

DEVELOPMENT OF A NON-INERTIA MASS
FIBRE BRAGG GRATING ACCELEROMETER
BASED ON A SINGLE DIAPHRAGM
MECHANISM AND ITS VIBRATION
RESPONSE ANALYSIS

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SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science.

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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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ABSTRAK

Pembangunan penderia gentian parutan Bragg (FBG) sebagai sebuah penderia pecutan telah mendapat perhatian yang besar memandangkan penderia FBG amat peka terhadap terikan. Pengenalan jisim inersia ke dalam pecutan FBG jenis diafragma meningkatkan kerumitan mekanisme pecutan. Selain itu, kajian berangka dan eksperimen tidak dilaporkan dan diterbitkan secara komprehensif, walaupun beberapa aspek penderia pecutan perlu disiasat dengan teliti. Objektif keseluruhan tesis ini adalah untuk membentangkan reka bentuk baharu penderia pecutan FBG jisim bukan inersia (FBGA-SD) jenis diafragma yang kecil dan boleh fabrikasi yang didatangkan dengan ciri baharu, serta analisis berangka dan eksperimen yang komprehensif. Penyelidikan ini bermula dengan pembangunan lima reka bentuk FBGA-SD dan pemarkahan konsep mereka. Dinamik reka bentuk FBGA-SD yang akhir kemudiannya dikaji menggunakan analisis modal unsur terhingga diikuti dengan analisis tindak balas harmonik untuk menentukan lokasi terikan maksimum pada diafragma untuk meletakkan penderia FBG. Kefungsian FBGA-SD akhirnya dikaji melalui analisis tindak balas sementara dan kerja eksperimen serta penentuan kepekaan. Reka bentuk akhir FBGA-SD dengan dimensi $16 \text{ mm} \times 16 \text{ mm} \times 10 \text{ mm}$ dan berat 4-gram telah menghapuskan kelemahan empat reka bentuk FBGA-SD sebelumnya, dengan ciri-ciri baru diperkenalkan terutamanya dalam pemanjangan terowong FBG dan ciptaan lubang telus untuk memantau penderia FBG di dalam poket diafragma. Analisis modal unsur terhingga telah memastikan bahawa frekuensi semulajadi pertama diafragma adalah lebih rendah (13, 380 Hz) dan jauh daripada perumah (20, 689 Hz) untuk mengelakkan dinamik perumah yang menjejaskan tindak balas penderia pecutan. Lokasi terikan maksimum untuk meletakkan penderia FBG pada diafragma ditentukan, dengan dua kedudukan terbaik didapati berada di tengah dan di sepanjang tepi diafragma. Disebabkan fakta bahawa pinggir diafragma adalah kawasan yang diapit, meletakkan penderia FBG di tengahnya adalah lebih sesuai. Tindak balas anjakan panjang gelombang yang diperolehi daripada analisis tindak balas sementara dan eksperimen menunjukkan persetujuan yang baik dari segi corak dan fasa, tetapi berbeza sebanyak 50% dari segi amplitud. Didapati juga bahawa pecutan asas dan anjakan panjang gelombang kedua-duanya menunjukkan bahawa ianya adalah juga sefasa. Perbezaan 50% dalam amplitud anjakan panjang gelombang mencerminkan kepekaan FBGA-SD, di mana kepekaan eksperimen ialah $9.64 \times 10^{-5} \text{ nm/g}$ dan analisis tindak balas sementara memberikan $4.79 \times 10^{-5} \text{ nm/g}$, sah untuk julat frekuensi pengujaan 10 hingga 147 Hz dan pecutan asas maksimum 10.5 m/s^2 . Dalam julat ini, kepekaan tidak bergantung kepada frekuensi.

ABSTRACT

The development of the fibre Bragg grating (FBG) sensor as an accelerometer has received considerable attention since the FBG sensor is remarkably sensitive to strain. The inclusion of inertia mass in the diaphragm-type FBG accelerometer increased the complexity of the accelerometer mechanism. Moreover, numerical and experimental studies are not comprehensively reported and published, despite the fact that several accelerometer aspects should be thoroughly investigated. The overall aim of this thesis is to present a new design of a small and fabricable, diaphragm-type non-inertia mass FBG accelerometer (FBGA-SD) that comes with new features, as well as its comprehensive numerical and experimental investigation. This research begins with the development of five FBGA-SD designs and their concept scoring. The dynamic of the final FBGA-SD design is then investigated using finite element modal analysis followed by harmonic response analysis to determine the location of maximum strain on the diaphragm to place the FBG sensor. The functionality of the FBGA-SD is finally investigated through transient response analysis and experimental work as well as sensitivity determination. The final design of FBGA-SD with dimensions of 16 mm × 16 mm × 10 mm and a weight of 4 grammes has eliminated the weaknesses of the previous four FBGA-SD designs, with new features introduced particularly in the lengthening of the FBG tunnel and the invention of a through-hole for monitoring the FBG sensor inside the diaphragm pocket. Finite element modal analysis has ensured that the first natural frequency of the diaphragm is low (13, 380 Hz) and far from that of the housing (20, 689 Hz) in order to avoid the dynamic of the housing affecting accelerometer response. The location of the maximum strain for placing the FBG sensor on the diaphragm is determined, with the two best positions found to be in the middle and along the edges of the diaphragm. Due to the fact that the edge of the diaphragm is a clamped area, positioning the FBG sensor in its middle would be ideal. The response of the wavelength shift obtained from transient response analysis and experiment agrees well in terms of pattern and phase but differs by 50% of amplitude. It should also be mentioned that the base acceleration and the wavelength shift both demonstrate that they are in the same phase with one another. The 50% difference in amplitude of the wavelength shift reflects the sensitivity of the FBGA-SD, where the experimental sensitivity is 9.64×10^{-5} nm/g and the transient response analysis gives 4.79×10^{-5} nm/g, valid for the range of excitation frequencies of 10 to 147 Hz and maximum base acceleration of 10.5 m/s^2 . Within these ranges, the sensitivity is not frequency dependent.

TABLE OF CONTENT

DECLARATION	
TITLE PAGE	
ACKNOWLEDGEMENTS	ii
ABSTRAK	iii
ABSTRACT	iv
TABLE OF CONTENT	v
LIST OF TABLES	ix
LIST OF FIGURES	x
LIST OF SYMBOLS	xiii
LIST OF ABBREVIATIONS	xv
LIST OF APPENDICES	xvii
CHAPTER 1 INTRODUCTION	1
1.1 Research Background	1
1.2 Problem Statement	3
1.3 Objectives	4
1.4 Scope of work	4
1.5 Summary of Thesis Structure	5
CHAPTER 2 LITERATURE REVIEW	6
2.1 A Brief History of the Development of Optical Fibre Technology	6
2.2 Introduction of FBG Sensor	7
2.3 FBG Sensors and Their Industrial Applications	11
2.4 Sensing Acceleration Principle of FBG	16
2.5 Types of Structures Used in Developments of FBG Accelerometer	17
2.5.1 The beam structure mechanism	18

2.5.2	The cylindrical structure mechanism	23
2.5.3	Embedded encapsulation	29
2.5.4	Double-point encapsulation	30
2.5.5	Summary for the current related FBG accelerometer diaphragm-type design	32
2.6	Interrogation and Base Excitation Systems for Actual Measurement of FBG Accelerometer	33
2.7	Dynamic Analysis of the FBG Accelerometer	34
2.7.2	Modal analysis on housing and sensing mechanism	35
2.7.3	Harmonic response analysis on the diaphragm	36
2.7.4	Transient response analysis on the transducer	37
2.8	Transmissibility of Acceleration Signal	38
2.9	Summary	38
CHAPTER 3 METHODOLOGY		40
3.1	Introduction	40
3.2	Flowchart	40
3.3	Designing of an FBG Accelerometer Based on a Single Diaphragm (FBGA-SD)	42
3.3.1	FBGA-SD v1 design	43
3.3.2	FBGA-SD v2 design	45
3.3.3	FBGA-SD v3 design	46
3.3.4	FBGA-SD v4 design	47
3.3.5	FBGA-SD v5 design	48
3.4	Fabrication of FBGA-SD	49
3.4.1	Machining Process	49
3.4.2	3D Printing Process	51

3.4.3	Installation of FBG sensor into FBGA-SD	54
3.5	Free Vibration Response Analysis of the Diaphragm FBGA-SD	55
3.6	Harmonic response analysis	60
3.7	Force Transient Response Analysis of the Diaphragm for Validation with Experimental Data	62
3.8	Experimental and Measurement Setup	64
3.8.2	Harmonic base acceleration and acceleration measurement	65
3.8.3	Wavelength measurement	68
3.9	Data Processing	70
3.10	Summary of the methodology	70
 CHAPTER 4 RESULTS AND DISCUSSION		71
4.1	Introduction	71
4.2	Evaluation of the FBGA-SD Pros and Cons	71
4.2.1	Concept scoring	72
4.2.2	Problem when installing FBG sensor on the diaphragm	75
4.2.3	The material problem when exchanged with FBG sensor	77
4.3	Dynamic Analysis of the Diaphragm and Housing of the FBGA-SD	78
4.4	Result of Harmonic Analysis of the Diaphragm	81
4.5	Validation of the Experiment Results with Transient Analysis	84
4.6	Sensitivity of the FBGA-SD	95
4.7	Summary	99
 CHAPTER 5 CONCLUSION		100
5.1	Introduction	100
5.2	Research Summary	100
5.3	Recommendation for Future Work	101

REFERENCES

102

APPENDICES

107

LIST OF TABLES

Table 2.1	Working frequency band classifications	18
Table 2.2	Summary of the FBG accelerometer diaphragm-type	32
Table 3.1	Properties of FBGA-SD v5 design taken from data sheet	59
Table 3.2	Item description of the experimental set-up in Figure 3.18	65
Table 4.1	Design evaluation based on scoring table	73
Table 4.2	Tabulation of FBGA-SD sensitivity	98

LIST OF FIGURES

Figure 1.1	Inclusion of an inertia mass on the surface diaphragm	2
Figure 2.1	Working principles of optical fibre	6
Figure 2.2	Illustration of the writing method of the grating	8
Figure 2.3	Illustration of how the FBG sensor works to reflect Bragg's wavelength	10
Figure 2.4	Tsing Ma bridge, Hong Kong	11
Figure 2.5	Dongsheng Garden A5 Building located in Fushan Bay Area Qingdao, China	12
Figure 2.6	FBG pressure sensor	13
Figure 2.7	FBG Liquid level sensor based on cylindrical diaphragm	14
Figure 2.8	The FBG sensor is based on shape sensing purposes	14
Figure 2.9	FBG accelerometer biaxial sensor	15
Figure 2.10	FBG accelerometer triaxial sensor	15
Figure 2.11	(a) Cantilever beam FBG accelerometer, (b) A modified cantilever beam FBG accelerometer	20
Figure 2.12	(a) FBG accelerometer with L-shaped cantilever beam, and (b) FBG accelerometer cantilever beam with bending plates	21
Figure 2.13	(a) Fixed-ended beam FBG accelerometer, (b) simply-supported beam FBG accelerometer and (c) Y-shaped beam FBG accelerometer	22
Figure 2.14	The FBGA-SD with the FBG sensor beside the mass	24
Figure 2.15	FBGA-SD added temperature sensor	25
Figure 2.16	(a) FBGA-SD with L-shaped beam and (b) FBGA-SD with U-shaped beam	26
Figure 2.17	FBGA-DD with a FBG sensor on the surface between the diaphragm and the housing	28
Figure 2.18	FBGA-DD with FBG sensor inside the mass via a hole	29
Figure 2.19	Illustration of installation using embedded encapsulation and double-point encapsulation	30
Figure 2.20	(a) Theoretical model of SDOF mass spring system, (b) Eigenmode analysis by FEA and (c) Mesh model for FEA	36
Figure 2.21	(a) FEA of the fibre optic 3D accelerometer and (b) Mesh model for FEA of the FBG accelerometer diaphragm	37
Figure 3.1	Flow chart of the study	41
Figure 3.2	FBGA-SD v1 design (a) Exploded view (b) View of a fully clamped structure	44

Figure 3.3	FBGA-SD v2 design (a) Exploded view (b) View of a fully clamped structure	45
Figure 3.4	FBGA-SD v3 design (a) Exploded view (b) View of a fully clamped structure	46
Figure 3.5	FBGA-SD v4 design (a) Exploded view (b) View of a fully clamped structure	47
Figure 3.6	FBGA-SD v5 design (a) Exploded view (b) View of a fully clamped structure (c) Base view	48
Figure 3.7	Illustration process of shaping housing using machining process	50
Figure 3.8	Product of housing v1	51
Figure 3.9	Fabrication using 3D machine	52
Figure 3.10	Product PLA housing v2, v3, v4 and v5	53
Figure 3.11	FBG sensor is mounted on surface diaphragm FBGA-SD v4	54
Figure 3.12	Platform interface for dynamic analysis in ANSYS Workbench	56
Figure 3.13	Modelling and FEA of FBGA-SD housing in SOLIDWORKS and ANSYS workbench	57
Figure 3.14	FEA of FBGA-SD diaphragm in ANSYS Workbench	58
Figure 3.15	Setup in harmonic response analysis in applied external load	61
Figure 3.16	Example of base acceleration from actual measurement using accelerometer is fed into y-component	63
Figure 3.17	Example of base acceleration plot (data taken from Figure 3.16) and direction of the applied base acceleration (indicated by yellow like-arrow in top figure)	63
Figure 3.18	Experimental set-up for FBGA-SD	64
Figure 3.19	Measurement configuration using FBGA-SD	65
Figure 3.20	The base excitation and acceleration measurement system	66
Figure 3.21	Excitation and acceleration measurement set-up in DASyLab	67
Figure 3.22	Analogue modules NI and accelerometer used in experiment	67
Figure 3.23	The interrogation system of FBGA-SD with OSA	68
Figure 3.24	Wavelength shift measurement in sense 20/20 software	69
Figure 3.25	The piezoelectric accelerometer was placed together with FBGA-SD during measurement	69
Figure 4.1	Illustrated FBG sensor on the diaphragm for three different FBGA-SD designs	76
Figure 4.2	Illustration of unclamped area	77
Figure 4.3	Relationship between natural frequency of the diaphragm, diameter and thickness	79
Figure 4.4	First three natural frequencies and its mode shapes for stainless steel diaphragm (a), (b), (c) and fifth actual design housing (d), (e), (f)	80

Figure 4.5	Equivalent elastic strain of the diaphragm at different excitation frequencies of 50 Hz, 100 Hz, 5000 Hz and 13 000 Hz	81
Figure 4.6	Total deformation of the diaphragm at the excitation frequency of 50 Hz (low excitation frequency)	82
Figure 4.7	Equivalent elastic strain of the diaphragm at the excitation frequency of 50 Hz (low excitation frequency)	83
Figure 4.8	The ratio between the radius of maximum equivalent elastic strain and the radius of the diaphragm at the excitation frequency of 50 Hz (low excitation frequency)	83
Figure 4.9	Wavelength shift obtained from experiment and transient response analysis at the excitation frequencies of 10, 20, 29, 39, 49, 59, 69 & 78 Hz	87
Figure 4.10	Respective base acceleration at the excitation frequencies of 10, 20, 29, 39, 49, 59, 69 & 78 Hz	89
Figure 4.11	Frequency spectrum of wavelength shifted at the excitation frequencies of 10, 20, 29, 39, 49, 59, 69 & 78 Hz	91
Figure 4.12	Frequency spectrum base acceleration at the excitation frequencies of 10, 20, 29, 39, 49, 59, 69 & 78 Hz	93
Figure 4.13	Sensitivity of the FBGA-SD computed from experiment and transient response analysis at the excitation frequencies of 10, 20, 29, 39, 49, 59, 69 & 78 Hz	96

LIST OF SYMBOLS

a	Radius of the diaphragm
A	Area of the diaphragm
d_{\max}	Deformation maximum
E	Young's modulus
h	Thickness of the diaphragm
g	Gravitational acceleration
i,j	Nodal diameters
Hz	Hertz
L_g	Length of the grating FBG sensor
L_T	Length of the tunnel FBGA-SD
N	Newton
r	Length measured from centre diaphragm
R	Radius of the hole
THRU	Through hole
V	Volume
λ_B	Bragg wavelength
$\Delta\lambda_B$	Change of Bragg wavelength
Λ	Grating period
ρ	Density
ρ_ε	Strain-optic coefficient
α_f	Thermal expansion coefficient
ξ	thermal-optic coefficient
ε	Strain
ε_{FBG}	Strain of the FBG sensor
ε_{\max}	Strain maximum
n_{eff}	Effective refractive index
$\lambda_{i,j}^2$	Dimensionless natural frequency parameter
γ	Mass per unit area
ν	Poisson's ratio of diaphragm
\varnothing	Diameter of the hole
\downarrow	Depth of the hole

$\Delta\varepsilon$	Change of strain
ΔT	Change of temperature
$\Delta\lambda_B$	Change of Bragg wavelength

LIST OF ABBREVIATIONS

3D	Three-dimensional
3D-FE	Three-dimensional finite element
BLS	Broadband light source
CAD	Computer aided drawing
CNC	Computer Numerical Control
DAQ	Data Acquisition
dB	Decibel
EDM	Electro discharge machine
EMI	Electromagnetic interference
FBG	Fibre Bragg grating
FBGA-DD	Fibre Bragg grating accelerometer double diaphragms
FBGA-SD	Fibre Bragg grating accelerometer single diaphragm
FBGIA	Fibre Bragg grating Interrogation analyser
FE	Finite element
FEA	Finite element analysis
G-code	Geometry-code
GPa	Gigapascal
KHz	Kilohertz
kS/s	Kilo samples per second
M2	Metric thread of 2 mm
M5	Metric thread of 5 mm
mm	Millimetre
mV/g	Millivolt per gravitational acceleration
mW	Milliwatt
m/s ²	Acceleration
nm	Nanometre
nm/g	Nanometre per gravitational acceleration
PLA	Polylactic acid
PSRF	Product of the sensitivity and natural frequency
pm/g	Picometre per gravitational acceleration
pm/με	Picometre per micro strain

SDOF	Single degree of freedom
SLSR	Side lobe suppression range
STL	Standard Triangle Language
Ti-6Al-4V	90% titanium, 6% aluminium, 4% vanadium,
UV	Ultraviolet
v1	FBGA-SD first design
v2	FBGA-SD second design
v3	FBGA-SD third design
v4	FBGA-SD fourth design
v5	FBGA-SD fifth design
$\mu\epsilon/g$	Micro strain per gravitational acceleration

LIST OF APPENDICES

Appendix A: Technical drawing housing design v1, v2, v3, v4, and v5 (scale in mm)	108
Appendix B: Estimated cost	110
Appendix C: Apparatus specification	111
Appendix D: Equipment used for fusion splicing	113
Appendix E: Specification of the FBG sensor used from data sheet	114
Appendix F: Referring table for I and J for Blevin's formula	115
Appendix G: List FBG accelerometer based on diaphragm has been build	116
Appendix H: List of Publication	117

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