UNIVERSITI PUTRA MALAYSIA

SCANNING LASER THERMOGRAPHIC SYSTEM FOR NONDESTRUCTIVE EVALUATION OF INCIPIENT THERMAL DAMAGES IN AIRCRAFT COMPOSITE PANEL

AFIQAH MUSA

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By

AFIQAH MUSA

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia in Fulfillment of the Requirements for the Degree of Master of Science

May 2018

DEDICATION

This work is dedicated

To my parents

Family, friends, and husband

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Master of Science

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Chairman : Chia Chen Ciang, PhD
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Composite materials applied in aerospace structure are getting popular due to advantages such as high specific strength and stiffness with favorable strength to weight ratio. However, incipient thermal damage (ITD) that can cause reduction of 60% of composite mechanical strength are still unable to be detected using conventional NDT&E method.

This project aims to develop an effective NDT&E tool that can detect or evaluate ITD through these three objectives. First, to synchronize laser system, laser scanner system and thermal imager as an active infrared imaging system. Second, to develop corresponding data acquisition and noise removal algorithm for extraction of local temperature-time profiles. Third, to validate the effectiveness of the system and algorithm for non-destructive evaluation of ITD in glass fiber reinforced composite plate (GFRP). In correspondence to research objective, laser pulse was implemented as a powerful thermal energy source in thermography method for evaluating ITD. GFRP plate was insulted with high temperature at range of material glass transition temperature, $0.8T_g$,$1.0T_g$,$1.1T_g$,$1.2T_g$ and $1.3T_g$(T = 97°C,121°C,133°C,145°C and 157°C) at time t = 120, 60, 30, 15, 10 and 5 minutes to prepare ITD as well as thermal damage (TD) for reference. Focus was done on ITD which are insulted at borderline temperature of $T_g$with relatively longer insult time; $0.8T_g$ and $1.0T_g$ at t = 120,60,30 minute. ITD evaluation in this study are realized in the form of percentage difference between damage and reference derived from thermal contrast base principle. Following this, result gained represents outliers with respective to reference area and thus indicate detection of damage. Result gained for ITD at $0.8T_g$ are 1.93851%, 0.30561% and 0.20913% meanwhile 2.02966%, 1.73518% and 0.53167% at

$1.0T_g$ for $t = 120,60,30$ minute. A gradual decrement trend can be seen from longer insult time to lower insult time to indicate level of severity on damage detected. According to system resolution and capability, these values are within the range and thus proves the detection of ITD. Further verification done using ultrasonic method also proves the inability of conventional NDT&E method to detect ITD as expected. Hence, with proposed Scanning Laser Thermographic system, all ITD that were insulted with temperature at borderline of T_g at relatively longer insult time had been successfully detected at minimum of 0.20913% at insult temperature; $0.8T_g$ with insult time t = 30 minute and at maximum of 2.02966% at insult temperature; $1.0T_g$ with insult time t = 120 minute.

Abstrak tesis yang dikemukakan kepada Senat Univiersiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

SISTEM IMBASAN LASER TERMOGRAFI UNTUK UJIAN TIDAK MEROSAKKAN KEATAS KEROSAKAN TERMAL AWAL PADA PANEL KOMPOSIT KAPAL TERBANG

Oleh

AFIQAH MUSA

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Bahan-bahan komposit yang diaplikasikan pada struktur aeroangkasa semakin meningkat populariti disebabkan oleh kelebihan-kelebihan seperti spesifik kekuatan dan kekenyalan yang tinggi serta nisbah berat kepada kekuatan yang berpatutan. Walaubagaimanapun, kerosakan termal awal (ITD) yang boleh mengakibatkan pengurangan 60% daripada kekuatan mekanikal bahan komposit masih lagi tidak boleh dikesan menggunakan cara ujian tidak merosakkan konvensional.

Tujuan kajian ini adalah untuk membangunkan alat NDT&E yang berkesan serta dapat mengesan atau menilai ITD menerusi tiga objektif ini. Pertama, untuk menyegerakkan sistem laser, sistem pengimbas laser dan pengimejan termal sebagai sistem pengimejan inframerah yang aktif. Kedua, untuk membangunkan algoritma pemerolehan data dan penghapusan hingar yang bersesuaian untuk pengekstrakan profil suhu setempat-masa. Ketiga, untuk mengesahkan keberkesanan sistem dan algoritma untuk penilaian tidak merusak ITD pada plat komposit polimer gentian kaca (GFRP). Dalam perkaitan pada objektif penyelidikan ini, sumber laser telah digunakan sebagai sumber tenaga haba yang kuat dalam kaedah termografi untuk menilai ITD. Plat GFRP dirosakkan dengan suhu tinggi pada julat suhu peralihan kaca bahan, $0.8T_g$,$1.0T_g$,$1.1T_g$,$1.2T_g$ dan $1.3T_g$(T = 97°C,121°C,133°C,145°C and 157°C) pada masa t = 120, 60, 30, 15, 10 dan 5 minit untuk menyediakan ITD serta kerosakan termal (TD) untuk rujukan. Tumpuan telah dilakukan pada ITD yang dirosakkan pada suhu sempadan T_g dengan masa yang lebih lama; $0.8T_g$ dan $1.0T_g$pada t = 120,60,30 minit. Penilaian ITD dalam kajian ini direalisasikan dalam bentuk peratusan perbezaan antara kerosakan dan rujukan yang diperoleh dari prinsip asas perbezaan termal. Berikutan itu, keputusan yang diperoleh mewakili keluarbatasan berbanding kawasan

rujukan, dengan itu menunjukkan pengesanan kerosakan. Hasil yang diperolehi untuk ITD pada $0.8T_g$ ialah 1.93851%, 0.30561% dan 0.20913% manakala 2.02966%, 1.73518% dan 0.53167% pada $1.0T_g$ untuk $t = 120,60,30$minit. Gaya penurunan secara beransur-ansur boleh dilihat bermula dari masa kerosakan yang lebih lama kepada masa keroskan yang lebih sebentar untuk menunjukkan tahap keparahan kerosakan yang dikesan. Menurut resolusi dan keupayaan sistem, nilai-nilai ini berada dalam lingkungannya dan dengan itu membuktikan pengesanan ITD. Pengesahan selanjutnya yang dilakukan menggunakan kaedah ultrasonik juga membuktikan ketidakupayaan kaedah NDT&E konvensional untuk mengesan ITD seperti yang dijangkakan. Oleh itu, dengan sistem pengimbasan Laser Termografik yang dicadangkan, semua ITD yang dirosakkan dengan suhu di sempadan T_g pada masa kerosakan yang lebih lama telah berjaya dikesan dengan sekurang-kurangnya 0.20913% pada suhu kerosakan; $0.8T_g$ dengan masa kerosakan $\boldsymbol{t}$ = 30 minit dan maksimum 2.02966% pada suhu kerosakan; $1.0T_g$ dengan masa kerosakan t = 120 minit.

ACKNOWLEDGEMENTS

All praise to Allah S.W.T, the Almighty God, and May peace and blessing are upon His beloved Prophet Muhammad. I would like to express my deepest gratitude to my parents for their never-ending support throughout this journey.

I would like to extend my thanks to Dr. Chia Chen Ciang for his encouragement, valuable advice, and guidance through this journey. Not to forget, thanks to my lab member, Gan Chia Seng for his supporting assistance in research work. Last but no least, thanks to all who have helped me in this journey.

This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

T_g	Glass transition temperature
AE	Acoustic emission
AWPI	Anomalous wave propagation imaging
CFRP	Carbon fiber reinforced polymer
DAQ	Data acquisition
FAA	Federal aviation administration
FOV	Field of view
GFRP	Glass fiber reinforced polymer
ITD	Incipient thermal damage
LDV	Laser doppler vibrometer
LIF	Laser induced fluorescence
LMS	Laser mirror scanner
NDT&E	Nondestructive testing and evaluation
NI	National instrument
POM	Polyoxymethylene
PZT	Piezoelectric
Ref	Reference
ROI	Region of interest
SBS	Short beam shear
SLT	Scanning laser thermography
TC	Thermocouple
TD	Thermal damage
TNDT	Thermal nondestructive testing
ULW	Ultrasonic lamb wave

UPI	Ultrasonic propagation imaging
UT	Ultrasonic thermography
UWPI	Ultrasonic wave propagation imaging
VTWAM	Variable time window amplitude mapping
WUPI	Wavelet ultrasonic propagation imaging

CHAPTER 1

INTRODUCTION

This chapter presents introduction of research done on incipient thermal damage detection on composite aerospace structure using laser based thermography. *Section 1.1 Research Background* describes current deployment and usage scenario in aerospace structural parts. The deployment difficulties are highlighted at the end of the session, and the core of the problems is stated in *Section 1.2 Problem Statement*. Hypothesis on solving problems is described in *Section 1.3 Hypothesis* followed by detailed objectives as well as scope of research in *Section 1.4 Research Objectives* and *Section 1.5 Scopes of Research*. Finally, *Section 1.6 Thesis Organization* shall provide brief flows and statement throughout chapters in this thesis.

1.1 Research Background/Introduction

Composite materials such as carbon, glass, and Kevlar fibers reinforced plastics are getting popular in aerospace sector nowadays. Composite materials are gaining such popularity primarily because they provide much higher specific strength and specific stiffness over metallic counterparts. These characteristics could be translated into significant improvement of fuel efficiency, which is a great concern for aerospace sector due to hike of fuel price and the fact that fuel cost is the major cost for aerospace structures ownership and operational cost ("A350XWB Special Edition," 2013). Other advantages of composite materials include corrosion resistance and ability to withstand harsh chemical. This provide benefit over metallic structure that are exposed to corrosion over time especially over uncontrolled severe weather. Also, because composites are build based on part consolidation, a single piece of composite material can replace an entire assembly of metal parts resulting to reduction of number of joints and mechanical fastener to save more time and maintenance.

In aerospace structure, composite have been applied in both primary and secondary part of aircraft. Graph illustrated in Figure 1.1 stated number of composite weight percentage over time since 1980s ("No Title," 2009). Initially, composite was applied on secondary part only where composite percentage is lower than 5%. In 60 years, number of composite percentage has been increasing up to 50% and used at both primary and secondary structure. Primary structures in aircraft are structure that carries flight, ground, loads and whose failure would reduce the structural integrity of the aircraft or may causes injury and death to passenger or crew (Cutler, 2006). This part will carry critical load bearing structure on an aircraft and plays important role during service. Examples of primary structure of an aircraft are fuselage, wing spar, and wing rib. In other hand, secondary part is non-primary part and mainly functionalize to provide enhanced aerodynamics to aircraft. Differ from primary structure, failure at this part will be less critical and would not reduce the structural integrity of the aircraft. Among listed secondary parts are floor and other ancillary structure such as windows and fairing (Cutler, 2006)(Rupke, 2002). Figure 1.2 shows illustration by Airbus company of structure that deploy composite material in Airbus A380 and proves high percentage of composite as it has been applied to both primary and secondary part (*Jane's All the World's Aircraft*, n.d.).

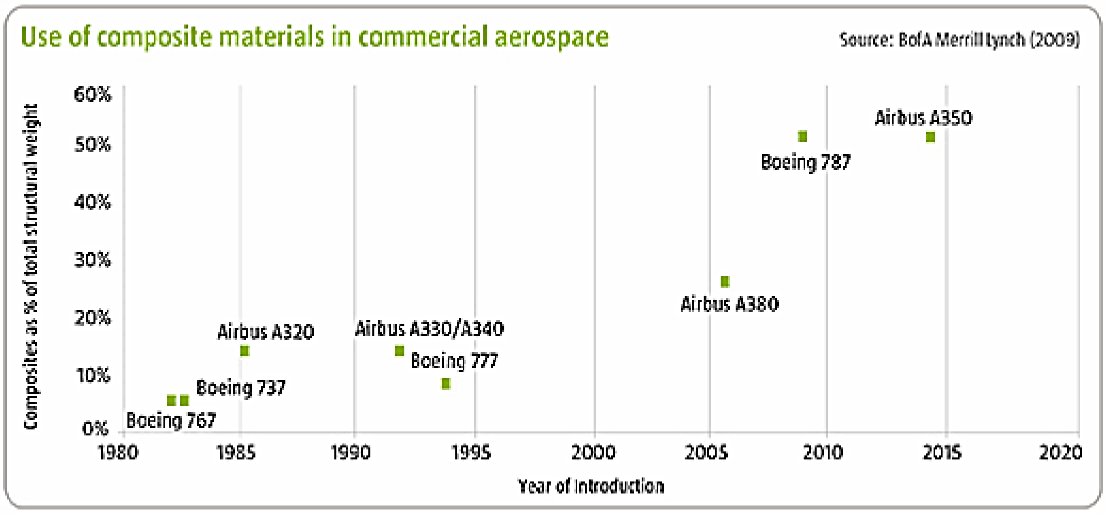

Figure 1.1 : Percentage of composite per weight over time ("No Title," 2009)

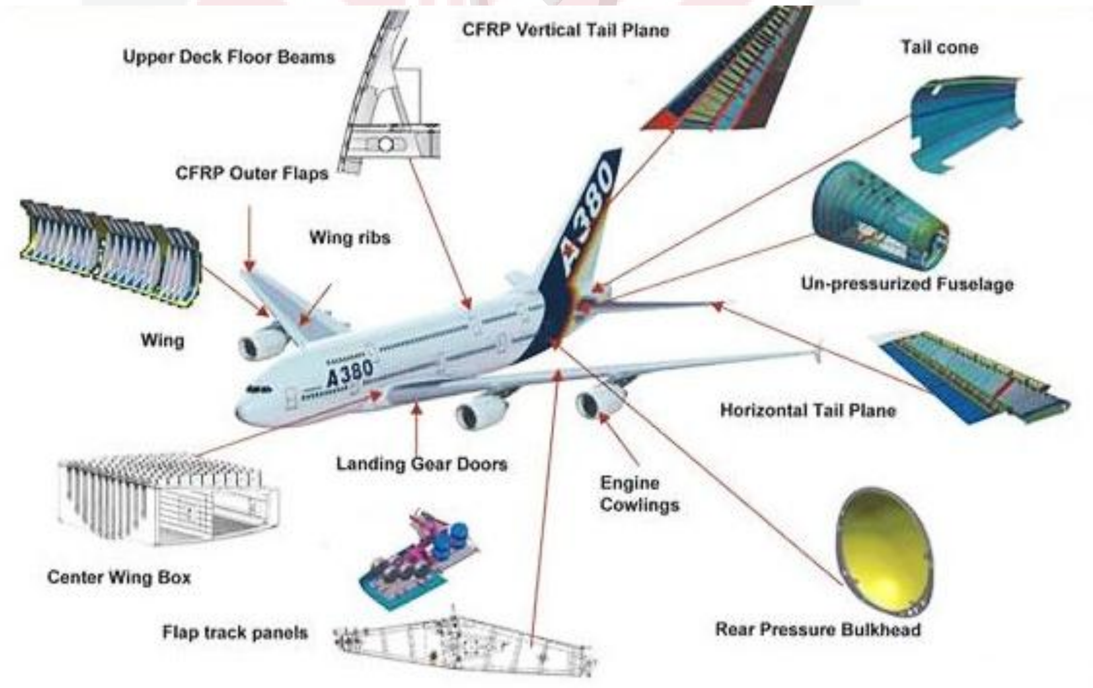

Figure 1.2 : Composite deployment in Airbus A380 including primary and secondary part of aircraft structure (*Jane's All the World's Aircraft*, n.d.)

Similar to conventional metallic structures, composite structures are also susceptible to damages that are classified into manufacturing and in-service damages. Manufacturing damages are introduced during manufacturing and fabrication processes meanwhile in-service damages occur during service or operation of a structure within its lifetime (Ghobadi, 2017). Common damages in manufacturing damage are porosity and inclusion that results to reduction of material and structural strength. For in service damages, three major damages that commonly happens in-service are impact, fatigue, and lightning & thermal damage. These damages are usually interrelated to each other and most possibly leads to other extensive damages such as delamination, cracks, and debonding.

In recent research, lightning and thermal damage are given more focus due to detrimental effects that it may consume on composite aerospace structure. These damage that shares the same effect of high thermal exposure have been considered lately as significant damage because it may lead to catastrophic effect to aircraft at the range of visible to non-visible for current damage detection technique. Non-visible damage or so called incipient thermal damage (ITD) are damage specially occurred at early stage of thermal damage. Even though it is invisible to current damage detection technique, reduction of mechanical properties from these damages are significant and had been proven to have reduction values as high as 60% (Maria, 2013) (Tucker Howie, Pate, Morasch, & Flinn, n.d.). At this level, mechanical properties of composite had already changed and deteriorated to reduce composite strength. Hence, detection of ITD in aerospace had been focused to overcome any severe damage that it may lead or any irreversible damage to happen.

In accordance to the fact that each material is highly exposed to imperfections and damages at different stages, NDT&E technique provides a systematic damage detection method. Ultrasonic scan, eddy current, dye penetrant and infrared thermography are among technique used in NDT&E and found to be the most effective way for a precise and non-intrusive damage detection especially for conventional material (Cutler, 2006; “FAST 32,” 2003; Maria, 2013). Nevertheless, in the advancement of material development of composite material, there are numbers of limitation in damage detection. As for nowadays NDT&E technique, only severe damage such as delamination, crack and debonding can be excellently recognized leaving incipient thermal damage undetected.

In this regard, an effective NDT&E tool that can evaluate incipient thermal damage is needed for a better safety and maintenance. This research explores NDT&E techniques specifically infrared thermography in evaluating incipient thermal damage by considering the aspect of conventional and advance technology in thermography.

1.2 Problem statement

Incipient thermal damage (ITD) could reduce mechanical strength of composite materials for up to 60%, but conventional non-destructive test and evaluation (NDT&E) techniques established for composite material inspection are not capable of detecting it. This problem posts a potential catastrophic structural failure and fatal accident, hence an effective NDT&E tool that can detect or evaluate ITD is imperatively needed.

Due to thermo-mechanical properties of ITD, it's local changes or discontinuities caused by heat are very small and are outside of conventional NDT&E capability. Understanding that there are local changes due to ITD, thermography method was chosen with the implementation of laser as an active source.

Using laser pulse as localized heat source and thermal imager as sensor, it is possible to acquire local temperature-time profile at specific points of inspection. In method such as flying laser spot thermography and ultrasonic wave propagation imaging, laser had been used and proves it's effectiveness in detecting less severe damage such as lightning damage which are closely related to ITD. Thus, the implementation of laser source in proposed Scanning Laser Thermographic System with appropriate noise removal algorithm should be able to detect and evaluate ITD.

1.3 Hypothesis

Thermal damage (TD) and incipient thermal damage (ITD) in composite materials are local changes or discontinuities of material properties caused by heat. These changes or discontinuity prevents normal continuous, uniform flow of heat flux. Hence, by using laser pulse as localized heat source and thermal imager as sensor, it is possible to acquire local temperature-time profile at specific points of inspection. Comparing the profiles could highlight outliers and hence indicate TD or ITD.

1.4 Research Objectives

This project aims to develop an effective NDT&E tool that can detect or evaluate ITD through the following objectives:

1. To synchronize laser system, laser scanner system, and thermal imager as an active infrared imaging system suitable for non-destructive evaluation purposes.
2. To develop corresponding data acquisition and noise removal algorithm for extraction of local temperature-time profiles.
3. To validate the effectiveness of the system and algorithm for non-destructive evaluation of ITD in glass fiber reinforced composite plate.

1.5 Scopes of Research

This study covered the development and application of a laser-based, active thermography system with noise removal algorithm for non-destructive detection of TD and ITD inflicted with controlled insult time and temperature on thin (~1 mm), flat plate of glass fiber reinforced polymer as a simple representation of aircraft skin. In damage preparation, especially thermal damage, term 'insult' is most appropriately used to describe specifically to damage (Pelivanov, Ambrozinski, & O'Donnell, 2016). Note that, term 'insult' was used to describe damage throughout this study. This study was conducted to only one category of ITD at insult temperature in borderline of T_g and long insult time. Temperature in borderline of T_g shall be based on fabricated GFRP plate properties insulted to time higher than 30 minutes to 120 minutes. Finally, validation was done with reference to existing conventional NDT&E method used for composite material that is ultrasound method.

1.6 Thesis Organization

This thesis work will be divided into 5 chapters. *Chapter 2 Literature Review* discuss briefly on introductory and conceptual understanding in regarding to research scope. Included, previous research and significant finding in damage detection of composite aerospace structure. Lightning, thermal and incipient thermal damage are given focus in accordance to objectives and problem statement stated in *Chapter 1 Introduction*. Damage detection method in composite are also discussed especially for ultrasonic and thermal imaging method.

Chapter 3 Research Methodology describes the process design for scanning laser thermographic system. Fabrication of composite material (glass fibre reinforced plastic) with aerospace standard was explained including damage preparation on specimen. Then, image processing steps was explained in accordance to noise removal algorithm. Damage detection calculation using thermal contrast base algorithm was presented here. Comparison using conventional method, ultrasonic method is also presented for verification purpose.

Chapter 4 Result and Discussion discuss results collected and processed from scanning laser thermographic system. Observation and analysis throughout image processing algorithm of thermographic data on thermal damage and incipient thermal damage was discussed. Damage detection is presented in the form of percentage difference (%) between damage and reference area. Also included result and discussion of ultrasonic method for verification.

Lastly, *Chapter 5 Conclusion and Recommendation for future work* summarize final result and findings of incipient thermal damage as well as thermal damage detection in composite material specifically GFRP in developed scanning laser thermographic system. Ultimately, the ability of developed system to detect incipient thermal damage in GFRP will determine the relevance of the results for future studies.

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