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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.
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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.

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Pouria Aryan

Date

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## Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<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>
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<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>
<tr>
<td><strong>Greek Alphabet</strong></td>
<td></td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Coefficient of thermal expansion</td>
</tr>
</tbody>
</table>
$\lambda$  Wavelength
$\nu$  Passion’s ratio
$\rho$  Density
$\mu$  Shear modulus of elasticity
$\omega$  Angular frequency
$\varphi$  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
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Chapter 1

Introduction
1.1 Background and Motivation

By identifying damage at an early stage, many structural failures can be avoided. Although there has been huge effort from both the industry and the research community itself into the area of damage detection and failure prevention, structural failures still occur and impose a significant burden on the economy and on quotidian life.

The following is an example of the disastrous consequences arising from the structural failure of a pipeline. In July 2010, the Kalamazoo River oil spill occurred (Figure 1.1) when a pipeline fractured and the oil flowed into the Kalamazoo River. A very large break (six feet or 1.8 meters, see Fig. 1.1) in the pipeline caused one of the largest and most expensive inland oil spills in U.S. history.

Figure 1.1: Kalamazoo pipeline failure (Courtesy of the National Transportation Safety Board 2010)
Chapter 1: Introduction

The US National Transportation Safety Board (NTSB) published an investigation report in July 2010 [1]. The report blamed corrosion fatigue damage as the fundamental cause of the structural failure. The cost of the repair and clean-up operation was estimated at over $700 million. Early identification of the corrosion damage could have prevented this disaster [1].

The detection of damage is considered to be a part of the maintenance procedures, which are necessary for the safe and efficient operation of current and future machines and structures. Historically, damage has been detected by performing an inspection with sensors, which are placed temporarily on the surface of a structure and removed after all the required measurements have been conducted. This procedure is repeated if subsequent inspections are required.

The increasing age of existing infrastructure, as well as the need to ensure a high level of safety and the reliability of complex and hazardous structures, have together led to the development of a growing number of non-destructive defect detection techniques, including the implementation of new non-destructive methods for new materials, specifically for composites. As a result, the on-going cost of maintenance procedures represents a major concern for the engineering community. For example, the United States spends over 200 billion dollars each year on the maintenance of civil infrastructure [2]. Maintenance and repairs represent about 25 per
cent of commercial aircraft operation costs [3]. Therefore, this area is worthy of innovative solutions.

One of the solutions to address the mounting maintenance costs is the use of Structural Health Monitoring (SHM). SHM is an emerging area of research. SHM normally refers to a process, and sometimes extends to the equipment and instrumentation, for *in-situ* monitoring of the structural integrity of the equipment under consideration, using real-time data obtained from an embedded sensor network. Thus, there is no need for disassembly of components to be inspected, as the sensors are permanently attached, becoming a part of the structure and thereby allowing for a continuous and automated monitoring of its critical components. This embedding of the process leads to a substantial reduction in the amount of time that the structure is out of operation. SHM can assess the state of the equipment’s structural health and predict the remaining life of a structure by applying the appropriate data processing and evaluation techniques.

In a global sense, SHM is capable of changing the maintenance paradigm, which is currently dominated by schedule-driven inspections for condition-based maintenance inspections, thereby saving the cost of unnecessary maintenance procedures. SHM also enables the operation of machines and structures beyond their assigned design life and so greatly reduces the life-cycle cost. For new systems, the application of SHM can completely change the design architecture and provide considerable savings in weight, size and cost.
In recent years significant progress in *in-situ* damage detection has been achieved with the development of SHM based on guided waves [4-10]. Guided waves arise from the interaction of normal and shear waves in bounded media. Lamb waves, which are the guided waves propagating in traction-free thin plates, are the most widely used for damage detection [11, 12]. The potential for using guided waves for non-destructive testing (NDT) was realised shortly after their existence was proven experimentally by Schoch in 1951 [13]. In 1961, Worlton [14] was the first to utilise Lamb waves for damage detection. Over the past 20 years, guided waves have found many applications in SHM, driven by a rapid advance in the fabrication technologies of piezo-electric devices. These new technologies have enabled the miniaturization of classical ultrasonic bulk sensors and actuators and therefore led to a significant reduction in cost for mass production. Compared with different types of sensors utilised for *in-situ* systems, such as strain or vibration gauges, which record data passively, piezo-electric devices can function as both the actuator and the sensor [8, 15-18].

Many past studies have demonstrated a very high level of sensitivity for guided waves to various types of structural damage, such as corrosion [19, 20] and cracks [21-24] in metallic structural components, and both debonding [25, 26] and delamination [27-31] in composites. The ability of guided waves to propagate over large distances without significant decay offers the possibility of interrogating large volumes of the structure using a
small number of sensors. Other properties of guided waves, which are very attractive for SHM applications, include low energy consumption requirements and the ability to inspect the entire cross-section of the component. The fact that the entire thickness of a component can be interrogated makes it possible to detect damage that is hidden (e.g. embedded cracks and delamination in composites) as well as on the surface (e.g. corrosion or wear).

A typical guided wave based SHM system comprises a number of transducers permanently bonded to the surface of the structure. One of the transducers (the transmitter) is excited with a tone burst of a few cycles, generating a guided stress wave that propagates along the structure. The time-domain responses (time traces) from the transmitter and other transducers are then recorded. This process is repeated using different transducers as transmitters. The detection techniques are based on the analysis of algebraic differences between the current time trace and a baseline time trace recorded from a defect-free structure. The signal remaining after the subtraction of a baseline time trace is referred to as a residual time trace. It is attributed to the effect of damage, provided that the residual time trace is not affected by coherent noise or changing environmental and operational conditions, which conditions are the subject of the current research.

Guided wave based SHM systems can operate in two modes: in a pulse-echo mode where damage is detected by examining waves reflected
and/or scattered from the damage, or in a pitch-catch mode, when transmitted waves, instead of reflected waves, are analysed for the presence of damage. In both modes, the damage detection is based on the following prerequisites: (i) that baseline time traces are available from the pristine condition of the structure to be monitored; (ii) that the residual time traces can be detected and related to damage; and (iii) that the threshold level of the residual time trace, which indicates the presence of critical damage, can also be established by utilising the available baseline time traces.

The current limiting factor of these SHM systems is the difficulty in differentiating the residual time traces due to damage and those caused by changing environmental and operational conditions (EOC). Many of the SHM systems, which have been developed in the last two decades under laboratory conditions, can fail in real-world situations. The influence of changing temperature, humidity, boundary conditions and the degradation of material properties are all capable of masking the damage to such a degree that a critical defect might not be detected. A number of recent studies (for example, Konstantinidis et al. [32] and Sohn [33]), demonstrate that the signal attenuation and time of flight, which are commonly used as damage-sensitive indicators, are also highly sensitive to EOC. Thus, a disregard of the effect of EOC on damage detection algorithms (for example, its effect on the residual time traces) can lead to expensive false alarms, decrease damage sensitivity and significantly reduce the cost-efficiency of SHM.
Several techniques were developed in the past to address the issue of changing temperature conditions, specifically. Despite certain limitations, these techniques are capable of compensating for the effect of ambient temperature variations on damage diagnosis. However, other factors, such as humidity, degradation of material properties or progressive PZT debonding, or, indeed, a combination of these, have received little attention so far, and appropriate compensation strategies and techniques are yet to be developed. The present thesis presents a new method to address the challenges above.

1.2 Thesis objectives

The overall aim of this PhD project is to develop and validate a general method, which is capable of compensating for the effects of changing EOC on damage detection, using a guided wave based SHM system. The research approach has utilised the latest developments in 3D scanning laser vibrometry (SLV) and transient high-fidelity finite element (FE) simulations of guided wave propagation. To achieve the main aim of the thesis, the following objectives have been set:

- Investigations into the fundamentals of 3D laser vibrometry and the application of this non-contact measurement technique for damage imaging and detection;
Chapter 1: Introduction

- A numerical feasibility study is to be undertaken to identify the effect of various parameters of the proposed method on the accuracy of reconstruction (restoration or updating) of the baseline time traces;

- Demonstration of the proposed method for the reconstruction of the baseline time trace for beams and plates;

- Implementation of the proposed method for damage detection in isotropic and composite plates in the presence of temperature variations.

The conceptual idea of the new method is based on a physical recording of the actual 3D velocity/displacement fields around the PZT (scanning area) and prescribing these fields to the corresponding finite element model, representing the free-from-defect structure. The scanning area encapsulates the PZT, avoiding the necessity to model the PZT response, which is often extremely complex and can be affected by EOC, as discussed earlier. The physical properties of the materials that are needed for the numerical simulations are extracted from the analysis of the wave propagation in the scanning area. Thus, the method can compensate for progressive changes in the material properties of the inspected component, over time. With this method, there is no need for either differentiation or compensation procedures for damage detection.
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It is recognised that the use of SLV or other 3D measurement systems, as well as high-fidelity transient FE simulations, can significantly increase the cost of defect diagnostics. However, with the advance of computational power, numerical approaches and laser technologies, this cost will decrease exponentially with time. Moreover, this method is useful for damage inspections of hard-to-reach locations, or for the generation of periodical updates of the baseline time traces, in the case of changing EOC.

1.3 Thesis outline

The thesis incorporates seven Chapters, the sequence of which highlights the chronology of the knowledge development and research undertaken to meet the principal aim formulated in the previous section. The purpose of the present Chapter (Chapter 1, Introduction) is to provide an overview of the research area and specify the research problem and principal aim of the research.

Chapter 2 presents a critical review of the literature relevant to the principal aim of this thesis (the development of a new compensation method). The focus of the chapter is on the fundamentals of guided wave (GW) propagation, leading to damage detection using GW-based SHM. It also describes the existing EOC compensation strategies and techniques. From a careful analysis of these strategies and techniques, the current challenges in GW-based SHM, as well as the research gaps, are formulated.
Chapter 1: Introduction

Chapter 3 describes the fundamentals of 3D laser vibrometry and demonstrates an application of this non-contact measurement technique for damage detection and imaging. The outcomes of an experimental study are presented in this chapter.

Chapter 4 introduces a new method for the reconstruction of the baseline time trace, which is capable of compensating for a wide range of changing EOCs. The method, as mentioned above, is based on 3D laser vibrometry and high fidelity transient finite element simulations. This Chapter describes a practical method to recover material properties from the characteristics of Lamb wave propagation. Later in this Chapter, a numerical feasibility study is presented to identify the effects of various parameters of the method on the accuracy of the numerical reconstruction of the baseline time trace.

Chapter 5 presents the outcomes of a practical implementation of the proposed method for the reconstruction of the baseline time trace for isotropic beams (a 1D waveguide). Furthermore, the Chapter provides examples of the compensations made for the effects of changing ambient temperatures on damage detection and diagnosis. This Chapter also extends the method to isotropic plate components. The numerical reconstruction of the baseline time trace is affected by the plate boundaries. It demonstrates that the progressive failure of the bond can be compensated for effectively by the proposed method.
Chapter 1: Introduction

Chapter 6 outlines the application of the new method for composite plates, which is the main focus of SHM. This application represents a challenge, as the anisotropic material properties and the reconstruction of the baseline time trace are significantly affected by the temperature variations in a much more complicated way than is the case for isotropic structures. This chapter also describes a practical application of the method under development for a practical identification of delamination damage under changing temperature conditions.

Finally, Chapter 7 summarises the main outcomes of the research, providing detailed conclusions, along with recommendations for future developments.

1.4 Publications

The research discussed in this thesis has led to the generation of five journal papers and three peer reviewed conference papers, as detailed below:

Journal papers


Conference papers


1.5 Thesis format

In compliance with the formatting requirements of The University of Adelaide, the print and online versions of this thesis are identical. The online version of the current thesis is available as a PDF. The PDF version can be viewed in its correct fashion with the use of Adobe Reader 9.
Chapter 1: Introduction

References


Chapter 1: Introduction


Chapter 1: Introduction


Chapter 1: Introduction


Chapter 2

Literature Review
2.1 Introduction

This chapter will first outline common damage detection techniques (DDTs) and then the concept of structural health monitoring (SHM). It is focused on DDTs utilising guided waves (GWs). These techniques have many advantages, and are currently under development to be implemented in maintenance strategies for aircraft, bridges, offshore wind power plants, pipes and rails. The theory and fundamentals of GW propagation in plates (Lamb waves) will be briefly summarised in this chapter. It will also provide a brief overview of GW sensing techniques, concentrating on 3D laser vibrometry, which has relatively recently become available for GW research. This advanced sensing technique is employed extensively in this PhD project.

The current literature suggests that one of the main challenges in applications of SHM using GWs is the compensation needed for environmental and operational conditions (EOC). Many previous studies have demonstrated that the effect of changing EOCs can sufficiently mask damage information in the measured signal such that a critical defect might not be detected. Several common strategies, specifically for compensating for ambient temperature variations, have been developed in the past and are discussed in this chapter. Nevertheless, many other environmental and operational factors, such as changing humidity, boundary or stress conditions, progressive or brittle PZT failure and degradation of material
properties of the structure, PZT or bonding, have not received much attention. This shortcoming represents the main research gap identified from the literature review. This research gap is addressed in the current thesis by developing a new method, which is capable of compensating for the above-mentioned factors. The method itself and its application in the detection of damage represent the main outcomes of this thesis.

2.2 Brief Overview of Common Damage Detection Techniques

As mentioned in the Introduction, structural failures can significantly reduce efficiency, increase the cost of operation and lead to economic losses and human casualties. Structural failures can be caused through many reasons and circumstances; and the accumulated or pre-existing damage, such as manufacturing defects, fatigue cracks, corrosion or delamination in composites, is one of the most common reasons. It is widely agreed that early detection of structural damage and its progression throughout the lifetime of the structure can prevent potentially catastrophic failures, thereby improving the efficiency of operation. As a result, the importance of damage detection systems has increased dramatically over the past two decades, across many industries and applications [1].

The primary goal of DDTs is to detect the presence, type, location and severity of damage as well as to evaluate the remaining life of the structure [2]. A number of DDTs have been developed in the past. In
general, the techniques which are used to assess the condition of a structural component can be divided into two main categories: Destructive Techniques (DTs) and Non-Destructive (defect detection) Techniques (NDTs). As these names suggest, DTs utilise the methods associated with a complete or partial destruction of the structure in order to identify the damage. DTs are dominant in failure investigations, as well as in the case of mass production when the cost of a few samples is insignificant in comparison with the benefits from the early damage detection and evaluation of the residual life of the rest of the similar structures/components. The latter can be accomplished with various mechanical tests and subsequent microscopic examinations. However, DTs are outside the scope of this thesis.

NDTs are based on physical principles and methods which do not cause any serious damage to the material or to the structure. NDTs are normally applied to situations when premature failures can lead to serious consequences, or when the cost of the structural component is relatively high. Some common NDTs will be outlined briefly in the following subsections. An emphasis will be placed on NDTs using GWs, which are the focus of this thesis.

2.2.1 Eddy Current

The Eddy Current (EC) defect detection technique is one of the most dominant electromagnetic inspection methods in industry. EC-based techniques are normally applied for the detection of surface and near surface
defects [3], and are based on the use of electro-magnetic coupling between an EC sensor coil and the inspected object (e.g. a plate). EC in general is suitable and sufficiently robust to detect various forms of structural damage in electrically conducting materials by comparing the measured impedance with the calibrated signal obtained for the specific damage severity [4]. Figure 2.1 shows a schematic configuration of an EC defect visualisation system. Examples of the practical applications of EC include the detection of different types of damage such as cracks [5-7] and corrosion spots [8-10] in isotropic materials; delamination and fibre fractures [3, 11] in composites. A very detailed review of this technique is presented in [12].

Figure 2.1: EC visualisation system for a non-destructive characterisation of carbon fiber reinforced plastics [11].
2.2.2 Conventional Ultrasonic

Conventional Ultrasonic (CU) inspections are grounded in detecting and analysing reflections from defects in high frequency waves generated by an ultrasonic transducer (a probe), as illustrated in Figure 2.2. Ultrasonic inspection usually operates in the 1 to 50 MHz frequency range. The damage location can be identified by measuring the time of flight of the signal reflected from the damage. A schematic of an ultrasonic inspection system is shown in Figure 2.2. This technique is generally robust and popular in industrial applications, but it is very time-consuming as an ultrasonic inspection can detect damage only in the vicinity of the probe/sensor (see, Figure 2.2). Therefore, the inspections may need to be conducted multiple times at different locations/angles in order to inspect the structural component fully. As a result, this is a relatively slow and laborious process, associated with high cost.

Figure 2.2: Schematic picture of an ultrasonic inspection system.
2.2.3 Acoustic Emission

Acoustic Emission (AE) inspection is a passive damage detection technique. AE can be applied to both metallic and composite structures [13-16]. The technique is based on the measurement of the intensity of acoustic emission signals (acoustic waves) generated under mechanical loading. These acoustic waves can be associated with dislocation movements, micro-cracking, internal friction, and so forth. The generated acoustic signal can be detected with piezo or fibre sensors. One of the advantages of AE inspections is that the entire body of the structure can be inspected without causing any disturbance to its operation. Therefore, AR inspections are normally performed while the structure is in operation and subject to loading. This feature is very attractive for online monitoring systems.

![Setup for ultrasonic and acoustic emission measurements](image)

Figure 2.3: Setup for ultrasonic and acoustic emission measurements [15].
A photograph of an example experimental setup for an AE inspection is shown in Figure 2.3.

AE can also be combined with other damage detection techniques. For example, a technique incorporating AE and the ultrasonic acoustic method for locating damage in cross-ply laminates was presented in Aggelis and Barkoula [15]. Another example is presented in Kordatos and Aggelis [14] where the AE technique was merged with thermography to characterise the crack growth rates in aluminium alloys. Though the method was reported to be successful, it was also concluded that the relationship between the crack growth and the AE signature needs further investigation. AE based techniques have been widely implemented in numerous industrial applications, notably for pipeline structures. However, the main drawbacks of these AE techniques are the difficulties in the differentiation of the various contributions to the AE. For example, the contribution of fracture processes to the intensity of an AE signal can be masked by micro-movements and friction due to bolt loosening. Another problem lies in the establishment of the threshold intensities of AE, corresponding to critical structural defects or damage. These thresholds can be significantly affected by the operating conditions as well as the stochastic noise.

2.2.4 Vibration Based Techniques

The family of vibration-based methods developed over the past fifty years is very broad [17-22]. Conceptually, all these methods exploit the effect of the
change of the dynamic (vibration) response of the structure to the presence and accumulation of mechanical damage [2]. This change can be established experimentally for a particular defect, or with the help of analytical or numerical models. Some of the most common methods are based on the effects of structural damage on natural frequencies [18], mode shapes and curvature [20, 23], as well as modal strain energy [24]. A schematic configuration of a typical vibration-based damage detection system is shown in Figure 2.4. Although vibration-based techniques have been applied successfully for damage detection in many types of structures [17, 19-21, 23-27], these techniques are not particularly sensitive to the presence of small-size defects and early detection of damage. In addition, in many cases, it is very difficult to distinguish between various types of structural damage, as well as to identify its precise location.
2.2.5 Other Common Methods

Radiography, thermography and shearography are examples of other common methods of damage detection in engineering structures. Although these methods have been successfully implemented for damage detection [28-31], there are many limitations associated with these methods. For
instance, the low x-ray absorption of epoxy/fiber represents a significant problem in radiography. In addition, many of the methods above require the removal of individual parts, disassembling or point by point scanning inspections, which can be time consuming and very costly [4].

2.2.6 Structural Health Monitoring

A brief overview of SHM has already been provided in the Introduction. The importance of SHM to enhance reliability and reduce life-cycle costs is widely recognised, as reported by Raghavan and Cesnik [1]. For example, it was estimated that an integration of SHM into maintenance procedures for civil aircraft can save up to 20% of current inspection costs [32].

SHM is rapidly proving itself to be a crucial feature of efficient quality maintenance, structural reliability and safety management approaches for many industries, across many engineering applications. Generally, an SHM system consists of a number of subsystems: a distributed sensor network, a computer processor for data acquisition and a signal processing unit. The recorded data serves as input to the damage forecast algorithm to assess the state of health of the structure.
Figure 2.6: Schematic picture of different steps for SHM using the pattern recognition approach [1].

SHM broadly can be divided into two main categories: active and passive, depending on whether or not a signal excitation is applied. Online Acoustic Emissions (AE) and stress monitoring with strain gauges are typical examples of passive SHM. Active SHM normally implements a transducer/sensor network to interrogate the structure with properly selected excitation parameters, e.g., frequency and duration. Among the second category, SHM using GWs in the tens to hundreds of kilohertz range, which are the subject of this thesis, are generally considered to be the most promising due to the low cost of their implementation and their versatility.
The physical principles (governing equations) of GWs and main features of SHM utilising these principles will be presented in the next sections. Figure 2.6 illustrates the damage diagnostic with an active SHM system utilising GW and a pattern recognition approach to detect damage. Transducers generate a high frequency signal (a tone burst). As a result, GWs propagate in all directions, reflected and detected by the same transducer or network of sensors. To distinguish damage from structural features, some form of comparison with damage-free reference data is required, and algebraic subtraction is often employed for this purpose. The detectability of damage is determined by the amplitude of the residual time trace from structural features remaining after the subtraction of reference data. Furthermore, the residual signal (or damage signature) can be analysed using pattern recognition approaches to characterise the type and severity of the damage, as illustrated in Figure 2.6.

2.3 Fundamentals of GW Propagation

Stress waves guided by the boundaries of the structure are referred to as GWs. According to Raghavan and Cesnik [1], "the stress waves are forced to follow a path defined by the material boundaries of the structure". The propagation characteristics of GWs depend on the geometry of the structure. GWs can be excited in various structural components such as plates, rods, beams and shells, which represent the typical elements in diverse designs across many engineering structures and applications.
The pioneering studies on 2D waveguides were conducted by a number of researchers in the beginning and middle of the 20th century, such as Rayleigh (1889), Lamb (1917), Love (1926) and Stoneley (1942). Special types of GW have been named after these researchers. For example, Lamb waves are GWs propagating in a semi-infinite plate. Horace Lamb first discovered this type of GW. Another example is Love waves, which are horizontally polarised shear waves, guided by different layers of a multi-layered composite.

An important characteristic of GW propagation, in comparison with bulk wave propagation, is that GWs often contain an infinite number of wave modes. Each of these modes propagates at its own wave speed, which is a function of the dimensions and the excitation frequency. In the following sections, a special type of GW – Lamb waves – will be considered, which essentially represent GWs propagating in plates and shells. The latter elements represent typical structural elements, which are widely utilised in engineering designs across many industries.

In an elastic isotropic plate, as shown in Figure 2.7, the propagation of GWs can be described by the classic governing dynamic equations of the theory of elasticity [33],

\[ \mu u_{i,jj} + (\lambda + \mu)u_{i,ij} + \rho f_i - \rho \ddot{u}_i = 0 \quad (i, j = x, y, z), \]

where \( u_i \) are the displacement components in a Cartesian coordinate system, and \( \mu \) and \( \lambda \) are Lamé constants, \( f_i \) is the body force and \( \rho \) is the density of
the material. The governing equation (2.1) has to be complemented by the boundary conditions, which depend on the geometry of the waveguide.

![Figure 2.7: Schematic picture of a thin isotropic plate with a thickness of 2h and a coordinate system.](image)

One efficient approach to decomposing Equation (2.1) into two uncoupled equations is to introduce displacement potentials \( \varphi \) and \( \psi \) [33, 34] as follows:

\[
\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial z^2} = \frac{1}{C_L^2} \frac{\partial^2 \varphi}{\partial t^2} \tag{2.2}
\]

\[
\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial z^2} = \frac{1}{C_T^2} \frac{\partial^2 \psi}{\partial t^2} \tag{2.3}
\]

where:

\[
\varphi = \left( A_1 \sin(pz) + A_2 \cos(pz) \right) \exp(i(kx - \omega t)), \tag{2.4}
\]
\[ \psi = (B_1 \sin(qz) + B_2 \cos(qz)) \cdot \exp(i(kx - \omega t)), \quad (2.5) \]

\[ p^2 = \frac{\omega^2}{C_L^2} - k^2, \quad q^2 = \frac{\omega^2}{C_T^2} - k^2, \quad k = \frac{\omega}{\lambda} \quad (2.6) \]

where \( A_1, A_1, B_1 \) and \( B_2 \) are four constants determined by the boundary conditions and \( k, \omega \) and \( \lambda \) are the wavenumber, circular frequency and wavelength of the GW, respectively. \( C_L \) and \( C_T \) are the velocities of the longitudinal and transverse/shear waves, respectively given by:

\[ C_L = \sqrt{\frac{2\mu(1-\nu)}{\rho(1-2\nu)}}, \quad C_T = \sqrt{\frac{\mu}{\rho}} \quad (2.7) \]

It can be concluded that Lamb waves are essentially the superposition of longitudinal and transverse/shear modes. Assuming plane strain conditions apply in the \( y \) direction, the displacements in the wave propagation direction (\( x \)) and transverse direction (\( z \)) (Figure 2.8) can be written as displacement potentials:

\[ u_x = \frac{\partial \varphi}{\partial x} + \frac{\partial \psi}{\partial z}, \quad u_y = 0 \quad \text{and} \quad u_z = \frac{\partial \varphi}{\partial z} + \frac{\partial \psi}{\partial x} \quad (2.8) \]

and the corresponding stress components as:

\[ \sigma_{xz} = \mu \left( \frac{\partial u_z}{\partial x} + \frac{\partial u_x}{\partial z} \right) = \mu \left( \frac{\partial^2 \varphi}{\partial x \partial z} - \frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial z^2} \right) \quad (2.9) \]
\( \sigma_{zz} = \lambda \left( \frac{\partial u_x}{\partial x} + \frac{\partial u_z}{\partial z} \right) + 2\mu \frac{\partial u_z}{\partial z} \)

\[
= \lambda \left( \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial z^2} \right) + 2\mu \left( \frac{\partial^2 \phi}{\partial z^2} - \frac{\partial^2 \psi}{\partial x \partial z} \right) \tag{2.10}
\]

For a plate with stress free lateral surfaces:

\( \sigma_{xx} = \sigma_{zz} = 0 \) at \( z = \pm h \), \( \tag{2.11} \)

After some manipulation with algebra, the following dispersion equation can be obtained:

\[
\frac{\tan(qh)}{\tan(ph)} = -\frac{4k^2qp}{(\lambda k^2 + \lambda p^2 + 2\mu p^2)(k^2 - q^2)} \tag{2.12}
\]

Substituting Equations (2.6) and (2.7) into Equation (2.12), the wave motion can be decomposed into two uncoupled equations corresponding to symmetric (2.13) and anti-symmetric (2.14) wave modes [33]:

\[
\frac{\tan(qh)}{\tan(ph)} = -\frac{4k^2qp}{(k^2 - q^2)^2} \tag{2.13}
\]

\[
\frac{\tan(qh)}{\tan(ph)} = -\frac{(k^2 - q^2)^2}{4k^2qp} \tag{2.14}
\]
Equations (2.12) - (2.14) are known as the Rayleigh-Lamb equations. Schematic drawings of two fundamental Lamb wave modes ($S_0$ and $A_0$) are shown in Figure 2.8. Arrows in this Figure indicate the displacement direction of the particles, generating the resulting motion, occasionally. Symmetric modes are often referred to as compressional and anti-symmetric modes are known as “flexural” waves [35]. An example of Lamb wave dispersion curves for two frequency-thickness ranges are shown in Figure 2.9. All modes, except the fundamental, have so-called cut-off frequencies, below which the corresponding modes cannot be excited. These properties of higher order modes are often utilised in GW research to exclude the generation of multiple modes, which are difficult to analyse and interpret, specifically, in the presence of complex reflection, dispersion or mode conversion.
Figure 2.9: Lamb wave dispersion characteristics for the frequency–thickness range of: (a) 6 MHz mm, (b) 1.6 MHz mm [36].

In composite structures, due to their anisotropic nature, wave propagation is more complex. For example, in a layered composite laminate, the dispersion equation for a GW can be derived by applying the same Navier displacement equations given by Equation (2.1) for each layer [33] and enforcing the continuity boundary conditions across the interfaces. Generally, the excitation of GWs in composites is a very complex process. For example, the directional amplitude is significantly affected by any fibre or ply orientation close to the source of the excitation.
2.4 SHM using Lamb Waves

In recent years, significant progress has been achieved in the development of SHM procedures based on GWs [1]. The potential for using GW for Non-Destructive Testing (NDT) was recognised shortly after Schoch [37] proved their existence experimentally in 1951. In 1961, Worlton [38] was the first to utilise Lamb waves for damage detection. Over the past 20 years, GWs have found many applications in SHM, driven by a step advance in fabrication technologies of piezo-electric transducers (PZTs). These new technologies have enabled the miniaturization of bulk ultrasonic sensors and actuators and a significant reduction in the cost of mass production. Compared with different types of sensors utilised for in situ systems, such as strain or vibration gauges, which passively record data, piezo-electric devices can function as both an actuator and a sensor [39, 40].

Many studies in the past have demonstrated the good sensitivity of GWs to various types of structural damage and their ability to propagate over large distances without significant decay. This opens up the possibility of inspecting the entire cross-section of a beam, plate or shell component using a small number of sensors [1]. The fact that the entire thickness can be interrogated makes it possible to detect hidden damage (e.g. embedded cracks [41-45] and delamination [46-51] in composites, as well as surface defects (e.g. corrosion [52-54]).
The fundamental modes at relatively low frequencies are normally employed in SHM, as at higher frequencies the presence of multiple modes (see Figure 2.9) makes the resulting signals extremely complex and therefore difficult to analyse and interpret. The wavelength of the excited signal has to be smaller than the characteristic dimensions of the targeted damage. Thus, the fundamental anti-symmetric mode or flexural mode ($A_0$) is preferable and more sensitive to damage, as its wavelength is shorter at the same frequency than that of the symmetric mode ($S_0$). In particular, it is reported in Ng and Veidt [55] that the $A_0$ mode is very efficient for detecting delamination damage in composites and surface damage in isotropic plate and shell components. However, the $A_0$ mode is highly dispersive and requires stringent conditions in experiments to prevent energy dissipation. In addition, FE simulations involving the $A_0$ mode require a higher mesh density than the $S_0$ mode due to a substantial variation of stresses across the thickness, which significantly increases computational time. In contrast, the stress distribution across the thickness corresponding to the $S_0$ mode is largely uniform, especially at low frequencies, and is preferable for damage detection of through-the-thickness defects, such as cracks and through-the-thickness holes [56].
Figure 2.10: Illustration of the subtraction approach for damage detection with GWs.

A typical GW SHM system comprises a number of transducers permanently bonded to the surface of a structure. One of the transducers (acting as a transmitter) is excited with a tone burst of a few cycles, generating a guided stress wave that propagates along the structure. The time-domain response (time trace) is then recorded by either the transmitter and/or other transducers. This process is repeated, using different transducers as the transmitters.

As mentioned above, to distinguish damage from structural features, some form of comparison with damage-free reference data is required. The
majority of the GW damage detection techniques utilise the baseline subtraction approach. Detection of damage is based on the analysis of the algebraic difference between the current time trace and the baseline time trace (or reference data) recorded for the structure, as illustrated in Figure 2.10. The signal remaining after the subtraction of a baseline time trace is referred to as a residual time trace. This residual time trace can be related to the effect of damage provided that it is not affected by coherent noise or changing environmental and operational conditions (EOC).

![Diagram showing Pulse-echo and Pitch-catch modes](image)

Figure 2.11: Schematic configuration of two operational modes.

A GW SHM system can usually operate in two modes: in a pulse-echo mode where damage is detected by the appearance of a new reflected signal, or in a pitch-catch mode, which normally utilises separate send and receive elements, and damage is detected by the appearance of a new, diffracted signal. These two modes of operation are illustrated in Figure 2.11.
Over the past two decades, a large number of research studies have been conducted focusing on damage detection and SHM using Lamb or GWs [40, 47, 54, 57-74]. It is not possible to outline or summarise all these studies in this work. Therefore, only those articles and studies which are important and closely relevant to this project are reviewed in the following sections of this chapter.

2.5 Sensor Technology for Lamb Waves

Various sensors, roughly categorised as ultrasonic, piezoelectric, piezoceramic and piezocomposite (which are briefly detailed below), as well as fiber optic, can detect Lamb waves [40, 55, 75-77]. Another way to characterise GWs is based on 3D scanning laser vibrometry (SLV) which only recently became available for GW research. This sensing technology will be considered in detail as part of the current study and its outcomes to be presented in the following chapters, which are all based on 3D SLV.

2.5.1 Ultrasonic Probe

Ultrasonic probes are distinguished by their ability to generate high precision and controllable wave modes. Ultrasonic probes can be coupled with Hertzain contact transducers [40], or angle-adjustable Perspex wedges to generate and sense GWs in experimental studies [73, 74, 78], (Figure 2.12).
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Figure 2.12: Conventional angled wedge ultrasonic transducer [1]

Some issues related to the use of these devices have been reported frequently in the literature associated with transducer-structure coupling. To overcome these issues, non-contact air-coupled [79], fluid coupled [80] and also electro-magnetic acoustic transducers (EMATs) [81] were developed. Amongst the above-mentioned transducers, EMATs are also capable of producing shear horizontal wave modes. However it should be noted that the applications of ultrasonic probes were generally limited to metallic structures where a good contact with the structure can be achieved [40]. Despite significant advantages in GW generation, these devices are relatively expensive, bulky and heavy. These features largely prevent their applications for SHM systems, which can often require the installation of a large number of sensors.
2.5.2 Piezoelectric, Piezoceramic and Piezocomposite Transducers (PZT)

PZT are the most commonly utilised transducers for SHM purposes. PZTs can be either embedded or attached to the surface of a structure. Due to their low cost, weight and energy consumption, PZTs are very suitable for integration into online monitoring systems (Figure 2.13).

![Figure 2.13: PZTs and PVDFs of various shapes and sizes [1].](image)

There are many studies on GWs which employ PZTs for GW excitation and sensing [49, 67, 68, 71, 73, 76, 82, 83]. In some studies, it is noted that PZTs can exhibit a strong non-linear behaviour such as hysteresis, specifically under large strains/voltages or at elevated temperatures. Relatively small driving force/displacement and brittleness are among other considerations restricting the application of PZTs [84].
2.5.3 Fiber Optics

Fiber optic sensors are small, lightweight devices, resistant to electromagnetic interference, with a wide bandwidth, good compatibility, low power consumption and cost. These sensors have become very popular in many applications including damage detection. The structure of a fiber optic grating (FBG) sensor is shown in Figure 2.14 [85].

![Figure 2.14: Picture of FBG sensors (Courtesy of Stanford CDR Haptics).](image)

As an example, Gachagan and Pierce [86] used embedded fiber optic sensors to detect and characterise GWs. The performance of fiber optic sensors was also compared with conventional PZTs. An important advantage of fiber optic sensors highlighted in Gachagan and Pierce [86] is a broader bandwidth diapason, in comparison with PZTs (which can spread up to 25 MHz) as a result of the absence of mechanical resonances.
However, due to a low sampling rate of the normal optical spectrum analyser, applications of fiber optics as sensors to monitor Lamb wave signals are limited [87-89].

### 2.5.4 Laser Vibrometry

Malinowski and Wandowski [90] were amongst the first researchers to utilise 1D SLV for the measurement of GWs in structural elements and piezoelectric transducers to excite the Lamb wave modes. Barth and Köhler [91] introduced and implemented a method for 3D measurement displacements on surfaces using one Scanning Laser Vibrometer (SLV) sequentially, instead of three laser heads simultaneously. Olson and DeSimio [92] conducted a comparison between 1D and 3D measurements of Lamb waves’ characteristics in an aluminium plate. It was concluded that 3D systems provide superior understanding of the mode conversion and dispersion on various defects.

The further development of 1D and 3D scanning vibrometry (3D SLV) over the past fifteen years has provided a non-invasive, non-contact, highly accurate tool for GW characterisation [93, 94]. However, the cost and weight of 3D SLV systems are currently the main constraints for wider practical applications. Nevertheless, these will eventually be improved with the rapid advances in laser technology: the utilisation of 3D laser vibrometry in industrial applications is just a matter of time. One envisages that such a
system, for example, could form a non-contact platform for non-destructive aircraft inspection, as illustrated in Figure 2.15.

Figure 2.15: An example of a 3D SLV mounted on a gantry-operated, seven degree-of-freedom serial manipulator.

In addition to the ability to measure full 3D displacement or velocity fields, 3D SLV systems (see Figure 2.16) have many other advantages over conventional sensor elements. These advantages include a superior spatial resolution (up to nanometer range), better accuracy and the non-contact nature of the measurements, which eliminates the influence of the conventional contact transducers on the test object motion dynamics. The PSV-400 Polytec, shown in Figure 2.16, is utilised in all experimental studies conducted within the current PhD project.
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Figure 2.16: Photography of a 3D laser vibrometer (PSV-400 Polytec).

In a number of recent studies, SLV systems were applied to detect and visualise damage in both metallic and composite components [47, 95-99]. For example, Sohn and Dutta [48] have explored the feasibility of utilising a non-contact GW imaging system to detect delamination in multi-layer composites. SLV systems have been employed to create wavefield images around structural defects with a high spatial resolution [47, 48, 100, 101], as well as to investigate the mode conversion effects as a result of wave scattering from various types of defects [102-104]. In addition,
advanced signal and post processing techniques have been developed over the past five years to improve the accuracy and resolution of structural defect imaging systems based on 1D and 3D SLV [101, 105-108]. Sohn [109] provided an overview of laser based SHM. The development of a fully non-contact damage detection system, based on the adoption of laser ultrasonics, laser based wireless power and data transmission methods for remote GW measurements, and also extension to embedded laser ultrasonic excitation and sensing, were focused on in the research work.

2.6 The Effect of Changing EOC on Damage Diagnostics

As mentioned before, most of the SHM using GWs utilise some form of comparison with damage-free reference data to assess the state of health of the structure and detect the presence of structural damage [55, 110-112]. This is often accomplished with the signal or envelope subtraction approach. In this approach, the previously recorded signal for a defect-free structure or structural component (the baseline signal) is subtracted from the actual signal obtained during routine inspections. A significant difference between these two signals (the critical or threshold level of this deviation depends on the particular application) is treated as an indication of the presence of (critical) damage. Figure 2.11 shows a schematic illustration of GW-based damage detection with the signal subtraction approach.
For damage detection, it is possible to implement a signal envelope rather than a signal subtraction. This process normally gives a significant improvement in sensitivity, typically in the order of 20 dB, when compared with signal subtraction. On this basis, envelope subtraction seems preferable, but there is a more fundamental reason as to why signal subtraction is currently used in all SHM systems: there could be blind spots in the case of envelope subtraction due to the loss of phase information in the enveloping process, resulting in interference effects between the directly transmitted signal and the scattered signal. Therefore, in this work only signal subtraction is considered.

The signal subtraction approach (see Figure 2.10) can easily be adopted in online health monitoring systems due to its simplicity and the aforementioned properties of GWs, which normally do not interfere with operational loads. The ability to detect damage in structural components with complex geometry is another significant advantage of the baseline signal subtraction method [64]. However, as is alluded to in the literature, the application of this approach in practice has many obstacles. For the damage detection techniques which utilise PZT transducers, the accuracy of the damage detection can be significantly compromised by a number of uncontrolled factors including the EOC [64] – [165]. Some of these common uncontrolled factors are:

- EOC changes, specifically, ambient temperature variations, which can affect GW propagation in different ways, which will be discussed later
in this chapter. Other factors include humidity and UV radiation. These factors can affect the material properties of composite structures and bonding properties, which, for example, rapidly degrade in high humidity environments.

- Inconsistencies in PZT adhesive bond thickness and mechanical properties, which can result in large differences in the baseline signals for otherwise identical structural components and;
  - Time in service, as well as the severity of loading, which can change the mechanical properties of the structure, affect the properties (or lead to failure) of the bonding layer and PZT, or in some cases even the geometry of the structural component, due, for example, to local buckling.

In the following sections, the effects of EOC on SHM using GWs will be reviewed. These include the effect of temperature and the effect of inconsistencies in the PZT installation procedures. Unfortunately, there is little information available regarding other environmental and operational effects, since they are largely dependent on the type of PZT or properties of the bonding layer. These effects are often reported in the literature but it seems there is a very limited number of systematic studies of these issues. It will be concluded from this review that some form of EOC compensation is essential for guided-wave SHM systems to be viable.
2.6.1 Effect of Changing Temperature

GWs have been shown to be very sensitive to temperature variation and this has been confirmed as one of the dominant factors affecting the baseline time traces [113]. The influence of temperature variations on damage detection with PZTs is well known and has been extensively documented in the literature [114-118]. The primary effect of a temperature variation on GW propagation involves changes in the amplitude and arrival times, or time of flight, (TOF) of the signal, leading to stretching or compressing of the signal envelope [115]. It was also highlighted that temperature changes can even mask damage to such a degree that it becomes undetectable [119].

Generally, the influence associated with ambient temperature variations can be split into two main categories: (I) their influence on the PZT and the adhesive bonding, and (II) the modification of material properties of the structure and, as a result, a change of wave speeds. In composite laminates, for instance, an increase in amplitude of the recorded signal up to 50% was reported when the ambient temperature increased from -90°C to 25°C [120, 121]. In other research studies [121, 122], significant TOF changes were reported. The difference in thermal expansion coefficients of the PZT transducer and the structure can also contribute to these phenomena [35]. In the following pages, several selected studies are listed, which confirm that significant problems in damage detection could be associated with the effect of changing temperature on GW characteristics and PZT responses.
Blaise and Chang [123] investigated Lamb wave propagation speeds in the presence of moderate temperature changes experimentally. It was shown that both the TOF and the amplitude of Lamb waves significantly increase with an increased temperature. The same conclusions were reported in Lee, Manson [124]. As an example, Figure 2.17 shows the typical effect of temperature on the time trace. Obviously, the application of signal subtraction will lead to a false conclusion of the presence of damage.

![Figure 2.17: Temperature effects on PZT sensor signals at f=300 kHz [117].](image)

In another study, Schulz and Sundaresan [125] focused on the performance of PZT sensors (typical commercial PZT patches) under ambient temperature fluctuations. The sensors were tested from room temperature up to 450°F (232°C). It was concluded that a sudden degradation in sensor mechanical properties take place at 250°F (121°C). The effects of changing temperature on SHM using GWs were also
investigated experimentally and analytically in Raghavan and Cesnik [126]. Isotropic metallic plates and lead zirconium titanate PZT sensors were utilised for this study. The thermal sensitivity parameters were identified and quantified in the temperature range from 20°C to 150°C. The outcomes of this study also indicated the significant influence of temperature fluctuations on GW and, subsequently, on damage detection.

The sensitivity of GWs to temperature variations (from 25°C to 75°C) and to the thickness of the PZT adhesive layer were also reported in [117]. Also, stiffness change in the PZT adhesive layer due to temperature change has been reported as the most influential parameter in comparison with other mechanical properties of the bonding layer [117].

2.6.2 Quantitative Assessment of the Signal to Noise Ratio due to Temperature Variations

In a recent paper [127] a simple model was developed to evaluate the noise after reference signal subtraction caused by the first-order temperature effect. The authors have applied this model to different wave modalities and sensor geometries. They demonstrated how detection limits can be related to both temperature and propagation distances and the effect of a temperature compensation technique on required sensor spacing to enable the detection of defects.

In the case of signal subtraction, the signal to noise ratio (SNR) can be calculated approximately from the following equation [127]:

$$\text{SNR} = \frac{S}{N}$$
\[ SNR = 2\pi f \frac{d}{C_p} \left( \alpha - \frac{k_p}{C_p} \right) \delta T \]  

(2.19)

where \( \alpha \) is the coefficient of thermal expansion, \( f \) is the central frequency of the tone burst, \( d \) is the distance from the actuator, \( C_p \) is the phase velocity of the GW and \( k_p = \delta C_p/\delta T \) is the coefficient relating changes in \( C_p \) to temperature and \( \delta T \) is the change in temperature.

The value of \( k_p/C_p \) (for metals) is typically one to two orders of magnitude larger, so the change in velocity with temperature is the dominant effect rather than the thermal expansion of the structure. Also, the presence of \( d \) in the numerator indicates that the SNR with a change in temperature is proportional to the propagation distance; hence the performance of reference signal subtraction decreases as the propagation distance increases. Finally, the presence of \( C_p \) in the denominator suggests that faster modes are less affected by temperature than slower modes.

From Equation (2.19) the maximum distance between the transducers/sensor can be evaluated at the required SNR. Quantitative examples for aluminium plates provided in Croxford and Wilcox [127] indicate that in the presence of moderate temperature variations, say \( \delta T = 10^0 \text{C} \), and in the case of the \( S_0 \) mode, the minimum number of sensors per square metre is 97 in order to detect damage reliably. Despite this, SHM systems become economically and practically feasible, requiring something in the order of one sensor per square metre. In the case of temperature compensation, this number can be reduced to 0.2, resulting in a separation
of the distance between each sensor of approximately 2.3 m. Therefore, with the temperature compensation, the costs of implementing a guided wave SHM can be reduced by roughly two orders of magnitude. This demonstrates the importance of the development of EOC compensation strategies for real world applications.

2.6.3 Effects of Variation of Thickness and Mechanical Properties of Adhesive Bonding on GW

Inconsistencies in PZT adhesive bonds can also affect GW propagation to a great extent. Significant research effort has been undertaken to investigate the aforementioned phenomenon. For example, a comprehensive study on the adhesive interface layer effects in PZT-induced Lamb wave propagation was carried out in Ha and Chang [128]. The study demonstrated that even small variations in the thickness of the PZT adhesive layer from 10 µm to 40 µm can influence the generated signal significantly (see Figure 2.18).

The same conclusion has been made in a number of other studies focusing on different aspects of the sensors’ (PZTs) installation procedures [129, 130]. Bhalla and Soh [129] studied the force transfer mechanism through the bond layer of the adhesive and suggested greater control of the bond layer thickness during the installation of the PZT patch was needed in order to avoid any variations in the measured signals. Furthermore, Rabinovitch and Vinson [130] also provided a mathematical formulation for the analysis of adhesive layers in active panels with surface-mounted
piezoelectric layers. This paper suggests some practical recommendations for analysis, design and utilising bonded PZT actuators in structures.

Figure 2.18: The effect of adhesive layer thickness changes on sensor signals (for 10 µm to 40 µm) [128].

Islam and Huang [131] performed parametric studies to investigate the effects of the adhesive layer on the frequencies and amplitudes of resonances in piezoelectric wafer active sensors’ (PWAS’) resonances. Manual adjustment of the adhesive layer parameters (shear transfer parameter and the thickness-shear modulus ratio) was suggested to match the simulated resonant frequencies of the PWAS with experimental measurements. This means that identical structures, having the same material properties, could have completely different baseline time traces,
due to slight and uncontrollable differences in the PZT installation procedures. The same conclusion was found in a number of past studies focusing on different aspects of PZT installation procedures, such as variations in the mechanical properties of the adhesive sourced from different batches [128-131].

2.7 Previous Strategies for EOC Compensation

The main effort in the development of EOC compensation techniques has been directed towards the avoidance of the influence of ambient temperature fluctuations on the baseline time traces, which are often employed to detect damage. In order to compensate for the temperature fluctuations, two main strategies have been developed over the past decade: Optimal Baseline Selection (OBS) [115, 121, 132, 133] and Baseline Signal Stretch (BSS) [115]. Both methods are based on various numerical optimisation procedures and signal processing algorithms. These compensation strategies essentially attempt to minimise the error caused by EOC.

In the OBS method, a measured signal is subtracted from several recorded baseline signals (time traces) previously obtained for different temperatures in order to minimise the residual time trace. However, this method requires a large number of baseline time traces to ensure the accuracy of the method [116]. This might represent a formidable task, especially for retrofitting an SHM system into a structure. In another study,
Clarke and Simonetti [116] presented a strategy for the reduction of the number of the recorded baseline time traces, which can provide some practical advantages in the implementation of OBS.

In the BSS method, only one baseline signal is required, however its application is limited to a specific temperature variation range [113]. To improve these strategies, Croxford and Moll [119] present a combination of the OBS and BSS methods and provide some experimental evidence of its efficiency.

There are also many recent studies focusing on temperature compensation methods for SHM using GWs [113, 134-136]. For example, Roy and Lonkar [134] introduced a physics-based temperature compensation model that utilises the matching pursuit algorithm with Gabor atoms to decompose the signal response into main elements. The limitation of the method is that prior data is required to train the algorithm, which is not always feasible in the real world environment. Another compensation technique [113] combines an adaptive filter and optimisation of the baseline time trace to minimise the influence of temperature variations on damage detection.

There are limited numbers of studies focusing on compensation for the effects of operational conditions, such as stress (due to the acousto-elastic effect), fatigue loading, humidity and UV radiation. For example, Chambers et al. [137] investigated the durability (time in service) of SHM
systems in the presence of changing EOC. Various GW characteristics were studied, and, in particular, notable changes in TOF were observed with time. However, the general strategies to mitigate these effects on damage detection are normally reduced to the selection of stronger, less brittle, UV resistant sensors and actuators or applying protective coatings to the main structure.

2.8 Summary

A brief literature review was conducted in this chapter, which focused on SHM using GWs. As mentioned above, it is beyond the scope of this thesis to present a comprehensive review of the thousands of articles published in this area over the past two decades. Therefore, this literature review was focused on selected topics, which are closely associated with the present PhD project. These include, in particular, an introduction to SHM and sensor techniques, fundamentals of Lamb waves and the effect of changing EOCs on damage detection.

The key conclusions from the Literature Review are summarised below. It has been shown that SHM using GWs are capable of significantly increasing the reliability of structures and substantially reducing operating costs. One of the main reasons why SHM systems developed in the laboratory environment often fail to operate in the real world environment is changing OECs.
Many research studies have confirmed that changing the EOC can make the application of SHM systems using GW impractical. The research efforts so far have largely been focused on the development of strategies compensating for ambient temperature variations. Several effective compensation strategies have been suggested previously. These strategies are largely based on signal processing algorithms. However, at present, there is no strategy to compensate for any EOC other than temperature effects; none for progressive failure of PZTs or the effect of humidity, let alone the combined effects of EOCs, which can be very different in nature.

The rest of the chapters in this thesis will address the above-identified problem by developing a new approach to compensating for changing EOCs. The approach is based on merging 3D laser vibrometry with high fidelity FE of GW propagation in a defect free structure. In the next chapter, the experimental technique for the characterisation of Lamb waves with 3D SLV will be described and applied to defect imaging. After that, the concept of the new method for compensation for changing EOCs will be presented, followed by suggestions for the application of this method with isotropic and composite structures.
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Chapter 3

Lamb wave Characterisation

and Damage Imaging with 3D

Scanning Laser Vibrometry
3.1 Introduction

The development of 1D SLV over the past twenty years has provided a non-invasive, non-contact, highly accurate experimental tool to guided wave research. In the past five years, laser technologies have been significantly improved, as was highlighted in the previous chapter (the Literature Review). The latest developments have resulted in a radical increase in sampling frequency, up to 25 MHz, and the possibility of full and very accurate 3D measurements of the displacement and velocity fields, due to Lamb wave propagation. This chapter attempts to utilise the latest technological advances and describes an application of 3D SLV for the detection and imaging of various structural discontinuities in beams and plates made of isotropic and composite materials.

Distinct features of the scattering field from typical structural defects are investigated with the purpose of identifying the most effective strategies for their detection and imaging using Lamb waves. The damage imaging procedure is based on the calculation of the root mean squares (RMS) of velocity fields, also known as the quadratic mean, in statistics. The sensitivity of the in-plane and out-of-plane velocity components of the scattered field to the presence of various types of mechanical defects and discontinuities are investigated, and recommendations for practical implementation of the developed procedures and outcomes of the investigations are summarised in the conclusion section of this chapter. The
experimental procedures developed in this chapter are further applied throughout this thesis.

3.2 Lamb Wave Characterisation and Damage Imaging with 3D SLV

As highlighted in the previous chapters, guided waves have the ability to propagate over large distances without significant energy decay and are found to be very sensitive to the presence of various types of structural defects, such as fatigue cracks, delamination damage or corrosion spots [1-6]. In recent years, guided waves have been successfully employed in the development of effective structural health monitoring techniques across many industries and applications [7-12]. 3D SLV uses the Doppler effect for non-contact optical vibration measurements. The measurement principle is based on the change in frequency of the laser light when it is scattered from a moving object. Within a 3D SLV, a high precision interferometer detects the frequency shift of the backscattered laser light. To achieve this, the interferometer splits the light into two parts; a reference beam and a measurement beam. The reference beam propagates directly to the photo detector, while the measurement beam is incident on the test object, where it is scattered by the moving surface. Depending on the velocity and displacement, the backscattered light is changed in frequency and phase. The characteristics of the motion are completely contained in the backscattered light. The superposition of the measurement beam with the
reference beam creates a modulated output signal, revealing the Doppler shift in frequency. The velocity decoder resolves the Doppler shift in the frequency to a voltage proportional to the measured velocity. Signal processing and analysis then provides the vibrational velocity and displacement of the test object.

As the path length of the reference beam is constant over time, any movement of the object under investigation generates a dark and bright pattern, typical of interferometry, on the detector. One complete dark-bright cycle on the detector corresponds to an object displacement of exactly half of the wavelength of the light used. The displacements or velocities in three perpendicular directions, corresponding to the laser heads, can then be resolved into the displacement or velocity fields in an arbitrary coordinate system.

The three laser beams are all directed to the desired measurement location. Vibration at this point modulates the backscattered light from each laser. This modulation is measured by the photodetector of each laser head and is directly proportional to the velocity of the point. By using scanning (pan-tilt) mirrors, the light from all three heads is focused sequentially on every point on a measurement grid to measure the motion of a surface. The 3D measurement head samples each grid point in three separate directions uniquely to determine the vector motion of that point. The velocity of one measurement point is measured from three different angles, as shown in
Figure 3.1. An orthogonal decomposition leads to the 3D velocity field in a Cartesian coordinate system.

Figure 3.1: Schematic of the experimental arrangement for the measurement of the velocity fields on a flat plate over the specified damage area, using 3D SLV.

The time traces of the three orthogonal velocities at each point of the measurement grid are recorded and then processed. Using suitable interpolation techniques for the point-by-point surface velocities, the discrete velocity for each measurement point can then be presented as 2D or 3D colour-coded contour plots. The excitation of the guided wave is fully repeatable; this makes it possible to measure the vibrations at each grid point sequentially and then combine them into one image. The SLV system
is able to measure the velocity of the measurement points over the desired surface in a very short period of time (e.g. around 30 measurement points per second for the Polytec PSV-400 system).

In addition to the ability to measure full 3D displacement or velocity fields, 3D SLV systems have many other advantages over conventional sensor elements, including a superior spatial resolution, better accuracy and the non-contact nature of the measurements, which eliminates the influence of conventional contact transducers on the test object’s motion dynamics. The use of SLV technology naturally avoids many obstacles associated with the traditional sensing elements (PZT or fiber optic (FO)), such as the need for a high fidelity baseline signal or compensation systems to avoid the effects of temperature change or applied loading.

In a number of recent studies, SLV systems were applied to detect and visualise damage in both metallic and composite components [13-18]. In particular, SLV systems were employed to create wavefield images around structural defects with a high spatial resolution [16, 19-21], as well as to investigate mode conversion effects experimentally, as a result of wave scattering from various types of defects [22-24]. In addition, advanced signal and post-processing techniques have been developed over the past five years to improve the accuracy and resolution of structural defect imaging systems based on 1D and 3D SLV [21, 25-28]. A more detailed review of the current literature regarding 3D SLV and its application for sensing of guided waves was provided in the previous chapter.
Chapter 3: Lamb wave Characterisation and Damage Imaging with 3D SLV

The purpose of this chapter is to apply 3D SLV for Lamb wave characterisation, as well as for detecting and imaging defects in typical structural components. The detection method is based on the evaluation of the root mean square values (RMS) of the velocity fields of guided waves using advanced 3D SLV. This chapter demonstrates that 3D SLV, in conjunction with the RMS approach, provides a simple and effective method for imaging and sizing various structural defects using Lamb waves.

3.2.1 Experimental Approach

The guided wave measurement system consists of a Polytec PSV-3D 400 SLV (comprising three separate laser heads and velocity decoders, a computer and a built-in function generator), a power amplifier along with a test specimen and PZT transducer, as illustrated in Figure 3.1.

Three different test specimens with typical structural defects were fabricated from large aluminium plates, with in-plane dimensions of 400 mm by 800 mm and 3 mm in thickness. The plate dimensions were selected to avoid the effect of wave reflections from the plate’s boundaries on the imaging and mode conversion within the short time window used for the measurements. A blind hole of 1.5 mm depth and 10 mm diameter, representing a corrosion type defect, was milled in the first plate. A surface crack of 10 mm length and 1.5 mm depth was introduced in the second plate and three different dents of 1 mm, 2 mm and 3 mm in diameter were fabricated in the third aluminium plate specimen (Figure 3.2)
Figure 3.2: Pictures of three different defects for the test samples (a) blind hole (b) crack and (c) three assorted dents (1mm, 2mm and 3 mm).

In addition to the aluminium plate specimens, an 8-ply carbon fibre reinforced composite beam, with dimensions of 285 mm by 12 mm by 2 mm, with a hidden delamination located between the 3rd and 4th layers, was fabricated. The delamination is one of the most common forms of damage in composites due to their low transverse strength and fracture toughness. In composite components, delaminations can either be caused during manufacture or during service. The manufacturing defects often occur due to improper lamination and curing processes, or may be introduced by machining fastener holes and design cut-outs etc. Service damage may result from the impact of runway debris in the case of aircraft, hailstones, bird strike, ground service vehicles, ballistics etc. In many instances, the damage caused by such impacts may not be visible or only visible on the surface but such damage may significantly reduce the strength of the structural component. Therefore, the availability of practical and robust non-destructive evaluation techniques for damage detection and monitoring is
critical to ensure the acceptable performance of such structures in terms of serviceability, reliability, durability, and prevention of catastrophic failures. The composite specimen used in the experiments is shown in Figure 3.3.

![Figure 3.3: Photograph of the carbon fibre reinforced composite beam specimen with a delamination used in this study.](image)

### 3.2.2 Experimental Set-up

A Polytec PSV-400 3D SLV was used to measure the structural response of the test specimens and is shown with a plate specimen in Figure 3.4. To generate the guided waves, a five and a half cycle Hanning windowed tone burst signal, at frequencies between 100 - 300 kHz with a 50 kHz increasing step, was used. The tone bursts were generated by the Polytec PSV-400 3D SLV built-in signal generator and amplified to ±50 V using a power amplifier to drive the piezoelectric transducer (PZT).
Two types of PZT transducers were used for the specimens in the current study. For the plates, a disk-shaped PZT with dimensions of 10 mm in diameter and 2 mm thickness with a brass backing mass of 10 mm in diameter and 3 mm thickness was used. For the composite beam, a rectangular–shaped PZT with dimensions of 6 mm by 12 mm and 2 mm thickness with a brass backing mass of 6 mm by 12 mm and 3 mm thickness was used. The PZTs convert the amplified electrical signal from the amplifier to the surface displacements that generate the guided waves in the specimens. The specimens were sprayed with Ardrox to increase the scattered light and to improve the signal to noise ratio (SNR).
The velocity components were measured at grid points in a rectangular area covering the defects and the surrounding surface regions, as shown in Figure 3.1. In order to achieve a high quality resolution image of the wave propagation in the structure, a sufficiently small uniform measurement grid size was selected to ensure that at least 8 measurement points exist per wavelength of the incident $A_0$ guided wave. To improve the SNR, 200 time responses were averaged for each measurement point. Band pass filters, with low and high cut off frequencies based on the signal energy envelope, were applied to reduce the measurement noise outside of the frequency band (e.g. ±50 kHz for the 200 kHz excitation frequency). A sampling rate of 2.5 MHz was used in all the experimental measurements.

3.3 Results and Discussion

This section describes the outcomes of this preliminary experimental study devoted to guided waves scattering at typical structural defects, as described in the previous section. The results are presented in terms of the Root Mean Square (RMS) of the velocity field components. Furthermore, the results will be analysed in order to develop an effective strategy for the detection and imaging of various defects.

3.3.1 Wave scattering at a Blind Hole

The fundamental anti-symmetric mode ($A_0$) guided wave was excited and facilitated by the use of a backing mass within a designated frequency range from 100 to 300 kHz. The appropriate range of the excitation frequencies
can be selected initially, based on the targeted defect sizes. In the present experimental studies, the characteristic size of the structural defects was 10 mm. The wavelength of the $A_0$ guided wave at a frequency of approximately 200 kHz has a similar value to the characteristic defect size. Therefore, several excitation frequencies around this initial value of 200 kHz were tested and the frequency providing the best SNR was finally selected to produce the experimental results, which are presented in the following sections.

The $A_0$ guided wave has a relatively large magnitude of out-of-plane displacement, or $V_Z$ component, when compared with the two other velocity components ($V_X$ and $V_Y$), due to the use of the backing mass. The PZT was mounted 70 mm from the blind hole with characteristic dimensions, as described in the previous section for the plates. The wave propagation in the structure is shown in Figures 3.5 and 3.6. The snap-shots in these Figures represent the instantaneous in-plane velocity field ($V_X$ component) and out-of-plane velocity field ($V_Z$ component) at different times. The actual location and size of the blind hole is marked with a circle. The presence of the hole can be noted directly from these pictures.
Figure 3.5: Snap shots of the instantaneous $V_X$ (in-plane) velocity component at 200 kHz. The size and location of the blind hole is marked by a circle.

Figure 3.6: Snap shots of the instantaneous $V_Z$ (out-of-plane) velocity component at 200 kHz. The size and location of the blind hole is marked by a circle.

To improve the visualisation of this structural discontinuity and investigate the sensitivity of the in-plane and out-of-plane scattered fields to the presence of various types of structural features, damage and defects, the RMSs of the velocity fields were calculated from the experimental
measurements. There are various types of averaging that can be utilised, depending on the situation. The RMS, also known as the quadratic mean, is a type of average measure that provides an average value of the magnitude of a variable (a time variable in this case). The RMS can be calculated either for a series of discrete values or for a function. The RMS calculation represents an average measure, which eliminates the difference between negative and positive magnitudes of the measured values. In the case of a discrete set of \( n \) values, \( \{a_1, a_2, a_3, \ldots, a_n\} \), the RMS value is given by [29]:

\[
    a_{RMS} = \sqrt{\frac{1}{n} \left( a_1^2 + a_2^2 + \ldots + a_n^2 \right)}
\]  

(3.1)

The important features of the RMS are:

- The RMS over all of the time of a periodic function is equal to the RMS of one period of the function and;
- The RMS value of a continuous function or signal can be approximated by taking the RMS of a series of equally spaced samples, which is important for the current study.

For the three components of the velocity fields, \( V_X(t, x, y) \), \( V_Y(t, x, y) \) and \( V_Z(t, x, y) \), the RMS field (continuous or at discrete points) can be calculated as:

\[
    \text{RMS} = \sqrt{\frac{n_S}{\sum_{n=1}^{n_S} V_n^2}} / (n_S)
\]  

(3.2)

where \( V_n \) represents the magnitudes of the velocities in the time domain and \( n_S \) is the number of samples.
Figure 3.7: The RMS of the a) x (in-plane), b) y (in-plane) and c) z (out-of-plane) direction velocity field components of 200 kHz guided waves at the blind hole, where the x-direction is aligned with the direction of the incident wave. The circle represents the size and location of the blind hole.

In this study, 2048 samples were taken for each measurement point at 2.5 MHz, resulting in a 819.2 µsec time window. The measurement grid density was set to approximately 10 points per wavelength of the excited $A_0$ mode.
Figure 3.8: Section views of the RMS of the velocity fields along (a) the $x$-direction and (b) the $y$-direction, through the centre of a blind hole.

The RMSs of the $x$, $y$ and $z$-components of the surface velocity field are shown in Figure 3.7. In this Figure, the location of the damage is clearly visible, when compared with Figures 3.5 and 3.6. As shown in Figure 3.7, the right hand side of the three plots in the Figure are disturbed by the reflected wave due to the relatively short distance between the PZT and the blind hole. Further effort was undertaken to identify the characteristic sizes of the observed damage. Figure 3.8 shows the RMS values plotted along two lines passing through the centre of the hole, one in the direction of the incident wave (the $x$-direction) and one in the transverse direction (the $y$-direction). The actual location of the hole in these diagrams is indicated by dotted lines.
As shown in Figure 3.8, the diameter of the hole can be identified from the RMS plots with any of the three components comprising the scattered 3D velocity field. From the comparison of the RMS values, it can be concluded that the in-plane ($x$-velocity) component of the scattered field, which is a result of mode conversion, is the most sensitive to the presence of the blind hole. It is interesting to note that the section views of the $x$- and $y$-directions have very similar patterns to the RMS value. Thus the above observations, for instance, can be useful in the selection of defect detection strategies with guided wave techniques for identification and characterisation of corrosion-type damage.

### 3.3.2 Wave scattering at a Crack-Like Defect

A similar analysis was conducted for the second specimen. Different snapshots of the out-of-plane velocity field ($V_Z$) around the crack, described in the previous section, are shown in Figure 3.9. The location of the crack is marked by an ellipse.

![Figure 3.9: Snap shots of the $V_Z$ (out-of-plane) component of the velocity at 250 kHz. The location and size of the crack is marked by a white ellipse.](image-url)
The corresponding RMSs of the velocity fields of the three components are shown in Figure 3.10. The PZT is located at 70 mm from the crack and the disturbance on the right hand side of Figure 3.10 is due to the effect of the reflected wave.

Figure 3.10: RMS of the a) $x$ (in-plane), b) $y$ (in-plane) and c) $z$ (out-of-plane) direction velocity field components of a 250 kHz guided wave at a crack, where the $x$-direction is aligned with the direction of the incident wave. The ellipse marks the location and size of the crack.

Furthermore, Figure 3.11 shows the results of the RMS of the scattered fields along two lines passing through the centre of the crack, one in the direction of the incident wave (the $x$-direction) and the other in the transverse direction (the $y$-direction). The size and location of the crack in these diagrams is indicated by dotted lines.

The results are very different from the blind hole case. In the case of the crack-like defect, the sensitivity of the in-plane velocity components
(V_{X,\text{RMS}} \text{ and } V_{Y,\text{RMS}}) \text{ are quite similar and much more sensitive to the presence of this structural defect than } V_{Z,\text{RMS}}. \text{ The length of the crack (10 mm) is not easily identified from the directional RMS plots presented in Figure 3.11. From a comparison with the previous results, it is difficult to distinguish between these types of structural damage since they have very similar characteristics in terms of mode conversion and intensities. One distinct feature is a much lower sensitivity of } V_{Z,\text{RMS}} \text{ to the presence of crack damage in comparison with the blind hole (corrosion type) damage.}

![Figure 3.11: Section views of the RMS velocity field along (a) the x-direction and (b) the y-direction, through the centre of the crack.](image)

**3.3.3 Wave Scattering at Dents**

Guided wave scattering from dents of three different sizes (1 mm, 2 mm and 3 mm in diameter) was investigated using the 3D SLV. Similar to the previous cases of the blind hole and the crack, the A_0 guided wave was excited with a PZT transducer. The guided wave propagation and selected
snapshots of the in-plane and out-of-plane velocity field across the surface of the plate are presented in Figures 3.12 and 3.13.

Figure 3.12: Snap shots of $V_X$ (in-plane) component of the velocity at (a) 30.25µs (b) 34.30µs (c) 38.28µs (d) 42.03µs, (e) 48.05µs, (f) 51.95µs and (g) 57.42µs at 250 kHz. The sizes and locations of the dents are marked by different circles of different diameters.

The corresponding RMS of the velocity fields along the incident wave direction and the transverse direction are presented in Figure 3.14. The locations of the dents are marked by different sizes of circles and the high values appeared at the locations of the dents in all three RMS components. In Figure 3.15 the RMS values of all the velocity components are plotted along two directions, cut through the centres of the dents, both parallel and transverse to the direction of the incident wave.
Figure 3.13: Snap shots of $V_Z$ (out-of-plane) component of the velocity at (a) 30.25µs (b) 34.30µs (c) 38.28µs (d) 42.03µs, (e) 48.05µs, (f) 51.95µs and (g) 57.42µs at 250 kHz. The sizes and locations of the dents are marked by differently sized circles.

Figure 3.14: The RMS of the a) $x$ (in-plane), b) $y$ (in-plane) and c) $z$ (out-of-plane) direction velocity field components of 250 kHz guided waves at the dents, where the $x$-direction is aligned with the direction of the incident wave.
Figure 3.15: Section views of RMS of the velocity fields along the $x$-direction and $y$-direction through the centre of the dents with 1 mm diameter (a & b), 2 mm diameter (c & d) and 3mm diameter (e & f).
Chapter 3: Lamb wave Characterisation and Damage Imaging with 3D SLV

The results, presented in Figure 3.15, indicate that the $V_{Z,\text{RMS}}$ values are not sensitive to the presence of the dents of the specified sizes. However, this type of damage can be characterised with $V_{X,\text{RMS}}$ and $V_{Y,\text{RMS}}$ fields. The values, plotted along the $x$-direction and the $y$-direction, clearly indicate the presence of all three dents.

For all three dents, the amplitudes of the RMS of the velocity fields of the in-plane components were higher than the RMS of the out-of-plane component. As a result, for the plate with the dents, the in-plane scattered field was also found to be more sensitive to this type of defect than the out-of-plane component of the velocity field. This observation is very similar to the case of the blind hole and the crack considered earlier.

3.3.4 Wave Scattering at a Delamination

Finally, the $A_0$ guided wave at 200 kHz was excited for the case of the carbon fibre reinforced laminated composite beam specimen with a delamination defect, as described in Section 3.1.1 (see Figure 3.3). Similar to the previous results, the snap shots of the $z$-velocity component are shown in Figure 3.16. The RMS fields of these velocity components are presented in Figure 3.17. Figure 3.17 clearly demonstrates the advantages of using RMS to characterise wave scattering, as it provides a much better signature of the defect.
Figure 3.16: Snap shots of the $V_Z$ (out-of-plane) velocity component at (a) 46.35μs (b) 49.62μs (c) 51.28μs (d) 54.03μs and (e) 57.05μs at 200 kHz. The location of the delamination is marked.

Figure 3.17: The RMS of the velocity field components for the hidden delamination in the (a) $x$, (b) $y$ and (c) $z$ components. The location of the delamination is marked with a rectangular box.
The RMS values along two lines passing through the centre of the defect parallel and perpendicular to the incident wave direction are provided in Figure 3.18. From a comparison of the RMS for different components, it can be concluded that the in-plane velocity \( y \)-component of the scattered field is the most sensitive to the presence of the hidden delamination damage.

![Figure 3.18: Section views of the RMS of the velocity fields along (a) the transverse direction and (b) the incident wave direction for hidden delamination in the carbon fibre reinforced composite beam.](image)

All the RMS curves corresponding to different velocity components clearly indicate the boundaries of the delamination. It is interesting to note that both the incident wave and transverse directions provide very similar patterns and can be utilised for the detection and sizing of this type of damage. The results of this analysis can also be useful in the selection of a
strategy for composite delamination detection with guided wave techniques, in particular, sensor polarisation and their locations, with respect to the expected damage.

The outcomes of this experimental investigation on damage detection and imaging with 3D SLV generally confirm the results of numerous previous studies utilising 1D and 3D laser vibrometry [13, 15, 22, 24]. Specifically, that the wave responses from various types of damage can be acquired reliably using SLV and that the post-processing stage of the measured data is one of the crucial elements in damage imaging [19]. Proper interpretation of SLV data scans can lead to a clearer understanding of guided wave propagation and also improve understanding of mode conversion effects as well. This can significantly affect damage detection and imaging methods using laser vibrometry. Many recent studies have indicated that the move from 1D to 3D measurements will enable the registration of not only anti-symmetric waves but also symmetric and even shear horizontal waves, (due to the mode conversion effect) [30]. The current work is partially motivated by these expectations and represents a study of 3D wave scattering of guided waves and defect imaging utilising the RMS of the 3D velocity field components, instead of just 1D, for typical structural defects. The main result of this chapter, which highlights this step as well as the differences between 1D and 3D laser vibrometry, are summarised in the following section.
3.4 Summary

In this chapter a non-contact technique for Lamb wave characterisation and imaging defects in various structures based on 3D velocity measurements was investigated using a Polytec 3D SLV. In all cases the $A_0$ guided wave mode was excited below the cut-off frequency to avoid the generation of higher order harmonics, which can significantly increase the complexity of the analysis and image interpretation. Mode conversion effects and the sensitivity of the in-plane and out-of-plane components of the scattered field to the presence of different types of mechanical defects were investigated. The present study has confirmed that the characterisation of Lamb waves with 3D SLV has many advantages for damage detection and imaging, in comparison with 1D SLV systems. Thus, that utilising the RMS of the velocity fields as a possible and effective way for the detection and imaging of structural discontinuities in isotropic and composite material has also been demonstrated. The main conclusions from the experiments described above are summarised below:

(1) The conducted investigations confirmed that the use of RMS values of the velocity components, without the need for baseline information, provide good quality damage signatures for all the structural defects considered;

(2) For all the types of structural damage considered, the RMS values of the mode converted in-plane velocity components ($V_X$ and $V_Y$) were
found to be much more sensitive to the presence of the defects than the out-of-plane velocity components ($V_Z$).

(3) The sensitivity of the RMS of the velocity components to the presence of the damage along different directions (parallel or transverse to the incident wave propagation) was found to be quite similar for each case study. For all the aluminium plate specimens, it has been found that $x$-components are the most sensitive, while for the delamination defect in the composite beam case study, the $y$-component is the most sensitive;

(4) It is still difficult to distinguish between the damage signatures of the blind hole and the crack. One feature, which is quite promising and needs to be investigated further, is the much lower sensitivity of the $V_{Z,RMS}$ to the presence of cracks;

(5) In the case when the targeted defect size is unknown or undefined, then the structural component can be inspected with a wide range of central frequencies. However, in practice, not all defects represent a threat to the structure, therefore, the practical range can be determined based on the damage tolerance approach, which is generally adopted in maintenance procedures across many industries. This will specify the minimum and maximum defect sizes and will provide an estimate of the central frequency range for a particular structural component and loading conditions.
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(6) The outcomes of the present experimental study clearly demonstrate the advantages of capturing the full 3D velocity field for the detection, characterisation and sizing of mechanical structural damage, in comparison with the 1D systems often utilised in the previous studies.

The above conclusions clearly demonstrate the advantages of 3D SLV in comparison with 1D laser systems, which are capable of measuring only one component. A brief summary of the outcomes of the experimental study is presented in Table 1. The table shows the normalised peak levels by spatial RMS levels for all the cases of structural damage considered in this chapter. The signal ratio (SR) is calculated as the ratio of the maximum RMS values of the velocity components to the spatial average of the RMS values of the velocity components. The SR is specified as:

\[ SR_\beta = \frac{\text{Max}(V_{\beta,RMS})}{\text{Average}(V_{\beta,RMS})}, \]  

(3.3)

where the subscript \( \beta \) represents \( x, y \) or \( z \).

The ratio was calculated parallel and perpendicular to the incident wave direction. As shown in Table 3.1, the \( SR_x \) values are usually higher in comparison with the other directional components for all defects and damage considered in this study.
Table 3.1: Signal ratio, $\text{SR}_B$, for different velocity components along the incident wave and transverse directions for all the different types of damage considered.

<table>
<thead>
<tr>
<th>Damage type</th>
<th>Parallel with incident wave direction</th>
<th>Transverse with incident wave direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\text{SR}_x$</td>
<td>$\text{SR}_y$</td>
</tr>
<tr>
<td>Blind hole</td>
<td>2.30</td>
<td>1.40</td>
</tr>
<tr>
<td>Crack</td>
<td>2.30</td>
<td>1.40</td>
</tr>
<tr>
<td>Dents 1mm</td>
<td>1.21</td>
<td>1.20</td>
</tr>
<tr>
<td>Dents 2mm</td>
<td>1.18</td>
<td>1.18</td>
</tr>
<tr>
<td>Dents 3mm</td>
<td>1.18</td>
<td>1.15</td>
</tr>
<tr>
<td>Delamination</td>
<td>1.72</td>
<td>1.73</td>
</tr>
</tbody>
</table>
Chapter 3: Lamb wave Characterisation and Damage Imaging with 3D SLV

References


Chapter 3: Lamb wave Characterisation and Damage Imaging with 3D SLV


18. Chia C.C., Jeong H.M., Lee J.R., Park G., Composite aircraft debonding visualization by laser ultrasonic scanning excitation and


Chapter 4

A Method for Compensation of Changing Environmental and Operational Conditions
4.1 Introduction

This chapter introduces a new method for compensating for the effects of changing environmental and operational conditions (EOCs) on damage diagnostics, using guided waves. The compensation techniques developed in the past, which were outlined in the literature review, are largely focused on the application of the signal processing algorithms to make distinctive the alterations in the time traces caused by changing EOCs and the presence of structural damage. The current method is conceptually new. It involves the construction of a baseline time trace corresponding to the current properties and conditions of the structure and transducer/sensor network, using a numerical model. The method is based on advanced 3D velocity/displacement measurements, with laser vibrometry taken over the area surrounding the wave transducer (PZT), coupled with high fidelity transient finite element simulations of the defect-free structure. A numerical feasibility study is conducted to identify the broad range of the method’s parameters, which can be employed to create an accurate reconstruction of the baseline time trace in real world situations. The outcomes of this study are applied in subsequent chapters (5 and 6), which are focused on the practical applications of the method in the detection of damage in isotropic and composite components, under changing EOCs.
4.2 Conceptual Idea

The concept of the proposed method can be explained by dividing the problem into two domains: the physical and the modelling spaces [1]. The physical space represents the actual plate or shell component to be inspected, which is equipped with a PZT(s) generating a burst signal of a certain wavelength, $\lambda$, (or angular frequency, $\omega = 2\pi f$). The modelling space represents an accurate FE model of the defect free structural component, with the exception of the dummy region (see Figure 4.1). The corresponding boundary conditions are applied to the points where the physical measurements were taken in the physical space.
The method requires very accurate 3D measurements of the transient velocity/displacement field, which can currently only be realistically achieved with an advanced 3D Scanning Laser Vibrometer (3D SLV) system (with a sampling frequency of 2.5MHz). This measurement system records the time-dependent velocity/displacement over the scanning area, encapsulating the wave transducer (PZT), and at a remote location(s) (P), as illustrated in Figure 4.1. The time trace at P, which also can be recorded with a traditional PZT, is then utilised for defect signature analysis or
damage diagnostics of the component, using, for example, the algebraic subtraction approach described previously in Chapter 2 (2.4).

The recorded transient surface displacements over the scanning area serve as the input to the modelling space, in which the numerical reconstruction of the baseline time trace takes place. The modelling space, shown in Figure 4.1, represents an accurate Finite Element (FE) model of the undamaged structural component, excluding a cylindrical volume (the dummy volume in Figure 4.1), which is located inside the scanning region. The recorded transient displacements are prescribed to the corresponding nodes of the FE mesh. The modelling results to be presented in the following sections indicate that what happens in the dummy volume does not affect the time traces at remote locations if the width of the surface area with the prescribed boundary conditions (corresponding to the scanning area in the physical space) is larger than approximately half of the wavelength of the excitation signal (the tone burst). Thus, this volume, which includes the PZT, can be simply ignored in the numerical simulations generating the baseline time trace. Therefore, there is no need to analyse the sometimes very complicated response of the PZT, including the interaction between the PZT, the bond layer and structure. In particular, this interaction can be severely affected by EOCs, as highlighted in the Literature Review, and its modelling currently represents a formidable task for analytical and numerical approaches. Nevertheless, the effect of EOCs on the material
properties of the structure needs special consideration. This will be described in the next section.

4.3 Determination of Material Properties

In the case of degradation of material properties with time or due to changing EOCs, the current material properties, needed for the numerical reconstruction of the baseline time trace, can be identified from the wave propagation characteristics within or outside of the scanning area. There are several well-known techniques for the recovery of elastic, visco-elastic and anisotropic properties from the wave propagation characteristics [2-5]. The most simple is based on the fitting of the measured phase velocities to the theoretical dispersion relations, which are functions of the elastic properties of the material [6]. The elastic constants can be found as the best fit to these theoretical equations. This technique is implemented in the current study, and, therefore, is outlined briefly below.

Phase velocity can be obtained by measuring the complex wave amplitude of at least two nearby locations along a radial line passing through the excitation source location (PZT). A linear signal, $s$, as a result of the propagation of cylindrical waves, i.e. activated by a point source, in an isotropic plate can be described by the following equation [7]:

$$s(r, \omega, t) = A \sqrt{\frac{2}{\pi |kr|}} e^{-i|kr-\omega t|}, \quad (4.1)$$
where $A$ is the amplitude of the signal, $r$ is the distance from the source, $k$ is the wavenumber associated with angular frequency, $\omega = 2\pi f$. In particular, this equation, which represents an exact point source solution to the classical wave equation in cylindrical coordinates, predicts that the amplitude of the signal decreases with the distance as $r^{-1/2}$. This was found to agree very well with the experimental results, even at distances of only a few wavelengths from the wave source.

The measurement phase of the signal $s(x, \omega, t)$ is:

$$
\psi(r, \omega) = \arg[s(r, \omega)] = k(\omega)r . \tag{4.2}
$$

If $\Delta r$ is the distance between the measurement points, then the relative signal phase change between these points is:

$$
C_p(\omega) = \frac{-\omega}{\partial \psi(r, \omega)} \frac{\partial}{\partial r} = \frac{-\omega \Delta r}{\psi_2(r_2, \omega) - \psi_1(r_1, \omega)} . \tag{4.3}
$$

In practice, it is desirable to have more than two measurement points/locations to minimise the influence of adverse factors, such as stochastic noise and finite resolution of experimental measurements, on the accuracy of $C_p(\omega)$ data. Various techniques based on statistical methods can be applied to improve the accuracy and repeatability of the measurements, if required. In addition, in order to remove $\pm 2\pi$ ambiguity in the phase differences, the measurement points should be closer than the wavelength, $\lambda$.

The obtained experimental data $C_p(\omega)$ for a certain wave mode, as described above, can be related to the corresponding theoretical predictions.
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regarding Lamb wave propagation. For example, the theoretical dispersion equation describing the fundamental anti-symmetric mode, \( A_0 \), can be written as [7]:

\[
C_p(\omega) = \left[ \frac{\rho}{E} \frac{12}{\mu} (1 - \nu^2) - \frac{\rho}{h^2} \frac{1}{2\pi f^2} \right] \frac{1}{\sqrt{\frac{E}{\rho} (1 - \nu^2)}}
\]  

(4.4)

where \( f \) is the excitation frequency, \( \rho \) is the density of the material, \( h \) is the plate thickness, \( \mu \) is shear modulus, \( E = 2\mu(1 + \nu) \) is Young’s modulus, and \( \nu \) is Poisson’s ratio. \( E/\rho \) is the coefficient of determination in the following case.

![Figure 4.2: Phase velocity measurements and the fitted curve using (4.4) for the 3 mm thickness aluminium plate. The dots represent the measured phase velocity at discrete frequencies.](image)

In the case of the beam, according to Glushkov et al. (2015) [8], the phase velocity between a beam and plate are not identical, but the difference is very small, especially at lower frequency ranges (including 200kHz).
Hence, for a beam it is still possible to use the material properties obtained from the phase velocity curve of a plate.

The material parameter(s), such as $E/\rho$ or $(\mu/\rho)$, can be identified from the best fit of the theoretical equation to the experimental data. This can be carried out by using, for example, the standard least square optimisation method, provided all other parameters, such as thickness and Poisson’s ratio, are known. An example of the application of the technique described above to the identification of the ratio $E/\rho$ is given in Figure 4.2. In this example the phase velocity as a function of the frequency, $C_p (f \text{ or } \omega)$, was measured for a 3 mm thickness aluminium plate subjected to a predominant $A_0$ mode of excitation with a cylindrical PZT. Assuming Poisson’s ratio, $\nu = 0.3$, (in general, it does not significantly affect the optimisation result) $E/\rho = 27.2$ MN/kg is obtained from the best fit of the experimental data using Equation (4.4). If several parameters are unknown, then a multi-parametric optimisation can be conducted in order to recover the current material parameters of the structure [3, 9, 10].

4.4 Details of the Numerical Approach and Validation

Before presenting the results of the feasibility study of the proposed method, the details of the numerical approach and its validation are outlined below for the simplest case of a straight beam. This geometry was selected to avoid time-consuming simulations of 3D problems and to simplify the
interpretation of the outcomes of the numerical tests. It is believed that the obtained results provide a good evaluation of the main parameters of the method, which can be utilised for the accurate reconstruction of the baseline time traces in the case of more complex geometries.

A beam-like structure of 3 mm thick is considered. The $A_0$ and $S_0$ mode guided waves were excited by applying the corresponding nodal displacements at one end of the beam. A number of meshes with different densities were tested to optimise the calculations, since the analysis is significantly affected by the mesh density (or number of FE nodes). A 2D explicit finite element model was developed with the ANSYS 15.0 software package. The FE model utilised a 3D hexahedral type of element with hourglass control. Each node of the hexahedral element had two displacement degrees of freedom.

The transient (guided wave propagation) problem was analysed with the AutoDyne solver. The typical elastic properties of aluminium alloy are used in the numerical simulations: Young’s modulus ($E$) of 72 GPa and Poisson’s ratio ($\nu$) of 0.3. A five-cycle sinusoidal tone burst, a pulse modulated by a Hanning window, was utilised to excite anti-symmetric, $A_0$ and symmetric $S_0$ modes of Lamb waves [7]:

$$U_z(t) = A w(t) \sin(2\pi f t)$$  \hspace{1cm} (4.5)

where:
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\[ w(t) = \begin{cases} 
\frac{1}{2} \left( 1 + \cos \frac{2\pi ft}{N} \right) & \text{for } |t| \leq \frac{N}{2f} \\
0 & \text{for } |t| > \frac{N}{2f} 
\end{cases} \]  \hspace{1cm} (4.6)

where \( U_z(t) \) are the prescribed \( z \)-displacements, \( A \) is the amplitude of the pulse, \( w(t) \) is the Hanning window, \( f \) is the pulse centre frequency, \( t \) is the time and \( N \) is the number of generated cycles. Figure 4.4 shows an example of pulse excitation in accordance with Equations (4.5) and (4.6) for \( N = 5 \).

![Graph](image)

Figure 4.4: An example of a generated 5-cycle 200 kHz Hanning windowed tone burst pulse.

The anti-symmetric mode, \( A_0 \), is generated by applying the same displacements on both free surfaces of the beam, while the symmetric mode, \( S_0 \), is generated when the sign of the applied displacement on the free surfaces of the beam is opposite. In this case, the deformations are dominated by in-plane displacements rather than the out-of-plane deflections, which are dominant for the anti-symmetric mode.
Figure 4.5: Time snapshots of wave propagation in an isotropic 1D beam at (a) 19 μsec (b) 33 μsec and (c) 45 μsec for $f = 200$ kHz.

The time step was automatically controlled by ANSYS/AutoDyne and was dependent on the smallest element size. For the selected frequencies of the tone burst, the time step was approximately 3 ns throughout the simulations, and, based on the preliminary sensitivity study, this was sufficient to model the guided wave propagation accurately. Snapshots of FE simulations for different times are shown in Figure 4.5.

Mesh convergence studies were carried out to evaluate the accuracy of the numerical calculations. Figure 4.6 shows a typical mesh convergence test performed for a 100 kHz excitation centre frequency. The results in Figure 4.6 show the dependence of the maximum signal amplitude as a function of the number of nodes (the mesh density). A good convergence of the numerical calculations can be observed with approximately 10,000 nodes (which corresponds to a mesh size of $0.25 \times 0.25 \times 0.25 \text{ mm}^3$).
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Figure 4.6: Mesh convergence test performed for 100 kHz excitation centre frequency simulations based on the maximum out-of-plane signal amplitude (µm).

Table 4.1: Analytical predictions and the present numerical (FEA) results for phase and group velocities of a 3mm thickness aluminium plate and beam for different frequencies and Lamb wave modes.

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>$C_p$ (m/s)</th>
<th>$C_g$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Analytical</td>
<td>FEA results</td>
</tr>
<tr>
<td>$A_0$</td>
<td>$A_0$</td>
<td>$A_0$</td>
</tr>
<tr>
<td>$S_0$</td>
<td>$S_0$</td>
<td>$S_0$</td>
</tr>
<tr>
<td>100</td>
<td>1548</td>
<td>5399</td>
</tr>
<tr>
<td>200</td>
<td>2003</td>
<td>5376</td>
</tr>
<tr>
<td>300</td>
<td>2266</td>
<td>5339</td>
</tr>
</tbody>
</table>
To further validate the numerical calculations, the phase and group velocities for two fundamental modes, $A_0$ and $S_0$, which were obtained from the present numerical simulations, were compared with the analytical results (see Table 4.1). The group velocity is calculated based on the time delay between the arrivals of the maximum amplitude signal at two nearby locations. The procedure for the evaluation of the phase velocity was provided earlier in Section 4.3 of this chapter. The analytical predictions were obtained using the WaveFormRevealer 3.0 software package [11], which essentially solves the theoretical dispersion equations for any given frequency, mode and elastic constants. The comparison, summarised in Table 1, demonstrates a very good agreement between the numerical and analytical results. The difference between the current numerical results and analytical predictions is generally less than 3%. This provides confidence in the accuracy of the current numerical approach.

4.5 Feasibility Study

This section presents selected outcomes of extensive numerical simulations focusing on the sensitivity of the reconstructed baseline time trace to the size (width) of the scanning area in the physical space or the corresponding area within the prescribed boundary conditions in the modelling space, (see Figure 4.1). The purpose of these simulations is to help to identify the approximate size of these areas, which is necessary for the accurate reconstruction of the baseline time trace, as well as to demonstrate the
feasibility of the proposed method for simple geometries virtually, before attempting the experimental demonstration of the method. The current study is focused on the use of the fundamental modes $A_0$ and $S_0$, which will be further utilised in the experimental studies.

![Figure 4.7: Virtual implementation of the proposed method for a 2D isotropic homogeneous beam.](image)

With this aim, two FE models are developed with their dimensions shown in Figure 4.7; one represents the physical space (Model 1) and the other represents the modelling space (Model 2), as illustrated in Figure 4.3. The differences between the models are: (1) Model 2 ignores the area encapsulated by the scanning area (shown by dashed lines in Figure 4.7), and (2) the boundary conditions (displacements) in Model 2 are extracted...
from the scanning area (presented by large dots in Figure 4.7) of Model 1. These arrangements simulate the proposed method for the reconstruction of the baseline time trace in the simplest case of a 2D structural component, virtually. In this case, the scanning area is reduced to a line with a characteristic length, $L = a\lambda$, where $\lambda$ is the wavelength of the generated tone burst and $a$ is a coefficient. It is assumed that the modelling results are related to the wavelength.

Symmetry boundary conditions are applied along the edges of the beam, to avoid the variation of the displacement/velocity fields across the width of the beam in order to simplify the problem. For the same reasons of simplicity, the simulations were limited to a linear-elastic, isotropic and homogeneous material with elastic properties, as described in the previous section (4.3). The 2D surface velocity components from Model 1 (the physical space), $U_z(t, x, z = \pm h/2)$ and $U_x(t, x, z = \pm h/2)$ on both the bottom and top surfaces, were prescribed as boundary conditions for Model 2 (the modelling space) to generate the fundamental modes, as described previously. The frequency range was selected below the cut-off frequencies for the fundamental modes to make sure that only one wave mode is excited at a time. The cut-off frequencies for $A_1$ and $S_1$ modes were evaluated using the WaveFormRevealer 3.0 software package and these were found to be approximately 500 and 900 kHz, respectively. The Lamb wave modes are generated by applying the corresponding nodal displacements to the surface nodes representing the PZT transducer area (see Figure 4.7). The length of
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this area is 6 mm, and it is located at the left end of the beam. Two signals (time traces of the displacements) $U_{xz}^{(a)}(t)$ and $U_{xz}^{(r)}(t)$, as obtained from Models 1 and 2 respectively, are compared at a remote point, $P$ (Figure 4.7).

Based on the mesh convergence test result described in the previous section, the typical element size of the FE mesh is selected to be $0.25 \times 0.25 \times 0.25$ mm$^3$. This element size corresponds to approximately $0.05\lambda$, (or 20 nodes per wavelength). The selected length also exceeds the minimum required length or the number of nodes per wavelength recommended (10 nodes per wavelength) in the literature [12, 13]. The time step was automatically controlled by ANSYS/AutoDyne and depended on the smallest element size (3 ns).

Typical results of the numerical simulations are presented in Figure 4.8 for the selected excitation frequency of 200 kHz. Similar results were also obtained for other excitation frequencies (100 and 300 kHz). Figures 4.8-4.10 show the influence of the width ($L = a\lambda$) of the scanning area on the accuracy of the reconstructed baseline time trace.

Different lengths of the scanning area ($L$) were considered. At $L = 0.1\lambda$, large discrepancies were observed between the reconstructed signal and the actual response. After consideration of various wave modes and lengths of the scanning areas, it was concluded that the reconstruction results were converged at $L = 0.5\lambda$. Hence, the main outcome of the present numerical simulations (or virtual implementation of the proposed method) is that the baseline time trace can be reconstructed reliably when the length of
the scanning area is $L a \geq \lambda/2$. At $L = 0.5\lambda$, the differences between the actual response (Model 1) and the reconstructed signal (Mode 2) are negligible. The accuracy is slightly lower for the in-plane displacements (or $S_0$ mode), which have a much lower amplitude than the out-of-plane displacements corresponding to the $A_0$ mode. It should be mentioned that the parameter “$a$” is problem dependent, and for these cases (beams and plates) has been considered as $a=1/2$. 
Figure 4.8: Comparisons of the generated baseline time trace (from Model 1) with the reconstructed baseline time trace (from Model 2) at a remote point, $P$, for an $f = 200$ kHz excitation frequency, (a) out-of-plane displacement $U_z$, and (b) in-plane displacement $U_x$. 
Figure 4.9: Comparisons of the generated baseline time trace (from Model 1) with the reconstructed baseline time trace (from Model 2) at a remote point for \( f = 100 \) kHz excitation frequency, (a) out-of-plane displacement \( U_z \), and (b) in-plane displacement \( U_x \).
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Figure 4.10: Comparisons of the generated baseline time-trace (from Model 1) with the reconstructed baseline time trace (from Model 2) at a remote point for $f = 300$ kHz excitation frequency, (a) out-of-plane displacement $U_z$, (b) in-plane displacement $U_x$. 

<table>
<thead>
<tr>
<th>Actual response (Model 1)</th>
<th>Reconstructed signal at $L= 0.1\lambda$ (Model 2)</th>
<th>Reconstructed signal at $L= 0.5\lambda$ (Model 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalised amplitude $U_z(t)$</td>
<td>Normalised amplitude $U_x(t)$</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>-1</td>
<td>-0.5</td>
<td>0</td>
</tr>
</tbody>
</table>

REVIEW LAYOUT: NUMBERS SLIGHTLY MASKED
4.6 Summary

A new method, which can be applied to generate periodical updates of the baseline time traces corresponding to the current EOC, is presented in this chapter. The proposed method is based on very accurate measurements of the displacement/velocity fields near the transducer and high-fidelity transient numerical simulations. This method is capable of overcoming the main limiting factor identified in the Literature Review, which restricts the application of SHM systems in the real-world environment. This is the effect of changing the EOCs on the baseline time trace.

This chapter also describes the outcomes of the validation and mesh convergence studies for a simple geometry, as well as the feasibility study of the virtual implementation of this method to reconstruct the baseline time trace. It was demonstrated that it is possible to reconstruct the baseline time trace for the fundamental anti-symmetric and symmetric modes accurately if the size of the area within the prescribed boundary conditions exceeds half of the wavelength of the excited wave. This is an important result as the experimental and computational time are largely dependent on the number of measurement points, as well as on the FE mesh density. In practice, these two parameters have to be selected such that they do not compromise the accuracy of the numerical reconstruction whilst still providing reasonable computational time.
Further experimental studies will utilise the ratio $a = 1/2$ to demonstrate damage detection and temperature compensation. It has been demonstrated that this value, together with the specified mesh density (20 nodes per wavelength), provides sufficient accuracy for the numerical reconstruction of the baseline time trace. However, there are no conceptual difficulties to exploring the required or optimum mesh density and mesh sizes for any particular case. The next two chapters will demonstrate the application of this method to the detection of structural damage under changing EOCs.
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References


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Chapter 5

Reconstruction of Baseline Time Trace and Damage Detection in Isotropic Plates and Beams
5.1 Introduction

This chapter describes several applications of the proposed method for reconstruction of the baseline time trace and detection of damage in isotropic structural components subjected to temperature variations. In the opening section, the experimental set up is briefly described. The complete description of the experimental equipment for the characterisation of guided wave propagation and scattering has already been provided in Chapters 3 and 4. The details of the numerical approach were also presented in Chapter 4. Therefore, these two main elements of the proposed method are only briefly outlined in the current chapter, for the reader’s convenience.

In the following sections of this chapter, the proposed method will be applied to generate the baseline time trace in isotropic beams and plates. The numerically reconstructed baseline time trace will be also utilised for damage detection using the common subtraction approach, as described in the literature review (Chapter 2). The main purpose of this chapter is to demonstrate that the experimental data obtained from 3D SLV can be merged with high fidelity FE simulations to generate an accurate baseline time trace, which corresponds to the current EOCs. Therefore, this method is capable of compensating for the effect of changes in EOCs and, in particular, variations in the ambient temperature and bonding conditions of the PZT. For the work presented in this chapter, the methodology has been applied to relatively simple structures only, however, apart from the
additional amount of computational time and effort needed to develop an accurate FE model of the structure, it should be possible to implement this method for structures of more complex geometries and situations.

5.2 Details of the Experimental Set up and Specimens

The experimental arrangements are shown in Figure 5.1. The specimens for the experimental studies include a 3 mm thick square plate 500 mm by 500 mm, (see Figure 5.1(a)) and a beam of 3 mm × 12 mm cross-section and 300 mm long, (see Figure 5.1(b)). Both specimens were cut from the same bulk plate made of aluminium alloy (as delivered).

![Figure 5.1: Experimental rig with mounted (a) plate and (b) beam specimens.](image)

In order to generate the guided wave in the plate specimen, a disk-shaped PZT of 10 mm in diameter and 2 mm in thickness with a backing mass of the same size with 3 mm in thickness made of brass was glued onto
the surface in the centre of the plate (see Figure 5.1(a)). A rectangular-shaped PZT of in-plane dimensions 12 mm by 6 mm and 2 mm thick, with a brass backing mass of the same size but 3 mm in thickness was glued onto the surface of one end of the beam specimen. As mentioned previously, the backing masses are used to maximise the $A_0$ mode excitation of the Lamb waves which provides certain advantages, as discussed previously. In particular, this mode has the longest wavelength. As a result, considerably fewer elements had to be used in the numerical model to reconstruct the baseline time traces. This leads to a significant reduction in the computational time, which is currently one of the main technical restrictions of the proposed method. This restriction will eventually be overcome with a further increase in computer power, along with the development of more effective numerical approaches to simulate wave phenomena.

The experimental equipment includes a signal amplifier, 3D SLV and a built–in signal generator. A five-cycle sinusoidal tone burst, modulated by a Hanning window based on Equations (4.5)-(4.6), at frequencies between 100 and 300 kHz, was generated using a built-in signal generator and amplified using a standard power amplifier, as described in Chapter 4. This amplified signal was then applied to the transducer (PZT) mounted on the surface of the beam or plate specimen. The signal was typically excited and recorded 200 times for each set of experimental parameters, averaged and filtered to remove noise and systematic errors.
The interval between consecutive signals was around 9 ms, which is sufficient to avoid the interference between the subsequent signals and responses. The data recording and signal generation stages were synchronized accurately and controlled by the SLV computer. The measurements were taken with the PSV-400 SLV with a sampling frequency of 2.5 MHz, as described in Chapter 3.

With laser vibrometry, the best signal to noise ratio (SNR) would in theory be obtained for a highly polished surface. However, this only works for near-normal scanning angles, which are unachievable with 3D scanning laser systems, given that in order to resolve the measured velocities in three orthogonal components, none of the beams are ever normal to the surface. A rough or painted surface provides a more spatially uniform diffusive optical backscattered field compared with a polished surface, which gives a more consistent SNR over the scanned surface. In the current work, an Ardrox spray was used, which was applied to the surface of the specimens to achieve a better SNR (see Figure 5.1).
5.3 Reconstruction of Baseline Time Trace for a Beam

Initially, for the isotropic beam specimen, the measurements were conducted for one single central row of the mesh points on the top and bottom of the beam located in the middle of the scanning area, as shown in Figure 5.2.

Figure 5.2: Experimental implementation of the proposed method for a 2D isotropic beam.
Figure 5.3: Comparison between the results of the physical and modelling spaces (Model 1 and Model 2) for the out-of-plane displacements, $\bar{U}_z$ for $f = 200$ kHz, for (a) one row and (b) three rows of measurement points.

The experimental results (time traces at Point P, see Figure 5.2) have been compared with the results obtained from the numerical simulations using the proposed method, as described in the previous chapter (Chapter 4). Large discrepancies can be observed, see Figure 5.3 (a), between the actual and reconstructed baseline time traces. These discrepancies between the modelling and experimental results are attributed to the effect of wave
reflection from the beam edges, indicating that the wave propagation along
the beam is essentially a 3D process. The difference in the out-of-plane
displacements at three different points across the beam specimen (the
locations of the points were shown in Figure 5.2), $U_z$, can be observed in
Figure 5.4. The deformation pattern is not symmetrical, indicating the
existence of wave modes traveling between the beam edges.

![Graph showing displacement signals for three points](image)

Figure 5.4: Sample displacement signals for three different points across the
width of the beam for $f = 200$ kHz.

In order to increase the accuracy of the method, several rows of
measurement points across the width of the specimen were considered to
achieve a reasonable accuracy of the reconstructed signal. As an example, Figure 5.3 (b) shows the comparison of the actual $U_z^{(a)}(t,P)$ displacement recorded by the SLV with the displacement, $U_z^{(r)}(t,P)$, obtained from the corresponding FE model, in the case of three rows of measurement points across the beam width, exactly as shown in Figure 5.2.

Figure 5.5: The subtracted signal between the measured and reconstructed baseline time traces of the out-of-plane displacement, $\bar{U}_z$ demonstrating the error associated with the numerical reconstruction.

As can be seen from Figure 5.3 (b), the difference between the reconstructed and actual baseline time trace is reduced substantially, and can be further decreased with the application of a higher mesh density, reduction of the time step and improvement of the accuracy of the measurements with
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3D SLV. The algebraic subtraction of the two signals is shown in Figure 5.5, which essentially represents the noise associated with the numerical procedure. It is clear that for practical applications of the proposed method in damage detection applications, the amplitude of this noise, which represents the error associated with the reconstruction method, must be much smaller than the threshold signal adopted for the particular structure and the targeted damage. The threshold signal can be obtained from experimental or numerical studies, using the range of defects.

5.4 An Example of Damage Detection in Beams

This section provides a description of the application of the developed method to damage detection in a simple beam specimen. A half-cylindrical volume was milled at the free surface of the beam at a distance of 100 mm from the PZT (source). The cross sectional dimensions of the milled volume are $2 \times 1 \times 12$ mm$^3$, as illustrated in Figure 5.6.

![Figure 5.6: Schematic of the isotropic beam specimen with the introduced damage.](image-url)
Figure 5.7: Reconstructed baseline time trace (with the proposed method) and the actual signal of the out-of-plane displacement, $\bar{U}_z$ for a damaged structure at a tone burst frequency of $f = 200$ kHz.

Figure 5.7 shows the reconstructed baseline time trace for the defect-free structure (beam), based on the proposed method, as well as the signal recorded by the SLV for the fabricated damaged beam at the central tone burst frequency of 200 kHz. In Figure 5.8, the comparison of the subtracted signal and the error signal is provided. The amplitude of the error signal is of an order of magnitude lower than the amplitude of the subtracted signal. This confirms that the proposed method is capable of detecting this type and severity of structural damage. Despite the damage representing a single fault type, it is believed that similar results can be obtained for other types and severity of damage. However, every case should be analysed separately and
only general guidelines can be drawn from the conducted experimental and numerical tests.

![Residual time trace (subtracted signal) and Numerical error for the reconstructed baseline time trace](image)

Figure 5.8: Comparison of the subtracted signal of the damaged structure with a reconstructed baseline and error associated with the proposed method (the difference between the actual and reconstructed baseline time traces) for the out-of-plane displacement $\bar{U}_z$ at $f=200$ kHz.

### 5.5 Reconstruction of the Baseline Time Trace under Changing Temperatures

Figure 5.9 presents a schematic drawing comparing the experimental arrangements for the plate specimen. Two remote points, $P_1$ and $P_2$, are located at a distance of 100 mm from the PZT, equipped with a backing mass, as described in the beginning of this chapter. The scanning area
represents two rings of 5 mm width and 50 mm radius made on both sides of the plate.

Figure 5.9: Experimental implementation of the proposed method for an isotropic plate with damage (here, a blind hole).

A cylindrical blind hole with a radius of 5 mm and a depth of 1.5 mm was milled at a distance of 75 mm from the PZT to simulate structural damage, for example, due to corrosion or impact.

The time trace at point $P_1$ is used to compare the actual baseline time trace (for the free-from-damage plate) with the reconstructed one, as obtained from the numerical simulations in accordance with the proposed method. The residual time trace at point $P_2$ is used for testing the method’s ability to detect damage. The distance between the blind hole and $P_1$ (175
mm) is sufficient to avoid the influence of the discontinuity (blind hole) and the free plate boundaries on the baseline time trace recorded at $P_1$, within a sufficiently short time window.

The method is applied to demonstrate that it can also compensate for the ambient temperature variations. The required heating was introduced by using a heat gun. The uniformity of the temperature field was monitored at three discrete locations: near the centre of the plate, and at the measurement points $P_1$ and $P_2$. The temperature is assumed to be constant over the measured path and during the wave excitation.

Baseline time traces are collected for a set of equally spaced frequencies, covering a bandwidth of 100 – 300 kHz under two different temperatures. Figure 5.10 shows an example of the effect of temperature on the baseline time trace of the normalised out-of-plane displacements $\bar{U}_z$ at point $P_1$ for 20$^\circ$C and 60$^\circ$C.
Figure 5.10: Normalised out-of-plane ($\bar{U}_z$) baseline time traces at 20°C and 60°C, as recorded with SLV for point P$_1$ (see Figure 5.9) at $f=200$ kHz.

The in-plane displacement components ($U_x$ and $U_y$) have much lower magnitudes when compared with the out-of-plane components as a result of the dominance of the anti-symmetric mode, $A_0$, excitation, which largely involves the out-of-plane components of the displacement and velocity fields, as mentioned in Chapter 3. From Figure 5.10, it can be observed that the combined changes of the properties of the material, PZT and bonding due to the rise in temperature lead to a lower group velocity, and therefore stretching of the time trace. These effects are in agreement with the previous studies mentioned in the literature review (Chapter 2). All the components of the velocity field over the scanning area are averaged, filtered and conditioned for use in the numerical reconstruction of the baseline time trace.
The previous extensive numerical investigations provided a set of parameters, which can be utilised to reconstruct the baseline time trace numerically. The parameters represent a compromise between the required accuracy and the complexity of the modelling. The structural features, type of targeted damage, excited mode and the frequency of the guided wave characteristics utilised for damage detection, can significantly affect these parameters. It is impossible to provide a definite investigation of all these effects due to their broad diversity. Thus, the main purpose of the present study is to demonstrate the possibility of the reconstruction of the baseline time trace and damage detection under changing EOCs for selected structures and several types of damage.

For the reconstruction of the baseline time trace, a 3D finite element model, representing an isotropic homogeneous plate with the same dimensions as the physical plate specimen, was developed using the ANSYS 15.0 software package. The FE model utilises a 3D hexahedral type of element with hourglass control, with a characteristic size of 0.5 mm × 0.5 mm × 0.5 mm. The mesh density corresponds to 20 nodes per wavelength and six elements across the thickness of the plate, which was found to be sufficient in the previous numerical simulations. Each node of the hexahedral element has three displacement degrees of freedom. The finite element mesh was constructed to align the measurement grid with the corresponding surface nodes of the FE mesh (see Figure 5.11).
Figure 5.11: A view of the mesh used in the FE simulations, showing the mesh for the dummy volume and across the thickness of the aluminium plate.

The boundary-value transient problem was analysed with the AutoDyne solver. The elastic properties were calculated from the dispersion equation for both temperatures (20°C and 60°C), using the approach described in Chapter 4. Poisson’s ratio was set at 0.3. The time step was automatically controlled by ANSYS/AutoDyne. A typical snap-shot of the transient displacement field is shown in Figure 5.12.
Figure 5.12: Typical snapshot of FE simulations, showing the dummy volume and prescribed boundary condition area for the aluminium plate and a centre frequency of $f = 200$ kHz.

Figures 5.13 (a) and (b) provide a comparison of the baseline time traces as obtained from the experimental data (the out-of-plane displacements measured by the 3D SLV) and numerical simulations, respectively, at two temperatures and with the central frequency of the tone burst at 200 kHz. A very good agreement can be observed, specifically for the shape of the signal. Small discrepancies between the experimental and numerically reconstructed traces are attributed to unavoidable simplifications and assumptions associated with the development of any FE
model, as well as with any numerical errors due to discretisation and the approximate nature of the numerical calculations.

Figure 5.13: Comparison of the normalised out-of-plane baseline time traces as obtained from the experiments (solid line) and numerical simulations (dotted line) for two temperatures (a) $T = 20\,^\circ$C and (b) $T = 60\,^\circ$C, at $f = 200$ kHz.

Figure 5.14 shows a comparison of the error associated with the numerical reconstruction of the baseline time trace (solid line) and subtraction of the two baseline time traces corresponding to the different
temperatures. This comparison clearly indicates that disregarding the changing temperature can easily mask damage. The subtraction of two baseline time traces at different temperatures results in a residual time trace with even larger amplitude than the amplitudes of the baseline time traces.

Figure 5.14: Error associated with the numerical reconstruction of the baseline time trace (solid line) and subtraction of two baseline time traces of the normalised out-of-plane displacement, $\bar{U}_z$ at different temperatures, $T = 20^\circ\text{C}$ and $T = 60^\circ\text{C}$ (dotted line).

In addition, Figure 5.14 confirms that, with the proposed method, the relative error associated with the numerical reconstruction of the time traces is reasonably small. This allows for the application of the proposed method for damage detection. In practical damage detection, this error can be linked to the threshold level of the residual time trace, which indicates the presence of critical damage.
5.6 Damage Detection in Isotropic Plates

This section describes the outcomes of the application of the developed method for the detection of damage in isotropic plates. As previously mentioned, a cylindrical blind hole with a radius of 5 mm and depth of 1.5 mm, representing damage, was located at a distance of 75 mm from the PZT. Figure 5.15 shows a time trace at point, P₂, for various ambient temperatures, which are also affected by the presence of the damage (shown by the dotted line). These time traces, as previously discussed, were recorded with a 3D SLV, filtered and then conditioned to remove stochastic noise and systematic errors. In the same Figure, the baseline time traces are reconstructed numerically in accordance with the proposed method. The differences in the time traces, primarily in the shape of the signals, can be seen clearly.
Figure 5.15: Time traces of $\bar{U}_z$ corresponding to point, $P_2$ at the central frequency of a tone burst of $f = 200$ kHz and ambient temperatures (a) $T = 20^\circ C$ and (b) $T = 60^\circ C$.

The subtraction of the two time traces (the damage signature or residual time trace and the baseline time trace) is shown in Figure 5.16, together with the typical error associated with the numerical reconstruction of the baseline time trace. It can be seen from this Figure that the magnitude
of the signal associated with the numerical error is significantly less than the residual time trace.

Figure 5.16: The residual time trace and the numerical error in the reconstruction of the normalised out-of-plane displacements baseline time traces of $\bar{u}_z$ at $f = 200$ kHz and temperatures of (a) $T = 20 \degree C$ and (b) $T = 60 \degree C$. 
The study that has been conducted allows the researcher to draw the conclusion that the considered damage can be detected reliably with this method and it avoids the need for any additional compensation for changing temperature conditions. The obtained results also suggest that the governing parameters of the method were selected appropriately and there is no need for further refinement of the FE or measurement mesh in order to improve the accuracy of the baseline time trace reconstruction.

5.7 The Effect of Plate Boundaries on the Reconstruction of Baseline Time Traces

This section presents the outcomes of the implementation of the proposed method to the reconstruction of the baseline time trace in the case of wave scattering from the free boundaries of a plate specimen. The experimental set up is shown in Figure 5.17. The test specimen represents a thin plate of 230×175×1 mm³ made of an aluminium alloy. The rest of the experimental equipment is the same as in the previous sections. The measurement procedures were also described in the previous chapters and will not be repeated here.
Figure 5.17: Experimental set up showing the three laser heads of the SLV, focused on the thin aluminium plate.

Figure 5.18: Measurement grid and time snapshots of the out-of-plane displacement $U_z$ at $f=200$ kHz. Snapshots after 44.14 µsec show the effect of the free boundaries on the displacement field at the selected remote area.

To investigate the effect of wave scattering from the free boundaries on the time traces at remote locations, the measurements were carried out...
using the grid, as shown in Figure 5.18. This Figure also shows different time snapshots of the out-of-plane displacements. From these snapshots, the effect of scattering from the free boundaries can be observed after 44.14 µsec from the time of the signal excitation. This corresponds to the $A_0$ wave arrival time, after reflection from the free boundary.

The scanning area for the numerical reconstruction of the baseline time trace is shown in Figure 5.19. The recorded transient velocity components (the out-of-plane, $V_z(t)$, and in-plane, $V_x(t)$ and $V_y(t)$) were then utilised in the corresponding FE model as input data, in accordance with the proposed method. The comparison of the numerically reconstructed baseline time trace and the experimental measurements is shown in Figure 5.20. The accuracy was very good and can be further improved by reducing the mesh size and time step and increasing the number of the scanning points. It is impossible to provide a definitive study which investigates the effect of all these parameters on the accuracy of the reconstruction due to the large variety of possible combinations. Therefore, the current investigation utilises case studies to demonstrate the features and capabilities of the method under development.
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Figure 5.19: Measurement grid for the reconstruction of the baseline time trace at the point “P”.

Figure 5.20: Comparison of the normalised out-of-plane baseline time traces of out-of-plane displacements, $\bar{U}_z$ as obtained from the experiments (solid line) and numerical simulations (dotted line) at point “P” (see Figure 5.19) for a tone burst with a frequency of $f = 100$ kHz.
By comparing Figure 5.20 with Figures 5.3 and 5.13, it can be confirmed that the shape of the baseline time trace has been changed due to the presence of scattering from the boundaries. This scattering from the boundaries has been marked on the Figure. The method was reported as successful in reconstructing the baseline time trace in the presence of scattering from the boundaries.

### 5.8 Summary

Several applications of the new method in reconstructing the baseline time trace and compensating for the effects of temperature variation on damage detection using guided waves in isotropic structural components are presented in this chapter. The proposed method, as previously described in Chapter 4, is based on the application of 3D scanning laser vibrometry measurements in conjunction with explicit high-fidelity FE simulations of guided wave propagations in a defect-free structure. This method can help to overcome the current difficulties associated with the necessity to compensate for the uncontrolled factors affecting the baseline time trace, such as temperature or humidity variations, and PZT debonding or material degradation. In this chapter, in particular, it was demonstrated that the baseline time trace can be generated based on the measurements of the 3D velocity/displacement points near the PZT and applying these fields to the 3D transient FE model, which represents a defect-free structure.
In general, the accuracy of the reconstructed baseline time trace or, essentially, the complexity of the FE model, density of the measurement points and the accuracy of the measurements, have to be selected based on the magnitude of the residual time trace threshold accepted as the indication of damage in accordance with the common subtraction approach. The time trace residual magnitude depends on the particular application of SHM and the type of damage, as discussed above. Therefore, the selection of parameters such as the time step in a numerical simulation, or the density of the measurement points and the FE mesh, requires extensive preliminary numerical simulations, as well as experimental studies, in order to verify that the accuracy of the reconstructed baseline time trace is sufficient to detect any critical damage. However, once the level of accuracy is determined, the method can be applied routinely to similar structures working under changing EOCs. It is expected that, unlike many other techniques developed previously, the current method is capable of compensating for the variation of several EOCs.

The method avoids the need to model the PZT response, which can be very complex and affected by various EOCs. Another important aspect of the method is that the accuracy of the generation of the reconstructed baseline time trace can be controlled by selecting the appropriate mesh, measurement grid density and time step. It was confirmed through experiments that the method is capable of taking into account EOCs;
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specifically, temperature variation (which is the focus of the current chapter) as well as the changes in the material properties and PZT.

It is recognised that the utilisation of a 3D measurement system and transient FE simulations can significantly increase the cost of damage detection procedures. However, it is believed that with advances in computer and laser technologies, the cost-efficiency can be significantly improved, and, in the future, the method can find a wide application in many industries and scenarios. Currently, this method can be used for damage detection in hard-to-reach locations or for periodic updating of baseline time traces in the case of changing EOCs.
Chapter 6

Detection of Delamination in Composites
6.1 Introduction

This chapter focuses on the application of the proposed method to anisotropic materials and, specifically, on the detection of delamination damage in laminates. It is well-known that delamination is one of the most common forms of structural damage in fibre-reinforced composites. Delamination is easy to initiate due to a relatively low transverse inter-laminar strength and fracture toughness [1]. In practice, delamination damage can be introduced during manufacture, transportation, maintenance or operation. For example, delamination defects may occur due to improper lamination procedures or curing processes, or may be introduced when machining the components for fastener holes and cut-outs. Low speed impact is another common cause of delamination damage, which is often experienced by aerospace composite components. Delamination can lead to a loss of stiffness which can cause buckling and loss of strength. Delamination can also grow under fatigue loading, leading to catastrophic failures, similar to those found in metallic components. Lack of knowledge of the fatigue properties of composites is one of the main limiting factors of their wide and more efficient use in industry.

This chapter describes practical examples of the compensation of the effect of changing ambient temperatures on damage detection, which was carried out with the subtraction approach as well as by comparing the actual signal with the baseline time trace recorded for the damage-free structure.
The main aim of this work is to demonstrate that the proposed method works for a material which is highly anisotropic, and has a response that is very sensitive to temperature fluctuations.

### 6.2 The Details of the Experimental Set-up for Composites

The experimental set-ups are shown in Figure 6.1, which are very similar to the experiment arrangements used previously in Chapters 3 and 5.

![Experimental setups for (a) the CFRP beam and (b) the CFRP plate.](image)

The specimens employed in the current experimental studies represent an 8-ply carbon fibre reinforced composite (CFRP) beam, with dimensions of $285 \times 12 \times 2 \text{ mm}^3$ [0/90/0/90]s, with an artificially created subsurface delamination located between the 3rd and 4th layer, and an 8-ply CFRP composite plate with dimensions of $600 \times 600 \times 1.6 \text{ mm}^3$ [45/-
45/0/90]s, with a circular delamination spot of 11 mm in diameter located between the 4th and 5th lamina. Cycom® fabricated the specimens. The fabrication process utilised a Teflon film to create the artificial delaminations.

For the GW excitation in the beam, a rectangular-shaped PZT of 12 × 6 × 2 mm³ in dimension with a backing mass of the same size but 3 mm in thickness, made of brass, was glued onto the surface of one end of the beam specimen. Again, the backing masses were used to maximise the excitation of the A₀ mode guided wave (Figure 6.2(a)). For the Lamb wave generation in the plate sample, a disk-shaped PZT of 10 mm in diameter and 3 mm in thickness, with a backing mass of the same size, made of brass, was glued onto the surface in the centre of the plate, see Figure 6.2(b). The rest of the set-up is exactly as described in Section 5.2.

Figure 6.2: The location of the PZT and the measurement grids for the numerical reconstruction of the baseline time traces with the proposed method: (a) the CFRP beam and (b) the CFRP plate.
As described in the Literature Review (Chapter 2), the $A_0$ mode was preferable for the detection of delamination damage as it involves out-of-plane displacements, which are affected by the delamination (because of the change in bending stiffness). This type of damage does not affect the extensional stiffness which means that the $S_0$ would be largely unaffected.

### 6.3 The effect of temperature variations on the baseline time trace for composites

To demonstrate the strong effect of the ambient temperature changes on the baseline time–traces and the need to compensate for this effect in damage detection, the CFRP composite components were tested at various central frequencies of the tone burst, covering a bandwidth of 100–300 kHz and at three different temperatures.
Figure 6.3: Out-of-plane displacement ($U_z$) baseline time traces at 20°C, 25°C and 30°C, as recorded with the SLV for point P_1 (see Figure 6.5) at $f = 200$ kHz.

Figure 6.3 shows an example of the temperature effect on the time trace of the out-of-plane displacements $U_z$ recorded at 120 mm away from the PZT for different temperatures (20°C, 25°C and 30°C) at a 200 kHz excitation frequency. Similar results were obtained at other frequencies. Other displacement components ($U_x$ and $U_y$) normally have a much lower magnitude as a result of the predominantly anti-symmetric mode, $A_0$, excitation, which, as highlighted above, largely involves only the out-of-plane components of displacement and velocities.

From Figure 6.3 it is easy to observe that the combined changes of the material properties of the CFRP composite components, transducer and
bonding due to the temperature increase, leads to a lower group velocity and, generally, stretching of the time trace which is consistent with previous research. It is also apparent that the composite components are much more sensitive to temperature variations when compared with aluminium (or generally metallic materials), as investigated in Chapter 5. In addition, the obtained results suggest that even a small temperature fluctuation of the order of 5°C can affect the baseline time-trace significantly, and potentially lead to a false alarm if no temperature compensation is used. Therefore, some kind of temperature compensation for composite structures is critical. The above conclusions are in general agreement with the previous studies outlined in Chapter 1 (Introduction).

6.4 Identification of Material Properties

The application of the proposed approach requires the identification of material properties, which is not as simple as in the case of isotropic structural components, (see Chapter 5). Below, a general procedure will be described and applied to the composite specimens considered in this study.

Composites generally have many advantages such as being lightweight and having better specific strength and stiffness than conventional structural materials such as metals. The anisotropic nature of composites makes them more attractive for the optimisation of structural performance and weight reduction [2], specifically in the aerospace
industry. Recently the role of glass and carbon fiber reinforced plastic (GFRP and CFRP) composite materials has been increased dramatically in aerospace applications. Therefore, these materials are often the main focus of the development of effective non-destructive testing methods and structural health monitoring systems.

In order to utilize the advantages of composites in the design process, the characterisation of the material properties is essential. Generally, an anisotropic material has 21 independent elastic constants. However, in many particular cases, the number of the independent elastic constants can be reduced, based on symmetry considerations. For example, orthotropic materials can be fully described with 9 independent elastic constants, while a transversely isotropic composite requires only 5 elastic constants in the stiffness and compliance matrices [3].

Generally, there are two types of methods for the determination of elastic constants of anisotropic homogeneous materials; direct (destructive) and indirect (non-destructive). The direct methods use conventional mechanical testing to determine the material properties, which are based on mechanical testing of samples cut from the bulk material or structure in various orientations [3]. The indirect (non-destructive) methods often utilise vibration or wave propagation tests and the subsequent analytical or numerical analysis of the test results. From this analysis, the elastic constants are found, normally using some sort of optimisation procedure.
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This type of method is less accurate. However, for the purpose of the current work, it is the only way to implement the suggested method to practical applications.

Numerous studies have been devoted to the development of indirect methods [3-7]. For example, anisotropic elastic properties can be found from a bending test with strain gauge measurements, as reported by Barchan and Chatys [8]. In another study [4] an inverse procedure using genetic algorithm (GA) and finite element analysis (FEA) was applied. This procedure is based on static bending loading of an arbitrary-shaped orthotropic plate specimen. Vibration testing methods using natural frequencies and torsional vibrations in conjunction with an accurate FEA and optimisation algorithm are presented in [9], [10] and [11].

Another large group of indirect methods is based on the analysis of wave propagation phenomena e.g., Karabutov et al. [12], Wu and Liu [13] and Dahmen et al. [14]. Among this group, methods based on GW became very common. This popularity is due to the rapid advances in signal processing of GWs and the development of numerical algorithms of the simulation of GWs propagation in plate and shell components [5]. Methods using GWs are usually based on achieving the best correlation between the experimental dispersion curves for group or phase velocities and the theoretical equations through the variation of the independent elastic constants in these equations [5, 7, 15, 16].
In this chapter, the Nelder–Mead simplex method [3] was employed to derive the elastic constants of the composite samples, which were needed to implement the proposed method. In this work, the composite laminates were treated as homogeneous orthotropic materials. The system of coordinates was selected along the principal planes of material symmetry (Figure 6.4).

![Figure 6.4. Schematic of an orthotropic plate showing both geometry and axes.](image)

The stress–strain relationships for an orthotropic material are given by [3] and can be written using the following compliance matrix:

\[
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3 \\
\tau_4 \\
\tau_5 \\
\tau_6
\end{bmatrix} =
\begin{bmatrix}
C_{11} & \cdots & C_{16} \\
\vdots & \ddots & \vdots \\
C_{61} & \cdots & C_{66}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\varepsilon_3 \\
\gamma_4 \\
\gamma_5 \\
\gamma_6
\end{bmatrix}.
\]

or using the stiffness matrix:
The stiffness matrix \([C]\) and the compliance matrix \([S]\) are symmetrical and mutually inverse:

\[
[C] = [S]^{-1}.
\] (6.3)

The elastic constants in the compliance matrix are given by [3]:

\[
[S] = \begin{bmatrix}
\frac{1}{E_1} & -\frac{\nu_{21}}{E_2} & -\frac{\nu_{31}}{E_3} \\
-\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & -\frac{\nu_{32}}{E_3} \\
-\frac{\nu_{13}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{E_3}
\end{bmatrix}
\] (6.4)

where \(E_i, G_{ij}\) and \(\nu_{ij}\) are Young’s moduli, the shear moduli and Poisson’s ratios, respectively. The values of the independent elastic constants are subjected to certain thermodynamics constraints, following from the condition that the sum of the virtual work done by all stresses must be positive in order to avoid contradiction with the second law of
thermodynamics [2]. Based on these thermodynamics constraints, the stiffness matrix and the compliance matrix have to be positive definite.

The dispersion equations of Lamb waves for an orthotropic plate in direction 1 (Figure 6.4) are obtained from the linear equation of motion in an elastic material. This dispersion equation for the symmetrical mode can be written as:

\[
(C_{33} R_- k_x - C_{13} k_x)(R_+ k_x + k_z) \sin(k_z h) \cos(k_z h) \\
- (C_{33} R_+ k_z \pm k_x) \sin(k_z h) \cos(k_z h) = 0,
\]

(6.5)

and for the anti-symmetric mode as:

\[
(C_{33} R_+ k_x + C_{13} k_x)(R_- k_x + k_z) \sin(k_z h) \cos(k_z h) \\
- (C_{33} R_- k_z \pm k_x) \sin(k_z h) \cos(k_z h) = 0,
\]

(6.6)

where \( h \) is the half-thickness of the plate and:

\[
R_\pm = \frac{\rho \omega^2 - C_{11} k_x^2 - C_{55} k_z^2 \mp \sqrt{M^2 - 4N}}{(C_{55} + C_{13}) k_x k_z},
\]

(6.7)

\[
k_z^2 = \frac{M \pm \sqrt{M^2 - 4N}}{2} k_x^2,
\]

(6.8)

with:
M = \frac{c_{11}c_{33} - 2c_{55}c_{13} - c_{13}^2 - \rho \omega^2 (c_{33} + c_{55})}{k_x^2 c_{33} c_{55}} \quad (6.9)

N = \frac{\rho^2 \left( \frac{\omega^2}{k_x^2} - \frac{c_{11}}{\rho} \right) \left( \frac{\omega^2}{k_x^2} - \frac{c_{55}}{\rho} \right)}{c_{33} c_{55}} \quad (6.10)

Here, $k_x$ and $k_z$ are the wavenumbers in directions 1 and 3, respectively, and $\omega = 2\pi f$ is the angular frequency of the excitation. Dispersion equations for direction 2 can also be written in a similar form to Equations (6.5) - (6.10), but in the stiffness matrix, the indices for directions 1 and 2 must be switched.

The current study uses the fundamental Lamb wave mode $A_0$. The dispersion curves were obtained, based on the experimental procedure described in the previous chapter. As mentioned before, in order to determine the elastic constants from the experimental data, an optimization algorithm has to be applied. In the current work, an unconstrained nonlinear optimization was adopted, which is facilitated by the MATLAB built-in optimisation algorithm. This algorithm is based on the Nelder–Mead simplex method [17]. The optimisation procedure essentially attempts to find the minimum of a function with a number of independent variables, starting with an initial estimate. The scalar optimisation function is defined as:
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\[ F = \sum_{i=1}^{4} \left[ \frac{1}{n} \sum_{j=1}^{n} \left( \frac{(C_{p,i,\hat{j}}^g - C_{p,i,\hat{j}}^m)^2}{k_{i,j}} \right) \right] \]  

(6.11)

where \( i \) stands for various dispersion curves (\( A_0 \) in directions 1 and 2); \( j \) means the current measured point on a curve; \( n \) is the total number of measured points in a curve; \( C_{p,i,\hat{j}}^g \) and \( C_{p,i,\hat{j}}^m \) represent the guessed and measured phase velocities, respectively; \( k_{i,j} \) is the weight of a point. Based on the above-described procedure, the unknown variables, which were the elastic constants of the composite, can be identified. These elastic properties for the composite plate with a density of 1517 kg m\(^{-3}\) and a beam with a density of 1538 kg m\(^{-3}\) used in the current study are given in Table 6.1.

Table 6.1: The elastic properties of the CFRP composite beam and plate.

<table>
<thead>
<tr>
<th></th>
<th>( E_{11} ) (GPa)</th>
<th>( E_{22} ) (GPa)</th>
<th>( E_{33} ) (GPa)</th>
<th>( G_{12} ) (GPa)</th>
<th>( G_{13} ) (GPa)</th>
<th>( G_{23} ) (GPa)</th>
<th>( \nu_{12} )</th>
<th>( \nu_{13} )</th>
<th>( \nu_{23} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRP Beam</td>
<td>120</td>
<td>7.46</td>
<td>7.46</td>
<td>3.94</td>
<td>3.94</td>
<td>2.30</td>
<td>0.32</td>
<td>0.32</td>
<td>0.32</td>
</tr>
<tr>
<td>CFRP Plate</td>
<td>128.8</td>
<td>8.35</td>
<td>8.35</td>
<td>4.47</td>
<td>4.47</td>
<td>2.90</td>
<td>0.33</td>
<td>0.33</td>
<td>0.44</td>
</tr>
</tbody>
</table>
6.5 Reconstruction of Baseline Time Trace for CFRP Composites

A 3D Finite Element method was used to reconstruct the baseline time trace numerically using the ABAQUS/Explicit software package for the composite plate and beam, with the same dimensions as in the experimental study. The finite element model of the composite plate contains a circular dummy area in the middle of the plate, which allows disregard the PZT. The FE model utilised a 3D eight-node brick element of $0.5 \times 0.5 \times 0.2$ mm$^3$. The mesh density was sufficient to guarantee at least ten nodes per wavelength of the tone burst. Each node of the element has three displacement degrees of freedom. Similar to the previous study, the finite element mesh was constructed to align the measurement grid of the SLV with the corresponding surface nodes of the FE mesh.

The time traces of the physical measurements with the SLV were used as boundary conditions for the developed FE model. The ABAQUS/Explicit software automatically controlled the time step. A typical snap-shot of the transient displacement field for the plate sample is shown in Figure 6.5.
Figure 6.5: Time snap-shot of FE simulations showing the dummy volume and prescribed boundary condition area for the 8-ply CFRP composite and $f = 200$ kHz centre frequency.

In the beginning, the obtained experimental time traces for the plate (see Figure 6.3) were compared with the outcomes of the numerical simulations using the proposed method, as described in the previous section. For example, Figure 6.6 shows the comparison of the actual $U_z^{(a)}(t, P)$ displacement time trace recorded by SLV with the numerically reconstructed baseline time trace, $U_z^{(r)}(t, P)$, as obtained from the corresponding FE model. In the beam case, the three rows of measurement points across the beam were used, similar to Chapter 5. This is because the wave propagation in beams is affected by transverse traveling modes.
Figure 6.6 shows a comparison of the baseline time traces as obtained from the experimental studies and numerical simulations, respectively, at room temperature (T=20°C) for the central frequency of the tone-burst of 200 kHz. As can be seen from this Figure, the difference between the numerically reconstructed and the actual time trace is very small. It can be further decreased with the application of higher mesh density, reduction of the time step and improvement of the accuracy the measurements with the SLV.

Figure 6.6: Comparison between the results of the physical and modelling spaces (Model 1 and Model 2) for out-of-plane displacement $\bar{u}_Z$ and the 8-ply CFRP composite at $f = 200$ kHz.
The algebraic subtraction of the two baseline time traces is shown in Figure 6.7. It is clear that for the application of the proposed method in damage detection techniques for composites, the amplitude of this signal, which essentially represents the error associated with the reconstruction method, has to be much smaller than the threshold signal adopted for the particular structure and type of the damage. In addition, Figure 6.7 confirms that, with the proposed method, the relative error of the numerical reconstruction of the time traces is quite small, which allows for the application of this method for the detection of delamination damage. As highlighted in Chapter 5, in practical damage detection this error can be linked to the threshold level of the residual time trace, which indicates the presence of critical damage.

Figure 6.7: Subtracted signal between the measured and reconstructed baseline signals of the out-of-plane displacement $\bar{U}_Z$, demonstrating the error associated with the method.
6.6 Detection of Delamination under Changing Temperature Conditions

This section describes the application of the developed method for the detection of delamination damage in a CFRP composite plate.

Figure 6.8: Schematic implementation of the proposed method for the 8-ply CFRP composite plate with the delamination for $f=200$ kHz.

Figure 6.8 shows a schematic drawing of the experimental arrangement. Two measurement points, $P_1$ and $P_2$, were located at a distance of 160 mm from the actuator (PZT). The scanning area represents two rings on both sides of the plate of 5 mm width and 50 mm radius. A circular delamination of 11 mm in diameter, was located between the 4$^{th}$ and 5$^{th}$
lamina during the fabrication process for the 8-ply CFRP composite plate with dimensions of $600 \times 600 \times 1.6 \text{ mm}^3$ [45/-45/0/90].

The temperature increase was achieved with a standard heat gun, which was directed to the middle of the plate at a suitable distance. The temperature field was monitored with contact temperature probes at several locations including points $P_1$ and $P_2$. The baseline time traces were recorded for a set of equally spaced frequencies, covering a bandwidth of 100 – 300 kHz and two different temperatures.
Chapter 6: Detection of Delamination in Composites

Figure 6.9: Reconstructed baseline signal (with the proposed method) and the actual signal for a damaged structure for the out-of-plane displacement $\bar{U}_Z$ and $f = 200$ kHz at (a) $T = 20^\circ$C and (b) $T = 30^\circ$C.

The time trace at point $P_1$ was used to compare the actual baseline time trace with that reconstructed from the numerical simulations. The residual time trace at point $P_2$ is used for damage detection with the subtraction approach. The separation between the delamination and $P_1$ (175 mm) was sufficient to avoid the effect of the delamination and free plate boundaries on the baseline time trace recorded at $P_1$ and $P_2$. 
A comparison of the residual time trace of the damaged structure and the error associated with the proposed method at out-of-plane displacement $U_z$ and at $f=200$ kHz and for two diverse temperatures is presented in Figure 6.10. In the absence of damage, the subtracted signal does not exceed the corresponding threshold values (Figure 6.7). However, when the damage was introduced, the subtracted signal exceeds the corresponding threshold values significantly. Therefore, the damage can be reliably identified with the proposed method (Figure 6.10).
Figure 6.10: Comparison of the subtracted signal of the damaged structure with a reconstructed baseline and the error associated with the proposed method (the difference between the actual and reconstructed baseline signals) at out-of-plane displacement $U_z$ and for $f = 200$ kHz at (a) $T = 20^\circ$C and (b) $T = 30^\circ$C.
6.7 Summary

This chapter presented the application of the proposed method to composite components. Defect detection in composites, specifically detection of delamination damage, currently represents a significant problem in engineering, and in the application of new materials. One of the major challenges in SHM systems using GW is compensation for EOCs.

The outcomes of the experimental and numerical studies clearly indicate that the proposed method is capable of compensating for temperature fluctuations when attempting to conduct damage detection using GW for anisotropic materials. It is also clear that the method is capable of compensating for all EOCs on the PZT as it is fully excluded from the simulations. This chapter also describes a procedure for deriving material properties from the characteristics (dispersion curves) of GWs. The fundamental anti-symmetric mode of GW was used due to its high sensitivity to the delamination defects.

A CFRP composite plate and beam specimen were fabricated and utilised in the experiments. In a preliminary study devoted to the influence of temperature variations on the baseline time traces, it was demonstrated that the composite samples were very sensitive to temperature and therefore some sort of temperature compensation is likely to be necessary in real world applications. Examples of the numerical reconstruction of the
baseline time trace were presented for the beam specimen. Good accuracy was achieved. The difference between the experimental and numerical results was very small and can be further decreased with a high-density mesh and smaller time-step.

Finally, the method was applied to detect delamination damage in a plate sample at different temperatures. It has been demonstrated that the method is capable of detecting damage given a temperature variation of 10 degrees. There were no opportunities to investigate more complex geometries or materials as the computational time is quite long. However, it is believed that this will not be a restriction in the future with further increases and developments in computer power and laser technologies. Therefore, this work can be considered as an initial stage in the application of these technologies to an important engineering problem, which is the detection of damage in composites.
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References


Chapter 7

Thesis Summary

and

Future Work
7.1 Overall Outcomes of the Thesis

SHM techniques, which utilise the unique properties of guided waves, provide an effective way to detect damage anywhere in a structure using a sparse array of permanently embedded actuators and sensors. To distinguish damage signatures from the responses generated by structural features, some form of comparison or subtraction with the baseline time traces of a defect-free structure is essential. The detectability of damage can be estimated by the amplitude of the residual time trace remaining after the subtraction of the baseline time trace and the time trace collected during a routine inspection. This is usually non-zero due to changing environmental and operating conditions (EOCs) such as temperature, loading or the degradation of material properties. It is imperative to have a reliable way of compensating for all these changes to an acceptable level before any SHM system can be deployed for practical applications.

The main outcomes of this thesis are a feasibility study, proof of concept and the demonstration of a new method, which is capable of compensating for the effects of changing EOCs on the baseline time traces of defect-free structural components. The method is based on the integration of high-fidelity numerical simulations with 3D scanning laser vibrometry. Therefore, significant effort in Chapter 3 was directed towards the investigation and characterisation of Lamb wave propagation and damage detection with a 3D laser vibrometer, which became available for GW
research only recently. The rest of the chapters are focused on the development of the proposed method.

The feasibility of the method was demonstrated in Chapter 4 with the help of computer simulations. The method was applied virtually to a simple beam structure. Furthermore, this method was emulated on a real beam structure to compensate for the temperature changes, which have a significant impact on the fluctuations in the received signal during damage inspections with GW. The temperature affects the material properties of the structure due to thermal expansion of the structure, alteration of its mechanical properties and temperature-induced changes to the transducers and their bonds.

Practical demonstrations of the reconstruction of the baseline time-trace and damage detection utilised both isotropic and anisotropic plate components. It was shown that temperature variations can be effectively compensated for with the proposed method to a level necessary for the detection of the targeted structural damage. The applicability of this method is not restricted to variations in temperature alone. It is quite general and could easily be extended to compensate for other environmental or operating conditions, which could significantly affect the residual time trace.

All significant results of this work have been published in a number of journals on SHM, including the Journal of Smart Materials and Structures
and the Journal of Structural Control and Health Monitoring. These published or accepted papers also represent one of the main outcomes of the research work. Several other papers are under review.

Finally, the method is original and has great potential for application in future SHM systems. However, it is in the early stage of development and, consequently, in order to realise all the potential benefits, it needs further research, development and applications, specifically for more realistic structures and various types of changing EOCs. The specific outcomes achieved in each chapter of the thesis are summarised below.

### 7.2 Chapter-by-Chapter Summary

Chapter 3 described preliminary research conducted on damage detection and imaging using guided waves. It was focused on the application of 3D SLV for the detection and imaging of various defects in beams and plates using Lamb waves. Distinctive features of the scattered field from typical structural defects were investigated with the purpose of identifying the most effective defect detection strategies. The outcomes of the experimental investigation generally confirmed the results of the previous studies, utilising 1D and 3D laser vibrometry [1-4]. In particular, the research clearly demonstrated the advantages of capturing the full 3D velocity field for the detection, characterisation and sizing of mechanical structural damage in comparison with 1D systems, which were often utilised in previous studies. The present investigation also demonstrated that the use of
the RMS values of various velocity components provides a reliable detection and imaging approach for typical structural defects. The practical outcomes of this chapter include recommendations on the use of various components of the velocity fields for detection of different types of structural damage.

At the beginning of Chapter 4 a detailed description of the new method for the numerical reconstruction of the baseline time trace in the presence of EOC variations was given. For the sake of simplicity, the description utilised two idealisations: modelling and physical spaces. The physical space is where all the required measurements are taken and the modelling space is where the numerical reconstruction of the baseline time trace occurs. Further, in this chapter, a feasibility study and numerical implementation of the method have been conducted. The outcomes of the numerical simulations provided confidence that the method can be applied in practice. The elements identified during the numerical simulations of the parameters of the method were implemented in Chapters 5 and 6.

In Chapter 5, the proposed method was applied to the reconstruction of the baseline time trace and damage detection in isotropic beams and plates. This chapter included full descriptions of the experimental set-up, 3D SLV measurements, data acquisition and conditioning procedures, as well as the numerical techniques applied for the reconstruction of the baseline time trace. A standard technique for the recovery of material properties from guided wave propagation characteristics was also incorporated into the
reconstruction method. This chapter also provided several practical examples of the reconstruction of the baseline time trace and compensation for the effects of changing ambient temperature on damage detection. The challenge was to integrate the physical measurements taken by 3D SLV with the advanced computational models of Lamb wave propagation. This challenge was successfully addressed in this chapter.

In the Chapter 6, the applications of the proposed method were extended to composite plate components since these components are the main focus of Lamb-wave damage detection methods and future SHM systems. The numerical reconstruction of the baseline time trace is significantly more complex than in the isotropic case. The composite plates are very sensitive to ambient temperature changes. The recovery of the actual material properties was conducted using a multi-parametric optimisation, similar to the technique implemented in the previous chapter. A limited number of examples were presented in this chapter due to the complexity of and long computational time needed for the numerical reconstruction of the baseline time trace. These circumstances currently represent the main obstacles for the wider implementation of the developed method. However, both obstacles can be addressed in the future through increases in computational power, more effective numerical algorithms and advances in laser technology. A critical discussion of the outcomes of this thesis and directions for future work are presented in the following section.
7.3 Discussions and Future Work

As mentioned, the proposed method is currently time-consuming and computationally extensive. In general, it needs high-fidelity 3D modelling of Lamb wave propagation. Therefore, for the current practical applications, it is important to make the appropriate selection of the method parameters, such as the time step in the numerical simulation, the density of the measurement points for laser scanning, and the dimensions of the scanning area. These parameters, however, should not compromise the accuracy of the reconstructed baseline time trace, which has to be sufficient to detect critical or specified damage. The thesis and papers published by the author provide only an idea of what these parameters are. Therefore, in order to identify these parameters for a practical damage detection system, extensive preliminary numerical simulations will normally be required. However, once the accuracy of the time trace signal is verified, the method can be applied to similar structures working under similar EOCs, routinely.

Unlike many other techniques developed in the past, the current method is capable of compensating for the variations of several EOCs. For example, it can compensate for the effect of the change in material properties due to temperature and the degradation of the adhesive bond between the structure and PZT. The latter is possible as the scanning area encapsulates the PZT and prescribes the boundary conditions to the
mathematical model of the defect-free structure, which corresponds to the current state of the PZT and structure.

It is also recognised that the utilisation of 3D measurement systems and transient FE simulations can increase the costs of the damage detection significantly, if this method is employed. However, it is believed that with the current advances in computer and laser technologies, the cost-efficiency can be significantly improved, and, in the future, the method can find a wide range of application across many industries. To date this method can be applied to generate periodical updates of the baseline time traces. Therefore, it can now be employed in the existing compensation techniques, which were described in the literature review chapter.

The current thesis represents a fundamental step, based on comprehensive numerical and experimental studies, in the development of a general approach for compensation of EOCs. As a consequence of this pioneering development, the thesis was largely focused on feasibility, proof of concept and demonstration. It is realised that much more work needs to be done to expand the proposed concept and utilise it in practical applications and in real world environments. Hence, based on the current developments and achievements of the thesis, this section discusses the future research directions in this field. The recommendations can be utilised for further developments of the current research study. The instant future research direction can be to apply the proposed method for more complicated structural components and in real situations. Based on the
current developments of this thesis from Chapter 3 to Chapter 6, the recommendations for future work can be summarised as follows:

- The application of the proposed method can be considered for more complicated structural components such as a composite plate with stiffener;
- In this thesis the focus of the proposed method is all about a single damage situation where in real applications multiple-damage situations can exist. The future development of the method can consider structural components with multiple damage situations and other variations in EOC such as humidity, PZT adhesive bonding etc.;
- To consider the potential of the method for real applications, this method can be used for damage detection in hard-to-reach locations in the case of variations in EOC;
- The effects of PZT adhesive debonding on the proposed method can be investigated further, even to assess the accuracy of the PZT actuator, which is a crucial factor for damage detection purposes.
Chapter 7: Thesis Summary and Future Work

References


