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The Applications of Near Infra-Red Fibre Bragg Grating Sensors for Wave Propagation Based Structural Health Monitoring of Thin Laminated Composite Plates

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Abstract

This thesis contributes to the research and development towards achieving better structural health monitoring (SHM) system for composite structures. Composites are widely used in critical engineering applications due to the advantage of higher specific strength and stiffness compared to other conventional materials. However, composite laminates have a very high probability of unexpected damage development during service. This study uses fiber Bragg grating (FBG) sensor to create a practical and robust SHM tool based on monitoring the acoustic emission, in order to provide continuous information of the structure's condition. The remarkable capability of using the FBG sensors for dynamic sensing has been demonstrated, in particular for the wave propagation based SHM. Combined with FBG sensor technologies, the wave propagation based SHM such as acoustic emission (AE), ultrasonic evaluation and acousto-ultrasonics becomes more exciting. The FBG sensor has the ability of acquiring both static and dynamic strains with a single sensor. Besides, the physical size of FBG sensor provides greater access to embed them in composite structures without significantly affecting its structural properties. This study also emphasizes some drawbacks in the use of piezoelectric sensors in the wave propagation based SHM of composite structures, specifically in the AE applications. In most optical fiber based SHM applications to date, people have used only FBG sensors with wavelength 1550 nm. The FBG sensors with this wavelength are commonly used in industries such as telecommunications and health. However, there is an option of using near infra-red (NIR) FBG range which is comparably cheap in terms of total system design, yet offers the same performance of a conventional 1550 nm range FBGs. This research work presents the NIR FBG dynamic sensing system, as a wave propagation-based SHM system for monitoring the damages in thin glass fiber reinforced composite plates. The NIR-FBG sensor system has been validated successfully, in particular for thin composite plate's applications. The sensor system has shown its unique capability whereby it can be applied in the area which cannot be accessed by standard piezoelectric based system. The developed NIR FBG sensor system has shown its competitiveness and ability to replace the piezoelectric sensors in the 'wave propagation based SHM' of laminated composite plates.

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Notation

σ	Stress
ε	Strain
σ_{ij}	2×2 stress matrix
E	Young's modulus
C	Stiffness tensor
ν	Poisson's ratio
Q	Stress-reduced stiffness
τ	Shear stress
γ	Shear strain
G	Shear modulus
d	Plate thickness in Lamb's wave frequency equations
ω	Angular frequency
k	Wave number
c_p	Phase velocity
c_g	Group velocity
c_L	Longitudinal wave velocity
c_T	Transverse wave velocity
ρ	Density
u, v, w	Displacement components of a point on the midplane
ψ_i	rotations of the normal to the midplane about the i-axis. $i = x, y$
h	Thickness
N	Force on a plate

M	Moment on a plate
ϵ	Strains vector
K	Plate curvatures
A_{ij}	Extensional stiffness matrix
B_{ij}	Coupling stiffness matrix
D_{ij}	Bending stiffness matrix
r	Layer's of laminates
I_i	Moment of inertia
c_e	Extensional velocity
c_f	Flexural velocity
c_s	Shear wave velocity
$\kappa_{i,j}$	Shear correction factors
$f(t)$	Signal function in time domain
f, f_i	Frequency
t	Time
$\widehat{\tau}$	Time shift (in Continuous Wavelet Transform)
$F(\omega, \widehat{\tau},)$	Magnitude of Short Time Fourier Transform (STFT) in the function of ω and $\widehat{\tau}$
WT_f	Continuous Wavelet Transform (CWT) of a function
$\psi(t)$	Basic wavelet or mother wavelet
s	Scale
ω_0	Wavelet centre frequency
DWT_f	Discrete Wavelet Transform of a function
$b_i(f)$	Arrival time of a specific frequency, f
L, l_i	Length
A	Sound wave attenuation
α	Attenuation coefficient
$\widehat{\beta}$	Decay constant
$\widehat{E}$	Photon's energy

$\widehat{h}$	Planck's constant
λ	Wavelength
c	Speed of light in vacuum
$\widehat{E}_c$	Energy of the conduction band
$\widehat{E}_v$	Energy of the valence band
I	Current
P	Power
q or e	Electron charge
η	Quantum efficiency
T	Temperature
R	Responsivity
n	Refractive index
Λ	Grating period
$\widehat{k}$	Order of the grating
$\widehat{\alpha}$	Thermal expansion
ξ	Thermo-optic coefficient
p_e	Effective photo-elastic constant
p_n	Poisson probability distribution
N	Mean number of photoelectrons detected at $\triangle t$
SNR	Signal to noise ration
$\mathbf{k}$	Wavespace vector
nm	nanometer
Hz	Hertz
kHz	kilohertz
MHz	megahertz

Acronyms and Abbreviations

SHM	Structural Health Monitoring
NDE	Nondestructive Evaluation
FBG	Fiber Bragg Grating
AE	Acoustic Emission
ELE	Elastic Emission
MAE	Modal Acoustic Emission
MEMS	Microelectromechanical System
NIR	Near Infra Red
PZT	Piezoelectric Transducer
GFRP	Glass Fibre Reinforced Plastic
CFRP	Carbon Fibre Reinforced Plastic
NDT	Nondestructive Testing
FSDT	First-Order Shear Deformation Theory
CLPT	Classical Laminated Plate Theory
FFT	Fast Fourier Transform
STFT	Short Time Fourier Transform
CWT	Continuous Wavelet Transform
DWT	Discrete Wavelet Transform
FRP	Fiber Reinforced Polymer
PAC	Physical Acoustic Corporation
FTC	First Threshold Crossing