UNIVERSITI PUTRA MALAYSIA

A STRUCTURAL HEALTH MONITORING (SHM) OF COMPOSITE PATCH REPAIR FOR AIRCRAFT PART AND STRUCTURES USING PRINCIPAL COMPONENT ANALYSIS

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By

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March 2015

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The use of advanced composite structures on aircraft is increasing. New aircraft, such as the Airbus A350 and the Boeing B787, have more than 50% of their structure originating from composite materials especially carbon fiber reinforced plastic (CFRP). Delamination, disbonding, voids and barely visible internal damage (BVID) are some of the damages uniquely found in the composite structure. Once the repair is carried out, the structural health monitoring (SHM) has the ability to detect structural anomalies where human dependency can be minimized. However, most SHM works are concentrating on pristine structure on repaired structure. Therefore the behaviour of SHM at undamaged, damaged and repaired conditions on carbon fiber reinforced plastic (CFRP) are being investigated in this research.. The motivation of the research is to optimize the structural health monitoring (SHM) in comparing the structural response undamaged, damaged and repaired of CFRP structures by using Principal Component Analysis (PCA) through Amplitude Based Assessment (ABA) and Conditional Structural Index (CSI). The objectives of the research are to undertake a feasibility study on Lamb wave propagation over undamaged, damaged and repaired composite panels via smart PZT sensor by using PCA to evaluate the structural conditions of CFRP panels. PZT sensors are used to interrogate and retrieve the surface wave across the investigated structures via online and offline on the undamaged damaged and repaired structures of similar origin. Result shows that although the structural integrity has returned back to its pristine condition, the repaired structure response is diverging from the undamaged conditions. The novelty in this research is the comparative results between undamaged, damaged and repaired response of an aircraft structures originated from CFRP panels which will assist in interpreting the structural health status at maintenance level.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMANTAUAN KESIHATAN STRUKTUR PEMBAIKAN PERLEKATAN KOMPOSIT UNTUK BAHAGIAN PESAWAT DAN STRUKTUR MENGGUNAKAN ANALISA KOMPONEN UTAMA

Oleh

KHAIRUL DAHRI MOHD ARIS
March 2015

Pengerusi: Professor Madya Faizal Mustapha, Ir

Fakulti: Kejuruteraan

Penggunaan struktur komposit termaju di dalam pesawat semakin meningkat. Pesawat-pesawat baru, seperti Airbus A350 dan Boeing B787, menggunakan bahan komposit sebanyak 50% untuk struktur pesawat terutamanya dari serat karbon bertetulang plastik (CFRP). Kelompangan penyah-ikatan dan kerosakan dalaman yang tidak kelihatan (BVID) adalah sebahagian daripada kerosakan yang unik yang hanya boleh didapati pada struktur komposit. Setelah proses pembaikan dijalankan, Pemantauan Kesihatan Struktur (SHM) mempunyai keupayaan untuk mengesan anomaly-anomali struktur yang mana pergantungan kepada tenaga manusia dapat dikurangkan. Walau bagaimanapun, kebanyakan kerja-kerja penyelidikan kini lebih tertumpu kepada struktur-struktur yang normal. Oleh yang demikian, kajian ini bertumpu kepada tingkah laku untuk struktur CFRP yang normal, rosak dan dibaiki. Motivasi utama penyelidikan ini adalah untuk mengoptimumkan pemantauan kesihatan struktur (SHM) dalam membandingkan tindak balas struktur-struktur CFRP yang normal, rosak dan dibaiki dengan menggunakan Analisis Komponen Utama (PCA) melalui Penilaian Berasaskan Amplitud (ABA) dan Indeks Struktur Bersyarat (CSI). Objektif kajian ini adalah untuk menjalankan penyiasatan mengenai rambatan gelombang Lamb terhadap struktur-struktur panel komposit dari CFRP yang normal, rosak dan dibaiki dengan menggunakan sensor PZT pintar seterusnya mengaplikasikan prosedur PCA untuk menilai keadaan struktur panel CFRP. Terdapat dua sensor PZT yang digunakan untuk menyoal siasat dan mengambil gelombang-gelombang yang dihasilkan di permukaan struktur yang normal, rosak dan dibaiki asal. Keputusan menunjukkan bahawa walaupun integriti struktur telah kembali semula kepada keadaan asli, tindak balas struktur yang dibaiki adalah menyeleweng daripada keadaan normal. Novelti dari kajian ini adalah hasil perbandingan antara tindak balas yang dilakukan pada struktur CFRP yang normal, rosak dan dibaiki akan membantu dalam mentafsirkan status SHM untuk krew-krew menyelenggaraan dan pembaikan pesawat.

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I certify that a Thesis Examination Committee has met on 30th April 2015 to conduct the final examination of Khairul Dahri Mohd Aris on his thesis entitled "**A Structural Health Monitoring (SHM) of Composite Patch Repair for Aircraft Part and Structures using Principal Component Analysis**" in accordance with the Universities and Universities Collages Act 1971 and Constitution of the Universiti Putra Malaysia [P.U. (A) 106] 15 March 1998. The Committee recommends that the student be awarded the degree of Doctor of Philosophy.

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LIST OF ABBREVIATIONS

ABA	Amplitude based assessment
ANN	Artificial Neuro Network
AR	Auto Regression
ASTM	American Society of Testing Material
BITE	Built in Test Equipment
BMI	Bislamiamide
BVID	Barely visible internal damage
CAR	Civil Aviation Regulation
CBM	Condition based monitoring
CFRP	Carbon Fiber reinforced plastic
CM	Condition Monitoring
CRS	Certificate Release to Service
CSI	Condition Structural Index
CVM	Comparative Vacuum bagging
CWT	Continuous wavelet transform
DFT	Discrete Fourier Transform
DI	Damage Index
DP	Damage Prognosis
DSSL	Diode-pumped solid state laser
DWT	Discrete wavelet transform
EASA	European Aviation Safety Agency
ECM	Engine Condition Monitoring
EMI	Electrical and mechanical impedance
FAA	Federal Aviation Administrator
FAR	Federal Aviation Regulation
FBG	Fiber Bragg Grating
FD	Full damaged
FFT	Fast Fourier Transform
FR	Full repaired
FS	Factor of Safety
FT	Fourier Transform
FU	Full undamaged
GFRP	Glass Fiber Reinforced Plastic
GLARE	Glass Aluminum Reinforced
HFR	High frequency response
HMV	Heavy Maintenance Visit
HT	Hard Time
HUMS	Health and Usage Monitoring

ICAO	International Civil Aviation Organization
IVHMS	Integrated Vehicle Health Monitoring System
JAA	Joint Aviation Authority
LCC	Life Cycle Cost
LMS	Laser Mirror Scanner
MFAI	Metastabble Ferrous Alloy Inserts
MIL-HDBK	Military – Handbook
MRO	Maintenance, Repair and Overhaul
MSG	Maintenance Steering Group
MW	Morlet wavlet
NDE	Non Destructive Evaluation
NDI	Non Destructive Inspection
NDT	Non destructive testing
NN	Neuro Network
OA	Outlier Analysis
OE	Operational Evaluation
PCA	Principal Component Analysis
PD	Partial damaged
POD	Probability of Damage
PR	Partial repaired
PU	Partial undamaged
PZT	Lead Zincornate Titanate
SD	Spoiler damaged
SHM	Structural Health Monitoring
SM	Service Manual
SMART	Stanford Multi Actuator Receiver Transduction
SPC	Statistical Process Control
SPR	Statistical Pattern Recognition
SR	Spoiler repaired
SRM	Structural Repair Manual
SU	Spoiler undamaged
UD	Uni-directional
UPI	Ultrasonic Propagation Inspection
UV	Ultra violet
V_{pp}	Voltage peak to peak

CHAPTER 1

INTRODUCTION

This chapter represents the research background, problem statement, objectives, scope of the research work and the importance of the study to the Structural Health Monitoring (SHM) system implementation especially in the Maintenance, Repair and Overhaul (MRO) research studies in academia and by the SHM enthusiast in particular.

1.1 Research Background

Structural Health Monitoring (SHM) is defined as the “acquisition, validation and analysis of technical data to facilitate life cycle management decisions” (Sohn et al., 2001). According to Farrar and Worden, (2007), SHM denotes a system with the ability to detect and interpret adverse “changes” in a structure in order to improve reliability and reduce Life Cycle Costs (LCC). The most fundamental challenge in designing an SHM system is knowing what “changes” to look for and how to identify them. The characteristics of damage in particular structures play a key role in defining the architecture of the SHM system. The resulting “changes” or damage signature dictates the type of sensors that are required, which determines the requirement for the rest of the components in the systems.

The present research project concentrates on the use of PZT sensors on an aircraft structural part, which in this case is the Airbus A 320 spoiler. The sensors are used to detect the changes in the materials behavior under undamaged, damaged and repaired conditions. Others types of sensor have been cited throughout the literature such as the Fiber Bragg Grating (FBG), non-contact laser, comparative vacuum monitoring (CVM), Shape Memory Alloy (SMA) etc. These sensors detect structural anomalies through a variety of techniques which have different advantages over the others. PZT sensors are chosen due to their versatility, conformability, low power consumption and high bandwidth. Other sensors are also mentioned in the later chapter.

1.2 Problem Statements

SHM is widely used in worldwide engineering applications. Currently, the aerospace industry is gearing towards using SHM systems to tap their benefits in detecting damage more effectively. An investigation by Hall and Conquest (1999) noted that 27% of the average military and commercial aircraft LCCs are spent on inspection and repair excluding the cost associated with unscheduled maintenance visits and defect rectification. In aviation economics this event leads to a hefty cost to ensure the aircraft’s readiness and airworthiness for its intended operation.

Current commercial and military aircrafts are using more composite materials for their structural parts. Based on the JEC Composite Report (2010), beyond 2010, the use of advanced composite materials in heavy primary structures have reached more than 50% of the aircraft's structural weight with the current examples are the Boeing 787 and the Airbus A350 However, composite materials pose unique challenges and defects. (Goulios and Marioli-riga, 2001). Examples of damage are delamination, disbonding, barely visible impact damage (BVID) and interacting damage modes. In addition, damage detection in a composite structure has been complicated by the conductivity of the fibers, matrix insulations and the BVID. Nondestructive Inspections (NDI) are one of the effective tools used to detect damage in composite structures such as ultrasonic, x-ray and thermography techniques. However, NDI consumes time and man power as the scope of inspections is concentrating in one area. One technique may not be feasible to conclude the findings. Additional inspection methods are required to confirm the defects since the damage is very much related to the type of inspection, the level of the inspectors and the type of equipment, especially for composite materials when compared to metallic structures.

In order to improve detectability of damage in the composite structure, Structural Health Monitoring (SHM) techniques have been developed by using embedded or mounted sensors. An ideal SHM system takes advantage of active-online in which continuous information can be retrieved and processed for evaluation. Airbus are still investigating and testing such a system with the intention to test flight it in 2018 with fully integrated systems. Boeing Inc. is currently exploring and integrating SHM as part of its Integrated Vehicle Health Monitoring System (IVHMS) (Maley et al., 2007).

The current state of the SHM systems is mainly to detect damage in the structure. A damaged structure needs to be repaired in order to return the aircraft back to flight. Any repair of composite materials requires material removal and replacement. Therefore, the structural integrity is compromised although the damage has been repaired. Therefore, the sensors' behaviors are likely to change within the undamaged, damaged and repaired states due to the integration of parent structures and repair structures. Recent development in SHM technology in repair category is still limited to metallic structures and metallic bonding due to the availability of the structures on current aircraft. As the use of advanced composite structures are increasing, the implementation of SHM systems on these structures is yet to be concluded in terms of type, location, suitability and reliability as indicated by Wang and Yuan, (2007). This is due to anisotropic properties, different material compositions, fiber orientation, and matrix formulation, which lead to multiple responses compared to metallic structures. In addition, the local area is changed physically when damaged structures are repaired, thus the response from the SHM registers a anomaly. Therefore, an investigation of the SHM system response both at before and at post repair is needed, with the intention of assessing the health status of the structure. The state of the problem can be portrayed as follows:

1. Does the compromised structural integrity interfere with the sensor response between the undamaged, damaged and repaired structures?

2. Can the new sensor placement identify the true structural status or the health state of the compromised composite structures?
3. Does the result lead to differentiation between the typical undamaged, damaged and repaired composite structures?

All of these issues are being investigated in this thesis. The above problem statement shows originality regarding damage detection in the post repair situation, and the novelty of implementing PZT sensors to develop the sensors and of the interpretation algorithm developed to assess the structure's condition.

1.3 Scope of the Work

The research work focuses on the use of smart PZT sensors of a circular disc type (produced by APC International, USA) which are bonded on the desired panels. The bonded sensors act as an actuator for interrogating and a receiver for data acquisitioning on undamaged, damaged and repaired panels made from carbon fiber reinforced plastic (CFRP) pre-impregnating materials. The CFRP panels originated from Hexcel's graphite/epoxy composite pre-preg materials s and the Airbus A320 spoilers are provided by Spirit Aerosystem (M) Sdn. Bhd. The research covers the experimental analysis of the mechanical properties and signal analysis from coupon sizes to the actual aircraft component. The interpretation algorithm incorporating wavelet analysis is carried out by using Principal Component Analysis to analyze the Lamb wave generated by the PZT sensors. A time and frequency domains analysis using Statistical Pattern Recognition (SPR) by using the multivariate analysis through Principal Component Analysis (PCA) is used to identify features of the structures' conditions.

1.4 Limitations

The limitations of the research are:-

1. All experimental analysis was conducted in a lab environment which does not simulate external forces and at room temperature.
2. Due to limitation of the CFRP pre-preg materials, the selected studied conditions were tailored to give maximum response for the PZT.
3. The assessment of the PCA was concentrate on the waveform produced by the actuated PZT. It is assumed uninterrupted at its time of flight from the actuator to the receiver.

1.5 Research Objectives

The overall objectives of this research are to acquire the Structural Health Monitoring response from the experimental structural integrity point of view in order to characterize the surface conditions of the tested panels and structure by using PCA. The specific objectives of this research are:

1. To fabricate CFRP panels for the feasibility study on Lamb wave propagation over undamaged, damaged and repaired composite panels via smart PZT sensors.
2. To assess the effectiveness of the advanced signal processing technique in differentiating the structural status for the patch repair of CFRP panels and inherently an aircraft component.
3. To characterize the CFRP component and parts by using Principal Component Analysis under undamaged, damaged and repaired conditions.

1.6 Thesis Organization

The overall thesis covers the development of one of the SHM tools in order to evaluate the repair integrity of a damaged part. This is due to the removal and replacement of the plies and/or core which can change the reliability of the component strength. The thesis is organized in the following way.

Chapter 2: Literature Review
This chapter represents the background of the research which is divided into three main sections. The first section depicts the application of composite materials in today's aero structures, challenges in the structure from the maintenance, repair and overhaul (MRO), and current damage assessment through various NDT. The second section represents sensors technology for the SHM approach. The final section describes the Statistical Pattern Recognition approach using the PZT sensors.

Chapter 3: Methodology
This chapter highlights the methodology used in implementing the experiment. More detailed information on the materials used, the apparatus, the software and the programming is given in this section.

Chapter 5: PZT Smart Sensors in Damage Detection
This chapter examines the results obtained by applying the PZT sensors on CFRP panels and aircraft parts. Principal Component is used to identify the studied conditions. It also provides indications which can act as the seeding research for future endeavors in this area.

Chapter 6: Conclusions and Recommendations
The final overview of the thesis findings provides a comprehensive conclusion in which all the steps taken in preparing this thesis are aligned with the problem statement and objectives.

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