Design and Development of a Novel Packaged Fibre Bragg Grating Based Acoustic Emission Monitoring System for Crack Detection in Engineering Applications

Sagar Jinachandran

University of Wollongong

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Design and Development of a Novel Packaged Fibre Bragg Grating Based Acoustic Emission Monitoring System for Crack Detection in Engineering Applications

Sagar Jinachandran

Msc (Eng), B.E.

Primary Supervisor:

Dr. Ginu Rajan

Co-Supervisors:

Prof. Jiangtao Xi

Prof. Huijun Li

This thesis is presented as part of the requirement for the conferral of the degree:

Doctor of Philosophy

University of Wollongong
School of Electronics, Computer and Telecommunication Engineering

02/2020
Dedicated to my grandmother Kalliani Maniyalath who passed away in 2017 during my PhD; she played a crucial role in my upbringing.
ABSTRACT

Structural health monitoring (SHM) is an important aspect in ensuring the safety and integrity of structures. Amongst the many existing methods of monitoring the health of the structures, fibre Bragg grating (FBG) sensors are emerging as a promising method due to their small size, immunity to electromagnetic interference, high temperature stability, multiplexing capability and intrinsic safety. The FBG based acoustic emission (AE) detection technique is gaining attention and is a potential tool for measuring cracking activity in engineering structures. The objective of this thesis research is to develop novel methods based on FBG sensors to determine micro and nano cracks in engineering structures in the early phase of their development to prevent catastrophic failure of the structures.

In this thesis, a new generation means of metal packaging of FBG sensors, using stainless steel and tin, together with high temperature resistant samarium cobalt (SmCo) magnets is proposed. The inclusion of high temperature tolerant SmCo magnets enables the metal packaging of the FBG sensors with magnetic capabilities, allowing this sensor to be placed in direct contact with the substrate structure such as iron pipelines and other ferromagnetic structures without any adhesives, making them easily detachable and reusable. This is a significant improvement compared with other commercially available fibre optic sensors for such applications. The packaged sensor is designed, simulated and analysed using finite element methods in ANSYS and then fabricated and experimentally characterised for load, temperature and vibration. It was demonstrated that our fabricated sensors can measure load, temperature and vibration with reasonable resolution and sensitivity.

As an approach to AE source localisation, and thereby crack detection and localisation in welded joints, the directional sensitivity and the AE sensing capability of unpackaged and packaged FBG sensors were also studied using finite element modelling with explicit dynamics in ANSYS and validated experimentally. AE events were generated using metal ball drop impact on an aluminium plate where the unpackaged and packaged FBG sensors are attached and are measured using a high sensitivity FBG AE interrogation system. The directional sensitivity of the unpackaged and packaged sensors was demonstrated and found that at 0° and 180° the directional sensitivity is highest and is the lowest at 90° and these were verified using FEM simulation in ANSYS.
To demonstrate the potential application of the developed packaged AE sensor, the sensor system is used to detect and analyse cold cracks that occur during the welding process. The fabricated sensors are magnetically surface attached on to the substrate on which the welding is done and the AE events due to hydrogen induced cold cracks are detected by the attached sensor and processed using a high speed FBG AE interrogation system. An attempt was also made to identify and locate micro and nano scale-cracks and a scheme to accurately map the crack location in welded joints is developed with the aid of the magnetic metal-packaged FBG.

In summary this thesis proposes and demonstrates a new generation of packaged sensor which can be used for crack monitoring and it has the potential in future health monitoring of structures involving high temperature applications.
ACKNOWLEDGMENTS

First of all, I would like to thank my supervisor Dr Ginu Rajan for his guidance through-out my PhD without whom my PhD won’t be complete. I would also like to thank my co-supervisors, Prof Jiangtao Xi and Prof Huijun Li for their valuable support and guidance.

Also I would like to thank the School of Electrical, computer and telecommunication engineering (SECTE), Signal processing for instrumentation and communication research (SPICR) group and the members for their valuable comments and feedbacks during the group meetings I would like to thank Matthew Berryman for providing me access to a High Performance computing for the processing of the data for my research. I would also like to thank Abheek Basu for his guidance on modelling and simulation part in ANSYS and helping me learn a lot about finite element modelling (FEM) in general.

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CERTIFICATION

I, Sagar Jinachandran, declare that this thesis submitted in fulfilment of the requirements for the conferral of the degree Doctor of Philosophy, from the University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualifications at any other academic institution.

Sagar Jinachandran
21st February 2020
TABLE OF CONTENTS

ABSTRACT .................................................................................................................. ii
ACKNOWLEDGMENTS ............................................................................................... iv
CERTIFICATION ......................................................................................................... vi
LIST OF PUBLICATIONS .......................................................................................... xi
LIST OF ACRONYMS ................................................................................................. xiii
LIST OF FIGURES ...................................................................................................... xv
LIST OF TABLES ......................................................................................................... xviii

Chapter 1 - Introduction & Objectives ...................................................................... 1
  1.1 Background and Motivation .................................................................................. 1
  1.2 Introduction to Structural Health Monitoring ...................................................... 3
    1.2.1 Significance of SHM ....................................................................................... 4
    1.2.2 Sensors for Structural Health Monitoring Applications ................................ 5
  1.3 Introduction to Optical Fibre Sensors ................................................................... 6
  1.4 Fibre Bragg Gratings ............................................................................................ 8
    1.4.1 Reflectivity of FBGs ........................................................................................ 9
    1.4.2 Sensing using FBGs ....................................................................................... 10
    1.4.3 FBG sensors for SHM applications ................................................................ 11
  1.5 SHM in Welding .................................................................................................... 13
    1.5.1 Hydrogen Induced Cold Cracking in Welding .............................................. 13
    1.5.2 Acoustic Emission based Cold Crack Monitoring ....................................... 15
    1.5.3 FBGs for Cold Crack Monitoring ................................................................ 16
  1.6 Research Objectives of the Thesis and Overview of Chapters ............................. 16

Chapter 2 - Fibre Bragg Grating based Acoustic Emission Measurement System for Structural Health Monitoring Applications ......................................................... 19
  2.1 Introduction ........................................................................................................... 19
  2.2 AE Sources and Events ....................................................................................... 20
  2.3 AE Monitoring Methods for SHM ...................................................................... 21
  2.4 Traditional FBG Interrogation Systems and their Inability for AE Monitoring ... 23
  2.5 FBG Interrogation Systems for AE Monitoring ................................................... 24
    2.5.1 Power Detection and Edge Filter Detection Methods ................................... 24
    2.5.2 AE Detection Using an Optical Fibre based F-P Sensor and Quadrature
        Recombination Technique .................................................................................. 25
2.5.3 FBG Acoustic Sensors by Altering the Physical Configurations of Gratings 26
2.5.4 Spectrometric FBG interrogation system ................................................. 29
2.5.5 Bragg Grating based laser sensor system with interferometric interrogation and WDM .................................................. 30
2.5.6 Intensity demodulation fibre ring laser sensor system for AE detection ...... 31
2.5.7 Commercial FBG AE interrogation systems ............................................. 33
2.6 Applications of FBG based AE monitoring system and its market potential ..... 34
2.7 Conclusion .................................................................................................. 39

Chapter 3 - AE Data Analysis Methodology .................................................... 40
3.1 Introduction ............................................................................................... 40
3.2 FBG AE Interrogation System and AE Data Acquisition ......................... 42
3.3 Signal Processing Techniques ................................................................. 44
3.4 A MATLAB based GUI for data processing and analysis ......................... 50
3.5 Application of the Signal Processing Methodology to AE Data ................. 52
3.6 Conclusion ................................................................................................ 58

Chapter 4 - Design, Fabrication and Characterisation of Magnetic Metal Encapsulated FBG sensor .............................................................. 59
4.1 Introduction ............................................................................................... 59
4.2 Design and Fabrication of the Packaged Sensor ...................................... 60
4.3 Analysis on the effect of the embedding process on the FBG spectrum ....... 63
4.4 Analysis of Design Using FEM ................................................................. 64
4.5 Experimental Setup for Characterisation of the Metal Packaged FBG Sensor .... 67
4.6 Experimental Results and Discussions ..................................................... 69
  4.6.1 Load Characterisation .......................................................................... 69
  4.6.2 Temperature Characterisation ............................................................... 69
  4.6.3 Vibration Characterisation .................................................................... 70
4.7 Conclusion ................................................................................................ 72

Chapter 5 - The Study of the Directional Sensitivity of Fibre Bragg Gratings for Acoustic Emission Measurements ............................................. 73
5.1 Introduction ............................................................................................... 73
5.2 Sensor Design and Fabrication ................................................................. 74
5.3 Design and Construction of Packaged Sensor ......................................... 75
5.4 Experimental Study on Directional Sensitivity of Packaged and Unpackaged Sensors ................................................................. 76
5.5 Finite Element Analysis Model of AE Event ............................................. 78
  5.5.1 Geometry of the design ....................................................................... 78
  5.5.2 FEM using Explicit dynamics exporting to LS-DYNA ......................... 79
  5.5.3 Transient structural analysis ................................................................. 79
5.5.4 FEM using explicit dynamics exporting to ANSYS ........................................... 81
5.6 Analysis of AE Wave through the Substrate......................................................... 82
5.7 Results and Discussion ....................................................................................... 85
5.8 Conclusion ........................................................................................................... 89

Chapter 6 - Applications of FBG based Acoustic Emission Detection System in
Crack Monitoring in Welding ..................................................................................... 90
6.1 Introduction .......................................................................................................... 90
6.2 Mapping of Cracks using AE ............................................................................. 92
6.3 Estimation of the ToA of the AE Signal and Source Localisation ....................... 94
6.4 Experimental arrangement .................................................................................. 95
   6.4.1 Welding Procedure ..................................................................................... 95
   6.4.2 FBG sensors ............................................................................................... 95
6.5 Preparation of the Samples for SEM Imaging ..................................................... 98
6.6 Results and discussion ......................................................................................... 98
   6.6.1 Time domain response of cold crack induced AE events form unpackaged
       FBGs .............................................................................................................. 98
   6.6.2 Signal amplitudes measured by individual sensors ....................................... 100
   6.6.3 Frequency analysis of the cold crack induced AE events ............................ 103
   6.6.4 Time domain response of cold crack induced AE events from packaged FBGs
       ..................................................................................................................... 104
   6.6.5 Identification of cold cracks using SEM imaging ....................................... 106
6.7 Conclusion ............................................................................................................ 107

Chapter 7 - Conclusion and future work ................................................................ 108
7.1 Key findings and conclusions ............................................................................. 108
7.2 Limitations of packaged FBGs .......................................................................... 111
7.3 Future scope for research .................................................................................. 111
REFERENCES ......................................................................................................... 113

Appendix A: I-MON 256 USB.................................................................................. 129
Appendix B: FAESense M400 interrogator............................................................... 131
Appendix C: Welding Equipment............................................................................ 133
“This page has been left intentionally blank”
LIST OF PUBLICATIONS

Journal Articles (Published and submitted)


Conference papers


xi
7) Sagar Jinachandran, Huijun Li, Jiangtao Xi, Ginu Rajan, “Fabrication and characterisation of a magnetic metal encapsulated FBG sensor for Structural health monitoring” 9th Australasian Congress on Applied Mechanics (ACAM 9), Nov 27-29th, UNSW, Sydney Australia (poster presentation)

# LIST OF ACRONYMS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>OFS</td>
<td>Optical fibre sensors</td>
</tr>
<tr>
<td>FBG</td>
<td>Fibre Bragg gratings</td>
</tr>
<tr>
<td>AE</td>
<td>Acoustic emission</td>
</tr>
<tr>
<td>SHM</td>
<td>Structural health monitoring</td>
</tr>
<tr>
<td>NDT</td>
<td>Non-destructive testing</td>
</tr>
<tr>
<td>PZT</td>
<td>Lead Zirconate Titanate</td>
</tr>
<tr>
<td>SmCo</td>
<td>Samarium Cobalt</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength division multiplexing</td>
</tr>
<tr>
<td>HICC</td>
<td>Hydrogen induced cold cracking</td>
</tr>
<tr>
<td>H</td>
<td>Monatomic Hydrogen</td>
</tr>
<tr>
<td>PWHT</td>
<td>Post weld heat treatment</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical user interface</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite element modelling</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite element analysis</td>
</tr>
<tr>
<td>ToA</td>
<td>Time of arrival</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning electron microscope</td>
</tr>
<tr>
<td>F-P</td>
<td>Fabry Perot</td>
</tr>
<tr>
<td>OSA</td>
<td>Optical spectrum analyzer</td>
</tr>
<tr>
<td>TLS</td>
<td>Tunable laser source</td>
</tr>
<tr>
<td>AWG</td>
<td>Arrayed waveguide grating</td>
</tr>
<tr>
<td>FRL</td>
<td>Fibre ring laser</td>
</tr>
<tr>
<td>TOBPF</td>
<td>Tunable optical band pass filter</td>
</tr>
<tr>
<td>ERF</td>
<td>Erbium doped fibre</td>
</tr>
<tr>
<td>SMA</td>
<td>Shape memory alloy</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to noise ratio</td>
</tr>
<tr>
<td>HLT</td>
<td>Hit lock out time</td>
</tr>
<tr>
<td>HDT</td>
<td>Hit definition time</td>
</tr>
<tr>
<td>PDT</td>
<td>Peak definition time</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>WT</td>
<td>Wavelet transform</td>
</tr>
<tr>
<td>TWM</td>
<td>Two wave mixing</td>
</tr>
<tr>
<td>STFT</td>
<td>Short term Fourier transform</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier transform</td>
</tr>
<tr>
<td>SLSR</td>
<td>Side lobe suppression ratio</td>
</tr>
<tr>
<td>UHT HHA</td>
<td>Ultrahigh toughness high hardness</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

1.1 Elements of SHM ................................................................. 4
1.2 Schematic representation of FBG ........................................... 9
1.3 Failure due to cracks in a pipeline ........................................ 14
1.4 Location of cold cracks and their causes ................................ 15
2.1 AE wave with noises ................................................................. 21
2.2 Optical circuits of (a) Edge filter method (b) Power detection method .... 25
2.3 Fabry-Perot and quadrature recombination method for AE monitoring .... 26
2.4 FBG AE sensor by altering the gratings ...................................... 27
2.5 FBG interrogation system using an AWG ..................................... 29
2.6 Interferometric interrogation along with WDM ............................... 30
2.7 FBG interrogation using FRL sensor for AE detection .................... 32
2.8 Configuration of the flying test bed and sensors ......................... 35
2.9 FBGs used for bridge monitoring ............................................. 37
3.1 (a) FAESense interrogator (b) Schematic of the AE interrogation experiment .... 43
3.2 The user interface from FAESense interrogator system showing the various channels ........................................................... 44
3.3 Flowchart depicting the signal analysis process carried out in this thesis ........ 45
3.4 Principle of the proposed AE signal processing approach ................. 45
3.5 Time frequency plane for (a) FT windowing technique .................. 46
3.5 Time frequency plane for (b) wavelet transform ........................... 47
3.6 Original and thresholded signals ............................................. 48
3.7 Varying threshold levels of Daubechies wavelet while de-noising AE signal .... 49
3.8 GUI to plot the time domain data ............................................. 51
3.9 Option on the GUI for (a) Denoising and STFT, (b) de-noising DB or Haar .... 51
3.10 (a) Time domain data from the tuning fork, (b) FFT plot before de-noising .... 53
3.11 (a) The time domain data from the tuning fork, (b) FFT plot after de-noising .. 54
3.12 The STFT plot obtained (a) before de-noising, (b) after de-noising ............ 55
3.13 (a) The time domain plot for the data from the ball drop experiments (b) the corresponding de-noised data .................................................. 56
3.14 STFT plot obtained (a) before de-noising, (b) after de-noising .................. 57
4.1 The Schematic (a) stainless steel cylinder region (b) cross section view of the tin disc (c) placement of SmCo magnets with the cylinder (d) the fabrication of the metal packaged magnetic FBG sensors components before embedding, indicating the location of the SmCo magnets (e) the metallic packaged sensor .................................. 62

4.2 The schematic diagram of FBG interrogation system ........................................... 63

4.3 Reflection spectra of FBG Sensor, before and after packaging.............................. 64

4.4 (a) Thermal strain profile of packaged sensor due to applied temperature (b) the thermal strain along the embedded fibre containing FBG ........................................ 65

4.5 (a) Strain profile of packaged sensor with applied load (b) strain experienced by embedded optical fibre (c) simulated load vs strain plot of the packaged sensor..... 66

4.6 The photographs of the set up for characterisation; (a) load (b) temperature (c) vibration.............................................................................................................. 68

4.7 Measured wavelength shift and calculated strain due to applied load calculated strain from the experiment and its comparison with the simulation......................... 69

4.8 Measured temperature induced wavelength shift of the packaged sensor.......... 70

4.9 (a) The wavelength versus time plot of the vibration experiment; (b) FFT plot for the measured vibration at 500Hz (c) FFT plot for measured vibration at 1 kHz...... 71

5.1 The parts of the packaged sensor (a) stainless steel base with FBG (b) tin plate (c) Packaged sensor after heating .................................................................................. 75

5.2 The experimental arrangement for the metal ball drop test using the FAESense interrogator system ........................................................................................................ 76

5.3 (a) the AE waves obtained from the ball drop using the PZT transducer and Oscilloscope ............................................................................................................. 77

5.3 (b) the corresponding STFT plot ........................................................................... 78

5.4 The x displacement along the aluminium and packaged sensor ....................... 80

5.5 The schematic of aluminium substrate with the metal ball which was modelled in ANSYS geometry for (a) unpackaged FBG sensors (b) packaged FBG sensor...... 82

5.6 The modelled propagation of acoustic wave through the substrate at (a) 1.08 ms (b) 1.14 ms................................................................................................................. 83

5.7 The Directional Sensitivity for (a) unpackaged FBG sensor (b) packaged FBG sensor .................................................................................................................. 84

5.8 The amplitude vs. time plot from unpackaged sensor with (a) a 6mm ball 50 mm distance (b) 6 mm ball 100 mm distance (c) 12 mm ball 50 mm distance (d) 12 mm ball 100 mm distance................................................................. 85

5.9 The STFT containing an AE from unpackaged FBG with (a) 12mm ball 50mm distance (b) a 6mm ball 50mm distance......................................................... 86
5.10 The amplitude vs. time plot containing an AE from the packaged sensor at (a) 6mm ball 50 mm distance (b) 6mm ball at 100mm distance (c) 12mm ball at 50 mm distance (d) 12 mm ball at 100 m distance ......................................................... 87

5.11 The plot for the directional sensitivity obtained after the ball drop tests with 12 mm and 6 mm balls (a) unpackaged FBGs (b) packaged FBG sensors .................. 88

6.1 The location of the sensors with respect to the crack location ..................... 93

6.2 The schematic arrangement of the welds and the FBG sensors on the welded region (b) photograph of the welded region ................................................. 94

6.3 The photograph of the welding with (a) bare FBGs (b) packaged sensors ....... 96

6.4 The final prepared welded areas after polishing and moulding .................... 98

6.5 The time domain response for the welding with cracks occurring at various locations (a) for weld 1 (b) weld 2 (c) weld 3 ................................................. 99

6.6 Amplitude plots vs the events for various FBGs (a): During welding, (b): After welding ............................................................................................................. 101

6.7 Frequency analysis of selected AE events measured by the FBG sensors for weld 2 (a) Event 2 (b) Event A2 ................................................................................. 102

6.8 Amplitude vs event plot obtained from array having packaged sensors......... 103

6.9 Amplitude vs event plot obtained from the packaged sensors ..................... 104

6.10 The time domain response for the packaged sensor for welding crack monitoring detection ........................................................... 105

6.11 Confirmation of cold cracks from SEM imaging and its correlation with time domain response ............................................................... 106

A.1 I-MON 256 USB interrogator system ..................................................... 130

A.2 Wire feeder 3 ....................................................................................... 134

A.3 The interface of the TIG MLS 2000 displaying the welding current used in the experiment ................................................................. 135
 LIST OF TABLES

1.1 Parameters of SHM page numbers right margin should be same ......................... 4
1.2 Classification of optical fibre sensors based on working principle .................. 7
2.1 Effect of physical configuration of the sensor on sensitivity ......................... 28
2.2 Some commercial FBG AE Sensors ................................................................. 33
2.3 Comparison of different FBG AE interrogation techniques ......................... 38
3.1 Performance specifications of FAESense M-400 ............................................. 43
4.1 Material properties of the samarium cobalt magnets .................................... 61
4.2 Material data for ANSYS Simulation ............................................................... 65
4.3 Summary of results .......................................................................................... 72
5.1 Material properties for FEM modelling ......................................................... 81
6.1 Calculated time of arrival of AE to the FBGs .................................................. 95
6.2 Specifications of FBGs used in this experiment ............................................. 97
A.1 Specifications of the I-MON 256 USB interrogator system ................................ 129
A.2 The specification of the FAESense M400 interrogator system ....................... 131
A.3 The specifications for the Wire Feed 3 system .............................................. 133
Chapter 1

Introduction & Objectives

1.1 Background and Motivation

Optical fibre sensors (OFSs) and particularly fibre Bragg grating (FBG) based acoustic emission (AE) detection technology is gaining popularity because of their advantages such as light weight, small size, immunity to electromagnetic interference, resistance to harsh environments, ease of embedding, high sensitivity and high frequency measurement capability [1,2]. Research on FBG based AE detection is emerging and is particularly important in high-temperature applications where it can provide solutions to existing problems faced by industry, such as in welding and pipeline monitoring.

Among the different techniques to detect the defects in structures, AE is a well-known technique in detecting stress waves generated by defects in materials, thereby allowing continuous and real-time structural health monitoring (SHM) [3-5]. Current non-destructive testing (NDT) technologies to measure AE involve Lead Zirconate Titanate (PZT) based systems. However, PZT-based sensors are susceptible to electromagnetic interference (EMI), bulky and have high energy consumption [6, 7] and damage identification can be accurately quantified only to some extent where the cracks/damages are above the microscale. The SHM industry is also currently seeking to reduce its energy footprint and this requires lightweight, embeddable sensors. Other traditional NDT techniques are ultrasonic scanning, the eddy-current method, radiography and passive thermography [8] and these techniques are effective in detecting damage in materials and structures but would be unable to detect the microcracks and minuscule defects in the system. Therefore, there is a strong interest in the development of an FBG based crack monitoring system that is capable of operating at high temperatures that would allow in-situ monitoring of early minuscule defects in the materials.

As a proof-of-concept, in this thesis work, we have developed a technology to monitor micro/nano scale-cracks within a metallic structure during the welding process by measuring crack induced acoustic emissions using surface attached FBGs. The developed technology is intended to be translated to use as an SHM method for
future high temperature applications. Therefore, the primary focus of this thesis includes research on techniques to improve the sensitivity of a fibre optic crack monitoring system and the design and fabrication of novel magnetic metal packaged FBG sensors which can yield the highest AE measurement sensitivity and can be attached to weld structures. Development of this novel surface attached packaged sensor is accomplished through thorough research work. A novel way of metal packaging of FBG sensors using stainless steel, tin and samarium cobalt (SmCo) magnets is developed and the proposed configuration provides a packaged FBG sensor that can be directly employed in a range of applications, without any installation complications while other similar commercial sensors are surface-attached using epoxies or welded to the substrate structure. The developed configuration can be effective up to a temperature of 200 °C and is re-usable compared to existing packaged FBG sensor types. However by using other compatible materials the operating temperature can be enhanced. The primary focus of the development of this packaged sensor was for the use in high pressure pipelines which are prone to the cracks so in order to apply this sensors in pipelines as a result the characteristics of the sensors which are important are namely the load and temperature measurement capability at the lower range of the load sensing, which gives the sensors the capability to measure AE and temperatures, and hence it was important to do a load and temperature characterisation on this packaged sensor. This enables the early detection of failure of structures and therefore a possibility of repair before the occurrence of any catastrophic damage. The outcome of the project will underpin a new way to determine the presence of micro/nano cracks in high-temperature applications by measuring AE more accurately than before, using fibre-optic sensing methods and also to estimate the exact location of the cracks leading to the development of state-of-the-art SHM methods. This will pave the way for establishing new generation devices for live diagnostics of aerospace, welding, temperature and pressure sensing for deep and hot oil bores, power plants, furnaces and chemical reactors.

A condensed general overview of the specific accounts of the concepts and analysis of literature pertaining to the work in the coming chapters is presented in this chapter.
1.2 Introduction to Structural Health Monitoring

The process of implementing a damage detection strategy for structures in various industries such as aerospace, civil and mechanical engineering infrastructure is referred to as SHM. SHM is described as a damage identification strategy which amalgamates sensing and intelligence so as to enable the structure loading and damage producing conditions to be recorded, analysed, localised and predicted in such a way that NDT becomes an integral part of the structure [9]. Thus SHM can be defined as a permanent, continuous, periodic or periodically continuous recording of the loading conditions and damage occurring in the system. The monitoring can be undertaken over the short term for a few days, medium term for few weeks, long term for few years and also over the whole lifespan of a structure [10]. Such a system must be able to detect the damage, characterise it and report it automatically or on demand. The resultant data from this surveillance program can be used to maximize the performance, maintenance, overhaul, and renewal of the structure based on reliable and objective data. According to the serviceability and complicacy of the system, SHM is organised into five levels, where higher the level, the higher the complexity. This hierarchy is referred to as the staircase of SHM, which is shown in Fig. 1.1. In a typical SHM system the first level is the detection of the presence of the damage without locating it, and in the second level along with detection the defect can be located. In advanced SHM which consists of higher levels, such as a third level system will detect and localise the damage together with a diagnosis of the severity of the damage. Level 4 SHM systems carry out the prognosis or estimation in remaining service life, whereas level 5 are constituted by complex hardware and custom algorithms and software to enable diagnosis or prognosis and self-healing functions [10].

When developing reliable SHM systems, the salient features to be considered are the behaviour and implementation of the structures, the loads they are subjected to, the design principles, the preservation requirements and the available systems or devices for structural assessment and the various developing technologies suitable for use with SHM. This organisation of selecting the parameters for assessing SHM depends on many factors such as the category and type of the structure, anticipated loads, construction materials such as metals or composites, environmental factors, expected degradation phenomena and available sensing systems. The commonly used
parameters can be mechanical, physical or chemical and are given in Table 1.1. Measured parameters are assessed according to certain algorithms, compared with predetermined values or ultimate values to establish normal and abnormal operating regimes [11]. Nowadays, it is a standard practice to employ statistical techniques to analyse SHM data. In statistical analysis, the data need to be normalised as they are acquired under different conditions and as the data will be obtained over an extended period of time and in real time, methods should be developed to condense the data for accurate and detailed analysis.

**Table 1.1 Parameters of SHM**

<table>
<thead>
<tr>
<th>Category</th>
<th>Parameters</th>
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<tr>
<td><strong>Mechanical</strong></td>
<td>Strain, deformation, crack opening, stress, displacement, load</td>
</tr>
<tr>
<td><strong>Physical</strong></td>
<td>Temperature, humidity, pressure</td>
</tr>
<tr>
<td><strong>Chemical</strong></td>
<td>Penetration of chloride, sulphate, and carbonation, pH, rebar oxidation, steel oxidation and timber decay</td>
</tr>
</tbody>
</table>

**1.2.1 Significance of SHM**

All the built and constructed structures are susceptible to failure. The failure of engineered structures can be of great consequence to humanity as it can have an impact on the economy and on human life alike. To design structures that are safe for
public use, building codes and methodologies are practiced, however structures are often subjected to harsh loading scenarios and severe environmental conditions which can lead to failure. Examples of operational failure of a structure and thereby loss of human lives can be found worldwide. As an example, in 2018 a Southwest Airlines Boeing 737-700 experienced a failure of the left CFM International engine (CFM-56-7B) and the loss of an engine inlet and cowling during ascent resulted in the fatality of one crew member and a passenger. The National Transport Safety Board’s initial examination of the airplane revealed that the majority of the inlet cowl, including the entire outer barrel, aft bulkhead, and the inner barrel of the containment ring was missing. Fan blades recovered from the flight showed signs of fatigue cracking which was detected by ultrasonic methods [12]. Also some of the recent studies conducted by industry [13] show that early detection of damage can save great expense and increase the lifespan of a structure, thereby providing value to industry and society in general. Therefore, a technologically and economically feasible SHM method to identify and assess defects/cracks in structures at an early stage of formation is essential to safeguard the structural integrity and operation throughout the service life. These SHM systems can be widely adopted to monitor the behaviour of structures during forced testing conditions.

1.2.2 Sensors for Structural Health Monitoring Applications

Various sensors which are being utilised for SHM include strain gauges, acceleration sensors, MEMS (micro-electromechanical systems) together with wireless data acquisition systems [14, 15], PZT sensors, electrical time domain reflectometers, laser Doppler vibrometer (LDV) and fibre optic sensors. Other traditional NDT techniques are ultrasonic scanning, the eddy-current method, radiography and passive thermography are also used in SHM applications. Among these PZTs are one of the prevalent technologies for SHM in many engineering fields, due to their unique integrated functions for sensing and actuating, their light weight and variety of shapes and sizes [16].

PZT works on the principle of piezoelectric effect and measures changes in pressure, acceleration, temperature, strain, or force by converting them to an electrical charge. PZTs were proposed into SHM of civil infrastructures as an active sensing technology based on the measurement of electrical impedance and elastic waves [17,
However PZT sensors require pre amplifiers and signal conditioning units for all the sensors and they also have limitations to be used in harsh environments like at high temperatures or high-voltage environments and also have a low power handling capacity [19, 20].

Other sensors that often used in SHM are strain gauges and accelerometers, which are relatively mature, but their wiring is cumbersome for advanced SHM applications[7]. Non-contact measurements using LDV, ultrasonic scanning etc have been investigated by several researchers, but their use in in-service conditions is often limited due to the harsh operating condition and also as it is time consuming [21]. MEMS accelerometer are also often used which measures structural vibration induced acceleration and the signal can be electronically integrated.

Compared to these existing technologies optical fibre sensing technology are particularly advantageous since they are capable of carrying out integrated, distributed, quasi distributed and remote sensing operations. Further details of optical fibre sensors are provided in section 1.3 and 1.4.

1.3 Introduction to Optical Fibre Sensors

Sensing has become a key empowering technology in many areas, from entertainment technology to health, transport, architectural and many industrial technologies. In countless such advanced applications where miniaturization, sensitivity, and remote measurements are vital, OFS–based sensing techniques can provide novel solutions [2]. Optical fibre sensors can be described as a system through which physical properties interact with the guided light propagating through an optical fibre to produce an optical signal which is modulated by information related to the measurement parameters. OFSs have the potential to measure strain, pressure, force, rotation, acceleration, electric and magnetic fields, acoustics and vibration, temperature, humidity, pH and viscosity and can detect biological molecules, chemicals, viruses, bacteria and DNA [2]. As a result of this, optical fibre sensors have developed as a powerful and rich technology that is currently being implemented in a wide variety of applications [22,23]. The other useful characteristics of the OFS technologies include invulnerability to many types of interference, reliability and versatility, small and light weight, robustness and resistance to harsh environments, high sensitivity, ability to sense a lot of parameters such as strain, pressure, corrosion,
temperature and acoustic signals, chemical inertness and bio compatibility. OFSs are classified in many ways and one such classification depending on their working principle is given in Table 1.2.

Table 1.2: Classification of optical fibre sensors based on their working principles

<table>
<thead>
<tr>
<th>Type of OFS</th>
<th>Working principle</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity modulated</td>
<td>Variation of light intensity</td>
<td>Evanescent field sensor, micro bend sensor, macro bend sensor</td>
</tr>
<tr>
<td>Polarimetric</td>
<td>Changes in state of polarisation of light</td>
<td>Polarimetric sensors</td>
</tr>
<tr>
<td>Spectrometric</td>
<td>Changes in wavelength of light</td>
<td>Bragg grating, fluorescence and black body sensors</td>
</tr>
<tr>
<td>Distributed</td>
<td>Rayleigh, Brillouin and Raman scattering in optical fibres</td>
<td>OTDR based Rayleigh, OFTDR based on Raman and Brillouin</td>
</tr>
</tbody>
</table>

OFSs operate by modifying one or more properties of light propagating through the fibre and depending on the optical signal property they modify are classified mainly into four categories namely intensity modulated sensor [24], phase modulated or interferometric sensor [25, 26], polarisation modulated (polarimetric) sensor [27], and wavelength modulated or (spectrometric) sensors [28-29]. Intensity modulated sensors are affected by power fluctuations of the source, coupler loss and absorption effects [30] and changes in temperature and vibrations influence interferometric sensors.

Another approach to classifying OFSs is based on their spatial positioning and they are classified into point, distributed, quasi distributed and integrated sensors. A point sensor can sense measurands from discrete points and has spatial multiplexing capability depending on the type of sensor used. Distributed sensors can provide
spatial and temporal information of measurands from any point along a fibre with a certain resolution. This type of sensor has more weight and space efficiency and hence is one of the best options in SHM of civil infrastructure and aviation. Distributed fibre optic sensors (DFSs) are often categorized based on the interrogation method and the physical effect supporting the operating principle which are optical time domain reflectometry (OTDR) and optical frequency domain reflectometry (OFDR), based on Rayleigh, Raman and Brillouin scattering [31, 32]. Quasi distributed sensors can obtain information from particular and predetermined points along a fibre and it is considered to be intermediate between point and distributed sensors. Integrated sensors can measure perturbation over the sensing length of the fibre. Among the different types of fibre-optic sensors, the spectrally modulated quasi distributed fibres based on grating technology are the FBGs and they are widely used and considered as the most popular technology for implementing health-monitoring systems due to their localized and multiplexed sensing capability [2, 33-34], good linearity and resistance to harsh environment in comparison with other sensors [35].

OFSs are used to monitor the conditions within oil wells and pipelines, railways, aircrafts, and wind turbines. Fibre optic sensors can contribute to improving safety, by detecting and locating impending failure or damage in critical structures and components, for example, in the aeronautical and civil engineering sectors. Therefore, SHM application has emerged as a promising field of application for optical fibre sensors.

1.4 Fibre Bragg Gratings

FBGs are the most commonly employed fibre optic sensors in SHM applications since their invention in 1978 [36]. An FBG in its most basic form comprises a short section of single-mode optical fibre, in which the core refractive index is modulated periodically using an intense optical interference pattern [37], typically at UV wavelengths in the range of 244 nm to 248 nm. This periodic index-modulated structure enables light to be coupled from the forward propagating core mode into a backward propagating core mode, thereby generating a reflection response. The peak reflected Bragg wavelength $\lambda_B$ is given by:
\[ \lambda_B = 2n_{\text{eff}} A, \quad (1.1) \]

where \( A \) is the grating period and \( n_{\text{eff}} \) is the effective refractive index of the fibre. The basic principle of an FBG is illustrated in Fig 1.2.

In standard FBGs the diameter of the core is circa 8 \( \mu \text{m} \) and that of cladding is 125 \( \mu \text{m} \) and length is about 1 to 20 mm with a grating reflectivity above 90\% [37]. FBG sensors have mainly two types of protective coatings, acrylate and polyimide with outer diameter of \( \sim 250 \mu \text{m} \) and \( \sim 150 \mu \text{m} \), respectively [38,39]. Typical acrylate coated FBGs can operate in a temperature range of -20 °C to 85 °C, whereas, polyimide coated FBG sensors can withstand a greater temperature range, from -200 °C to 350 °C.

![Figure 1.2: Schematic representation of FBG and its operating principle](image)

1.4.1 Reflectivity of FBGs

The reflectivity of an FBG can be calculated using the equation [40],

\[ R = \tanh^2 \Omega, \quad (1.2) \]

where \( \Omega = \pi n_{\text{eff}} (L/\lambda_B)(\Delta n_{\text{eff}}/n_{\text{eff}})\eta(V) \) \( (1.3) \)

The factor \( \eta(V) \approx 1 - 1/V^2, V \geq 2.4 \) is the fraction of the integrated fundamental mode intensity contained in the core (\( V \) is the normalized frequency of the fibre). It is seen that \( R \) is directly proportional to the grating length \( L \) and the index perturbation
\( \Delta n_{\text{eff}} / n_{\text{eff}} \) which is normally determined by the exposure power and time of the UV radiation for a specified fibre.

The full width half maximum (FWHM) bandwidth, \( \Delta \lambda \), of a grating is approximately given by [41],

\[
\Delta \lambda = \lambda_B s \sqrt{\left( \frac{\Delta n_{\text{eff}}}{2 n_{\text{eff}}} \right)^2 + \left( \frac{1}{N} \right)^2 }, \quad (1.4)
\]

where \( s \sim 1 \) for strong gratings (near 100% reflection) and \( s \sim 0.5 \) for weak gratings, and \( N \) is the number of grating planes. Because the change in the index is small, the main contribution to the spectral width change is attributed to the change in the modulation depth of the index perturbation.

**1.4.2 Sensing using FBGs**

The peak reflected Bragg wavelength is sensitive to a range of physical parameters, such as strain, pressure, temperature, vibration and other external parameters. The sensitivity of the Bragg wavelength to temperature arises from the change in the period associated with the thermal expansion of the fibre, coupled with a change in the refractive index arising from the thermo-optic effect. For the measurement of a temperature change \( \Delta T \), the corresponding wavelength shift is given by,

\[
\Delta \lambda_T = \lambda_B (\alpha_0 + \beta_0) \Delta T \quad , \quad (1.5)
\]

where \( \alpha_0 \) and \( \beta_0 \) are the coefficient of thermal expansion and the thermo-optic coefficient of the fibre, respectively.

The strain sensitivity of the Bragg wavelength is due to the change in the pitch of the FBG and changes in the refractive index of the FBG can arise due to the strain-optic effect when an external strain is applied. The strain-induced wavelength shift is given as,

\[
\Delta \lambda_{BS} = \lambda_B (1 - \rho_a) \Delta \epsilon, \quad (1.6)
\]

where \( \rho_a \) is the photo-elastic coefficient of the fibre and \( \Delta \epsilon \) is the induced strain. The photo-elastic coefficient is given by,
\[
\rho_\alpha = \frac{n^2}{2} \left[ p_{12} - \nu (p_{11} - p_{12}) \right], \quad (1.7)
\]

where \(p_{11}\) and \(p_{12}\) are the components of fibre optic strain tensor and \(\nu\) is the Poisson ratio. Thus by measuring the wavelength shift of the peak reflected signal from the FBG, a change in temperature or strain can be calculated.

The AE measurement capability of an FBG is correlated with the strain sensitivity where the Bragg wavelength exhibits a change due to the change in the grating pitch and refractive index via the strain optic effect, when an AE induced dynamic strain is experienced by the FBG.

Compared with other OFSs, FBG sensors have multiple advantages such as simplicity, compactness, light weight, intrinsic sensing and multiplexing capability and their ability to be written into the fibre without changing the fibre diameter. Therefore, FBGs are considered as one of the most propitious developments in the area of the sensing. However, for any fibre-optic sensor, the cross-sensitivity to temperature and strain is a critical issue that needs to be addressed [42]. This issue has been a subject of intensive research and there have been many researchers who have worked on this problem and proposed a number of configurations. Various methods to overcome the cross sensitivity include design of sensors with multiple superimposed FBGs at various wavelengths. Such approaches have reported ±5 °C and ±10 µε errors for temperature and strain respectively. Other approaches for solving the cross sensitivity of FBGs is to design sensors insensitive to temperature or to develop interrogation methods to aid in the differentiation of temperature and strain. Most such techniques rely on two different types of FBGs, that involve either complex gratings or special fibres and some require optical elements [43]. Using more fibre elements or other devices can increase the system cost and complicate fabrication of the sensor head, therefore it is highly desirable to use a single intrinsic fibre technology rather than extrinsic techniques to distinguish between strain and temperature.

1.4.3 FBG sensors for SHM applications

FBG sensors are now emerging from the laboratory to real world applications such as sensing elements for SHM in civil infrastructures like high rise buildings,
bridges, tunnels and dams and in applications like aerospace engineering, mining, oil and gas industries and offshore platforms [35]. For operating structures FBGs can be surface attached and for state of the art sensors they can be embedded into the structure during construction without any serious effect on the structural integrity [35]. FBG based acoustic emission measurement sensors are potentially a new area of research which overcomes the shortcomings of the conventional methods such as PZTs. FBG sensors seem to be ideal for realising so-called ‘fibre-optic smart structures’ where fibre-optic sensors are embedded in (or attached to) the structure for achieving a number of technical objectives, such as health monitoring, impact detection, shape control and vibration damping, via the provision of real-time sensing information, such as strain, temperature and vibration [44]. FBGs were bonded to the pre stressing tendons and embedded in the concrete. FBG sensors have been used in SHM of bridges by many researchers [45-47]. an example of which is the first bridge in Canada to be monitored with FBGs: the Bennington trial bridge in Alberta. A total of 20 FBGs were fitted and measurements were made and no damage to the structure was found [48].

Changes in various parameters like load and displacement can be assessed to ascertain the health of excavation and mines and FBGs are ideal for this compared to strain gauges or other electrical sensors due to their ability to be multiplexed and to their property of resistance to electromagnetic interference. FBGs are ideal for marine SHM due to their ability to resist corrosion and their multiplexing capability. A 16-channel wavelength division multiplexing (WDM) FBG dynamic strain sensing system with interferometric detection has been successfully developed by researchers and used in the design and fabrication of a catamaran [49]. Many researchers have conducted studies into the SHM of aircraft using embedded and surface attached FBGs. The use of composite materials with embedded FBG systems can lead to reduction in weight and maintenance expenditure of the aircraft, increased inspection intervals and therefore to enhanced performance [50]. FBG strain sensors also have an important application in the field of geodynamical monitoring [51]. Some examples are the study of rock deformation, fibre-optic geophones and vertical seismic profiling [52]. Geodynamic monitoring in seismic areas has been proved to be an effective aid in forecasting major hazards.
Scientists have found that FBG sensors through AE monitoring can be effectively used for SHM of metallic and composite structures and such sensors are gaining popularity [53-55]. All the current studies reviewed so far have focused on the application of unpackaged and embedded FBGs in various SHM applications. To date, no research has been reported on the application of packaged FBGs, especially magnetic surface attached ones for SHM. The research reported in this thesis, therefore, aims to examine the reliability of magnetic packaged FBGs for on-line process monitoring, in-situ defect identification, and simultaneous measurement and mapping of crack induced AE. Though considerable work has been done on FBG based AE sensors, the thermal erasure of FBGs at high temperatures is a stumbling block to their use in high temperature applications. State of the art devices that operate in harsh environments should be able to resist high temperatures and must be able to endure annealing, degradation and ageing. We have investigated these magnetic metallic packaged FBGs for use in welding as a proof of concept with a temperature range up to 200 °C (using a high temperature capable FBGs, packaging thus materials temperature range can be enhanced). Such high temperature capable sensors will establish a new generation device for live diagnostics of aerospace, welding, temperature and pressure sensing for deep and hot oil bores, power plants, furnaces and chemical reactors.

1.5 SHM in Welding

1.5.1 Hydrogen Induced Cold Cracking in Welding

Presence of hydrogen atom contamination in alloys has adverse effects on material properties, which can cause damage at the nanometre scale levels and therefore it is difficult to observe the final fracture in a structure in the initial stages. Hydrogen (H$_2$) embrittlement occurs during welding when hydrogen is trapped between the welded regions and as the weld cools down the trapped gas releases a force which grows to break the metal since the strong force spreads in all directions. A photograph of cracks in a pipeline due to poor welding quality is shown in Fig 1.3. A specific area which this thesis focuses on is hydrogen induced cold cracking (HICC).
HICC can be prevented by welding towards areas of less constraints, preheating the weldments, using austenitic fillers and using a weld metal which is more ductile. Sufficient preheat allows more time for hydrogen to diffuse out of welds and forms less susceptible microstructure (non martensitic). Austenitic weld metal is less susceptible to HICC as it prevents hydrogen from entering the heat affected zone (HAZ). HICC can be repaired by removing the elements and re-welding them. There are several methods by which hydrogen makes the way into the material among which the main way is through welding consumables [56]. Monoatomic hydrogen (H) or diatomic hydrogen (H₂) is introduced into the weld from hydrogenous compounds in the vicinity of the weld like paint, corrosion, moisture and grease. This H tries to attain equilibrium and will be attracted to high energy areas in the microstructure of the matrix of the weld and in doing so interacts with other microstructural features and this migratory diffusion of monoatomic hydrogen is thought to be the basis of formation of HICC [57]. This hydrogen also decreases the cohesive force between metal atoms. There are various parameters which affect the rate of diffusion of hydrogen, namely temperature, microstructure of metal, solubility, residual stress and the trapping effect and this is shown in Fig 1.4. HICC can be avoided by using low hydrogen electrodes, or preheating the substrate above 150 °C [58]. The hydrogen content can also be treated by post weld heat treatment (PWHT) and it has been shown that PWHT at 740 °C for 2 hours brought down the effect of cold cracks significantly [59].
1.5.2 Acoustic Emission based Cold Crack Monitoring

In welding the level of defect in a weld determines the soundness of the weld. This is an example of high temperature environment where SHM is required. Welding defects the discontinuities that occur during the welding process and mainly depend on the parameters such as the type of the defect, the location of the defect, the orientation of the defect. Cracks in welds can be formed mainly during the welding process itself or later as a result of residual stress. NDT of the weld has been advancing to produce high quality and highly reliable welds. This includes post weld detection such as liquid penetrate inspection, film radiographic test, phased array techniques, application of a probing or inspection medium, radiography, scanning the welded plates and pipes sonographically and taking their digital image and by ultrasonic test [60]. Of these diagnostic and monitoring methods, ultrasonic phased array techniques are the most advanced technique to detect and characterise the HICC in line pipe steels. In the ultrasonic phased array, an array of crystals is used to generate the ultrasonic waves which are controlled by software for time delays and can be focused to a definite depth [60].

The AE method to detect cracks during welding was employed a few decades ago by CK Fang et. al (1995) who accelerated the process of HICC electrochemically by cathodically charging the weldments with hydrogen [61]. The AE signals which were generated due to this cracking were recorded and the crack propagation was studied and monitored [62]. AE signals are generated while the welding process is in progress and are highly effective for real time and continuous monitoring [63]. A relationship between the AE parameters and fatigue crack propagation was also reported by Bruzelius and Mba in 2004 [64] and Robert and Talebzadeh in 2003 [65]. Nakagawa et. al. studied the time frequency analysis of AE and detected small cracks [66]. In surface cracks the defects are formed inside the heat affected zone (HAZ) which

![Diagram of cold crack formation](image-url)

**Figure 1.4:** The location of cold crack formation inside the metal and the causes of cold crack formation

The AE method to detect cracks during welding was employed a few decades ago by CK Fang et. al (1995) who accelerated the process of HICC electrochemically by cathodically charging the weldments with hydrogen [61]. The AE signals which were generated due to this cracking were recorded and the crack propagation was studied and monitored [62]. AE signals are generated while the welding process is in progress and are highly effective for real time and continuous monitoring [63]. A relationship between the AE parameters and fatigue crack propagation was also reported by Bruzelius and Mba in 2004 [64] and Robert and Talebzadeh in 2003 [65]. Nakagawa et. al. studied the time frequency analysis of AE and detected small cracks [66]. In surface cracks the defects are formed inside the heat affected zone (HAZ) which
makes it extremely difficult to detect the location of the cracks. Though several methods are available to minimize cold cracks during welding [67], it is still under research and the need to monitor the crack activities still exists. Typically, cold cracks are not detectable until the metal cools to a temperature of about 200 °C [68] and therefore real time monitoring of crack activities would enable engineers to control the welding parameters more accurately to minimize the cold cracks.

1.5.3 FBGs for Cold Crack Monitoring

The development of new methods has enabled engineers to control the parameters and thereby minimise cold cracks by employing optical fibre sensing methods in welding, especially using FBGs. Some previous work on FBG based sensors for welding applications such as residual stress and temperature monitoring shows the feasibility of employing optical fibre sensing methods in welding [69, 70]. Suarez et. al used FBGs bonded on the underside of the welding plate to measure both dynamic and residual stresses generated in the HAZ [69]. Moreira et. al used two FBGs having 30 mm long gratings to measure the temperature of welded plates and compared the value using thermocouples and thermography Results obtained with FBGs were in close agreement with other measured values [70].

1.6 Research Objectives of the Thesis and Overview of Chapters

The primary focus of this research is to develop a real-time novel state-of-the-art SHM system based on FBG for AE monitoring. Currently the existing AE measurement sensors including FBGs are not capable for use in high temperature applications, and lack self-adhesion characteristics such as magnetic attachment to the substrate structure. To overcome this, a novel new generation state-of-the-art metal encapsulated magnetic FBGs which is surface attachable and reusable is proposed. As a proof of concept of the proposed technology, crack monitoring in welding applications is selected due to its high temperature environment and further potential for use in oil and gas pipelines where self-adhesion is preferred. Therefore the primary objectives of this thesis study are as follows:

➢ Demonstration of the application of FBG based AE sensing system for SHM;
➢ Develop suitable signal processing tools for AE data processing analysis;
➢ Design and development of a unique way of embedding FBG in the metal without affecting the FBG’s sensing capacity and enabling its reuse;
➢ Crack monitoring at the micrometre and nanometre levels in welding using the developed system as a proof of concept of the technology;
➢ Mapping and locating the occurrence of cold cracks during the process of welding.

Thesis is organized as follows starting with Chapter 2.

Chapter 2: - Fibre Bragg grating based acoustic emission measurement system for structural health monitoring applications

This chapter presents a comprehensive literature review of the various FBG based AE sensors and their interrogation methods. Following this extensive literature review a gap is identified in the published research that must be filled for the usage of highly sensitive state of the art FBGs for SHM in high temperature applications such as welding.

Chapter 3: - AE data analysis methodology

This chapter presents a comprehensive study of the analysis, denoising and monitoring of acoustic emission data from the FBG sensing system using signal processing tools. Once the AE data is recorded, signal processing tools are used to analyse these signals. The AE signal thresholding and denoising are therefore significant steps in the data processing of AE data from FBG sensors measured by AE interrogators. A graphical user interface (GUI) in MATLAB for signal thresholding and wavelet denoising for processing the AE data has been developed and is presented in this chapter.

Chapter 4: - Design, fabrication and characterisation of magnetic metal encapsulated FBG sensors

This chapter presents the experimental development of a new generation metal packaged magnetic FBG sensor using stainless steel and tin, together with high temperature resistant samarium cobalt magnet. These packaged sensors can be placed in direct contact with the substrate structures such as iron pipelines and other ferromagnetic components without any adhesives, making them easily detachable and
The design of packaged FBG was characterised for load, temperature and vibration and these experiments were validated numerically using FEM through ANSYS [71].

**Chapter 5: The study of directional sensitivity of fibre Bragg gratings for acoustic emission measurement**

This chapter presents and highlights the unique property of directional sensitivity as observed in different types of FBGs towards AE induced by the impact of metal ball dropped onto a metallic substrate. The results obtained from the FBGs are validated by comparing them with FEM modelling and with analytical predictions.

**Chapter 6: Application of FBG based acoustic emission detection system in crack monitoring in welding**

This chapter presents a comprehensive study of crack monitoring during welding using a set of 3 FBGs including the framework, experimental arrangement, data acquisition and subsequent analysis. Cold crack monitoring of the welding is done using a set of 3 polyimide coated FBG sensors, both packaged and unpackaged. The crack locations are theoretically predicted using a method of linear localization based on the differences in the time of arrival (ToA) of the AEs on to different FBG sensors. For further clarification, the base plate on which welding is done is cut and a section of it is placed under a scanning electron microscope (SEM) to cross check the presence of the cracks.
Chapter 2

Fibre Bragg Grating based Acoustic Emission Measurement System for Structural Health Monitoring Applications

Fibre Bragg gratings are an excellent option to monitor micro cracks in engineering structures due to their ability to measure crack induced acoustic emissions and thereby have a great potential in SHM to ensure the safe operation of structures. In this chapter, various methods and technologies to monitor AE using FBGs have been reviewed and discussed. This comprehensive review provides a detailed evaluation of the evolution of various FBG based AE systems from the outset to state of the art for acoustic and ultrasonic sensing for their use in different SHM applications. Recent trends and future challenges for AE sensing interrogation methods are also discussed.

2.1 Introduction

It is known that civil, aerospace, marine, pipeline, and mechanical infrastructures deteriorate after being built due to ageing induced cracks, man-made hazards such as vehicle collisions and blasts, and natural disasters such as earthquakes or hurricanes as mentioned in chapter 1 [72-74]. As the above mentioned sectors are strategically important to human life and safety, it is important to establish procedures to assess the deterioration of the structures over their serviceable life to facilitate the maintenance and/or rehabilitation planning processes in this modern society that encourages sustainable development. With the advances in optical fibre sensor systems especially FBGs, data acquisition, data communication and computational methodologies, instrumentation based monitoring has been a widely accepted technology to monitor and diagnose structural health. For currently existing structures, FBG sensors can be affixed onto the exterior, and for new structures, these FBGs can be implanted into them during the construction phase without any deleterious effect on their structural integrity [35]. The data from such SHM systems can provide early warning for jeopardised integrity of structures and thus help avoid severe losses. Such information is also helpful to adjust and modify better designs of similar architectures [35].
2.2 AE Sources and Events

AE refers to the generation of transient elastic waves during the rapid release of energy from localized sources within a material, which occurs due to the initiation and/or propagation of a crack in metals, surface degradation, including corrosion and delamination and matrix cracking in the case of composite materials. These acoustic waves can travel through all materials except vacuum [75]. As a crack propagates in a material, molecular bonds are broken and thereby release small amounts of energy. The energy released spreads throughout the surrounding material in the form of strain waves. These waves are minute deformations in the material with frequencies ranging from a few kilohertz to 3MHz. Other phenomena which can generate AEs include plastic deformation, inclusion or precipitate fracture, de-bonding of coatings, reversible processes like crystallographic phase transformations, melting or solidification, thermo-elastic effects, ferromagnetic and ferroelectric domain wall motion and friction between surfaces, fabrication processes like welding noise, rolling, forging, machining, drilling, mixing, grinding and valve sequencing and leak and flow like flow of single and two phase fluids and particles, leaks, gas evolution and boiling [76]. The position of naturally occurring AE sources is normally unknown and in order to locate the spatial location of a source, its orientation and magnitude, the source in three dimensional space should be located. Source localization can be calculated based on the arrival time differences of AE signals to various locations where the sensors are placed. Many researchers have studied the evolution of the amplitude of AE signals received during bending tests and fatigue tests on various samples.

A typical AE waveform is shown in Fig 2.1, which is generally a mixture of signal and noise. In order to discriminate between the noise and the signal a threshold value is set up assuming any signal which goes above the threshold value is to be considered as an AE. The amplitude of the AE represents the magnitude of the event and rise time is the interval between the time a signal is set off and the time when it reaches the maximum amplitude. AE duration and energy will also provide crucial information about an event. AE duration is the time taken from the triggering of the signal to the time the signal falls below the threshold value, while energy is measured as the area under the rise time and above the threshold. Transient AE waves can be of
three types - bursts, continuous and mixed [77]. Bursts are generated by defects according to the damage mechanisms and have shorter durations than the other types of transient waves. Continuous AE transients are produced when various signals emitted from many sources overlap in such a way that the amplitude does not fall below the threshold level. The background noise and rubbing in the structure are the main sources of continuous emission. Relevant AE information might be buried by noise preventing the identification of particular damage. Mixed AE transients combine bursts and continuous signals. They can be provoked by damage growth and accumulation and are often superimposed with ambient noise and rubbing [78, 79].

2.3 AE Monitoring Methods for SHM

There are several technologies being used for SHM currently such as methods based on the measurement of elastic waves, electromechanical impedance, vibration, strain sensitivity, magnetic particle, eddy current, radiography, ultrasonics and many others that can determine the location, severity, and extent of damage [80]. NDT is emerging as a key player in SHM due to its ability to establish correlations between non-destructively measured physical or derived parameters and quantitative information about anomalies [81]. Among the different techniques of NDT to detect the defects in the structure, the AE measurement technique, which detects stress waves generated by defects in materials and thereby allows continuous and real-time structural monitoring is well-known.
Current NDT technologies to measure AE employ sensors based on piezoelectric ceramics, especially PZT systems, field-programmable gate arrays, and Fabry–Perot (F-P) interferometers [82-84]. Though PZT based systems are the most common ones, they are not well suited to monitoring micro/nano crack activities and are unable to determine cracks deep inside the structures, have a tendency to de-bond or fracture under large stress and are bulky and susceptible to EMI. In addition to the above limitations, their size is not suitable for being embedded into a material without adversely affecting the material’s integrity. They also have limitations when used at high temperatures or in high-voltage environments and also have a low power handling capacity [85, 86]. These NDE techniques as discussed in chapter 1 are effective in detecting damage to materials and structures but less effective in monitoring the micro crack nucleation and propagation. Moreover these methods are more suited for laboratory conditions and due to their size and weight have certain constraints to be used for in situ SHM [8, 87]. Therefore, there is a great need to implement advanced and new types of sensors that can be integrated with structures, such as the ones based on optical fibres, allowing the in-situ monitoring of structures for micro cracking activities that are precursors to major failure.

OFSs are considered as an excellent technology with the highest potential for continuous real-time monitoring owing to their accuracy in carrying information, invulnerability to different types of interference, high reliability and versatility, small and light weight, high bandwidth, robustness and resistance to harsh environments, high sensitivity, ability to sense several parameters—strain, pressure, corrosion, temperature, and acoustic signals—chemical inertness, bio compatibility, and ability to be integrated into the system [88,90]. As mentioned in chapter 1 among the different types of OFS’s, FBGs are widely used and considered the most popular technology for implementing health-monitoring systems [33]. Furthermore, their multiplexing capability offers the possibility to dramatically reduce the cumbersome wiring requirements of traditional OFSs [34].

There are different kinds of AE OFS technologies such as F–P cavity sensors, fibre optic ring resonator sensors, fibre optic coupler AE sensors, and FBG AE sensors [91-99] which have their own advantages and disadvantages and are discussed in detail in the following sections. There are still many concerns to be resolved for developing a compact, accurate, stable and economical FBG AE interrogation system for large scale commercial engineering applications. This review provides the current
landscape of the various FBG based technologies for AE detection and its advantages and pitfalls.

2.4 Traditional FBG Interrogation Systems and their Inability for AE Monitoring

The interrogation system for FBGs plays an important role in determining measurand parameters such as sensitivity and range as it extracts the measurand information from the optical signals collected from the sensor heads. This information is typically encoded in the shift of the Bragg wavelength; therefore, interrogators are typically used to create a readout of the wavelength shift and provide measurand data [100]. The general requirements for an ideal interrogation method are high resolution and accuracy with a large measurement range, compatibility with multiplexing, high measurement speed, and cost effectiveness. Typically, a wavelength shift detection resolution ranging from sub-pico meters is required for most applications. A wide wavelength range (tens of nanometers) is required when the interrogating multiple FBGs have different Bragg wavelengths and should be able to cope with multiplexing topologies, such as WDM. The cost of an interrogation system should also be competitive with that of other optical sensors or conventional electrical sensors [101].

In order to measure an AE-induced strain wave, the main hurdles to overcome are high data acquisition rate and sensitivity that is needed to recreate the AE signal and the amount of extraneous noise that the sensor detects through vibration and other interference. The conventional commercial FBG interrogation system is limited by its measurement frequency range of operation (most commercial systems are in the range of 1-10 kHz) and sensitivity (1-10 με) that would limit the system to measure AE signals. An ideal acoustic interrogation system should be one that can at the best be able to work in a frequency range of upto 10 MHz or higher and should have the capability to detect pico and femto strains as the AE induced strains from micro and nano-cracks/defects in structures would be in this range. Hence FBG interrogation system typically needs sub-micron wavelength resolution and high-frequency measurement capability for AE detection. The standard spectrum interrogation methods utilizing an optical spectrum analyser (OSA) and any other commercial interrogation systems with low resolution, low strain sensitivity, and low data acquisition rate cannot satisfy the
requirements of accurately detecting dynamic variations in an FBG’s central wavelength that are induced by AE events.

2.5 FBG Interrogation Systems for AE Monitoring

There are several approaches to effectively measure AE events using an FBG based system. Most FBG interrogation systems for detecting an AE signal operate on the principle of converting the dynamic shift in reflected Bragg wavelength into intensity variation of the output signal using an optical filter. Approaches have also been made by using an interferometer, where the dynamic shift in the reflected Bragg wavelength is converted to a change in phase of the output signal. In either of these methods, the acoustic signal-induced shift in the Bragg wavelength corresponds to either intensity or phase shift of the output wavelength and can be interpreted using signal processing systems to detect the defect in the structure [102]. Based on this operating principle we have classified the technologies into major groups as listed below.

2.5.1 Power Detection and Edge Filter Detection Methods

In the power detection [103] method, a broadband source is used to illuminate an FBG and a filter is used to demodulate the Bragg wavelength shift by converting it to an optical intensity shift. This method has multiplexing ability, but it has relatively low sensitivity because of the physical nature of the broadband light source. On the other hand, in the edge filter technique [45, 104, 105] a tunable laser source (TLS) is used to adjust the source wavelength to the linear region of the FBG signal spectrum. In this method, a spectrally dependent filter is used to detect any dynamic shifts in the FBG wavelength spectrum and converted to intensity variation by the wavelength dependent filter. The sensitivity is relatively high for edge filter detection compared to power detection method as the noise level in the TLS is lower than that of the broadband laser source. A number of different edge filters are reportedly used, such as a matched FBG, a linear edge absorption filter, an interference filter, a WDM coupler, an arrayed-wave guide grating (AWG), and a dense wavelength division
multiplexing (DWDM) filter. Optical configurations of the edge filter and power detection methods are illustrated in Fig 2.2 (a) and (b) respectively [105]. One of the earliest studies of FBG-based AE was conducted by Perez et al. in 2001 [98] where a matched FBG was used to demodulate the detected optical signal. C.Hu et al. and Wilde et al. also used the edge filter interrogation methods to measure AE events [105, 106]. A multi-parameter all fibre optic-based structural health monitoring (AFOSHM) was also demonstrated by C.Hu et al. Their system was used to measure the strain, temperature, and cracks using a single mode-multimode fibre configuration and employing an edge filter interrogation technique [106].

2.5.2 AE Detection Using an Optical Fibre based F-P Sensor and Quadrature Recombination Technique

The working principle of this system is to combine and launch two optical signals with different wavelengths through a 3dB coupler in a FBG-FP cavity. Raja et al. demonstrated that setting the laser wavelengths in quadrature can enhance the
AE sensitivity of the system [107]. This is achieved by having one of the lasers tuned to the most sensitive region of the spectrum of the cavity and one laser tuned to the least sensitive region, as shown in Fig 2.3. Therefore, the first laser signal can be expressed as the function of \( \sin (\phi) \), and the second laser signal can be expressed as a function of \( \cos (\phi) \), where \( \phi \) is the phase shift due to AE. The reflected signal from the two lasers gathered from the photo detector is processed and recombined employing a signal processing system. A fixed frequency (\( \omega_c \)) oscillator carrier signal is combined with these signals to generate the \( \sin (\omega_c t + \phi) \) signal, which corresponds to the change caused by the AE signal [108]. As the wavelengths of the laser are set in quadrature, the sensitivity can be improved and measurement of high acoustic frequency is possible. However, the disadvantage is that the lasers should be tuned manually to the quadrature point and further research needs to be done to make the

![Figure 2.3: Fabry-Perot and quadrature recombination technique for AE monitoring [107]](image)

system more compact and to increase its acoustic frequency range.

2.5.3 FBG Acoustic Sensors by Altering the Physical Configurations of Gratings

The principle behind this ‘modified FBG sensor’ is the relation between the spectral response of the FBG and the ratio of the grating length to the AE/ultrasonic signal wavelength. If the wavelength of the ultrasound becomes similar to the grating length, the FBG spectrum can be highly distorted because the grating will be subjected to a differential internal longitudinal strain gradient. Typically, shorter FBGs are chosen
to enhance the sensitivity to temperature and AE induced strain. An AE sensor with wider temperature and strain sensitivity, capable of pure AE detection and having high mobility similar to commercially available PZT, has been designed and experimentally demonstrated by J. Lee et. al [30]. The FBG based AE interrogation system used in this study employs a narrow band tunable laser diode (TLD) source. The pitch of the FBG is modulated by the AE generated and the reflected intensity variation is detected by the photodiode. The wavelength of the laser is tuned to the mid reflection wavelength of the FBG and the strain sensitivity is on the order of \( \frac{p\varepsilon}{\sqrt{Hz}} \), thus suited for acousto-ultrasonic measurements. Lee et. al. reduced the size of the FBG to 1 mm length and 125 \( \mu \)m diameter in order to compensate for the fade out problem faced by a 10 mm-long FBG as the temperature sensitivity of the FBG is 10pm/°C. 1 mm FBG has an operating range of 280 pm which corresponds to ±14 °C.

To make the FBG acoustic sensor mobile, a special sensor head was created where FBG was glued onto a small 1.6 mm-thick acrylic plate by Lee et. al, as shown in Fig 2.4. This light weight design allows easy propagation of the acoustic waves through the acrylic plate. This acrylic plate and the test structure coupled with a liquid interphase material such as vacuum grease or water, which makes the sensor head highly mobile as any gripping device is totally unnecessary. For this modified FBG to be used as an AE sensor for monitoring of structures, the strain sensitivity of the FBG should be isolated from the mechanical load induced strain. This changes the Bragg wavelength, making the narrowband demodulation impossible. The acrylic base plate, introduced to make the FBG acoustic sensor more mobile, also becomes ideal to solve

**Figure 2.4:** A method for monitoring the AE using FBG [30]
this problem, because the mechanical strain cannot be transferred into the FBG sensor coupled with the silicon grease or water. This design of the FBG sensor head has an operating region of 280 pm, highly mobile, immune to interference by mechanical strain, allowing the wider operating ranges of ±14 °C and ±112 με in terms of the temperature and AE wave-induced strain amplitude, respectively.

The sensitivity of FBGs was compared by varying the length of the sensor part by DC Seo et. al who found that the sensitivity of the longer grating part was higher. They also compared using 2 types of sensor heads where one was fully bonded to the sensing element and the other was only partially glued at one end and the other end was lying free acting like a cantilever. They have shown that cantilever type sensor has high resonance frequency and greater sensitivity [109]. Cusano et. al have demonstrated that the sensitivity of FBGs in pressure and acoustic detection can be enhanced by coating the grating region with a material of lower elastic modulus than the optical fibre [110]. For a given acoustic pressure, the basic effect of the FBG coating is to enhance the dynamic strain experienced by the sensor of a factor given by the ratio between the fibre and the coating elastic modulus. According to this, an opportune coating can tailor the sensor directivity, the bandwidth and the acoustic sensitivity in water [111]. Sensitivity can be improved by different packaging techniques [112]. Sensitivity of FBGs can be enhanced by reducing the diameter of the FBG and thereby that of the FBG itself which can reduce the mechanical resistance of the FBG [113]. The effects of modifying the various configurations of the sensors on the sensitivity are shown in table 2.1.

<table>
<thead>
<tr>
<th>Modification</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increasing length of the grating</td>
<td>Higher</td>
</tr>
<tr>
<td>Fully bonded</td>
<td>Less</td>
</tr>
<tr>
<td>Cantilever type</td>
<td>Higher resonance frequency</td>
</tr>
<tr>
<td>Coating material of less elastic modulus</td>
<td>Higher, can tailor directivity and bandwidth</td>
</tr>
<tr>
<td>Magnetic packaging</td>
<td>Enhances</td>
</tr>
<tr>
<td>Reduced diameter</td>
<td>Enhances</td>
</tr>
</tbody>
</table>
2.5.4 Spectrometric FBG interrogation system

One of the major challenges when dealing with the AE signal is that the interrogation measurement speed should be in the scale of hundreds of kHz to sense an acoustic signal, as discussed in section 2.3. In recent years, high speed wavelength interrogation techniques have been developed with speeds over 100 kHz. These techniques include Fourier-domain mode-locked lasers, wavelength-tunable mode-locked lasers and wavelength-swept lasers based on fibre vibration which are bulky, costly and highly complex. For frequencies below 1 kHz, wavelength sweeping by mechanical moving parts such as TLS and F-P filter wavelength interrogation techniques are typically used. For the measurement frequency over 1 kHz, Bragg wavelength shifts should be converted into optical power by means of suitable optical filters without introducing any mechanical moving parts. Suitable filters include matching FBGs [98], long period fibre gratings [114], laser diodes [115], and AWGs [116]. Schematic of FBG interrogation systems using an AWG are shown in Fig 2.5. The reflected optical intensity at the photo detector is altered depending on the shift in the FBG spectrum and thus the wavelength shifts can be recorded. The laser diode can be replaced with a TLS, which has high resolution and accuracy, but it is costly and cannot interrogate multiple FBGs. An AWG can address these disadvantages and acts as a wavelength dependent optical filter which has two channels, a rising edge and a falling edge. The Bragg wavelength is set halfway between two AWG channels.

![Diagram of FBG interrogator system using an AWG](image)

**Figure 2.5**: FBG interrogator system using an AWG [7]
Therefore, if there is any shift in the FBG reflection spectrum, it will be detected as a change in the optical intensity of the reflected laser source. The AWG is one of the main components used in optical multiplexing, such as WDM [7]. A wavelength interrogation system, based on an echelle diffraction grating (EDG) based on planar light wave circuits technology has been designed recently. This interrogation system based on this EDG chip has the same functions and is able to achieve a wavelength resolution of less than 1 pm with a measurement accuracy of ±10 pm.

### 2.5.5 Bragg Grating based laser sensor system with interferometric interrogation and WDM

The potential of FBGs to be used as spectrally narrow band reflectors for creating in-fibre cavities for fibre lasers has been utilized in this configuration. As an example, Koo et al described the use of FBG based lasers as sensors [117] An interferometric detection technique is demonstrated for interrogating laser wavelength shifts due to measurand induced laser cavity strain with high resolution. WDM approach is adopted to demonstrate the principle of integrating multiple sensors to make FBG arrays. The FBG laser sensor (FBGLS) consists of a finite length of erbium-doped fibre with an optically matched FBG on either end, that act as the laser

![Figure 2.6](image)

**Figure 2.6:** Interferometric interrogation along with WDM [117]
The light from the FBG source is diverted through a WDM coupler to the Mach-Zehnder interferometer (MZI) interrogation system as shown in Fig 2.6. Any shift in wavelength is converted to interference pattern phase shifts by the MZI [117]. The phase modulation is determined by the product of the laser cavity strain and the imbalance in the path of the interferometer. For a single-mode FBGLS, the interferometer phase shift is dependent on the output wavelength (or optical frequency) and the interferometer optical path difference (OPD). The line width of the laser emitted is very narrow with correspondingly large coherence length, so that a large OPD can increase the sensitivity of the system. A $2\pi$ phase shift was introduced at the MZI output by applying a test signal to produce strain on the fibre laser cavity and the spectral output from the MZI was recorded by a dynamic signal analyzer. This interferometer phase noise corresponds to a FBGLS strain resolution of $5.6 \times 10^{-14}/\sqrt{\text{Hz}}$. The strain resolution was limited by the thermally induced cavity length fluctuations of the laser. Similarly, in the multimode FBGLS a strain resolution of $7 \times 10^{-15}/\sqrt{\text{Hz}}$ was obtained.

### 2.5.6 Intensity demodulation fibre ring laser sensor system for AE detection

One of the issues relating to AE is the availability of low cost, high sensitivity AE measurement systems. A commonly used FBG interrogation system uses a narrowband laser source whose spectrum is tuned to match the central wavelength of the linear region in the reflected FBG spectrum, thus performing an intensity-based demodulation. As explained in the previous sections, detection sensitivity also becomes unstable when the acoustic signal wavelength becomes comparable to the length of the gratings, grating wavelength. Having a narrow bandwidth tunable laser source also increases the cost incurred for the system; therefore, a fibre ring laser (FRL) with a narrow bandwidth tunable optical band-pass filter (TOBPF) was demonstrated by Han et. al [118]. The system contains a conventional FBG sensor as the sensing element in the cavity of the FRL, which modulates the intensity in accordance with the presence of an ultrasonic signal. The extremely narrow bandwidth of TOBPF ensures that the FRL strictly sources a frequency in the linear region of the reflected spectrum of the FBG. The key benefit of this approach is a highly sensitive tool to capture AE signals at low cost.
As shown in the Fig 2.7, the FRL consists of an erbium doped fibre that is fed by a laser diode along with an optical fibre isolator to ensure that unidirectional lasing occurs in the system. When an AE is detected by a conventional FBG, which causes the reflected spectral wavelength to shift, the TOBPF in the lasing cavity loop ensures that the laser source transmitted spectrum is so narrow that it falls exactly on the linear region of the FBG reflection spectrum. In accordance with the strength of the AE signal, a spectral shift is observed in the FBG. Furthermore, due to the highly align the laser spectrum, or the misalignment caused in the loop, the AE signal causes a modulation of the loss of the cold cavity of the FRL. Therefore the output intensity of the FRL varies according to the loss modulation. A photo detector placed in the loop can detect the variation in output power from the laser, which, in turn, detects the presence of an ultrasonic signal. This proposed idea has been theoretically demonstrated to be effective in detecting the presence of a high-frequency ultrasonic signals as well as low-frequency strain applied on a structure [118].

Figure 2.7: FBG Interrogation using FRL Sensor for AE Detection [118]
Table 2.2. The commercial FBG AE sensors and their specification [102,119-123]

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Frequency property (kHz)</th>
<th>Resolution</th>
<th>Wavelength accuracy</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ibsen Photonics A/S</td>
<td>I-MON 256 HS</td>
<td>35 (Measurement frequency)</td>
<td>&lt; 0.5 pm</td>
<td>5 pm</td>
<td>Impact</td>
</tr>
<tr>
<td>Smartfibres Inc.</td>
<td>Smartscan</td>
<td>25 (Scan frequency)</td>
<td>&lt; 5 pm</td>
<td>Impact</td>
<td></td>
</tr>
<tr>
<td>Redondo Optics, Inc.</td>
<td>FBG-TransceiverTM-500</td>
<td>20 (Sampling rate)</td>
<td>5 pm</td>
<td>5 pm</td>
<td>Impact</td>
</tr>
<tr>
<td>FAESense</td>
<td></td>
<td></td>
<td>585 (AE frequency)</td>
<td>0.1 με/Hz</td>
<td>Ultrasonic</td>
</tr>
<tr>
<td>Intelligent Fibre Optic Systems Corporation</td>
<td>I*Sense® HS48M</td>
<td>Maximal 3000 (detection speed)</td>
<td>0.1 pm</td>
<td>2 pm</td>
<td>Ultrasonic</td>
</tr>
</tbody>
</table>

2.5.7 Commercial FBG AE interrogation systems

Commercially available FBG AE interrogation systems are evolving from bench top laboratory instruments that were too cumbersome and heavy to be permanently installed in an operational platform to field deployed models with rugged designs. Now there are several commercially available FBG-based AE interrogators as summarized in Table 2.2 [102]. The AE frequency range of these devices varies up to 10 MHz, with a resolution ranging from 0.1 pm to 5 pm and accuracy from 2 pm to 5 pm. Several emerging applications of FBG sensors where dynamic/AE strain sensing is required have prompted many industries to improve their device specifications to compete with other traditional systems.
2.6 Applications of FBG based AE monitoring system and its market potential

OFSs have their applications in various fields such as SHM, seismic monitoring, transformer partial discharge diagnosis, underwater acoustic monitoring, aerospace safety, airborne acoustic detection, photoacoustic spectroscopy, photoacoustic imaging and other such fields [28,29], this section will discuss the applications of the FBG based AE monitoring system in detail. The most common applications of FBG AE systems are in SHM for smart structures to monitor initiation and propagation of cracks and micro fractures. FBG based AE detection has been successfully demonstrated in a wide range of applications such as SHM in the civil, aerospace, and marine engineering, human biometric health monitoring in the medical industry and several other applications [124].

In the aerospace sector, the rise in the demand is pushing aircraft to be used beyond their service life [124, 88] and hence there is an increasing need and effort to be made in inspection and maintenance to ensure the safety of the operating aircraft. Research has proven that monitoring of AE can be a low-cost and effective solution to this problem. The simplicity with which these sensors can be incorporated in both existing and new structures can increase the demand for this technology. The routine health inspections for these structures involve not only NDT but also disassembling and re-assembling, which may cause more damage to the parts of the vessel. Paving the foundation for next-generation technology, smart sensing technology can completely eliminate the conventional and complex costs associated with these routine inspections and replace them with real-time on board monitoring to improve operational life cycle, reliability and safety [125]. Recently, shape memory alloy (SMA) wires were integrated into composite structures to create “smart composites” with ability to control the shape and mechanical properties of composite structure. FBGs embedded into SMA based composites are highly reliable sensors as they are able to provide static and dynamic strain information on the SMA actuators’ operation [126]. Detection of impact damage either due to bird strike, hail or during ground service operations are also of great importance to the aerospace sector. Surface mounted FBGs and high speed interrogation systems were used to monitor this impact damage on aircraft. One such example is where FBG sensors were used to monitor dynamic strain in a structure simulating a typical aeronautical structure and employing a neural network based system to identify
damage in a composite specimen. An example of this is shown in Fig 2.8 where the FBGs are compared with strain gauges and thermocouples [127].

![Configuration of the flying test bed and sensors. Measurement position coordinate is for the FBG, strain gauges and thermocouples on the stringer [127].](image)

**Figure 2.8:** Configuration of the flying test bed and sensors. Measurement position coordinate is for the FBG, strain gauges and thermocouples on the stringer [127].

In marine engineering and marine applications, the effect of cavitation erosion has been the main challenge to structures. The cost incurred to these industries due to this cavitation erosion amounts to millions of dollars across the world [128]. Due to the damage inflicted by vortices, caused by cavitation, microbubbles build up gradually. The micro cavity, which produces ultrasonic shock waves, in turn erodes the solid material from the marine structure. These acoustic waves of high frequency are related to crack formation and propagation through the surface of the material. Therefore, effective AE detection and monitoring systems are required to prevent cavitation erosion.
There has been tremendous growth in research and development in the field of FBG based AE monitoring in SHM for civil engineering applications including buildings, piles, bridges, pipelines, tunnels and dams. Apart from the monitoring of bridges as discussed in chapter 1 and shown in Fig. 2.9, FBGs are used for monitoring of mines by measuring load and displacement using multiplexed FBGs. Civil infrastructures with embedded FB with embedded FBGs can predict structural failures. In order to protect buildings and structures from shocks which result from earthquakes, piles are used. 30 FBG sensors were multiplexed into arrays each containing 6 optical fibres for monitoring a 60 ft high and 2 ft diameter marine pile. Among these fibres were 4 FBGs which were used for monitoring strain and two were used for monitoring temperature. The FBGs were monitored using a FP TLS technology [129]. Safe monitoring of construction and maintenance of railway tunnels are also demonstrated using FBGs. Another example of testing of pile foundations was carried out in a new factory in Taiwan, where piles of diameter 1.2 m and length of 35 m were used and nine 4 m long gauge fibre optic sensors (LGOFS) were used to test compression and pull out on the pile and strain and load eccentricity. Sixteen 4 m LGFOSs were installed to monitor the average curvature, Young’s modulus, longitudinal strain and vertical displacement forces on the piles, as well as the properties of soil, critical strain when cracks occur in the pile, loading capacity of the pile and failure mode [46].

Another application of FBG AE systems is in road traffic monitoring. A dynamic traffic testing system was developed by Udd et. al. who used 28 specially designed FBG traffic sensors among which 26 survived. These sensors had a 0.1 micro-strain resolution with a 400 micro-strain range at 10 kHz sampling rate which can satisfy traffic monitoring requirements [130]. Another example of the traffic monitoring using FBGs was implemented in the I-84 freeway in the USA, to test the sensors and the traffic counter over a period of half a year. The sensors were capable of easily discriminating tractors, buses and trailers and also the traffic in adjacent lanes as well. The signal’s amplitude is closely proportional to the weight of vehicle, speed of a
vehicle and the direction of the driving vehicles. The applications of different FBG based acoustic sensors discussed are summarized in Table 2.3.

Figure 2.9: FBGs used for monitoring bridges using (1) hanger cable, (2) rocker bearing, (3) truss girders [46].
TABLE 2.3. Comparison between different FBG AE interrogation technique and their applications [7,24,106-107,114-117.]

<table>
<thead>
<tr>
<th>Application</th>
<th>Wavelength Interrogation Method</th>
<th>F-P Sensor with Quadrature Recombination</th>
<th>Interferometric and WDM Interrogation Approach</th>
<th>Intensity Demodulation Using FRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>- SHM in aerospace&lt;br&gt;- Operational load and damage detection</td>
<td>- Failure detection of structures in aerospace industry&lt;br&gt;- SHM in composite structures</td>
<td>- Detection of low-frequency impact/impact test&lt;br&gt;- Detection of acoustic range signals</td>
<td>- Application extended to SHM for composite structures, aerospace, marine etc.</td>
<td></td>
</tr>
<tr>
<td>Multiplexing capability</td>
<td>- WDM</td>
<td>- Not experimentally demonstrated</td>
<td>- WDM</td>
<td></td>
</tr>
<tr>
<td>Detectable sensitivity</td>
<td>1 με</td>
<td>-</td>
<td>- 7 x 10^{-15} ε/√Hz</td>
<td></td>
</tr>
<tr>
<td>AE frequency measurement</td>
<td>- Up to 500kHz</td>
<td>- Up to 600kHz</td>
<td>- Tested for up to 10kHz</td>
<td>- Suitable for &lt; 400kHz</td>
</tr>
<tr>
<td>Advantages</td>
<td>- Easy to multiplex multiple sensors&lt;br&gt;- Robust and low cost&lt;br&gt;- Easy to install on structures</td>
<td>- Capable of compensating for environment perturbation&lt;br&gt;- Compatible with different fibre optic sensors</td>
<td>- Very fast response&lt;br&gt;- Highly sensitive real-time system</td>
<td>- TOBPF compensates for unwanted low-frequency wavelength shifts&lt;br&gt;- Robust and simple setup&lt;br&gt;- Potentially low cost</td>
</tr>
<tr>
<td>Disadvantages</td>
<td>- Trade-off between sensitivity and accuracy&lt;br&gt;- Difficult in tuning the two lasers for initial setup&lt;br&gt;- Not cost effective</td>
<td>- Capable of detecting only low-frequency acoustic signals</td>
<td>- Not suitable for AE with low-frequency range</td>
<td></td>
</tr>
</tbody>
</table>
As seen above FBGs are one type of low cost sensors with the ability to sense various parameters like strain, temperature, pressure and acoustic emissions. FBGs possess useful characteristics like multiplexing ability, which make them supreme in being implemented in a variety of applications in various fields and industries. FBG market comprises sensors, interrogation systems and servicing. The combined present global market size of the FBG sensors and arrays segment is estimated to be in the range of $15M to $35M USD a year, with an annual growth rate of 15% to 25% [131]. Market surveys indicate that at 25.3% compound annual growth rate, the FBG market size is expected to reach 2070 million USD in 2024. With proper packaging and publicizing techniques, FBG sensing and interrogation industry will grow tremendously in the coming years.

2.7 Conclusion

This chapter provides an extensive review of the state-of-the-art technology for AE interrogation employing FBG optic sensors. The research evaluates the current conventional FBG interrogation systems and points out the limitations in terms of their application and implementation in AE. Upon advancement in technology, the rise in demand of industrial standards has necessitated a periodic structural monitoring for various industrial facilities. AE has proven to be an effective indicator and monitoring tool for SHM. Replacing the conventional PZT sensors with optical fibre sensors has proven to be more efficient in terms of the following: sensitivity enhancement of the system; ruggedness of the system; the possibility of multiplexing in sensing systems; enhancing the longevity of the installed sensing system; speed of capture/detection of an event; immunity to noise/capability to filter out noise as an inherent feature of the system. The current costs associated with FBG sensing systems is higher than for conventional systems, but with future research in the field of fibre optic sensing and wider application, this cost is anticipated to reduce exponentially. Therefore, a commercially cost-effective option should be rolled out soon, broadening the scope of its application in various fields of engineering.
Chapter 3

AE Data Analysis Methodology

This chapter presents the methodology for the analysis of AE data from an FBG based AE sensing system. Typical AE data consists of the original acoustic event contaminated with noise and various unwanted frequencies from the interrogator/analyser due to sampling and instrumentation related issues. Once the AE data is recorded, signal processing techniques are used to analyse and extract the true information from the data. The AE signal thresholding and de-noising are therefore significant steps in the data processing of AE data from FBG sensors and their related interrogators. Effective de-noising and pre-processing techniques will improve the signal to noise ratio (SNR) of the AE signal as well as eliminating the unwanted frequencies in the system originating from the instrumentation hardware processing. A GUI in MATLAB for signal thresholding and wavelet de-noising for processing the AE data is developed to process the data obtained in this thesis study. The objective of this chapter is to develop a signal processing technique that will eliminate the problems of noise in the analysis of AE data to allow the data to be tested in real time. Upon completion of the data analysis the amplitude and frequency of the AE signal will be known. This knowledge can be used to determine if an AE event has occurred and depending on its magnitude, the health of the structure under test can be evaluated.

3.1 Introduction

The increasing use of FBG based AE measurement for SHM subsequently implies the need to develop a signal processing technique that will aid in avoiding problems of noise in the analysis of the AE data. Several methods were implemented by researchers for eliminating the noise components present in the AE data. Different methods include AE hit lockout time (HLT), hit definition time (HDT), peak definition time (PDT) [77] and methods based on wavelet transformation (WT) tool such as Daubechies de-noising and Haar de-noising [132-134]. Among these methods, wavelet de-noising method is one of the most commonly used approaches. De-noising methods based on wavelet theory include the wavelet coefficient modulus maxima method [135], the wavelet correlation method [136], and the wavelet thresholding method [137]. The techniques of wavelet transforms have been used by many
Researchers for the processing of AE data [138,139]. The main property of the wavelet transform, as shown by González-de-la-Rosa et. al. in [140] and Qin et. al. in [141], is that the wavelet filters that are used to de-noise the signals is effective, although the AE signal does suffer some attenuation losses due to the wavelet de-noising transform, the AE signal is still sufficient for analytical purposes. Bianchi et. al. [142] proposes that the wavelet packet transform, which not only de-noises the signals but offers a high possibility for real time monitoring of AE signals in an event based scheme. The wavelet thresholding method was used to reconstruct useful AE events by threshold determination where the threshold has to be optimised. However if the threshold is too low, the noise is retained along with a signal. Alternatively, if the threshold is too large, a useful amount of information is filtered out.

AE measurement using FBG sensors has certain limitations since the typical AE data contains background noise from various sources such as Gaussian noise and white noise sources. Due to this noise contamination, signal processing and data analysis are tedious tasks. Other issues are the high data acquisition rate and difficulty of simultaneous data processing. This makes extracting the actual AE event from the measured data a daunting task. In the work presented in this chapter, a GUI in MATLAB for AE data analysis and de-noising has been propounded. The process of de-noising is performed by using a wavelet transform method, where an optimal threshold value is selected to eliminate the maximum noise. Once the data has been recorded and is ready to be evaluated, time-frequency techniques will be used to process the signal and a software package is used to complete wavelet transform de-noising and perform a short time Fourier transform (STFT) analysis on the signal. Misti et. al have emphasized that the disadvantage of STFT is that the time and frequency window are fixed [143]. The STFT can provide both the frequency analysis of the waveform not only with the amplitude but also at the given time of the event.

Due to the large amount of ambient noise that is also recorded by the sensor, when the signal is analyzed through de-noising methods the AE data is attenuated. This is a problem because whilst de-noising the data, the AE signal might also be lost or corrupted. As there are no current methods to monitor AE data in real time the data acquisition time taken to analyze and respond to an AE event is vital in all future research into AE data analysis. The following sections in this chapter provide an
overview of the data acquisition and analysis methodology used to process the AE data obtained in this thesis study.

3.2 FBG AE Interrogation System and AE Data Acquisition

In this research, a commercial fibre optic acoustic emission sensor (FAESense M400 from Redondo Optics Ltd) system possessing the ability to interrogate multiple FBG sensors sensitive to acoustic events that induce micro/nano level strains was used. The system has a maximum measurement rate capability of up to 1.16 MHz and a 3-dB acoustic frequency range up to 100 kHz and is shown in Fig 3.1(a). This AE interrogator operation is based on adaptive two-wave mixing (TWM) interferometry [144] and consists of a novel TWM interferometer waveguide design for the ultra-wide frequency FBG acoustic emission sensor. The correlation between the dynamic wavelength shift ($\Delta \lambda_B(z,t)$) and relative phase shift induced by the unbalanced interferometer in the interrogator is given by:

$$\Delta \lambda_B (z, t) = \Delta \phi(z, t) \lambda_B^2 / 2\pi nd, \quad (3.1)$$

where $d$ is the optical path length difference of the TWM interferometer, $\lambda_B$ is the peak reflected wavelength of the FBG, $\Delta \lambda_B$ is the dynamic wavelength shift and $\Delta \phi$ is the relative phase shift, $z$ is the axial direction along which longitudinal strain propagates and $t$ is the time.

The FAESense system uses an advanced micro-controller-based ultra-high sampling frequency optoelectronics PC board, which has high data rate signal processing for FBG sensor calibration and for the analysis of acoustic emission signals. The interrogator system also employs a custom developed Lab View based GUI that enables easy data acquisition and remote control from the FAESense system. This system also has an ultrafast USB data transfer interface, which displays both time and frequency domain status signals of the FBG sensor array in real time to enable detection. This enables the detection, localisation and triangulation of the dynamic AE signals. The basic experimental arrangement for the FAESense interrogator system is shown in Figure 3.1(b). The arrangement for a typical experiment consists of an FBG or an FBG array that is attached to a substrate on which the AE is to be generated and one end is connected to the FAESense interrogator system as shown in the fig 3.1(b). The interrogator system is subsequently connected to the computer where the data
acquisition is performed. The FAESense interrogator system provides the benefit of a higher sampling rate of 1.16 MHz that can aid in analysing the cracks at a higher frequency compared to the conventional PZT based AE detection techniques. The specifications of the commercial FAESense interrogator system are shown in Table 3.1.

Figure 3.1: (a) FAESense Interrogator (b) schematic of AE interrogation experiment

Table 3.1: The performance specifications of the FAESense M400[122]

<table>
<thead>
<tr>
<th>Monitoring Principle</th>
<th>Adaptive Two wave mixing interferometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>FBG Sensor channel</td>
<td>2-4 acoustic emission transducer per sensor fibre</td>
</tr>
<tr>
<td>AE Frequency range</td>
<td>DC to 5850 kHz</td>
</tr>
<tr>
<td>Frequency sensitivity</td>
<td>0.1 micro strain/Hz</td>
</tr>
<tr>
<td>Frequency resolution</td>
<td>1 kHz</td>
</tr>
<tr>
<td>Frequency accuracy</td>
<td>+ 1% of the reading</td>
</tr>
<tr>
<td>Frequency bandwidth</td>
<td>3 dB from 1 kHz to 300 kHz</td>
</tr>
<tr>
<td>Graphical interface software</td>
<td>Adaptive sensor fusion prognostic analysis (LabView)</td>
</tr>
<tr>
<td>Data communication</td>
<td>Ultra-fast USB, Ethernet wireless, Wi-Fi, Bluetooth</td>
</tr>
<tr>
<td>Power supply</td>
<td>Main plug Appliance NG 16, 12 V/500 @ 10 mA/ch.</td>
</tr>
<tr>
<td>Weight</td>
<td>&lt; 250 g</td>
</tr>
<tr>
<td>Dimensions</td>
<td>2 inch (W) x 2-inch (T) x 4 inch (L)</td>
</tr>
</tbody>
</table>
The data from the FAESense interrogator is in a processed data format and is stored in 6 channels. Channels 2–5 represent specific wavelengths namely 1520 nm, 1530 nm, 1540 nm and 1550 nm, respectively and are used for FBG sensor output. Channel 1 is for power, and channel 6 is for reference, as shown in Fig 3.2. Due to the large data size, a high-performance computing machine with a RAM of 64 GB was used to process the acquired data. To minimize the processing time and to establish a standard procedure for the analysis, a GUI using MATLAB code has been developed to convert the processed data file into a text file and for further processing which is discussed in later sections of this chapter.

![Image](image.png)

**Figure 3.2:** The user interface from FAESense interrogator system showing the various channels

### 3.3 Signal Processing Techniques

The signal processing and data analysis process followed in this thesis is shown in Fig 3.3. The recorded AE signal obtained during the course of this research is usually a mixture of background noise and the original AE signals. To extract the original acoustic signal, therefore, de-noising methods need to be applied. In this thesis work,
the de-noising was performed using a wavelet transform (WT). The GUI for this employs the steps depicted in the flowchart shown in Fig.3.4. The traditional de-noising methods use the technique of thresholding where the threshold values have to be set in such a way that noise is eliminated and data is extracted.

**Figure 3.3:** A flowchart depicting the signal analysis process carried out in this thesis

**Figure 3.4:** Principle of proposed AE signal processing approach
De-noising using wavelets is based on the WT theory, which uses a family of wavelets to obtain inner products of the signal to be de-noised $x(t)$. A family of wavelets consists of a series of son wavelets generated by dilating and translating a mother wavelet. The wavelet transform used to de-noise the signal represents a windowing technique with variable window size and is one of the most effective approaches for decomposing time series signals. The wavelet transform enables the decomposition, post-processing and further reconstruction of a signal. It is a tool that cuts up data, functions or operators into different frequency components and further studies each component with a resolution matched to its scale [145]. The WT deals with different frequency ranges by splitting the signal into shifted or scaled versions of the original (mother) wavelet. Unlike Fourier analysis of a signal, in which time and frequency have fixed windows over all types of frequency, the wavelet analysis allows a variation in the size of the window over different frequency-time relations [146]. Figs. 3.5(a) and 3.5(b) below show the difference between the windowing techniques that are used in the Fourier transform of a signal compared with the wavelet transform of the signal. STFT is represented in the two dimensional grid shown in Fig 3.5(a) where the horizontal axis represents the time extent of each window and the divisions in the y axis represent frequency. The intensity of the colour of each window is inversely proportional to the frequency of the signal, the darker the shade, the lower the frequency of the monitored signal component. If the width of the window is large, the information about different frequencies is greater. The time frequency representation of the WT is shown in Fig 3.5(b). The quantities $\Delta t$ and $\Delta \Omega$ represented in the figure denote a change in time and frequency, respectively.
To achieve an effective representation of a low-frequency signal, a larger time domain window is needed in relation to the length of the window in the frequency domain and similarly a smaller time domain window is needed for reconstruction of a high frequency signal [147,148]. In order to overcome the shortcoming of fixed window size, the window size was replaced by compressing and stretching the fixed size windows, leading to more accurate and reliable results. A dilated and translated function known as a wavelet was used for better analysis.

The procedure of signal de-noising using wavelet transform for this work includes the following steps. (i) The signal is decomposed to level N to obtain the coefficients. (ii) A thresholding is performed on the N signal details using threshold selection and either a soft or hard thresholding is then applied [149,150], by considering a basic model of the noise, hard thresholding is used as it is simpler than soft thresholding. If the threshold is denoted by \( th \), the hard threshold signal \( x \) is \( x \) if \( |x| > th \), and is 0 if \( |x| < th \).

The soft threshold signal \( x \) is \( \text{sign}(x) \frac{|x| - th}{|x| - th} \) if \( |x| > th \) and is 0 if \( |x| < th \). Hard thresholding is the operation of setting the elements to zero whose absolute values are lower than the threshold. Soft thresholding is an extension of hard thresholding, where the elements, whose absolute values are lower than the threshold, are set to zero and
then the non-zero coefficients are shrunk towards 0. The hard procedure creates discontinuities at $x = \pm th$, while the soft procedure does not. The hard and soft threshold functions are shown in Fig 3.6 for threshold $th = 0.5$

![Image of original and thresholded signals](image)

**Figure 3.6** Original and thresholded signals [150]

Finally, (iii) the signal is reconstructed using the original approximation coefficients of the N$^\text{th}$ level and the modified detail coefficients of all levels. The equation given below shows the representation of the WT with $x(t)$ being the signal and $\psi(t)$ being the mother wavelet.

$$X_\psi(a,b) = \int_{-\infty}^{+\infty} x(t)\psi_{ab}(t)dt$$

(3.2)

where:

$$\psi_{ab} = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right)$$

(3.3)

In relation to the mother wavelet signal, the variable $a$ is the scaling parameter and $b$ is the translation parameter. By varying these parameters, the wavelet can change the scales at which it can test for different frequencies and decompose an original signal into various elements of frequency [150].

When using the WT in signal processing, two parameters can be changed, the number of threshold levels and the percentage threshold levels. The larger the percentage threshold level, the greater the amount of noise that will be removed from
the signal. However, when noise is removed in this way, any AE event will be attenuated, with the possibility that it will be missed. The range of the percentage threshold level is from 0 to 100% while the maximum number of levels that can be chosen is 6.

In this research, the tests that were carried out consisted of three different types of wavelets; these were Daubechies 10, Daubechies 6 and Daubechies 2. The difference between these three wavelets is the value of the coefficients that are used when performing the transform. For example for a D N wavelet, the number of taps of the Daubechies N filter that is used to de-noise the signal is 2N. The larger the value of N, the more noise is removed from the monitored data, whilst the calculations also become more complex. Six tests were conducted on each wavelet consisting of single de-noising percentage threshold at 70% but when the threshold levels were varied. Levels 1, 3 and 6 were used for Daubechies 10 and Daubechies 6 and levels 2, 4 and 6 were used for Daubechies 2. After de-noising the signals were de-noised (or de-noised), and were plotted against each other in time domain. This shows the effect of the threshold level when percentage threshold and waveform are kept constant. Fig. 3.7 shows the de-noised data using the Daubechies 6 wavelet transform. From this it can be seen that by increasing threshold levels, we remove a larger amount of noise. From the results of the de-noising and STFT analysis, it can be concluded that the best result that was tested is a DB6 wavelet de-noising.

![Figure 3.7: Varying threshold level of DB wavelet while de-noising AE signal](image)

**Figure 3.7:** Varying threshold level of DB wavelet while de-noising AE signal
Once the de-noising is completed, the spectra of the data, namely the fast Fourier transform (FFT) is obtained along with the STFT. The FFT and STFT show the frequency at which the events take place. The STFT is carried out using a windowing technique. The STFT is given by the equation

\[ \text{STFT} g(\Omega, b)\{x(t)\} = X g(\Omega, b) \int_{-\infty}^{\infty} x(t) g(t - b)e^{-j\Omega t} dt, \quad (3.4) \]

where \( g(t) \) is a sliding window of fixed size and through the variation of the parameter \( b \), applies the Fourier transform locally to successive portions of the signal \( x(t) \), instead of applying it once to the entire signal. If we define

\[ \psi_{(\Omega,b)}(t) = g(t - b)e^{j\Omega t}, \quad (3.5) \]

then the STFT can be expressed as

\[ \text{STFT} g(\Omega, b)\{x(t)\} = X g(\Omega, b) \int_{-\infty}^{\infty} x(t) \psi_{(\Omega,b)}(t)dt. \quad (3.6) \]

The levels in the STFT can further be adjusted in order to obtain the peak of the frequency accurately.

### 3.4 A MATLAB based GUI for data processing and analysis

In order to do the signal processing, a graphical user interface was made using MATLAB, which can read .prc data from the FAESense M400 and plot the time domain data. This is done by the GUI, from which the user can choose from the following options:

i. Data from all the 6 channels of the interrogation system are analysed separately and plotted, and users can then select the channel of their choice, and the selected channel is then de-noised and FFT and STFT are applied.

ii. All the channels are analysed simultaneously by undertaking the de-noising, FFT and STFT together.

The GUI options for plotting the time domain response are shown in Fig 3.8. For most of the research work presented in this thesis, only instances where the single channels were used were analysed concurrently. Once the time domain response is obtained, the GUI will have an option (Fig 3.9) to apply the threshold, de-noising using different methods and subsequently it gives the FFT and STFT plots of the events.
**Figure 3.8:** The GUI to plot the time domain data

**Figure 3.9:** (a): The options seen on the GUI for (a): de-noising and STFT, (b): de-noising dB or Haar
3.5 Application of the Signal Processing Methodology to AE Data

The signal processing methods mentioned above in this chapter are illustrated in this section as a case study. Two sets of data are analysed in this section, the first of which is that of a known frequency which is induced by using a tuning fork of 500 Hz with an embedded FBG and excite the FBG. The second set is obtained by dropping a ball onto a substrate which has a induced frequency in the range of 30-40 kHz.

A tuning fork of frequency 500 Hz was used to induce AE waves in an aluminium substrate. The acoustic wave, which are picked up by using FBG sensors glued on to the substrate and are analysed using the FAESense M400 interrogator system. Once the data is recorded using the FAESense M400 interrogation system, the time domain data is analysed using the GUI mentioned above in section 3.3 as shown in Fig 3.10 (a) which shows a mixture of signal and noise. The corresponding frequency domain data which is the FFT of the time domain plot is shown in Fig 3.10(b) which shows frequencies of 500 Hz and resonant frequencies of 1000 Hz and 1.5 kHz, along with a lot of ghost frequency components at 800 Hz and 1.6 kHz. The data is subjected to appropriate de-noising and thresholding using the described GUI interface.
The time domain data which is obtained after the de-noising is shown in Fig 3.11 (a) which shows that the peak amplitude is at 5.6 seconds and has an amplitude of 0.8 V. The frequency domain data shown in in Fig 3.11 (b) which shows that the maximum amplitude is obtained at 500 Hz, with resonant frequencies at 1 kHz, 1.5 kHz and 2 kHz. The ghost frequencies at 800 and 1.6 kHz are eliminated by the de-noising.

**Figure 3.10:** (a) The time domain data as obtained from the tuning fork, (b) The corresponding FFT plot obtained before de-noising
The STFT plot is also generated which shows frequency components at 479 Hz and resonant frequencies at 913 Hz and 1404 Hz. The STFT shown in Fig 3.12 (a) has ghost noise components at 800 Hz and 1.65 kHz, which can be seen as a line and after carrying out the de-noising a further STFT is obtained as shown in Fig. 3.12 (b). In this plot there is a peak frequency at 500 Hz, and resonant frequencies at 1 kHz, 1.5 kHz, 2 kHz and 2.5 kHz and the ghost noise components are eliminated. From these results it can be seen that when noise is removed from the original signal, AE events are still present.

Figure 3.11: (a) The time domain data as obtained from the tuning fork, (b) The corresponding FFT plot obtained after de-noising
Figure 3.12: The STFT plot obtained (a): before de-noising, (b): after de-noising
The time domain data obtained from the FAESense M400 for a ball drop experiment, where an FBG is attached to a substrate where the ball is dropped, is shown in Fig 3.13 (a) and the corresponding de-noised time domain data is shown in Fig 3.13. (b). The time domain data has a peak of 3.3 V but is however a mixture of noise as well.

![Figure 3.13(a): The time domain plot for the data obtained from the ball drop experiments, (b): the corresponding de-noised data](image)

The dB de-noising was applied on to the data after proper thresholding using GUI. The STFT plot for the data and the de-noised data are shown in Fig 3.14 (a) and (b), respectively. From the STFT plot, the ball drop impact is visible at 0.53 seconds with a maximum frequency of around 30 kHz, but is prone to significant noise. The STFT of the signal after de-noising is shown in Fig 3.14(b), which eliminates all the background noise and ghost frequencies and the impact signal is much for clearer and would be suitable for analysis.
Figure 3.14: The STFT plot obtained (a): before de-noising, (b): after de-noising
3.6 Conclusion

Data analysis and signal processing are immensely important in this research work on acoustic emission-based crack monitoring of welded joints. The methods presented in this chapter are the basis and foundation that I will be utilizing in the rest of the experiments presented in this thesis. Although the wavelet analysis is a lot more complex with different decompositions and coefficients it is vital that the wavelet transform be used in AE analysis due to the large range of frequencies that occur in the signal data. The following chapters will provide more examples of AE data analysis including de-noising and signal processing of the various experiments conducted for this research work.
Chapter 4

Design, Fabrication and Characterisation of Magnetic Metal Encapsulated FBG sensor

This chapter presents the experimental development of a metal packaged magnetic FBG sensor using stainless steel and tin, together with high temperature resistant SmCo magnet. The inclusion of high temperature-capable SmCo magnets provides the metal packaging of the FBG sensor with magnetic mounting capabilities. This packaged sensor can be placed in direct contact with the substrate structures such as iron pipelines and other ferromagnetic components without any adhesives, making them easily detachable and reusable. This is a significant improvement compared to other commercial fibre optic sensors that are surface-attached using epoxies or welded to the substrate. A series of experiments were conducted using the designed metal packaged sensor to study the characteristic properties such as load, temperature and vibration sensitivity of the magnetic metal-packaged FBG sensor. The various parameters are studied numerically by FEM using ANSYS and validated experimentally. These experiments demonstrate the feasibility of using the encapsulated reusable FBGs for SHM of compatible structures.

4.1 Introduction

OFSs possess unique properties such as being lightweight, compact and having long-term durability, impressive linearity, immunity to external electromagnetic interference and resistance to corrosion as described in Chapter 1 [1, 2]. These properties help them to measure multiple parameters and make them attractive and commercially viable. However, along with these advantages, they have limitations such as degraded performance at elevated temperatures, lack of suitable packaging for direct field deployment and cross-sensitivity between strain and temperature [29]. Several methods have been proposed to package FBGs in metal [151–154] for field deployment applications. Li et. al. [141] illustrated the embedding of FBGs by layered manufacturing using nickel and stainless steel that was subsequently characterised for strain and temperature measurements. They found that this method of embedding will increase the temperature sensitivity of FBGs. Alemohammad et. al. [152] demonstrated a way of packaging FBGs in which a thin film of silver is deposited on
the fibre using a low-temperature laser micro-deposition method followed by nickel electroplating on steel using microscale a laser-based direct writing method before embedding. This method can be utilized for temperatures of about 200 °C. Some of the other methods reported are aluminium and nickel electroplating and brazing and ultrasonic welding with aluminium and tin substrates [152–154]. The strain sensitivity of FBGs can also be enhanced by using ceramic coatings such as an aluminium oxide sprayed coating that can be used in high-temperature applications requiring operation up to 600 °C [155-157]. It should be also noted that a typical FBG starts to deteriorate at temperatures close to 400 °C and with a further increase in temperature the degradation is rapid [158,159], and structural deterioration can occur [160, 161].

In this chapter extensive investigation on design, simulation, embedding and packing of the FBG sensors are presented. We present an experimental study to understand the feasibility of using the proposed magnetic self-attachable metal-encapsulated FBGs for SHM for use in high pressure pipelines which are prone to cracks. In order to use the sensors in engineering applications such as pipelines, it is important to determine the physical characteristics such as load and temperature capability, so that the developed sensor can operate within the prescribed limits. Section 4.2 presents the design and fabrication methods of the packaged FBGs. Analysis of the design is conducted using ANSYS workbench and is explained in section 4.3. The experimental arrangements for the characterization of the fabricated sensors are discussed in section 4.4 and results are discussed in section 4.5.

4.2 Design and Fabrication of the Packaged Sensor

A cylindrical stainless steel container is machined as shown in Fig 4.1(a) as the outer material of the packaged sensor. Stainless steel is used for the process due to its comparatively high melting points of approximately 1320 °C to 1530 °C which makes it a suitable candidate for the use in welding applications where temperatures can go high. Another reason that stainless steel was chosen was due to the fact that it can be magnetized easily. A disc was machined from tin to be inserted into the cylinder as shown in Fig 4.1(b). A 1 mm-diameter hole was drilled into the centre of the container base as well as the tin disc for insertion of the optical fibres. Prior to assembly of the sensor, the FBGs were sheathed in a 30 mm-long and 1 mm-outside diameter Teflon tube for protection and to impart strength to the optical fibre where it entered and exited the assembly.
SmCo was chosen as the magnetic material to be incorporated in this design due to its ability to withstand high temperatures and also because it allows a means to position a fibre in the centre of the stainless steel container. Typically, permanent magnets lose their magnetic abilities at higher temperatures. For commonly used neodymium magnets, the operating temperature is up to 150 °C. Recently, SmCo-based permanent magnets have attracted interest due to their superior high-temperature properties [162,163]. In SmCo, the interatomic exchange between the cobalt atoms gives rise to higher Curie temperatures that depend on the transition metal sub-lattice. Therefore, SmCo can have a Curie temperature of approximately 800 °C and an operating temperature of around 350 °C [164]. Hence, SmCo was chosen as the magnet to be incorporated in this design. Tin was used for the binding material as it does not react with stainless steel. The material properties of samarium cobalt magnets which are used in this packaging is shown in Table 4.1 [165].

Table 4.1: The material properties of the samarium cobalt magnets [165]

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curie Temperature (°C)</td>
<td>800-850</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>8.3-8.5</td>
</tr>
<tr>
<td>Recoil Permeability μ(rec)</td>
<td>1.00-1.05</td>
</tr>
<tr>
<td>Maximum working temperature (°C)</td>
<td>350</td>
</tr>
<tr>
<td>Electric Resistivity (Ω.cm)</td>
<td>8.6x10⁻⁵</td>
</tr>
<tr>
<td>Vickers hardness (Hv)</td>
<td>500-600</td>
</tr>
<tr>
<td>Thermal conduction rate (W/mK)</td>
<td>12</td>
</tr>
<tr>
<td>Coefficient of Thermal expansion (°C)</td>
<td>8x10⁻⁵-11x10⁻⁵</td>
</tr>
<tr>
<td>Rigidity Strength (N/m²)</td>
<td>1.5x10⁸</td>
</tr>
<tr>
<td>Compress strength (N/m²)</td>
<td>8x10⁸</td>
</tr>
<tr>
<td>Tensile Strength (N/m²)</td>
<td>3.5x10⁷</td>
</tr>
<tr>
<td>Young’s Modulus (N/m²)</td>
<td>1.2x10¹¹</td>
</tr>
<tr>
<td>Magnetization field (H)</td>
<td>1600</td>
</tr>
</tbody>
</table>
Four cylindrical SmCo magnets were positioned inside the container as shown in Fig. 4.1(c). Solid cylindrical magnets of 6.25 mm diameter and 12.7 mm height

Figure 4.1: The schematic (a) stainless steel cylinder region; (b) cross section view of the tin disc (c) placement of SmCo magnets with the cylinder; (d) the fabrication of the metal packaged magnetic FBG sensors components before the embedding, indicating the location of the SmCo magnets (e) the metallic packaged sensor.

Four cylindrical SmCo magnets were positioned inside the container as shown in Fig. 4.1(c). Solid cylindrical magnets of 6.25 mm diameter and 12.7 mm height
were used, thereby allowing for the FBG to be inserted between the magnets and easily accommodated as shown in Fig 4.1(c). For each sample, the sheathed FBG was inserted through the hole in the tin disc as depicted in Fig 4.1(b) and then into the central hole between the magnets. The entire assembly was subsequently heated in an oven to 270 °C, which is significantly higher than the melting point of tin (232 °C) so that the tin disc melts and fills the container. The sensor assembly was further allowed to cool to room temperature. The assembly process and the fabricated metal packaged sensor are shown in Figure 4.1(d) and (e) respectively.

4.3 Analysis on the effect of the embedding process on the FBG spectrum

The FBGs used in this work were obtained from DK Photonics Ltd and were 10 mm long with polyimide buffer coating and with peak reflected wavelengths of circa 1540 and 1550 nm, side lobe suppression ratio (SLSR) higher than 15 dB, peak reflectivity greater than 90% and a bandwidth of <0.3 nm. The maximum operating temperature of the polyimide-coated FBG sensors used in this experiment is 300 °C.

![Figure 4.2: The schematic diagram of FBG Interrogation System](image)

The reflection spectra of the FBG was monitored before and after packaging using a commercial FBG interrogator (I-MON 256, Ibsen Photonics). A schematic diagram of the FBG interrogation setup used in this study is shown in Fig 4.2. The interrogator has a wavelength resolution of 5 pm with a maximum data acquisition rate of 6 kHz and is connected to a broadband source with a spectral range of 1530–1580 nm. The reflected signal from the FBG was directed at the interrogator through a fibre circulator. The reflection spectra of the FBG before and after packaging are shown in Fig 4.3. Though the reflectivity signal is reduced, no peak distortion was
observed due to the packaging. It is observed that the peak reflected wavelength of the FBG before embedding was 1539.82 nm and the wavelength after embedding is 1539.76 nm. As the FBG was heated for only 3 hours at high temperature during the fabrication, the thermal decay to optical fibre material is not considered to be significant. However, the observed blue shift of 48 pm to the FBG signal after packaging indicates a residual strain developed within the material after the packaging and is a common phenomenon.

![Reflection spectra of FBG Sensor, before and after packaging](image)

**Figure 4.3:** Reflection spectra of FBG Sensor, before and after packaging

### 4.4 Analysis of Design Using FEM

The packaged FBG is subjected to strain during fabrication due to the thermal expansion of the encapsulating material. An ANSYS-based simulation tool was used to study the impact of stress and strain caused by heating on the embedded FBG sensor. FEM simulation of the proposed design was performed with the dimensions and materials, as discussed in Section 4.2. For the FEM analysis an automatically selected mesh size of 1.57 mm was used (approximately 99000 nodes and 34000 elements) and a triangular mesh is generated that encloses the structure. The material properties such as Young’s modulus, Poisson’s ratio and the density of the material used in the design are shown in Table 4.2. The temperature was applied using the transient structural toolbox to act on the whole of the structure. In both the cases, a path was defined along the length of the FBG and the resultant strains for both the temperature and load were calculated. The numerical model was analysed to calculate the induced thermal strain as the temperature is increased from 20 °C to 200 °C during fabrication. Fig 4.4(a) shows the overall thermal strain in the structure, while Fig 4.4(b) shows the thermal strain experienced by the fibre containing the FBG. As the
thermal expansion coefficients of the constituent materials are different, we have ensured proper thermal contacts between the materials in the simulation and the results shows the overall thermal strain in the structure. From Fig 4.4(b), the thermal strain induced on the fibre is calculated as $961.2 \ \mu\varepsilon$ over a temperature change of 20 to 200 °C that gives a thermal strain sensitivity of $0.4806 \ \mu\varepsilon/°C$ for the FBG that equates to a change of $4.005 \ \text{pm/°C}$. The standard temperature sensitivity for a polyimide coated FBG is $10 \ \text{pm/°C}$ and the total thermal sensitivity of an FBG is the sum of the free space temperature sensitivity and thermal strain sensitivity and is estimated to be $14.005 \ \text{pm/°C}$.

**Table 4.2. Material data for ANSYS simulation**

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s modulus (GPa)</th>
<th>Poisson’s ratio</th>
<th>Thermal Expansion Coefficient ($K^{-1}$)</th>
<th>Density (kg m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless Steel</td>
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<td>0.31</td>
<td>$1.7 \times 10^{-5}$</td>
<td>7750</td>
</tr>
<tr>
<td>Tin</td>
<td>50</td>
<td>0.25</td>
<td>$22 \times 10^{-6}$</td>
<td>7304</td>
</tr>
<tr>
<td>Samarium Cobalt</td>
<td>120</td>
<td>0.27</td>
<td>$13 \times 10^{-6}$</td>
<td>8300</td>
</tr>
<tr>
<td>Optical fibre</td>
<td>2.5</td>
<td>0.34</td>
<td>$50 \times 10^{-6}$</td>
<td>2650</td>
</tr>
</tbody>
</table>

**Figure 4.4:** (a) Thermal strain profile of packaged sensor due to applied temperature (b) the thermal strain along the embedded fibre containing FBG
To estimate the load sensitivity of the packaged FBG sensor, the load-induced strain was calculated numerically. The loads were simulated to act on the tin region of the packaged sensor, and a fixed support was placed at the base of the structure. The load range was selected from 0 N to 25 N in 5 N increments applied on the base of the structure, and the configuration was solved for the equivalent elastic strain on the FBG. The obtained elastic strain shows the expected strain values for the loads applied. It is calculated that for 25 N of applied load, the embedded FBG experiences a strain of 19.46 με that equates to a strain sensitivity of 0.7784 με/N.

Figure 4.5: (a) Strain profile of packaged sensor with applied load (b) strain experienced by embedded optical fibre (c) simulated load vs strain plot of the packaged sensor
The strain distribution in the FBG and in the packaged material with applied load is shown in Fig 4.5(a) whereas the strain distribution along the FBG is shown in Fig 4.5(b). A linear change in strain is experienced by the FBG with the applied load when the simulation is carried out. This linear change is shown in Fig 4.5(c).

4.5 Experimental Setup for Characterisation of the Metal Packaged FBG Sensor

The packaged FBG sensors were characterised for load, temperature and vibration. The experimental arrangements for characterisation are shown in Fig 4.6(a)-(c). For load characterisation, force was manually applied to the packaged sensor using a mechanical bench vise longitudinally along the sensor as shown in Fig 4.6(a). The applied forces are then measured using a button load cell SLB-100 with a measurement range of 440 N that is placed between the packaged sensor and the load application point. The theoretical percentage of error of the load cell used was ±0.25% R.O. (SLB-100). Loads of up to 25 N were applied with an increment of 5 N and the corresponding wavelength shift was measured. As fibre optic based load sensors are typically used for load measurements in the lower range (1-100 N), the packaged sensor is characterised only till 25 N, which was the limit of the current experimental setup. The applied load for each increment was measured using the load cell connected to a load cell conditioner unit SCC-SG24 and a data acquisition board (NI6321e) and controlled via a LabVIEW program. For temperature characterisation, the packaged sensor were placed in a carbolite laboratory chamber furnace, and the temperature is increased up to 200 °C in increments of 5 °C. As the melting point of tin is 232 °C, the packaged sensor was characterised only up to 200 °C. After the set up reaches the desired temperature, it is kept at the same temperature for approximately 10 minutes. This time was allowed between each temperature recording to make sure that the temperature was uniform throughout the packaged sensor structure. The temperature attained by the packaged sensor was then verified using an infrared temperature sensor. The shift in the peak reflected wavelength induced by the temperature change was recorded by the interrogator. To evaluate the vibration measurement capability of the packaged sensor, mechanical excitations were applied to the sensor using tuning forks of frequency 500 Hz and 1 kHz. The packaged FBG sensor was placed in the mechanical bench vise so that there is firm support for the packaged FBG sensor and then the tin region of the packaged FBG
sensors are excited using the tuning forks as shown in Fig. 4.6(c). The vibration-induced dynamic wavelength shift was then measured using an interrogator capable of measuring at frequencies of up to 1.2 kHz. The FFT of the experimental data was
also calculated, using a sampling frequency for FFT of 2.4 kHz, which is the same as the measurement sampling rate. The frequency resolution was 0.01667 Hz. No windowing, averaging or overlapping was used, to verify the applied and measured frequencies [166].

4.6 Experimental Results and Discussions

4.6.1 Load Characterisation

The load-induced wavelength shift of the FBG corresponding to the applied load is shown in Figure 4.7. Here, 2 sets of data were obtained in order to extract the for the data. After comparing the two sets of data, the corresponding strain is calculated and is shown in Fig 4.7. A linear fit to the measured data is shown in the figures. A strain value of 13.37 με is obtained for an applied load of 25 N. This corresponds to a sensitivity of 0.5348 με/N or 0.4456 pm/N. The trend agrees well with the simulation results that calculated a sensitivity of 0.7784 / με /N and are also shown in Fig 4.8. The difference between the simulation and the experiment can also be due to the different loading and boundary conditions. The load sensitivity of the FBGs reported in the literature is in the range of approximately 0.1285 pm/N–1.933 pm/N [167, 168]. Compared to these values, the sensitivity of the proposed packaged sensor is in the lower mid-range of the reported values. However, it can be enhanced by re-scaling the design and packaging dimensions.

4.6.2 Temperature Characterisation

![Figure 4.7](image)

Figure 4.7: Measured wavelength shift and calculated strain due to applied load calculated strain from the experiment and its comparison with the simulation.
The Bragg wavelength shift of the packaged sensor with temperature was measured and is shown in Fig 4.8. The temperature sensitivity of the metal-packaged FBG derived from the results is 11.16 pm/°C. This shows that the temperature sensitivity of the packaged FBG sensors is less than the simulated result of 14.00 pm/°C. The difference between the results may be due to the difference in the applied heating and boundary conditions.

![Figure 4.8](image)

**Figure 4.8:** Measured temperature induced wavelength shift of the packaged sensor

### 4.6.3 Vibration Characterisation

The vibration characteristics of the packaged sensor were measured. Fig 4.9(a) shows the dynamic wavelength change of the sensor. The sudden change in the wavelength at 5.5 seconds corresponds to the time when it is excited using a 500 Hz tuning fork and the corresponding FFT is shown in Fig. 4.9(b). From the figures, it is evident that the excitation event is resolvable with the FFT showing a measured peak at 502 Hz and its corresponding first harmonic. The measured frequency for a 1000 Hz excitation was 931 Hz. This confirms that the fabricated metal-packaged sensor can detect vibrations and upon being used with a suitable interrogation system, high frequency vibrations can be measured. Thus, the feasibility of the packaged sensor to pick up the vibrations was successfully demonstrated. The metal embedded sensors are expected to possess a wide range of applications and can be used in several industries such as the manufacturing industry, aerospace industry, oil industry, power industry, automotive industry and in the construction sector [169]. Thus, the proposed
and demonstrated design of the metal-packaged sensor with magnetic capabilities can simplify field deployments for FBG sensors in the above application areas.

Figure 4.9: (a) The wavelength versus time plot of the vibration experiment; (b) FFT plot for the measured vibration at 500Hz; (c) FFT plot for measured vibration at 1 kHz.
The results obtained from these experiments are summarised in Table 4.3, where the thermal and the load sensitivity of the newly designed packaged sensors are discussed.

<table>
<thead>
<tr>
<th>Experiments conducted and the Sensitivity observed</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermal characterisation</strong></td>
<td>Temperature sensitivity</td>
</tr>
<tr>
<td><strong>Load characterisation</strong></td>
<td>Load sensitivity</td>
</tr>
<tr>
<td><strong>Vibration characterisation</strong></td>
<td>✓</td>
</tr>
</tbody>
</table>

4.7 Conclusion

A novel means to fabricate a metal-packaged magnetic, reusable FBG is demonstrated in this chapter using stainless steel and tin together with SmCo magnets. The design of the structure is analysed by finite element analysis using ANSYS. The simulation results display a temperature sensitivity of 14.005 pm/°C and a load sensitivity of 0.7784 με/N. The stand-alone packaged sensor has been characterised for load, temperature and vibration and was compared with the simulation results. The measured load and temperature sensitivity of the packaged sensor were 0.4456 με/N and 11.16 pm/°C, respectively. The behaviour of the simulated and experimental packaged sensor was similar. The slight differences in the sensitivity values are attributed to the different boundary conditions in the experiment and simulation. The vibration measurement capability of the packaged sensor was also demonstrated by exciting the packaged sensor at two different frequencies and the measured frequency was in close agreement with the applied frequency. The ease of fabrication, low cost, detachability and reusability of the metal-encapsulated FBG can make it an excellent choice for SHM, especially for ferrous pipeline monitoring and for welded structures.
Chapter 5

The Study of the Directional Sensitivity of Fibre Bragg Gratings for Acoustic Emission Measurements

This chapter presents and highlights the unique property of directional sensitivity to acoustic emission as observed in FBGs. The experiments were carried out by dropping a metal ball onto the metal substrate, on which the FBGs are attached. The study on directional sensitivity is done as a stepping stone towards the study of localisation of AE sources and thereby the cracks, which forms the final part of my research work. The experimental results of the directional sensitivity study are compared to the mathematical simulation results derived using the FEM explicit dynamics simulation in ANSYS. The novelty of this work is the use of magnetic metal-packaged sensors for the study and the numerical simulation of these experiments. These experiments have confirmed the pre-existing theory that the FBGs are more sensitive to AE in the longitudinal direction, when compared to transverse direction.

5.1 Introduction

Damage mainly tends to occur in structures when they are subjected to stress which makes imperfections such as cracks in the material to grow and propagate; this should be monitored. The main part of my research work is to monitor the cracks in structures during the welding process and also to locate the source of those flaws in the structure. As mentioned in chapter 1, optical fibre sensors are appropriate for sensing high frequency AE as they have high sensitivity and bandwidth and can respond to strain-induced surface displacement in the sub pico-meter range, which is considered as a major challenge.

H.Achar et al. have demonstrated that FBGs are highly sensitive to AE induced strain in the longitudinal direction compared to that in the transverse direction [170]. As the AE measurement sensitivity of the FBG is direction dependent [162], in practice for most experimental conditions, the FBG sensor might be responding to only a component of the acoustic wave in the axial direction of the FBG. This is because optical fibres have cylindrical geometry. Other factors that affect the acoustic sensitivity of an FBG are the gluing material, which affects the strain transfer from the
substrate to the optical fibre and also the acoustic impedance of the materials involved. Using FBGs for AE detection facilitates accurate localisation of the source of the imperfections using FBGs’ directional sensitivity. Several studies have been conducted and the authors have propounded the directional sensitivity of FBGs [98, 171]. Perez et. al. demonstrated the AE measurement capability of the FBGs using a metallic ball drop [98]. C. Zhang et. al. showed that the directional responses of the FBG sensors make them suitable for determining principal strains and the direction of the AE source [171]. Analysis of Lamb waves can also determine the directional sensitivity of FBGs. When elastic waves travel in plate-like structures the top and bottom surfaces experience repeated alternating reflections. The guided waves propagating along the plane of an elastic plate with traction-free boundaries are called Lamb waves and are suitable for SHM applications of aircraft structures, oil tanks and pipelines as they can be confined inside a structure. Generally Lamb waves propagate in 2 modes, the symmetric mode or extensional $S_0$ waves and the antisymmetric mode or flexural $A_0$ waves, both of which are polarised perpendicular to the plate in the x-z direction. The other set of waves which is polarized in the plane of the plate (i.e. in the y-axis) are called the shear horizontal (SH) waves, which can also be symmetric or anti symmetric [172]. De Pauw et. al. [173] demonstrated a single fibre Bragg grating in a microstructured optical fibre which shows selective sensitivity to strain in the axial and transverse directions and helps to directly distinguish between fundamental Lamb waves modes. FBGs have the ability to detect strain changes to sense the in phase and out of phase asymmetric modes in a plate. However when detecting the transverse waves, FBGs are not sensitive to this mode.

In this chapter, the use of packaged and unpackaged FBG sensors for directional detection of acoustic waves has been investigated, with a view towards their implementation in practical applications such as pipeline monitoring. The directional response sensitivity of the FBGs to AEs is conducted by generating AE waves in the structure using metal ball impact and detecting the acoustic waves using the FBG AE interrogation system.

5.2 Sensor Design and Fabrication

In chapter 4 we have developed and characterised a magnetic metal packaged sensor, however in order to study the directional sensitivity of the FBGs a much simpler setup is required. Hence, in chapter 5, a simplified metal-packaged FBG is
designed and fabricated. In applications involving crack monitoring in welding and pipelines, directional sensitivity of the sensor significantly impacts the identification of cracks. A FBG, due to its directional property, selectively responds to different modes of propagating acoustic waves in the structure depending on their orientations. FBGs placed with different orientations are found to be sensitive to different modes of acoustic wave propagation [98]. To provide more clarification on these aspects for practical applications, the directional sensitivity of a metallic-packaged FBG and unpackaged FBG sensor are studied and quantified. The design and construction of a metallic-packaged FBG and a ball drop model to generate an AE wave on the packaged and unpackaged FBGs are presented and analysed in this chapter.

5.3 Design and Construction of Packaged Sensor

Considering the SHM application, the packaging for the sensor is designed with a stainless steel base and the FBG sensor is embedded in melted tin within the base. The stainless steel square base is machined having sides of 25 mm each and a

![Figure 5.1: The parts of the packaged sensor](image)

Figure 5.1: The parts of the packaged sensor (a) stainless steel base with FBG (b) tin plate; (c) packaged sensor after heating
thickness of 3 mm and a hollow region in the middle to accommodate the tin plate as shown in Fig. 5.1(a) and (b), respectively. A hole of 1 mm diameter is drilled through the side walls of the stainless steel base to insert the FBG. The FBGs used in this work are 3 mm long with polyimide buffer coating and with peak reflected wavelengths of circa 1550 nm, peak reflectivity greater than 70% and a bandwidth of < 0.5 nm. FBGs are inserted through the holes in the stainless steel base and the tin plate is placed on the top of the inserted FBG and is heated to a temperature of 270 °C, which is higher than the 232 °C melting point of tin [112]. This is to ensure that the tin has melted and been evenly distributed within the steel base. Thereafter, the entire assembly is allowed to cool down to room temperature. The final assembly after the fabrication is shown in Fig 5.1(c).

5.4 Experimental Study on Directional Sensitivity of Packaged and Unpackaged Sensors

The experimental setup for directional sensitivity is shown in Fig 5.2. The experiments were performed on a square aluminium plate of dimensions 220 mm x 220 mm x 3 mm dimensions on which the packaged FBG sensor (peak reflective wavelength 1550 nm, length 3 mm) is attached using cyanoacrylate adhesive at the centre of the plate. The packaged FBG was attached to the aluminium substrate using

Figure 5.2: The experimental arrangement for the metal ball drop test using the FAESense interrogator system
silicone adhesive. Metallic balls of size 6 mm and 12 mm were dropped on to the substrate from a height of 230 mm. The height and ball drop impact location on the substrate was also ensured by using a custom-made stand. Metallic balls were made to impact on to the substrate at a distance of 50 mm and 100 mm away from the centre of the FBG. The AE which was generated as a result of the ball drop was obtained using a commercial FBG AE interrogator system. Though the maximum data acquisition capability of the FAESense system is 1.167 MHz, the experiment data in this experiment was acquired at a sampling rate of 291.7 kHz based on the information from simulation results and also from a PZT AE transducer.

Reducing the sampling rate to the required level will significantly reduce the post-processing computing time. A PZT based transducer (B225.5) along with a high-speed oscilloscope (Tektronix DP070604C digital phosphor oscilloscope) was used to measure the frequency of ball drops on the substrate. From this experiment, it was found that the maximum AE frequencies resulting from the impact of the 6 mm and 12 mm ball drops were 20 kHz and 30 kHz, respectively. The measured AE waveforms of the ball drop using the PZT transducee and oscilloscope and the corresponding STFT spectrum are shown in Figs 5.3 (a) and (b), respectively. The interrogator system can only measure and record the data in voltage and conversion of this dynamic voltage change to equivalent strain is not possible as there is no calibration data available as the device was designed for dynamic frequency measurements.
5.5 Finite Element Analysis Model of AE Event

5.5.1 Geometry of the design

This section describes the modelling approach for impact-generated acoustic wave propagation in an aluminium plate with packaged and unpackaged FBGs attached to it. The numerical simulation of the aluminium plate impacted by a metal ball was performed using ANSYS 16.1 explicit dynamics. Using sketching options, an aluminium plate was modelled as a square of dimensions 220 mm x 220 mm x 3 mm and 2 circles of diameter 100 mm and 200 mm were drawn from its centre to mark the points of impact. A new plane was chosen at a height of 230 mm and the metal balls were modelled. Several methods were considered for the modelling of this experimental setup chosen from amongst the different methods in the literature for the simulation of AE waves. J. Wee et. al [174] demonstrated the simulation of the Lamb waves in a optical fibre 100 mm in length and 0.125 mm diameter, which was attached to a substrate, of length 70 mm with and without glue. Using a similar approach we modelled our system in ANSYS with explicit dynamics using the LS-DYNA toolbox.
5.5.2 FEM using Explicit dynamics exporting to LS-DYNA

The modelling was performed using stainless steel, tin and aluminium plate and the optical fibres before meshing of the materials are carried out. The numerical mesh has a size of 0.15 mm and is highly smoothed [175]. The AE waveform at the acoustic wave source is generally a sharp broad band pulse containing quantitative information about the wave source. The waveform used for the generation of the AE is similar to that of the Hsu-Nielsen lead break experiment, which employs the model as shown in equation 5.1 [166]

\[ f(t) = \begin{cases} 
0 & t < 0 \\
0.5 - 0.5 \cos \left( \frac{\pi t}{\tau} \right) & 0 \leq t \leq \tau \\
1 & t > \tau 
\end{cases} \quad (5.1) \]

This equation assumes that the waveform is 0 for time \( t < 0 \) and takes a sinusoidal form from time \( 0 < t < 1.5 \). For times later than 1.5 \( \mu \)sec, the waveform is assumed to be 1. After the frequency is set the model is exported and solved using the Mechanical APDL Product launcher and is accessed using LS-PREPOST [172,173]. After launching this in LS-PREPOST the results are then solved for X-Displacement as shown in Fig 5.4. The fringe levels are then studied at an 1 mm intervals from the source. The point of application of the frequency is varied based on the different directions where the frequency is applied. At first the frequency is applied along the Y-direction so as to have its effect felt on the packaged sensor. The resultant displacement is observed and is calculated as seen in Fig 5.4. It is observed that the maximum displacement which is observed was found to be \( 3.44 \times 10^{-6} \) m on the stainless steel structure, the minimum displacement is over the aluminium plate at \( 0.38 \times 10^{-6} \) m.

5.5.3 Transient structural analysis

A new design and transient structural analysis approach was carried out in ANSYS, in which we consider the impact forces of the ball drop onto the substrate. The mass of the ball was calculated and the gravitational force was also considered to calculate the kinetic energy which was transferred to the substrate and the resultant force was considered to replace equation 5.1, which now becomes

\[ f(t) = \begin{cases} 
0 & t < 0 \\
F & 0 \leq t \leq \tau \\
1 & t > \tau 
\end{cases} \quad (5.2) \]
where, $F$ is the force calculated for the metallic ball. With this method, the exact forces and the boundary conditions which were acting on the ball at the point of impact were observed.

In order to model the impact of the ball drop, unpackaged FBG sensors were modelled as silica cylinders of length 10 mm and diameter 125 µm. The FBGs were assumed to be bonded onto the substrate using cyanoacrylate adhesive. For the packaged FBG sensor, stainless steel and tin for encapsulating the FBG were modelled according to the dimensions described above, and the corresponding material properties provided in table 5.1 were assigned to them. Finally, a cylinder, as mentioned above, was also modelled at the centre of the stainless steel structure to represent the silica fibre. These structures were combined into a single part to ensure that it acts as a standalone structure which was attached to the substrate.

**Figure 5.4:** The X displacement along the aluminum and packaged sensor
5.5.4 FEM using explicit dynamics exporting to ANSYS

The schematics of the modelled substrate with the unpackaged and packaged FBG’s are shown in Fig. 5.5 (a) and (b), respectively. In order to model the impact, the velocity \( v \) of the metallic ball determined by the principle of conservation of energy by equating the kinetic energy to the potential energy is considered as follows:

\[
v = \sqrt{2gh} \quad (5.3),
\]

where \( g \) is acceleration due to gravity and \( h \) is the height from which the ball is dropped. In the experiment, the ball is dropped from a height of 230 mm; therefore, the same height was considered the simulation as well. We calculated the velocity to be 2.123 m/s and this was considered as the initial velocity and was made to act along the negative z-axis towards the aluminium plate. The mesh size used for the simulation was 4 mm in the solver which provides a total of 7000 nodes.

A metallic ball drop was selected to create an impact on the substrate and to generate elements in the mesh. The analysis time was calculated in such a way that there was still adequate time after the impact of the ball on the substrate for it to bounce back if

### Table 5.1: Material Properties for FEM Modelling

<table>
<thead>
<tr>
<th>Material</th>
<th>Usage</th>
<th>Density ((\text{Kg m}^{-3}))</th>
<th>Young’s modulus ((\text{GPa}))</th>
<th>Poisson’s Ratio</th>
<th>Tensile Yield ((\text{GPa}))</th>
<th>Compressive Yield ((\text{GPa}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium Substrate</td>
<td>Substrate</td>
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<td>71</td>
<td>0.33</td>
<td>0.28</td>
<td>0.28</td>
</tr>
<tr>
<td>Optical fibre FBGs</td>
<td></td>
<td>2650</td>
<td>70</td>
<td>0.15</td>
<td>0.231</td>
<td>0.04</td>
</tr>
<tr>
<td>Stainless Steel Metal Ball</td>
<td></td>
<td>7750</td>
<td>191</td>
<td>0.31</td>
<td>0.207</td>
<td>0.586</td>
</tr>
<tr>
<td>Tin Packaging</td>
<td></td>
<td>7287</td>
<td>45</td>
<td>0.33</td>
<td>0.220</td>
<td>0.015</td>
</tr>
<tr>
<td>Cyanoacrylate Adhesive</td>
<td></td>
<td>1090</td>
<td>1.34</td>
<td>0.33</td>
<td>0.014</td>
<td>0.005</td>
</tr>
</tbody>
</table>
required. In order to simulate AE events of different amplitude and frequency, different ball diameters (6 mm and 12 mm) were used, and to study the damping of the AE signal through the substrate, the distance of impact from the centre of the FBG was set to 50 mm and 100 mm.

5.6 Analysis of AE Wave through the Substrate

The equivalent elastic strain induced by the acoustic waves detected by the packaged and unpackaged FBG was calculated for the 6 mm and 12 mm ball drop impacts at distances of 50 mm and 100 mm from the FBG. The profile for the propagation of the AE waves through the substrate and packaged and unpackaged sensors was determined. For the 12 mm ball’s impact on substrate at a distance of 50 mm from the unpackaged FBG and packaged FBG, the strains obtained were 39.93 με and 16.72 με, respectively. The modelled acoustic wave propagating through the aluminium plate for an impact of 6 mm ball with a bare FBG is shown in Fig 5.6 (a) and (b) which is at varying time intervals at 1.08 ms and 1.14 ms respectively. From similar plots the frequencies of the impact of the balls were determined to be 16.7 kHz for the 6 mm ball drop and 21.4 kHz for the 12 mm ball drop impacts.

Figure 5.5: The schematic of aluminium substrate with the metal ball which was modelled in ANSYS geometry for (a): unpackaged FBG sensors, (b) packaged FBG
Figure 5.6: The modelled propagation of acoustic wave through the substrate at (a) 1.08 ms, (b) 1.14 ms

The simulation was repeated for various points from 0° till 180° and we obtained plots for the dependence of the strain on the angle of the applied impact.
For each of the two metal balls for the at distances of 50 mm and 100 mm the polar strain plots for (a) unpackaged and (b) packaged sensors are shown in Fig. 5.7 (a) and (b), respectively. From the plots, we can observe that the sensitivity was the highest for $0^\circ$ and $180^\circ$ and was the lowest for the force applied at $90^\circ$, thus demonstrating the directional dependence of the FBG’s sensitivity. From the results for the unpackaged FBG, it can be observed that the strain induced by the 12 mm ball impact at 50 mm is 17.29% higher than the impact at 100 mm distance, while for the 6 mm ball impact, the difference is 12.24%. For the same impact distance of 50 mm, the 12 mm ball impact-induced strain was 24.34% higher than that of the 6 mm ball, and similarly for 100 mm impact distance, the difference between the strains induced by the 12 mm and 6 mm balls was 25%.

With packaged sensors, the strain was 18% higher at 50 mm distance when compared to 100 mm for 12mm ball and 44% higher for the 6 mm ball at 50 mm distance. For impact distances of 50 mm and 100mm, the change in strains induced for the 12mm ball were observed to be 44% and 60% higher, respectively. When the ball size varies from 12 mm to 6 mm or the impact location varies from 50 mm to 100 mm, it is observed that the amplitude drops because the amplitude and the distance of the impact varies.

![Figure 5.7: The directional sensitivity obtained for (a): unpackaged FBG sensor; (b): packaged FBG sensors](image)

The predicted values of frequency calculated by the FEM method is are 21.4 kHz and 16.7 kHz for 12 mm and 6 mm ball impacts, respectively. These observed
frequencies from the simulation were in accordance with the frequency observed from the transducer.

5.7 Results and Discussion

The amplitude (in volts) vs. time plots for the ball drop impact, measured using the unpackaged FBG are shown in Fig 5.8 for different ball sizes and impact locations. Figs 5.8(a-d) shows the AE response of the unpackaged FBG for the 6 mm ball at 50 mm, the 6 mm ball at 100 mm, the 12 mm ball 50 mm and the 12 mm ball at 100 mm impact distance, respectively. The peak for the 6 mm ball drop at a distance of 50 mm and at an angle of 0° is shown and the amplitude vs. time plot is shown in Fig 5.8(a),

![Figure 5.8](image)

**Figure 5.8:** The amplitude vs. time plot of AE measured by the unpackaged sensor with (a) a 6mm ball 50 mm distance  (b) 6 mm ball 100 mm distance  (c) 12 mm ball 50 mm distance  (d) 12 mm ball 100 mm distance
in which the maximum amplitude is 3.45 V. From the figures, it is observable that the amplitude varies as the ball size is varied from 3 Vpp for the 12 mm ball and 2.8 Vpp for the 6 mm ball for the unpackaged FBG sensors at a distance of 50 mm and 1.1 Vpp for the 12 mm ball drop.

Selected STFTs of the AE events depicted in Figs 5.8(a) & (b) are shown in Figs 5.9 (a) and (b). The STFT shows that the AE wave has a maximum frequency of 29.7 kHz for 12 mm and 7.5 kHz for 6 mm ball drop impacts.

![Figure 5.9: The STFT of AE from the unpackaged FBG with (a): 12mm ball at 50mm impact distance; (b): a 6mm ball at 50mm impact distance](image)

The frequency changes may be due to the increase in size of the ball. The amplitude (in volts) vs. time plot for the ball drop impact of the packaged FBGs are shown in Fig 5.10 for different ball sizes and different locations. Fig 5.10(a-d) shows the AE response of the packaged FBG for 6 mm and 12 mm balls at 50 mm and 100 mm distances. From the figures it is observed that the amplitude varies from 1.1 vpp to 0.5 Vpp when the ball size is varied from 12 mm to 6 mm at 50 mm impact distance from the sensor. To study the directional sensitivity of the packaged and unpackaged sensors, we analysed sensor response for ball drop impacts with different ball sizes and distances at varying angles from 0° to 180° at 30° angle increments, measured with respect to the FBG axis direction. The results for the case of unpackaged and packaged FBGs are shown in Fig 5.11(a) and (b), respectively. It is observed that the highest peak-to-peak voltage occurs at 0° and 180° at 1.5 V for the 12 mm ball drop at 50 mm and at 2.5Vpp for 6 mm ball drop at 50 mm away from the FBG. It is observed that
the sensitivity is highest at 0° and 180° for both 12 mm and 6 mm balls using both sensors with a maximum amplitude of 3 Vpp and 2.5 Vpp, respectively.

It is noteworthy that the AE interrogator measures the amplitude signal in volts and in simulation it was in micro strain. Therefore, to compare the experimental and simulation results, the change in amplitude was compared. The change in voltage measurement using unpackaged FBG was approximately 13% more at 50 mm distance using different ball sizes in both cases during 6 mm and 12 mm metal ball impacts. However, for packaged sensors, the change in the voltage was found to be 25% higher at an impact distance of 50 mm for the 6 mm ball impact and 32% higher at 50 mm distance for the 12 mm ball impact.

Figure 5.10: The Amplitude vs. time plot of measured AE from the packaged sensor at (a): 6mm ball 50 mm distance; (b): 6mm ball at 100mm distance; (c): 12mm ball at 50 mm distance; (d) 12 mm ball at 100 m distance
The percentage increase in voltage for 12 mm ball impact was 21% compared to the 6 mm ball at 50 mm impact distance, 23% at 100 mm impact distance using unpackaged FBGs and 50% and 68% higher, respectively for packaged sensors. The percentage change in amplitude is consistent with the percentage change in strain obtained with the simulation as discussed in section 5.4. The time series data and the STFT spectra obtained from this directional study show that the frequency of the AE waves obtained is very close to that of studies by other researchers where the impact signal frequency was shown to be around 20 kHz. The plate geometry, edge reflections and source to receiver distances were some of the factors attributing to the change in the intensity of the AE signal.

Figure 5.11: The plot for the directional sensitivity obtained after the ball drop tests with 12 mm and 6 mm balls (a): Unpackaged FBGs; (b) FBG sensors
5.8 Conclusion

This study was undertaken to investigate the sensitivity of acoustic wave FBG sensors to the direction and distance of the AE source. Although many researchers have worked on the directional sensitivity of acoustic emission FBG sensors, this is the first time the experiments have been conducted with metal-packaged FBG sensors and the sensitivities compared with unpackaged FBG sensors. The experiments conducted here show that for the unpackaged sensor the change in the amplitude were approximately 13% whereas for the packaged sensor it was observed to be 25% at an acoustic source distance of 50 mm from the sensor. Generation and propagation of the AE wave is modelled using FEM. The successful verification of this method supports the view that this metal packaged FBG sensor can be used for monitoring and locating the micro cracks in welding and pipeline monitoring using fibre optic acoustic emission methods. This is a stepping stone to future experiments in source localisation of cracks using FBG arrays. Further modification should be undertaken to increase the measurement frequency range of the FBGs to help crack identification of engineering structures.
Chapter 6

Applications of FBG based Acoustic Emission Detection System in Crack Monitoring in Welding

This chapter presents a comprehensive study of cold crack monitoring using FBG sensors during welding. The chapter describes the design framework, experimental arrangement, data acquisition and subsequent analysis. Cold crack induced AE signals are detected by a multiple FBG sensor configuration and using a commercial FBG AE interrogation system. The crack locations are theoretically predicted using a method of linear localization based on the differences in the time of arrival (TOA) of the AE events to different FBG sensors and are experimentally validated by employing packaged and unpackaged FBG sensor array in a welding experiment with gas tungsten arc welding (GTAW) on an ultrahigh toughness high hardness armor (UHT HHA) steel. The weld region of the steel plate is diced into 1 mm cross sectional pieces and the positions of the cracks are identified using scanning electron microscope (SEM) imaging and then cross correlated with the AE signals, thereby confirming the correct identification of crack location using the FBG sensing method.

6.1 Introduction

Many studies have been conducted successfully by researchers on FBG based AE sensing in various materials such as composites, concretes and metal plates [176,177,30,54]. Various sources of AE waves in engineering structures are generation and propagation of cracks, yielding, fretting, impact damage and failure of bonds [76]. The process of locating the source of these acoustic waves, by recording the propagating acoustic signals by various sensors and properly analyzing them, is commonly known as the acoustic source localization technique [178]. These can be done by many methods like analytical modelling, signal processing, by applying artificial neural network, finite element simulation and by geometric methods [179-183]. The AE source localization is a successful technique in SHM and has attracted great interest among researchers [184,177]. One of the major challenges during crack induced AE signal analysis is the presence of signals from noise which
should be separated efficiently using signal processing methods as described in Chapter 3.

Successful monitoring of cracks in metals using AE was first discovered in metallurgy during twinning of tin, when an audible tin cry was produced due to plastic deformation. AE experiments to monitor cracking were first reported by Kaiser with the publication of his historical irreversibility theory, known as the “Kaiser effect” in 1950, which states that AE is not generated in a structure unless the previously applied load is exceeded [185]. Scholars have subsequently undertaken several studies on AE in various fields, and source localization using FBG sensors has been explained in various studies [186,187]. An improved AE location method based on the Gabor wavelet transform and threshold analysis was deduced and verified in AE linear location experiments using ultra-short FBG sensors by J Zhongwei et. al. [184]. Many studies based on intelligent algorithms to detect the source of AE are available in the literature [188,189]. As this type of localization method needs many training sensors, the results may not be reliable and the process is very complicated and source localization in plate-like structures needs multiple sensors. Kundu in 2014 propounded that for plate-like structures, if the speed of propagation of the acoustic wave is known, then the method of triangulation can be used for source localization. Wu et. al. identified the position of transverse cracks in carbon-reinforced plastics using phase shifted FBGs and waveform analysis [190]. The AEs can be mapped by a technique described by Sun et. al [191] which encompasses the theory of zone localisation using multiple evenly spaced sensors and detecting the time of arrival (ToA) of AE signals at the various sensors. The hit sequence is determined by using a time difference between hits, thereby resulting in more precise location [192].

NDT of welds has been advancing significantly in recent years to produce high quality and highly reliable welds so that operational safety of welded structures like oil and gas pipes, bridges and high pressure vessels can be ensured. Cold cracks occur in quench-sensitive areas, either in the weld metal or in the heat affected zone when the factors such as brittle microstructure, shrinkage upon cooling and hydrogen in sufficient concentration coexist. Typically, cold cracks are not detectable until the metal cools to a temperature of about 200 °C. Therefore real time monitoring of crack activities would enable engineers to control the welding parameters more accurately.
to minimize the cold cracks. As mentioned in chapter 1, the AE method to detect cracks during welding was done as early as 2 to 3 decades ago. For example, Fang et. al. in 1995 used AE to monitor cracks [61]. Some previous work on FBG based sensors for welding applications such as residual stress and temperature monitoring shows the feasibility of employing optical fibre sensing methods in welding [69-70]. As a proof of concept of FBG based AE detection for high temperature applications, we have conducted mapping of cold cracks occurring during welding. A linear localization method is used to locate the cracks and they are validated using scanning electron microscopy (SEM) imaging analysis.

In this chapter an experiment on welding is conducted and the locations of the cold cracks are estimated by three methods namely, the time domain response, time of arrival at three FBG sensors and SEM imaging. Through this approach, we have experimentally validated our theoretical estimation and calculations.

6.2 Mapping of Cracks using AE

A linear localisation method were applied to map the origin of cracks using the measured AE signals detected by three FBG sensors attached in a linear array to the weld substrate, as shown in Fig 6.1. Let us consider that the location of the cold cracks formed during welding is at the origin denoted by a coordinate $x_0$. The three FBG sensors are denoted as $S_1$, $S_2$ and $S_3$ each separated from the origin of the weld at a distance of $x_1$, $x_2$ and $x_3$, respectively. The sensors are configured in such a way that $S_2$ is half way between $S_1$ and $S_3$ at a distance of $D$ from each of them. When FBGs are placed at different locations with a definite sensor to sensor distance, AE signals are recorded by the system with different signal travelling times based on the distances of sensors to the AE source. This travelling time is termed ToA, and by measuring the ToA of the AE event using the FBG system and also by knowing the location of the embedded FBGs, the origin of the AE source can be estimated.

The time is an unknown factor as the cracks occur at an unknown time $t_0$. Assuming $t_1$ is the ToA at sensor 1 and $t_2$ is the ToA at sensor 2, the distances from the source of crack and the three FBG sensors can be denoted by $x_1, x_2$ and $x_3$ and can be written as eq (1-3) assuming $v$ is the wave velocity of the signal in the weld substrate.

$$x_1 = v(t_1 - t_0) \quad (6.1)$$
\[ x_2 = v(t_2 - t_0) \quad (6.2) \]
\[ x_3 = v(t_3 - t_0) \quad (6.3) \]

By applying basic trigonometry and arithmetic we calculate the time \( t_0 \) to be,

\[
t_0 = \left( \frac{t_1^2 - t_2^2 + D^2}{2(t_1 - t_2)} \right) \quad (6.4)
\]

However, this scenario is limited to the setup being in a right angled triangle configuration. For a more generalized scenario, we can apply the sine rule and cosine rule [183]. Applying the rules to Fig 6.1 we get

\[
\frac{\sin \angle x_0}{2D} = \frac{\sin \angle s_2}{x_1} = \frac{\sin \angle s_1}{x_2}, \quad (6.5)
\]

where \( \angle x_0, \angle s_2 \) and \( \angle s_1 \) represent the angles which are formed between the locations of the cracks and the sensors. After calculating \( t_0 \) from equation (8), origin of AE source \( x_0 \) can be found from equation 6.5. After calculating \( t_0 \) from equation 6.4, we can find \( x_0 \) by equating it to the product of travel velocity \( (v_t) \times \) time \( (t_0) \)

\[
x_0 = v_t * t_0 \quad (6.6)
\]

By solving equation 6.6 we can determine the source of the crack in the welded region.

**Figure 6.1:** The location of the sensors with respect to the crack location
6.3 Estimation of the ToA of the AE Signal and Source Localisation

In order to estimate the ToA of the AE signal, initial calculations are carried out using wave velocity of steel (the weld substrate in our experiment) and the time period resolution of the system for an experimental configuration as shown in Fig 6.2. This configuration has three weld regions (weld 1, weld 2 and weld 3) and three FBG sensors attached, each at a distance of about 60 mm from the corresponding weld regions. The sampling frequency of AE interrogation system was 1.167 MHz and as there are three different FBGs used for the experiment the sampling rate becomes 389 kHz per FBG which means that the system can distinguish events which are separated by a minimum time period of 2.56 µs. The wave velocity in steel is 4500 m/s [193] and based on the location of the FBGs from the centre of the welded regions, the ToA of the AE signal at the individual sensors are found as shown in Table 6.1. Given the time resolution of 2.56 µs, the estimated ToA for an AE event at weld 1 for FBG sensors 1 and 3 is feasible and the AE event can be distinguished. Similarly, for weld 3 the data from sensor 3 and 1 are distinguishable, but for weld 2 the events will not be distinguishable from the data from sensors 1 and 2 but it is distinguishable from sensors 2 and 3.

Figure 6.2: The schematic arrangement of the welds and the FBG sensors on the welded region
Table 6.1: The theoretical calculated time of arrival of AE signals between the welds and the FBGs (in µs)

<table>
<thead>
<tr>
<th>Weld</th>
<th>FBG 1</th>
<th>FBG 2</th>
<th>FBG 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13.3</td>
<td>15.5</td>
<td>24.4</td>
</tr>
<tr>
<td>2</td>
<td>15.5</td>
<td>13.3</td>
<td>17.7</td>
</tr>
<tr>
<td>3</td>
<td>24.4</td>
<td>15.5</td>
<td>13.3</td>
</tr>
</tbody>
</table>

6.4 Experimental arrangement

6.4.1 Welding Procedure

In this research work all the experiments are carried out on an ultrahigh toughness high hardness armor steel of dimensions 150 x 100 x 7 mm. UHT HHA steel is a quenched and tempered steel armour plate and is ideal for cold crack studies. The material was chosen in order to ensure the occurrence of cold cracks and subsequent AE signal generation. To induce sufficient cracks, no interpass temperature was applied to the welding as high interpass temperature assists in the diffusion of H₂ out of the areas of previous passes thus preventing cold crack formation. The welding method used was Gas Tungsten Arc Welding (GTAW). GTAW is the type of welding [194] commonly used to weld thin sections of non-ferrous metals such as aluminium, titanium, magnesium and copper alloys. A gas tungsten arc is used as the heat source for the welding. The welding is carried out by using pure aluminium and chromium wires (Stoody 101 HC) of diameter 2.8 mm in order to do the hard facing of the material. Multiple passes were made on the welded substrate, with each typical welding pass being 40 mm long, and successive passes separated by 10 mm. The wire is loaded with a speed of 260 mm/min and the arc has a travel speed of 87.4 mm/min. The arrangement of the substrate, FBGs on the substrate and the welded regions are shown in Fig 6.3.

6.4.2 FBG sensors

Two FBG sensing configurations were implemented in this study. Firstly, to understand the fundamentals and capability of FBG sensors to measure crack induced
AE signals and crack locations, an unpackaged FBG sensor array with three sensors of wavelengths 1530 nm, 1540 nm and 1550 nm were used. Secondly, in the other configuration, 3 FBGs were used, which comprised an array of a packaged sensor of wavelength 1530 nm, a bare FBG sensor of 1540 nm and another magnetic packaged sensor of wavelength 1550 nm. For practical applications, as discussed in chapters 4 and 5, we have developed packaged FBG sensors and those configurations are also

Figure 6.3: The photograph of the welding with (a) bare FBGs, (b) Packaged Sensors
implemented in this study. The details of the FBGs used for this experiment are as shown in Table 6.2.

The first experiment on welding was conducted with the unpackaged FBG array, where the FBG sensors were glued to the substrate using a high temperature withstanding epoxy. The details of which are given above. A photograph of the experiment is shown in Fig 6.3 (a). In the second welding experiment, AE events were measured using a metal packaged FBG sensor array with magnetic capability as mentioned in chapter 5 [47-57]. The array of 2 packaged sensors along with the unpackaged FBG sensor are placed on to the HHA steel as shown in Fig 6.3 (b). The magnetic packaged FBG sensor is simply placed on the steel plate while the unpackaged FBG sensor and the metallic packaged sensors are glued on to the substrate using a cyano-acrylate glue. The welding is carried out on the HHA substrate as mentioned in previous section. The AE from the cracks induced during welding is recorded using FAESense M400 interrogator system. Welding was carried out for a duration of 20 seconds per pass and the recording is kept on for a further 60 seconds in order to record the cracks which occur after the welding is finished.

**Table 6.2**: The specifications of the FBGs used in this study

<table>
<thead>
<tr>
<th>FBG</th>
<th>Type</th>
<th>Wavelength (nm)</th>
<th>Grating length (mm)</th>
<th>Reflectivity</th>
<th>Bandwidth (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bare</td>
<td>1530</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Bare</td>
<td>1540</td>
<td>10</td>
<td>Greater than 70%</td>
<td>0.3</td>
</tr>
<tr>
<td>3</td>
<td>Bare</td>
<td>1550</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Packaged</td>
<td>1530</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Bare</td>
<td>1540</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Packaged</td>
<td>1550</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6.5 Preparation of the Samples for SEM Imaging

![Image of polished and moulded sample]

**Figure 6.4:** The final prepared welded areas after polishing and moulding.

The scanning electron microscope (SEM) is one of the most versatile instruments used for microstructural analysis of solid objects. Hence, in order to validate the experimental determination of crack locations, we have used SEM imaging to ensure that crack actually exists at those locations. For this purpose the welds as described in Fig 6.3 are diced into smaller pieces, each of 1mm length, and the cut pieces are then encapsulated using Struers Citopress 20 mounting equipment, and multiple samples each having consecutive pieces from the same weld are then prepared by using Clarofast hot mounting resin. Before placing the samples in the SEM, their surfaces are polished and cleaned using a Metprep 4 grinder polisher system as per the standards. A few of the final prepared samples are shown in Fig 6.4 and are chosen for further analysis using the SEM. The encapsulated polished samples are then ensured to be in the standard size of 25 mm diameter x 20 mm height including the holder for the sample which is the standard requirement of the samples to be inserted to the JCM 6000 scanning electron microscope. The samples are then scanned and the images are analysed.

6.6 Results and discussion

6.6.1 Time domain response of cold crack induced AE events form unpackaged FBGs

The data acquired by the AE interrogation system are analysed following the methodologies explained in chapter 3 for obtaining the time domain response. For each of the welded regions there were multiple layers/passes of welding conducted to
induce maximum crack activities. From the AE data sets, we selected those with the highest number of AE events for further analysis. In Fig 6.5 we show the time domain response for the welding with cracks occurring at various locations (a) for Weld 1, (b) Weld 2, (c) Weld 3.
responses for three welding runs. For each run, we show several welding which were run for 20 seconds times followed by 60 second period after the welding ends. The change in voltage corresponds to the wavelength change experienced by the FBG due to the presence of cold cracks induced AE events. Sudden changes in amplitudes are caused by the acoustic emission events arising during welding.

Fig 6.5, shows multiple AE events taking place during the welding process, as well as afterwards, amongst which selected AE events are chosen for further analysis. Events 1, 2 and 3 are the events that occurred during the welding, while events A1, A2 and A3 are the ones that occurred after the welding, for welding regions 1, 2 and 3 respectively. The events obtained from the FBG AE interrogator were a mixture of AE signal and noise which was processed using Daubechies (DB) wavelet transform, applying DB-10 denoising using suitable thresholding. The time domain responses shown in Fig 6.5 are the denoised ones. However, it was noted that even after denoising, data from FBG2 for weld 3 were still noisy and hence were not considered for further analysis. By comparing the ToA of these events captured by different FBG sensors the location of the cracks on the welded substrate can be estimated. As seen in Fig 6.5 (a) the event 1 is recorded by FBG1 and FBG3 at 4.1105 seconds and 4.1114 seconds, respectively. By applying this data and FBG location to equations 6.4 and 6.6, the crack origin time can be calculated as 4.11102 seconds, which marks the beginning of the event and the event continues till a time duration of 4.1114 seconds. The event can be pinpointed to a distance of 5.77 mm from the start of the welded region. Similarly for the AE events obtained in Fig 6.5 (b), the ToA is 0.9848 seconds from the start of the welding which indicates the approximate location of the cracks to be around 1.43 mm from the start of the weld 2. Similar calculations were done for other events, namely A1, A2 and A3, which saw the crack initiation beginning at approximately 54.923 seconds, 49.984 seconds and 33.432 seconds respectively. Times of arrival calculated here are measured from the start of the observed welding in the time domain response.

6.6.2 Signal amplitudes measured by individual sensors

Signal amplitude plots comparing different sensors are shown in Fig 6.6, which shows the AE signal amplitude of different events measured by different FBGs. Here there are 2 graphs showing (Fig. 6.6 (a)) signal amplitudes during the welding process and (Fig. 6.6 (b)) after the welding process. As seen in the figure there is a variation
in the signal amplitudes measured by the different FBGs. Based on the plotted amplitudes we can see that the amplitude increases with decreasing distance from the FBG to the cracks. On comparing AE signal for Event 1, the signal amplitude measured by FBG2 (0.5 V) is higher compared to the ones measured by FBG1 (0.3 V) and FBG3 (0.2 V), although the crack location corresponding to Event 1 is closer to FBG2. Similarly, Event 2 has amplitudes of 0.6 V, 2 V and 0.1 V measured by FBG1, FBG2 and FBG3 respectively and amplitudes of Event 3 measured by FBG1 and FBG 3 are 1 V and 0.4 V respectively. For post welding, the measured amplitudes of the AE events are shown in Fig. 6.6(b) and the events are labelled as events A1, A2 and

![Amplitude plots vs event numbers for the three FBGs](image)

**Figure 6.6:** Amplitude plots vs event numbers for the three FBGs (a): During welding, (b): After welding
A3 corresponding to welds 1–3. In this plot, the data for FBG2 of weld 3 is ignored as it is contaminated with noise. Event A1 measured by FBG1, FBG2 and FBG3 has amplitudes of 1.9 V, 2 V and 1.8 V respectively and Event A2 has measured

![Frequency analysis of selected AE events measured by the FBG sensors for weld 2](image)

Figure 6.7: Frequency analysis of selected AE events measured by the FBG sensors for weld 2 (a) Event 2 (b) Event A2
amplitudes of 2.9 V, 2.3 V and 2.2 V respectively for FBG2, FBG3 and FBG1. Event A3 has amplitudes of 1.75 V and 1.6 V measured by FBG1 and FBG3 respectively.

It is evident from the results that the amplitude of the AE event is not directly proportional or linearly correlated to the distance between the AE source and the FBG sensor. As the FBG’s strain sensitivity is directionally dependent [98], the orientation of the crack and the FBG should be investigated to understand more about the measured amplitude of the AE event and its correlation with crack size, which is beyond the scope of this research work.

6.6.3 Frequency analysis of the cold crack induced AE events

The frequency analysis of selected measured AE events was carried out to understand the crack initiation frequencies during and after welding. AE events from weld 3 was not considered as the data was noisier and deemed not eligible for frequency analysis. The Short Term Fourier Transform (STFT) of Event 2 and Event A2 from weld 2 for all the three FBG sensors are shown in Fig 6.7. As seen in Fig 6.7(a) Event 2 shows an AE frequency range of circa 20-25 kHz measured by all the three FBG sensors. Similar frequency components were present in AE events from weld 1 during the welding process. The relative crack initiation time and duration of the AE events can also be clearly distinguished from the STFT plots and can compared with the time domain response in Fig 6.6.

![Figure 6.8: Amplitude vs event plot obtained from array having packaged sensors](image-url)
To understand the post welding crack induced AE frequencies, we have analysed Event A1 and A2 from weld 1 and 2 respectively. The measured frequency in this case was also found to be similar to that of during welding and is shown in Fig 6.7(b).

To provide an overview of the crack induced AE frequencies, the measured frequencies from Event 1, 2 and Event A1 and A2 for all the three FBG sensors are shown in Fig 6.8. It can be seen that for all the three welds the crack induced AE frequencies during and after welding are in 20-25 kHz region. As the AE frequencies depend on the welding wire and substrate properties and also the temperature, a minor difference in AE frequencies during and after welding is expected. The results are meaningful and can provide more insights to the characteristics of cold cracks in welding. To further study the frequency characteristics of cold crack induced AE events different materials and substrates can be used.

6.6.4 Time domain response of cold crack induced AE events from packaged FBGs

Fig. 6.9 depicts the time domain response of the crack induced AE events occurring during welding, as picked up by the FBG array containing two packaged FBG sensors as mentioned in section 6.4.2. Two selected AE events are marked as

![Figure 6.9: Amplitude vs event plot obtained from the packaged sensors](image-url)
Event P1 and Event P2, occurring during the welding and after the welding respectively for weld 3. The corresponding AE event amplitudes measured by the FBG sensors are shown in Fig 11. It can be seen that Event P1 amplitudes measured by the sensors FBG4, FBG6 and FBG5 are of 3.7 V, 3.1 V and 2.5 V respectively. Similarly, for the Event P2 the amplitudes Signal amplitudes from the experiment using the packaged sensors FBG 1, 2 and 3 are shown in Fig. 6.9. Three AE events at around 3 seconds, at 17 seconds and just after 40 seconds were identified and are shown in this.

Corresponding time domain responses for the three events are shown in Fig 6.10. The data is analysed for the amplitude and its plotted corresponding to the event location. From this plot it can be seen that for event 1 FBG 2 has higher amplitude compared to FBG1 and FBG3. For events 2 and 3 FBG1 has higher amplitudes than FBG2 and FBG3. It can be seen that Event P1 amplitudes measured by the sensors FBG4, FBG6 and FBG5 are of 3.7 V, 3.1 V and 2.5 V respectively. Similarly, for the Event P2 the amplitudes respectively measured by the sensors FBG4, FBG6 and FBG5 are 2.5 V, 2.4 V and 1.8V respectively.

It can be observed from the results that the packaging has not resulted in any significant difference in the AE events’ measurement, wherein the packaged FBG4 and FBG6 have shown similar behaviour compared to FBG5. As with the unpackaged

![Figure 6.10: The time domain response for the packaged sensor for welding crack monitoring detection](image-url)
FBGs, no direct conclusion can be drawn from the amplitude data without detailed analysis of the cold crack orientation. However, the results are promising, as the magnetic packaged FBG sensors are reusable and have the potential to be in used in practical SHM applications.

6.6.5 Identification of cold cracks using SEM imaging

Samples from multiple welds were taken and the images were analysed using the SEM. Samples from multiple welds from corresponding locations as discussed in section 6.5.1 were taken and the images were analysed using the SEM. A few selected SEM micrographs of the samples are shown in Fig 6.11, which correspond to welds 1 and 2 at 6 mm and 1 mm respectively. Cold cracks are clearly seen in both the SEM images, which are the sources of the AE signals measured by the FBGs. The crack location in weld 1 at 6 mm corresponds to Event 1 measured by the FBG sensor.

![SEM images of welds](image)

**Figure 6.11:** Confirmation of cold cracks from SEM imaging and its correlation with time domain response.
occurred at 4.11102 seconds after the start of the welding, as discussed in Section 6.6.1. Given the travel time of 87.4 mm/min of the arc welding system, the estimated crack location was at 5.98 mm and is in close agreement with the one identified through SEM imaging. Similarly, for weld 2, the estimated crack initiation time of 0.9848 seconds indicates a crack at 1.43 mm and from the SEM image we found a crack at 1 mm. The slight difference in the estimated and original crack locations might be due to the inaccuracies in dicing and also due to the limited dicing thickness resolution (1 mm). The synchronisation of the welding process and the FBG data acquisition could also induce some errors.

Given the close agreement between the crack location as estimated and measured, FBG measurement system is considered to be a viable option for cold crack monitoring in welding applications. However, further research is required in quantification of the crack size and crack orientation from the FBG sensor data.

6.7 Conclusion

In this research work an easily realizable AE source localisation method based on the AE waves detected by the FBG sensors was introduced. This methodology can help in future crack monitoring studies in high temperature applications. A brief history of AE techniques also is discussed. A fibre optic AE method to monitor hydrogen induced cold cracks during ultrahigh toughness high hardness armor welding was studied in this chapter. Here a high sensitivity FBG based fibre optic interrogation system was used to measure the cold crack induced AE events during the welding by studying the events and also the times of arrival, the locations of the sources of AE events and thereby cracks were mapped. To validate the location estimated with the FBG sensors, the positions of the cracks were verified by examining the plates using SEM. Further study on amplitude and energy of the crack using the FBG sensor can help in developing a dependable cold cracking monitoring system for industrial purposes and to improve the quality of the final weld.
Chapter 7

Conclusion and future work

The investigations described in this thesis are summarised in this chapter. The theoretical, simulation and experimental results reported in this work make significant contributions to our knowledge and understanding of FBG based AE studies and their potential for a new generation novel metal-encapsulated magnetic gratings for sensing applications at high temperature. This chapter also discusses the future research challenges and potential elaboration of the work presented in this thesis. FBG based AE sensing and magnetic sensors have clear research and technological development possibilities in many future applications and in this chapter some specific areas of interest for further research are focused upon.

7.1 Key findings and conclusions

The primary goal of this research work was to develop a novel FBG sensor for acoustic signal detection which has the potential to be used in high temperature applications. For achieving this, a new generation magnetic, metal encapsulated sensors capable of being surface attached on to the welded region was fabricated using samarium cobalt magnets, tin and stainless steel and was successfully implemented for AE detection. Through this process the following outcomes were demonstrated. The AE data has been analysed using various signal processing techniques. The magnetic packaged sensor was characterized for the various parameters and has been found ideal for crack monitoring in high temperature applications till around 2000 °C. Directional sensitivity of the packaged FBG sensor was studied, demonstrated and compared with unpackaged FBGs. The directional sensitivity studies were used to understand the importance of orientation of the embedded sensors in substrates and its corresponding AE sensitivity. Sources of AE and, thereby, the cold crack defects in welding, are demonstrated as a case study for the usage of the developed sensor technology.
Outcomes of the research described in this thesis are the following.

1. **Signal processing GUI designed and tested for AE data analysis**
   - We developed a graphical user interface (GUI) in MATLAB for signal thresholding and wavelet de-noising for processing. AE signals are high frequency waves that are emitted from the source of fatigue or cracks within a structure. Difficulties that arise in acoustic emission analysis are the high volume of output data that is needed to record the AE signals and the continuous noise that affects the system as the data is contaminated with various types of noise. A signal processing tool developed in this thesis was successful in considerably reducing the noise component of the signal. After significant de-noising was applied, we observed the elimination of the ghost noise components from the frequency domain plots. Upon completion of the data analysis the amplitude and frequency of the AE signal is known which is used to determine if an AE event has occurred and depending on its magnitude, the health of the structure under test could be evaluated.

2. **New generation metallic packaged FBGs for high temperature applications**
   A novel, new generation magnetic metal-encapsulated packaged sensor was designed and fabricated successfully using samarium cobalt magnets, stainless steel and tin. From the research it was concluded that this sensor has the ability to be surface-attached to magnetic structures without using any gluing material and is detachable and reusable. The peak wavelength results obtained using the FBGs before and after packaging were in close agreement. Thus, the sensor can be used in SHM of iron pipelines, welded structures and other ferromagnetic structures.

3. **Capabilities of the magnetic metallic FBG for monitoring various parameters**
   - The capabilities of this packaged FBG for the measurement of mechanical and thermal strains, temperature variations, and vibration were investigated and proved.
   - The measured load sensitivity of the packaged sensor was 0.4456 με/N.
   - Temperature sensitivity was 11.16 pm/°C.
   - The simulation results using ANSYS show a temperature sensitivity of 14.005 pm/°C and a load sensitivity of 0.7784 με/N. The experimental and simulated values were in close agreement thus the sensor’s capability to be used in SHM is proved.
The vibration sensitivity was analysed after applying different known frequencies and it was demonstrated that the measured and applied frequencies were in close agreement, thus emphasizing that this packaged sensor can be used successfully for FBG based AE monitoring. Simplicity of fabrication of this removable and reusable sensor underpins its ability to be used in pipeline monitoring and SHM of welded structures.

4. Directional sensitivity of the packaged FBG sensors

Directional sensitivity of FBGs towards AE was studied and it was concluded that the packaged sensors adequately demonstrated the property of directional sensitivity, similar to unpackaged FBG sensors and that these sensors are highly sensitive in the longitudinal direction compared to the transverse direction. Generation and propagation of the acoustic waves were studied and demonstrated using ANSYS explicit dynamics.

The FEM simulation of the directional sensitivity of both packaged and bare FBG sensors were carried out. Simulation results were in close agreement with the experimental results.

5. Cold crack monitoring in welding using FBG sensors

AE event source localisation is determined using the ToA method. The method is applied to cold crack monitoring in welding. The cold cracks, which are the source of the AE were accurately mapped from the data obtained from the time domain responses. The Crack locations were then verified by SEM imaging analysis. The study has confirmed that identification of the directional sensitivity helps in source localization, which is one of the biggest concerns in AE detection. It has been concluded that accurate location of the cracks can be found using packaged or unpackaged FBG sensors by accurate placement of the FBG sensors, calculating the arrival time and knowing the acoustic wave velocity in UHT HHA steel. The positions of the cracks pinpointed were validated using scanning electron microscope and time domain responses.

Overall outcomes

New generation magnetic metal-encapsulated FBG sensors were developed for use in high temperature applications;
➢ Samarium cobalt magnets were used as they retain their magnetic properties at high temperatures;
➢ Load, temperature and vibration characteristics of the packaged sensors were experimentally obtained and also verified by FEM simulations;
➢ A graphical user interface was developed using which ghost noises present in the original processed AE data were eliminated and is verified by observing the de-noised frequency domain data;
➢ Directional sensitivity is studied for both packaged and unpackaged FBG sensors;
➢ Directional sensitivity is verified both experimentally and using FEM simulations. We demonstrated that these sensors are highly sensitive in the longitudinal direction compared to the transverse direction;
➢ Applications of the packaged FBG sensors in locating the source of cold cracks occurring in welding was demonstrated;
➢ The source of cracks was located by using ToA method, and cross-verified using time domain response and using SEM;

7.2 Limitations of packaged FBGs

Packaged FBGs mentioned in this thesis despite having several advantages, also possess a few limitations such as
➢ Would require proper bonding between the materials to ensure adequate strain transfer between the packing material and the FBG;
➢ The AE amplitude measurement resolution depends on the mechanical and physical characteristics of the packaging materials;
➢ The design of the sensors can be further modified to improve the sensitivity and temperature range. Together with high temperature withstanding materials, magnets and FBGs based on speciality fibres the operating temperatures of the packaged sensors could be extended above 1000 °C.

7.3 Future scope for research

Future studies on improving the FBG AE interrogation system

➢ A commercial FBG interrogator FAESense was mainly used for this thesis work. After studying the different interrogator systems there is scope for research to implement a FBG AE interrogation system which has enhanced sensitivity and
bandwidth, is immune to environmental perturbations, acquires data in more user friendly format and is economically more feasible. Real time monitoring should be improved by enabling the real time plotting of the time domain and the frequency domain response.

➢ A wireless FBG interrogator system can also be developed which can enable remote, wireless and smart monitoring.

Use of FBGs in harsh Environments

The magnetically-mounted metallic-packaged FBG fabricated in this thesis can be improvised to be used in high temperature applications up to 800 °C (limited by the operating temperature of SmCo magnets) by used appropriate packaging materials. Further feasibility studies and implementation will help in the monitoring of structures in harsh environments such as aerospace, nuclear plants and steel industries. By incorporating FBGs with regenerated gratings and sapphire fibres, the sensor will be able to detect defects and cracks in structures in high temperature environment to give a better insight into the development and propagation of cracks due to temperature effect. Furthermore remote sensing of ultrasonic guided waves from the harsh environment using FBGs is one of the research areas which can be helpful for sensing in harsh environments.
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Appendix A: I-MON 256 USB

I-Mon 256 USB works on the high resolution spectrometer technology which utilizes Ibsen fused silica transmission gratings, I-MON splits the wavelength spectrum spatially allowing parallel processing of individual FBG sensor peaks which are measured by a diode array and embedded electronics.

Features of I-MON 256 USB interrogator system are a high measurement frequency, high resolution, large dynamic range with a compact size without any moving parts and works on broad wavelength ranges. This can be applied as a stand-alone interrogation monitor and/or OEM interrogation monitor modules for applications in vibration analysis, temperature measurements, pressure monitoring and strain measurements. The table below shows the specifications of the I-MON 256 USB interrogator system. The photograph of the I-MON 256 USB is shown in fig A.1

Table A.1: Specifications of the I-MON 256 USB interrogator system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>I-Mon 256</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength range</td>
<td>1525-1570 nm</td>
</tr>
<tr>
<td>Max no. of FBG and spacing</td>
<td>&gt;36 at 1200 pm</td>
</tr>
<tr>
<td>Wavelength fit resolution</td>
<td>&lt;0.5 pm</td>
</tr>
<tr>
<td>Wavelength linearity</td>
<td>3 (max) pm</td>
</tr>
<tr>
<td>Wavelength drift</td>
<td>1 (max) pm/degree C</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>30 dB</td>
</tr>
<tr>
<td>Input optical power range</td>
<td>-75 to -25 dBm</td>
</tr>
<tr>
<td>Measurement frequency</td>
<td>3 kHz max</td>
</tr>
<tr>
<td>Interface</td>
<td>GigE</td>
</tr>
<tr>
<td>Power supply</td>
<td>5 VDC, 3A</td>
</tr>
<tr>
<td>Temperature range</td>
<td>0-50 degree C</td>
</tr>
<tr>
<td>Size</td>
<td>124 x 94 x 59 mm</td>
</tr>
</tbody>
</table>
Figure A.1: I-MON 256 USB interrogator system
Appendix B: FAESense M400 interrogator

This is a four channel FBG AE sensor interrogation device based on Redendo optics International’s proprietary two wave mixing integrated optic microchip technology. The FAESense-M400 series features a high power broadband light source in C-band 1550 nm window and four individual high sensitivity detection channels for each FBG sensor in a fibre array.

Table A.2: the specification of the FAESense M400 interrogator system

<table>
<thead>
<tr>
<th>Model No FAESense-M400</th>
<th>M400</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sensing Channels</strong></td>
<td>4 FBG transducers on a single fibre strand,</td>
</tr>
<tr>
<td><strong>Monitoring Mode</strong></td>
<td>Stress-strain, vibration, and acoustics emissions</td>
</tr>
<tr>
<td><strong>Monitoring Principle</strong></td>
<td>Adaptive Two-Wave Mixing (TWM) interferometry</td>
</tr>
<tr>
<td><strong>Wavelength Range</strong></td>
<td>1530 nm to 1580 nm</td>
</tr>
<tr>
<td><strong>Bandwidth (FWHM)</strong></td>
<td>60 nm</td>
</tr>
<tr>
<td><strong>Output Power Max</strong></td>
<td>6 dBm</td>
</tr>
<tr>
<td><strong>Strain Sensitivity</strong></td>
<td>≤ 100-femtostrains</td>
</tr>
<tr>
<td><strong>Frequency Range</strong></td>
<td>0 to 585 kHz</td>
</tr>
<tr>
<td><strong>Frequency Accuracy</strong></td>
<td>± 1% of reading</td>
</tr>
<tr>
<td><strong>Frequency Bandwidth</strong></td>
<td>3 dB from 1-kHz to 100-KHz</td>
</tr>
<tr>
<td><strong>Sensor Sampling Rate</strong></td>
<td>585 kHz for 4 Channels or 2 MHz for single Channel</td>
</tr>
<tr>
<td><strong>Power Supply</strong></td>
<td>5 V/500 mA</td>
</tr>
<tr>
<td><strong>Data Communication USB</strong></td>
<td></td>
</tr>
<tr>
<td>---------------------------</td>
<td></td>
</tr>
<tr>
<td><strong>Optical Connector</strong></td>
<td>Fibre pigtail with FC/APC connector or FC/APC receptacle</td>
</tr>
<tr>
<td><strong>Package</strong></td>
<td>4.2-inch x 2.2-inch x 1.6-inch</td>
</tr>
<tr>
<td><strong>Data Display</strong></td>
<td>LabView Graphical Interface</td>
</tr>
</tbody>
</table>
Appendix C: Welding Equipment

MIG welding with shielding gas and a solid wire electrode produces a clean, slag free weld without the need to continually stop and replace the electrode as in stick welding. This method increases the productivity and reduces clean up.

Wire Feeder

Welding carried out in this thesis uses a Stoody 101-HC chromium wire, which is feeded on to the wire arc using the cold wire feeder WF-3 which feeds the wire on to the TIG torch. This system works independently using a standard TIG power supply using normal TIG welding parameters. This has an ON/OFF switch, pilot light, pulse/continuous feed switch, pulse wire on and off timers, remote switch receptable, delay wire start and wire retract. The benefits of using this cold wire feeder includes automation of adding filler metal in TIG welding, all weld parameters can be duplicated. dual groove drive roll system accepts multiple wire sizes, eliminates TIG rod stub loss, cabinet keeps filler wire clean, makes fully automatic machine TIG welding possible, results are consistent and high quality welds. The specification of this cold wire feeder are as shown in the table.

Table A.3: The specifications for the Wire Feed 3 system

<table>
<thead>
<tr>
<th>Voltage</th>
<th>115 V AC (220 V 50 Hz. –Special item)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase</td>
<td>Single phase</td>
</tr>
<tr>
<td>Frequency</td>
<td>50/60 Hz</td>
</tr>
<tr>
<td>Height</td>
<td>15” (38.1 cm)</td>
</tr>
<tr>
<td>Width</td>
<td>10” (25.4 cm)</td>
</tr>
<tr>
<td>Length</td>
<td>21” (53.3 cm)</td>
</tr>
<tr>
<td>Weight</td>
<td>54 lbs (17.7 kg)</td>
</tr>
<tr>
<td>Motor type</td>
<td>DC permanent magnet</td>
</tr>
<tr>
<td>Motor rating</td>
<td>1/3 hp at 4000 pm</td>
</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>----------------------------</td>
</tr>
<tr>
<td>Filler wire spool size</td>
<td>12” (30.5 cm)</td>
</tr>
<tr>
<td>Filler wire sizes</td>
<td>0.030” (0.8 mm) - 0.035” (0.9 mm)</td>
</tr>
<tr>
<td></td>
<td>0.045” (1.1 mm), 1/16” (1.6 mm)</td>
</tr>
<tr>
<td>Wire Feed speed range</td>
<td>0-500 ipm (0-1250 cm)</td>
</tr>
<tr>
<td>Feed time (pulsed mode)</td>
<td>Continuously variable</td>
</tr>
<tr>
<td>Dwell time (Pulsed mode)</td>
<td>Continuously variable</td>
</tr>
<tr>
<td>Delay start time</td>
<td>Continuously variable</td>
</tr>
<tr>
<td>Wire retract time</td>
<td>Continuously variable</td>
</tr>
</tbody>
</table>

The photograph of the wire from the wire feed 3 is fed on to the arc which is originating from Master TIG MLS 2000 from Kemppi here the current and the voltage at which the welding arc is discharged is set and adjusted. The current with which the arc is discharged is 100 A and a voltage of 100 V. the photograph of Master TIG MLS 2000 is shown in fig A.3
The benefits of using Master TIG MLS 3000 include DC TIG MMA power output, compact size which ensures effortless mobility. Excellent ignition quality even with long TIG torches, quick pulse function increases welding speed and quality and are suitable for use with power generators.

![Image](image.png)

**Figure A.3:** The interface of the TIG MLS 2000 displaying the welding current used in the experiment

**Shielding gas**

The shielding gas plays a crucial role in understanding the effect of the shielding gas and their unique properties. The main purpose of a shielding gas is to prevent the exposure to the molten weld pool to Oxygen, Nitrogen and hydrogen which are present in the air and atmosphere reaction to which with the weld pool can create a variety of problems including porosity and excessive spatter. These gases play an important role in determining weld penetration profiles, arc stability, mechanical properties of the finished weld and the transfer process you use and more.

The most commonly used types of shielding gases include Argon, Helium, Carbon dioxide and Oxygen, each having its own advantages. For the welding conducted in this thesis Argon gas has been used because of the advantages such as placing an emphasis on weld quality, appearance and reducing post weld clean up. A mixture between 75-95% Argon and 5-25% CO₂ which can provide a more desirable combination of arc stability, puddle control and reduced spatter than pure CO₂. This will also allow the use of a spray transfer process which can produce higher productivity rates.