................................................. 209
   References .................................................................................................. 212