

IMPROVED STATIC AND DYNAMIC FBG  
SENSOR SYSTEM FOR REAL-TIME  
MONITORING OF COMPOSITE  
STRUCTURES

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Master

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## **SUPERVISOR'S DECLARATION**

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## **STUDENT'S DECLARATION**

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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## TABLE OF CONTENT

<b>DECLARATION</b>	
<b>TITLE PAGE</b>	
<b>ACKNOWLEDGEMENTS</b>	<b>ii</b>
<b>ABSTRAK</b>	<b>iii</b>
<b>ABSTRACT</b>	<b>iv</b>
<b>TABLE OF CONTENT</b>	<b>v</b>
<b>LIST OF TABLES</b>	<b>viii</b>
<b>LIST OF FIGURES</b>	<b>ix</b>
<b>LIST OF SYMBOLS</b>	<b>xiii</b>
<b>LIST OF ABBREVIATIONS</b>	<b>xiv</b>
<b>CHAPTER 1 INTRODUCTION</b>	<b>1</b>
1.1 Background Study	1
1.2 Problem Statement	5
1.3 Objectives	7
1.4 Scope	8
1.5 Significant/Contribution of Study	8
1.6 Thesis Organization	8
<b>CHAPTER 2 LITERATURE REVIEW</b>	<b>10</b>
2.1 Introductory to Composite Material	10
2.2 Applications and Global Demand of Composite Material	11
2.2.1 Composite Material in Civil Engineering	13

2.2.2	Composite Material in Aeronautical Application	14
2.3	Problems Associated with Composite Material	15
2.4	Structural Health Monitoring (SHM)	16
2.5	Introduction to Fibre Optic Sensor (FOS)	19
2.5.1	Fundamental of FBG in Strain Sensing	22
2.5.2	FBG Interrogation System in Strain Sensing	28
2.5.3	Challenges of FBG Embedding in Composite Material	35
2.6	FBG Based Real-Time Monitoring System	39
2.6.1	Static Strain Sensing Real-Time Monitoring System	40
2.6.2	Dynamic Strain Sensing Real-Time Monitoring System	44
2.7	Chapter Summary	50
 <b>CHAPTER 3 METHODOLOGY</b>		 <b>52</b>
3.1	Organization of the Experimental Planning	52
3.2	List of Components and Equipment Adopted	54
3.2.1	Light Source	54
3.2.2	Optical Circulator	55
3.2.3	Optical Coupler	56
3.2.4	Optical Splitter	57
3.2.5	Photodiode or Photodetector (PD)	57
3.2.6	Optical Spectrum Analyzer (OSA)	58
3.2.7	National Instruments NI-9234 Data Acquisition Device	59
3.2.8	Acoustic Emission (AE) Broadband Sensor	60
3.3	Specimens Fabrication	60
3.4	Overall Static Strain Sensitivity Test Experimental Set-Up	63
3.5	Static Strain Sensing Experimental Set-Up	64

3.6	Overall Dynamic Strain Sensitivity Test Experimental Set-Up	67
3.7	Dynamic Strain Sensing Experimental Set-Up	68
3.8	Chapter Summary	73
<b>CHAPTER 4 RESULTS AND DISCUSSION</b>		<b>75</b>
4.1	Overall Static Strain Sensitivity Test Experimental Results	75
4.2	Static Strain Sensing Experimental Results	76
4.3	Overall Dynamic Strain Sensitivity Test Experimental Results	88
4.4	Dynamic Strain Sensing Experimental Results	90
4.5	Chapter Summary	104
<b>CHAPTER 5 CONCLUSION</b>		<b>105</b>
5.1	Conclusion	105
5.2	Future Work and Recommendations	106
<b>REFERENCES</b>		<b>108</b>
<b>APPENDIX A MESH-GRID COMPOSITE PLATE GUI LAYOUT</b>		<b>119</b>
<b>APPENDIX B VOLTAGE NORMALIZATION GUI LAYOUT</b>		<b>123</b>
<b>APPENDIX C CC-LSL ALGORITHM IMPACT LOCALIZATION GUI LAYOUT</b>		<b>126</b>
<b>APPENDIX D FFT FUNCTION OF COMPOSITE PLATE GUI LAYOUT</b>		<b>128</b>
<b>APPENDIX E GANTT CHART</b>		<b>130</b>
<b>APPENDIX F PUBLICATIONS</b>		<b>131</b>



## LIST OF TABLES

Table 2.1	The specifications of each optical fibre cable	25
Table 2.2	Summarization of comparison between optical sensing and electrical sensing technology	28
Table 3.1	Specifications of the ASE light source	55
Table 3.2	Specifications of the optical circulator	56
Table 3.3	Specifications of the optical coupler	56
Table 3.4	Specifications of the optical splitter	57
Table 3.5	Specifications of Thorlabs InGaAs photodetector	58
Table 3.6	Specifications of Bayspec optical spectrum analyzer	59
Table 3.7	Specifications of National Instruments NI-9234 data acquisition device	60
Table 3.8	Specifications of the acoustic emission (AE) sensor	60
Table 3.9	Physical properties of the composite plate	61
Table 3.10	Physical properties of the GFRP beam	63
Table 3.11	Mechanical properties of both the specimens	63
Table 3.12	The summarization of the impact points induced on the beam	69
Table 4.1	The summarized results of static strain mesh-grid function for composite plate	77
Table 4.2	The summarized results of static strain mesh-grid function for GFRP beam	78
Table 4.3	The summarized results of average load estimated and average percentage of error without voltage normalization algorithm (non-normalized)	87
Table 4.4	The summarized results of average load estimated and average percentage of error with voltage normalization algorithm (normalized)	87
Table 4.5	The natural frequency of the composite plate	90
Table 4.6	The summarization of the samples difference and time delay for all the impact points	95
Table 4.7	The comparison between FEA analysis, FBG sensor and AE sensor natural frequency values	99
Table 4.8	The summarization of linear source impact location results	100
Table 4.9	The comparison of natural frequency values obtained from Abaqus FEA, FBG sensor and AE sensor for composite plate	103

## LIST OF FIGURES

Figure 1.1	The illustration of FBG sensor as accelerometer	3
Figure 1.2	The edge filter detection method	4
Figure 1.3	The power detection method: (a) Linear edge source (b) Narrow bandwidth source	4
Figure 1.4	K-chart for the narrowing down process of this research study	7
Figure 2.1	Market research approach for CFRP	12
Figure 2.2	Market research approach for GFRP	12
Figure 2.3	Okinawa road park GFRP bridge	13
Figure 2.4	FRP water gate at Komagari dam	14
Figure 2.5	Manufacturing of Boeing 787 materials proposition	15
Figure 2.6	Smart system working components	18
Figure 2.7	Types of FOS sensors	19
Figure 2.8	The spectrum of the scattering light in distributed sensors	20
Figure 2.9	The Sagnac interferometric sensor interrogation system	20
Figure 2.10	The illustration of the Fabry-Perot interferometric sensors	21
Figure 2.11	Illustration of the multimode, single-mode and POF optical fibre	23
Figure 2.12	Light mode transmission in optical fibre	24
Figure 2.13	Optical fibre attenuation curve	25
Figure 2.14	The working principle of FBG sensor	26
Figure 2.15	The working principle of edge filter detection	30
Figure 2.16	The working principle of the edge filter interrogation system utilizing photodetector as signal converter	30
Figure 2.17	Illustration of the elongated embedded FBG due to strain	31
Figure 2.18	Shifting of the reflected Bragg wavelength due to strain	31
Figure 2.19	Light intensity as in shaded region identified by the photodetector	32
Figure 2.20	Matched-edge filter interrogation system by Hiroshi Tsuda	32
Figure 2.21	Interrogation system developed by Comanici et al	33
Figure 2.22	Interrogation system utilizing Tunable laser by Hiroshi Tsuda	33
Figure 2.23	Interrogation system developed by Frieden et al	34
Figure 2.24	Interrogation system developed by Ling et al.	35
Figure 2.25	Pre-preg layup method	36
Figure 2.26	Location of the FBG embedment: (a) Front view (b) Back view	37
Figure 2.27	Comparison of the reflected wavelength for: (a) OF <sub>1</sub> and (b) OF <sub>2</sub>	37
Figure 2.28	Insertion of bare optical fibre in Teflon tube	38

Figure 2.29	Embedded connector inside the composite together with optical fibre	39
Figure 2.30	Ultra small interrogation system unit	39
Figure 2.31	FBGs positioning on the top and bottom chords of the bridge	40
Figure 2.32	Spectrums of FBGs from the load test of trucks and locomotive for (a) Top position (b) Bottom position of the bridge's chord	41
Figure 2.33	Results of a six car-passenger train passes the railway	42
Figure 2.34	Inconsistency of output voltage	43
Figure 2.35	Time delay between two FBG signals	45
Figure 2.36	Digital oscilloscope used for signal logging process	45
Figure 2.37	The cross-correlation algorithm from two different vessels	48
Figure 2.38	Illustration of linear source location technique for impact detection	49
Figure 3.1	Flow chart of the overall experimental procedure	53
Figure 3.2	Amplified Spontaneous Emission (ASE) light source	54
Figure 3.3	Operating wavelength range of the light source	54
Figure 3.4	3-port optical circulator	55
Figure 3.5	2x2, 4-port optical coupler	56
Figure 3.6	1 x 8 optical splitter	57
Figure 3.7	Thorlabs InGaAs photodetector	58
Figure 3.8	Bayspec optical spectrum analyzer (OSA)	59
Figure 3.9	National Instruments NI-9234 data acquisition device	59
Figure 3.10	Acoustic emission (AE) broadband sensor	60
Figure 3.11	Specimen fabrication materials: (a) Woven fibreglass (b) Epoxy and hardener as resin	61
Figure 3.12	Cured sample of the composite plate	61
Figure 3.13	Mould forming process: (a) Polystyrene foam (b) Mould of the beam	62
Figure 3.14	Composite beam fabrication: (a) Woven fibreglass (b) Cured sample of the GFRP beam	62
Figure 3.15	The dog-bone aluminium tensile specimen with surface pasted FBG sensor	64
Figure 3.16	The overall static strain sensitivity experimental set-up: (a) Gripping of the specimen on the machine (b) The Instron 3369 50 kN tensile test machine	64
Figure 3.17	Experimental set-up: (a) Fixed edges of the composite plate, and position of the weight support stand (b) Loads of 10 N and 20 N	65

Figure 3.18	Fixture of the beam and placement of the weight support stand on the beam	65
Figure 3.19	The experimental set-up interrogation system configurations	66
Figure 3.20	The configuration of edge filter detection interrogation system	67
Figure 3.21	The experimental set-up for the overall dynamic strain sensitivity performance	68
Figure 3.22	Abaqus FEA simulation for the dynamic sensitivity test: (a) Fixed boundary conditions of the composite plate (b) Meshing of the composite plate for analysis	68
Figure 3.23	The schematic illustration of the impact localization interrogation system	69
Figure 3.24	The impact locations for: (a) Top and bottom (b) Left and right sides of the beam	70
Figure 3.25	The flow chart of the CC-LSL algorithm in GUI monitoring system	71
Figure 3.26	Surface mounting of the AE sensor for data validation with FBG sensor	71
Figure 3.27	Abaqus FEA simulation: (a) Fixed boundary conditions of the beam (b) Meshing of the beam for analysis	72
Figure 3.28	Natural frequency excitation experimental set-up: (a) Fixture of the composite plate with surface attached AE sensor (b) A set of impacts was hit 15 cm away from both the sensor placement	72
Figure 3.29	Abaqus FEA simulation: (a) Fixed boundary conditions of the composite plate (b) Meshing of the composite plate for analysis	73
Figure 4.1	The static sensitivity graph of the FBG sensor	75
Figure 4.2	The line graph of reflected Bragg wavelength against extension	76
Figure 4.3	Linearity response of voltage difference against load induced for composite plate mesh-grid function	77
Figure 4.4	Linearity response of voltage difference against load induced for GFRP beam mesh-grid function	78
Figure 4.5	Reflected wavelengths of the sensing FBG from optical components: (a) SET A, (b) SET B, (c) SET C and (d) Overlay of all the optical components	81
Figure 4.6	The reflected peak wavelength shifts for all the optical components across loadings of 0N to 50 N	81
Figure 4.7	Gaussian Bragg wavelength shift across the 50 N loadings and the increase in line's weight corresponding to the increase in loading	82
Figure 4.8	Reflected wavelength of the sensing and reference FBG	82
Figure 4.9	The mismatched reflected wavelength between reference and sensing FBG	83

Figure 4.10	Peak wavelength and intensity shift of the mismatched reflected wavelength with the straight lines representing the line of best fit	84
Figure 4.11	Gaussian Bragg wavelength shift of the mismatched reflected wavelength with the increase in line's weight corresponding to the increase in loadings	84
Figure 4.12	The five repetitions of voltage response against load induced without voltage normalization algorithm	85
Figure 4.13	The output voltage variations (data points) without voltage normalization algorithm where the solid line is the line of best fit, and the dashed line is the expected voltage obtained from the linearity equation	85
Figure 4.14	The five repetitions of voltage response against load induced with voltage normalization algorithm	86
Figure 4.15	The output voltage variations (data points) with voltage normalization algorithm where the solid line is the line of best fit and the dashed line is the expected voltage obtained from the linearity equation	86
Figure 4.16	The sensitivity response curve of the FBG sensor	88
Figure 4.17	The normalized power sensitivity response curve of the FBG sensor	89
Figure 4.18	The performance of cross-correlation function at certain SNR values where the raw impact signal was illustrated on the left and the cross-correlation function at the right	92
Figure 4.19	The response of raw impact signal for impact at: (a) Point A (b) Point B	93
Figure 4.20	The cross-correlation signals for impact at point: (a) A, J and B, K (b) D and E (c) G and H	94
Figure 4.21	The comparison of frequency spectrum between FBG and AE sensor at point C for frequency range of: (a) below 500 Hz (b) 500 to 1000 Hz	96
Figure 4.22	The comparison of frequency spectrum between FBG and AE sensor at point F for frequency range of: (a) below 500 Hz (b) 500 to 1000 Hz	97
Figure 4.23	The overlay of frequency response captured by FBG sensor for impact at point C and L for frequency range of: (a) below 500 Hz (b) 500 to 1000 Hz	98
Figure 4.24	The group velocity curve calculated from the PACshare Dispersion Curves	99
Figure 4.25	The illustration of discrepancies between actual and estimated impact points for: (a) Top and bottom surface (b) Left surface (c) Right surface	101
Figure 4.26	The natural frequency spectrum captured by: (a) FBG sensor (b) AE sensor	102

## LIST OF SYMBOLS

$\lambda_B$	Bragg wavelength
$^{\circ}\text{C}$	Celcius
$\Delta\lambda_B$	Change of Bragg wavelength
$\Delta T$	Change of temperature
$\Delta t$	Change of time
$\kappa$	Grating orders
$\eta_{\text{eff}}$	Grating refractive index
$C_g$	Group of velocity
$\Lambda_0$	Initial grating period
$\mu$	Micro
%	Percent
$\eta_0$	Refractive index
$F_s$	Sampling frequency
$\varepsilon$	Strain
$\hat{a}$	Thermal expansion
$\xi$	Thermo-optic coefficient

## LIST OF ABBREVIATIONS

AE	Acoustic emission
ASE	Amplified spontaneous emission
BVID	Barely visible impact damage
CO <sub>2</sub>	Carbon dioxide
CFRP	Carbon fibre reinforced plastic
cm	Centimetre
m <sup>3</sup>	Cubic metre
dB	Decibel
EMI	Electromagnetic interference
ET	Electromagnetic testing
FP	Fabry-perot
FFT	Fast Fourier Transform
FBG	Fibre Bragg grating
FOS	Fibre optic sensor
FRP	Fibre-reinforced polymer
Ge	Germanium
GFRP	Glass fibre reinforced plastic
g	Gram
GUI	Graphical user interface
Hz	Hertz
InGaAs	Indium-Gallium-Arsenide
JSCE	Japan Society of Civil Engineers
kg	Kilogram
kHz	Kilohertz
km	Kilometre
kPa	Kilopascal
LCCA	Life-Cycle Cost Assessment
MHz	Megahertz
MPa	Megapascal
MEMS	Micro-electromechanical systems
μm	Micro-metre
με	Micro-strain
mm	Millimetre
ms	Millisecond

mV	Millivolts
nm	Nanometer
N	Newton
NO <sub>x</sub>	Nitrogen oxides
NDE	Non-destructive evaluation
NDT	Non-destructive testing
OSA	Optical spectrum analyser
PD	Photodetector
Pe	Photo-elastic
pm	Picometre
POF	Plastic-based optical fibre
PTFE	Polytetrafluoroethylene
PVDF	Polyvinylidene fluoride
PLC	Programmable logic controller
RT	Radiographic testing
s	Second
SMA	Shape memory alloy
SMP	Shape memory polymer
SNR	Signal to noise ratio
Si	Silicon
SHM	Structural health monitoring
SLD	Superluminescent diode
UT	Ultrasonic testing
UV	Ultraviolet
VT	Visual testing
V	Volts



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## ABSTRAK

Gentian kaca polimer (GFRP) adalah sejenis bahan komposit yang memiliki nisbah kekuatan yang tinggi terhadap keseluruhan berat berbanding dengan bahan logam konvensional. Namun begitu, bahan komposit ini mudah terdedah kepada kerosakan yang mana memerlukan pemantauan keadaan struktur objek tersebut. Penderiaan FBG mempunyai potensi yang tinggi untuk disatukan dengan bahan komposit dalam pelaksanaan pemantauan berterusan kondisi struktur objek. Namun begitu, kajian mendapati sistem pemantauan berdasarkan FBG dilihat mempunyai beberapa kelemahan dari segi statik dan juga dinamik. Variasi dari keluaran voltan menyebabkan bacaan yang tidak tepat. Kaedah ilustrasi spektrum dalam pentafsiran statik juga dikenalpasti sebagai kelemahan dalam pengukuran statik. Bagi kelemahan dalam pengukuran dinamik, kesukaran dalam perbezaan masa antara dua isyarat menyebabkan anggaran sumber isyarat yang tidak tepat. Justeru, tujuan utama kajian penyelidikan ini adalah untuk meningkatkan serta penambahbaikkan dalam sistem pemantauan berdasarkan FBG dengan penggunaan fungsi dan algoritma tertentu seperti fungsi grid jaring, algoritma penormalan voltan, algoritma CC-LSL, dan fungsi FFT. Dua spesimen telah dibentuk iaitu plat komposit dan rasuk komposit yang berasaskan kaedah laminasi. Penderiaan FBG telah diintegrasikan ke dalam kedua-dua spesimen tersebut. Bagi penambahbaikkan dalam pemantauan secara statik, kedua-dua spesimen tersebut dikenakan beban. Secara hasilnya, fungsi grid jaring digunakan sebagai paparan interaktif yang mewakili struktur objek berkenaan dan akan memaparkan kondisi struktur semasa berlaku pesongan. Algoritma penormalan voltan pula berjaya mengurangkan variasi keluaran voltan dari 26 data/minit kepada 17 data/minit. Bagi penambahbaikkan dalam pemantauan secara dinamik pula, kesan penyetempatan dijalankan ke atas rasuk pada tempat tertentu. Secara hasilnya, algoritma CC-LSL mampu membuat anggaran impak secara tepat dengan peratusan kesilapan pada 2.47% dari impak sebenar. Perbandingan spektrum frekuensi antara sensor FBG dan sensor AE pula menunjukkan profil yang sama dengan peratusan kesilapan keseluruhan kurang daripada 10%. Manakala perbandingan spektrum frekuensi antaran sensor FBG, sensor AE, dan simulasi dari Abaqus FEA menunjukkan sensor FBG lebih sensitif kepada gelombang perambatan normal mod berbanding dengan sensor AE. Sensitiviti statik dan dinamik keseluruhan sensor FBG ini direkodkan pada  $1.21 \text{ pm}/\mu\epsilon$  dan mampu mentaksir frekuensi maksima pada nilai 5 kHz. Secara kesimpulan, dipercayai bahawa sistem bereputasi ini mampu mencapai konsep utama struktur pintar.

## ABSTRACT

Glass-fibre reinforced polymer (GFRP) composite materials certainly have the undeniable favour over conventional metallic materials, notably in light weight to high strength ratio. However, these composite materials are prone to sudden catastrophic damage that requires the structural health monitoring (SHM). FBG sensor has shown a great potential in embedding and integrating with the composite materials, performing real-time monitoring of the structural condition. However, a critical review on the current FBG based real-time monitoring system initiates that many attempts and intentions are still needed to bring the present monitoring system to a fully matured readiness level. The main problems are the drawbacks in static and dynamic strain sensing monitoring assessment. Error in desired readings due to variations in output voltage and spectrum illustration for static strain interpretation are the drawbacks in static strain sensing. On the other hand, due to the presence of noise in the signal spectrum, the estimation of time of arrival (TOA) through peak detection is pin-pointed as the drawback in dynamic strain sensing. Thus, the designation of this research study is to improve the current FBG based real-time monitoring system with the use of certain functions and algorithms, that are the instant mesh-grid function, voltage normalization algorithm, CC-LSL algorithm, and FFT function. Two specimens have been fabricated namely composite plate and composite beam which are based on hand lay-up lamination method. FBG sensors are embedded in both the structures. For improvement in static strain measurement, both the specimens are being subjected to load induced. As a results, the mesh-grid function utilized is capable of meshing any sizes and shapes of a structure, and display the deflection of the structure in an interactive way of artificial representation. The voltage normalization algorithm has reduced the output voltage variations from 26 data/minute to 17 data/minute with the elimination of pre-calibration each time before use. For the improvement in dynamic strain sensing, impact localization are being carried out on the beam at certain points. As a results, the merging of cross-correlation approach with linear source location technique (CC-LSL) has estimated the impact location close to the actual hit location with the largest relative error at only 2.47 %. The comparison of frequency spectrum between FBG sensor and AE sensor shows an identical profile with the percentage error of less than 10 %. The validation of frequency spectrums from FBG sensor and AE sensor with Abaqus FEA simulation shows that the frequency spectrums captured by FBG sensor are more sensitive to the normal mode wave propagation of the structure compared to AE sensor. Overall, the static and dynamic sensitivity of the FBG sensor was recorded at 1.21 pm/ $\mu\epsilon$  with maximum capturing frequency of 5 kHz. From the conclusion of the study, it is truly believed that with this reputable sensing system, it is one step closer to achieving the key concept of smart structure.

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