ABSTRACT

WU, XIANYU. Non-destructive Inspection in Adhesively Bonded Joints using Modulated Thermography. (Under the direction of Dr. Kara J. Peters.)

This thesis presents an infrared thermography based non-destructive inspection technique, modulated thermography, and investigates its ability for the inspection of adhesively bonded, carbon fiber-epoxy laminate, single and double lap joints. In previous pulsed phase thermography research studies, the phase images were mainly improved by adjusting the truncation window length, and changing the duration of the heat pulse. However, while increasing the contrast between the defective zones and non-defective zones, the effect of other factors was also increased, such as the twill weave in carbon fiber reinforced polymer (CFRP) laminates and specimen edges. These can lead to false detections or misinterpretation of other features as defects.

This project developed an active thermography technique which combined the advantages of pulsed phase thermography and lock-in thermography. Instead of a square heat pulse, a modulated thermal wave was used to heat the specimen, where the modulated thermal wave is determined from the blind frequencies of pulse phase thermography inspection. This research focused on defects occurring during the manufacturing process at the adherend-adhesive interfaces and in the adhesive layers in single and double lap joint specimens. Teflon tape artificial defects were inserted at different depths to simulate the manufacturing defects.

Initial PPT inspections were used to examine the specimen quality and generate the phasegram profile for the design of modulated thermal waves. The frequency components of the modulated thermal waves were determined from a threshold value and average phase
delay angle profile for different defective regions and non-defective areas. The modulated thermal waves were designed to concentrate the detection on the particular depth range of the adhesive layer, and to maximize the contrast between the artificial defects and non-defective areas. These modulated thermal waves were then applied in the inspections of the lap joints. The open source MATLAB program IRVIEW was used to obtain the phasegram profile from the raw thermal data acquired after the specimen was exposed to the modulated thermal wave. The results of modulated thermography showed that the artificial defects could be identified in the phasegrams, and a number of unintentionally created manufacturing flaws at the adhesive bond were also detected. Compared with benchmark PPT results, modulated thermography can improve the contrast between the defects in the adhesive bond (artificial defects and manufacturing defects) and the non-defective regions in the phase images. Calculation also demonstrates that the modulated thermography can significantly decrease the energy cost for thermography inspections. The ability to image the defects at adhesive bond through phase images can therefore provide reliable detection of manufacturing defects in adhesively bonded joints.
Non-destructive Inspection in Adhesively Bonded Joints using Modulated Thermography

by

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BIOGRAPHY

Xianyu Wu was born and raised in Fujian, China. He received his bachelor’s degree from University of Electronic Science and Technology of China in 2007. He joined the Smart Composites Laboratory under supervision of Dr. Kara Peters in 2013.
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CHAPTER 1 INTRODUCTION

1.1 OVERVIEW

The goal of this study is to investigate the ability of modulated phase infrared (IR) thermography to detect and determine the size and depth of manufacturing defects in carbon fiber reinforced polymer adhesively bonded lap joints. Specifically, manufacturing defects located in the adhesive bond and at the adherend-adhesive interface are studied. In modulated thermography, the excitation thermal wave is designed to maximize the image sensitivity to the region of interest. For this specialized case of adhesively bonded joints, the expected defects lie at depths between the two adherend boundaries, therefore the thermal excitation wave can potentially be designed to optimize images to features in this zone. The experiments in this research will focus on two small scale representation of aerospace structural lap joints: single and double lap joints. The inspection technique developed in this research can provide a precisely and fast defect detection with low energy cost for inspection on large aerospace vehicles.

This thesis is organized into 5 chapters. Chapter 1 presents the overall goal of this study, and provides an introduction to the basic theory behind lock-in thermography, pulsed phase thermography (PPT), and non-destructive inspection (NDI) studies on adhesively bonded joints. Chapter 2 describes the experimental instrumentation and procedures that were used for defect detection in adhesively bonded joints. Chapter 3 and Chapter 4 describe preliminary experiment results of pulsed phased thermography imaging of the lap joint
specimens, the selection of various modulated waveforms based on these results, and the performance of modulated thermography of the same specimens. Finally, Chapter 5 presents conclusions from this research.

1.2 MOTIVATION AND BACKGROUND

Carbon fiber reinforced polymer (CFRP) materials have been used in manufacturing of transport airplane components for decades, due to the fact that CFRP materials have a higher strength-to-weight ratio and lower weight than traditional metallic materials. These features improve fuel efficiency and extend flight autonomy by reducing the weight of the aerospace vehicle. With aircraft manufacturer’s increasing confidence in their performance, the application of composite materials in airplanes has been expanded from secondary structures (e.g. wing edges, tail section) to primary structural materials (e.g. fuselage, wings, tail, and interior), as shown in Figure 1.1. In 1988, the Airbus A320 became the first transport airplane in commercial service with an all-composite tail assembly [1]. In 2009, the Boeing 787 Dreamliner has become the first large transport airplane with a composite material primary structure; it is about 50 percent composite by weight (excluding the engines) [1]. In 2013, the Airbus A350XWB, also a mostly composite commercial transport airplane, was introduced; 53% of the airframe of A350XWB is comprised of composite materials [1]. CFRP is the primary composite material used in the Boeing 787 Dreamliner and Airbus A350. The increasing number of composite-intensive aircraft is therefore creating a demand for the service and repair of composite materials. However, damages and cracks in CFRP are difficult to repair and present unique challenges compared to metallic airframes.
An airplane is expected to encounter aging, vibration, and even accidents during its service life, leading to fatigue cracking, stress corrosion cracking, corrosion, wear and unexpected damage. For example, Boeing first repaired a commercial composite structure airframe in 2013, after damaged was caused by a fire that occurred on an Ethiopian Airlines Boeing 787 whilst on the ground at London Heathrow Airport. The composite fuselage towards the tail of the Boeing 787 airplane was seriously damaged [2].

Adhesively bonded fiber-composite patches are a common repair method for composite structures. The adhesive bond between the patches and parent composite structure distributes the load more efficiently and produces less load concentration on the parent composite structure as compared to standard repairs based on mechanically fastened metallic patches [3,4]. As a result of their excellent load transfer characteristics, adhesively bonded joints provide a stiff alternative load path so they can be used very effectively to repair cracks and damage [3,4]. When used in combination with fasteners or external wraps, adhesive bonds are also applied as a joining technique for airframe components.

However, environmental conditions during fabrication of adhesively bonded joints (e.g. the adherend surface preparation) have a great effect on the bonding strength and quality [5]. The environment conditions are extremely difficult to measure and may not be consistent throughout a structure. Manufacturing defects in adhesively bonded joints primarily occur at adherend-adhesive interface and adhesive layer. Defects (e.g. gaps, voids, porosity) are often introduced by air entrapment during the adhesive layup process or adhesive thermal shrinkage [6]. Adherend surface contamination by grease or a loose oxide layer often leads to weak bonding or disbanding of the two adherends.
Infrared thermography is a suitable technique for the inspection of adhesively bonded joint quality, since it is a rapid NDI technique with a capability for large surface inspection. Further, since the thermal excitation is at low frequencies, the thermal waves can propagate good distances through composite structures. Assuming that defects act as local thermal absorbers for a thermal wave propagating through the structure thickness, IR thermography uses the specimen surface temperature contrast between non-defective zones and defective zones to determine invisible subsurface defects. Previous studies demonstrate that infrared thermography technique provides accurate and reliable non-destructive inspection (NDI) information as compared to other NDI techniques for imaging damage in composite materials [7]. Active thermography is one class of infrared thermography techniques, in which a heat source provides thermal energy to the specimen. An infrared camera is applied to detect the infrared radiation reflected from or transmitted through the inspecting object. Pulsed thermography, one kind of active thermography, uses a short duration heat pulse to heat the specimen and measures the heating or cooling of the specimen surface temperature. Defective zones will appear at higher or lower temperatures in the temperature profile with respect to non-defective zones. However, pulse thermography data is sensitive to environmental reflections, emissivity variations, non-uniform heating, reflection from the specimen edges and variations in the surface geometry. Also, prior knowledge of a non-defective area location is required [8,9]. Several variations to active, pulse thermography have been developed to improve the image contrast and provide depth information for visible defects. These thermography techniques are described in the following sections.
1.3 LOCK-IN THERMOGRAPHY

Lock-in thermography (LT) uses periodic thermal waves at a fixed frequency to heat the specimen. The experimental setup for LT is illustrated in Figure 1.2. Each single thermal wave can be used to investigate defects at a corresponding depth. The surface temperature across the surface is measured as a function of time with the thermal camera. The amplitude and phase delay data of the reflected thermal wave at each pixel can be calculated from 4 data points per modulation cycle [10]. For instance, in Figure 1.3, when the excitation periodic waveform I and temperature response data S are both known to have a sinusoidal form, the amplitude A and phase delay angle φ can be recovered for every pixel in the thermal image:

\[ A = \sqrt{(S_1 - S_3)^2 + (S_2 - S_4)^2} \]  \hspace{1cm} (1.1)

\[ \phi = \tan^{-1} \left( \frac{S_1 - S_3}{S_2 - S_4} \right) \]  \hspace{1cm} (1.2)

Previous studies have shown that the phase delay angle is less sensitive than the amplitude information to reflections from the environment, surface emissivity variations and non-uniform heating [11].

In LT, the periodic thermal wave must be performed over several cycles to let the thermal wave propagate through the entire specimen thickness. A high frequency thermal wave can image shallow defective zones, and a low frequency thermal wave can detect deep defects. A high frequency wave is chosen for the first test, then the frequency of the heating thermal wave is progressively decreased until the entire thickness is covered. There exists a limiting frequency, referred as the blind frequency, \( f_b \), at which a defect at a particular depth
is first visible on the frequency spectra. At this limiting frequency, the defective zones present enough phase contrast from non-defective zones to be detected on the frequency spectra. Since a permanent regime has to be attained each time, an adequate measurement of the phase delay angle requires a long time. Since each periodic thermal wave can only detect the defects at its corresponding depth, LT requires multiple tests for all depth inspection which is time consuming because the structure must cool before each test. On the other hand, the post-processing of LT data to determine the phase image as a function of frequency is extremely rapid as only equation (1.2) needs to be solved.

1.4 PULSED PHASE THERMOGRAPHY

Pulsed phase thermography (PPT) can be thought as a combination of pulsed thermography and lock-in thermography. Figure 1.4 depicts a PPT experiment. It uses a square pulse thermal wave to heat the specimen, which can be treated as a sum of a multitude of individual sinusoidal waves using a Fourier series with frequencies ranging from 0 to $\infty$. The specimen surface temperature data acquired during the cooling period is truncated with a given window $w(t)$ and sampled at a temporal resolution $\Delta t$, as depicted in Figure 1.5. Fourier transforms are then applied to calculate the phase delay angle of each pixel in the image. As the thermal images are digital data, the discrete Fourier transform is applied to convert thermal image sequence to frequency components $F(n)$ for each pixel on thermal image, $f(t)$ (Figure 1.6). The discrete Fourier transform can be written as [12, 13],
\[ F(n) = \frac{1}{N} \sum_{t=0}^{N-1} f(t) \exp \left( -\frac{2i\pi nt}{N} \right) = R(n) + I(n)i \]  

(1.3)

where \( t \) is the image sequence index, \( n \) designates the frequency increment amongst \( N \) total frames, and \( R(n) \) and \( I(n) \) are the real and imaginary components of the corresponding frequency. The phase delay angle, \( \phi \), is calculated for each transform component terms by,

\[ \phi(n) = \tan^{-1} \left( \frac{I(n)}{R(n)} \right) \]  

(1.4)

The minimum frequency increment \( \Delta f \) is determined by data acquisition time increment \( \Delta t \) and the number of total thermal data sequence frames \( N \), \( \Delta f = 1/N\Delta t \). The advantage of phase angle images is that they present less sensitivity to surface coating, surface disturbances, and rapid data acquisition for high thermal conductivity materials [9]. Only one experiment is required to image damage at multiple depths. However, the post-processing requirements are significantly higher than those of LT. There is also some loss in resolution between defects at different depths in the specimens onto the phasegram. These may result in false detections or misinterpretation.

### 1.5 MODULATED THERMOGRAPHY

As an alternative, frequency modulated thermal wave imaging (FMTWI) [13], has been proposed to overcome some of the drawbacks associated with pulse thermography and lock-in thermography. FMTWI uses a linear or digitized thermal wave with a predetermined, limited range of frequencies, as shown in Figure 1.7, to heat the specimen surface. In FMTWI, thermal data are acquired in the cooling transient regime. The Fourier transform is
applied on each pixel of the thermal profile to extract the frequency components and calculate the phase data. Mulaveesala and Tuli [14] demonstrated that the linear FMTWI (Figure 1.7 (a)) was able to detect sub-surface defects on a mild steel specimen in much less time and with much less peak thermal power, as shown in Figure 1.8.

Based on the FMTWI, the digitized frequency modulated thermal wave imaging (DFMTWI) technique was introduced and validated by Mulaveesala and Tuli [15]. The DFMTWI technique was applied to detect Teflon inserts at various of layers in a 30 layers CFRP laminate and interface study of bonded wafers [16], which are frequently used in MEMS and VLSI. These experiments demonstrated that FMTWI was capable to detect sub-defects with good resolution, and the phasegram of DFMTWI can lead to actual defect depth estimation, as shown in Figure 1.9.

Ghali et al. [17] compared the FMTWI with other thermography inspection techniques, PPT and LT (Figure 1.10). These three NDT techniques were applied to detect sub-surface defects in a CFRP laminate. The results of the experiment demonstrated the capability of FMTWI for detecting the subsurface defects of CFRP laminates; the defects on the phase images of FMTWI, PPT, and LT were all clearly detectable and exhibit nearly equal SNRs. In comparison to lock-in thermography, FMTWI requires less experimentation time whereas in comparison with pulse thermography less peak power heat sources are sufficient.

In this thesis, we propose to design and test amplitude modulated thermography that combines the advantages of both pulsed phase thermography and lock-in thermography, however optimizes the energy input to the test specimen characteristics. In modulated
thermography, energy is delivered to the specimen’s surface in the form of a modulated thermal wave designed from the blind frequency properties of the depth of interest in the test specimen. Frequencies that image defects outside of the region of interest will not be included in the input thermal wave. A single cycle of this modulated thermal wave is used to heat the specimen and thermal data are acquired in the cooling transient regime. The phase delay data of each pixel in the image will be acquired by use of Fourier transforms. These thermal image sequences will be converted to frequency components using the discrete Fourier transform for each pixel as depicted in Equation 1.3 and the phase delay angle is computed for each transform component terms by Equation 1.4., following the method of PPT.

Lock-in thermography uses a thermal wave with a fixed frequency to detect the defect at a particular depth and can provide an accurate and reliable inspection for a particular depth. However, this technique is time consuming when multiple depths must be scanned. In PPT, the thermal wave can be decomposed into a multitude of individual sinusoidal waves with frequencies ranging from 0 to $\infty$. Therefore, all depths are imaged from a single experiment, however the depths outside of the region of interest are scanned, leading to wasted thermal energy and possibly to false detections. Modulated thermography combines the advantages of these two techniques, providing a rapid inspection on the defects at only the depths of interest. The phase information is still less sensitive to surface coating, surface disturbances, and quick data acquisition for composite materials.
1.6 OBJECTIVES

The primary goal of this research is to improve PPT for the inspection of manufacturing defects in adhesively bonded carbon fiber reinforced polymer lap joints through the introduction of modulated thermal excitation. In particular, the modulated thermal excitation will be applied to two structural joints: single lap joints and double lap joints. The single lap joints provide a single region for optimized detection, while the double lap joints provide a more complex condition of multiple adhesive regions and deeper interfacial defects. The specific research objectives are:

- To determine the optimal heat period and truncation window of PPT inspection for a particular experimental setup and adhesively bonded single lap joint specimens with artificial defects at different adherend-adhesive interfaces and generate benchmark phase image data for these specimens.

- To derive potential modulated thermal waves based on the frequency information from the pulsed phase thermography results for different defects and the known single lap joint geometry.

- To conduct modulated thermography on single lap joint specimens using these potential modulated thermal waves and evaluate the resulting phase image quality of defects at different adherend-adhesive interfaces as compared to the benchmark PPT data.

- To determine the optimal heat period and truncation window of PPT inspection for a particular experimental setup and adhesively bonded double lap joint specimens with
artificial defects at multiple adherend-adhesive interfaces and generate benchmark phase image data for these specimens.

- To conduct modulated thermography on double lap joint specimens using the subset of the potential modulated thermal waves that perform best for the single lap joint specimens and evaluate the resulting phase image quality of defects at different adherend-adhesive interfaces as compared to the benchmark PPT data.
Figure 1.1 Use of composite materials in commercial transport airplanes [1].

Figure 1.2 Experimental set-up for lock-in thermography [18].
Figure 1.3 Amplitude and phase retrieval from a sinusoidal thermal excitation [11].

Figure 1.4 Experimental set-up for pulsed thermography [18].
Figure 1.5 Temperature evolution: (a) data 3D matrix, and (b) temperature profile for a defective (dotted line) and non-destructive (continuous line) pixels [19].

Figure 1.6 Schematization of the data acquisition and processing states of PPT [20].
Figure 1.7 (a) Linear frequency modulated signal (b) Digitized frequency modulated signal [16].

Figure 1.8 Phase image at 0.04 Hz of FMTWI experiment on mild-steel sample [15].
Figure 1.9 Phase images of the CFRP sample with Teflon inserts, experimentally obtained using (a) 0.089 Hz, (b) 0.086 Hz, and (c) 0.001 Hz. Measurements are made over only one digitized frequency modulated cycle [16].

Figure 1.10 Phase images of different excitation schemes at a frequency of 0.02 Hz [18].
CHAPTER 2 EXPERIMENTAL METHODS

This chapter describes the specimen fabrication methods, as well as the experimental setup for pulsed phase thermography and modulated thermography. Two kind of adhesively bonded CFRP specimens were manufactured: single lap joint specimens and double lap joint specimens. The results from these experiments are presented in Chapter 3 and 4.

2.1 SAMPLE FABRICATION

The full dimensions of the single and double lap joint specimens are shown in Figure 2.1. All CFRP laminate adherends were manufactured from eight layers of 2 x 2 twill woven carbon fiber prepreg (Advanced Composites LTM22/CF0300). Each lamina layer was sized 215.9 mm x 177.8 mm with the plies aligned in the 0° orientation. Prior to the lamina layup, a layer of Nylon bagging film and a layer of peel ply were placed at the bottom to prevent excessive resin on laminates. Each pre-preg CFRP lamina was aligned with the 0° direction, sequentially stacked on top of each other, and covered by a layer of peel ply and a layer of nylon bagging film as the top layer, shown in Figure 2.2. Plumber’s putty was used to seal the edge of the nylon bagging film; and the air between two nylon film layers was drawn out using a vacuum line and a vacuum pump. Two 203.2 mm x 228.6 mm aluminum plates were used to evenly distribute the pressure and were placed at top and bottom of the assembly. The bulk specimen was placed in a hot press, which was preheated to 50°C, then pressurized at a constant pressure of 690 kPa. The applied temperature profile consisted of 15 minutes at 50°C, 15 minutes at 65°C, and 180 minutes at 80°C [23]. Then, the laminate was removed
from the hot press and allowed to cool to room temperature. The eight-layer CFRP laminates were then cut to 114.3 mm x 63.5 mm, 130.175 mm x 63.5 mm, and 76.2 mm x 63.5 mm pieces for the fabrication of these specimens using a tile saw, as shown in Figure 2.3. The adherend-adhesive interface of CFRP laminates were prepared by polishing and cleaning with Al₂O₃ 60 grit sandpaper and isopropyl alcohol. The thickness of all adherends was measured after polishing and cleaning to determine the level of variation due to the manual process and the average thickness of the adhesive layer.

Polytetrafluoroethylene (Teflon® PTFE) tape was used to create the defects in the adhesive bond, since it is a conservative approach to simulate the air gaps and other defects in the adhesive layer [21,22]. All the artificial defects were created from 12.7 mm x 12.7 mm polytetrafluoroethylene PTFE tape; each layer’s thickness is 0.089 mm. Two artificial defects at different adherend-adhesive interface were created in each specimen as shown in Figure 2.4 and Figure 2.5. All defects were placed 25.4 mm apart from each other and 25.4 mm away from the edges of the overlapping area of the adherends.

Prior to pasting the adhesive on the adherends, the bonding surface was cleaned by isopropyl alcohol and dried. Both single lap joint specimens and double lap joint specimens were joined using Hysol EA 9394 adhesive, which is a paste type thixotropic adhesive, commonly used in aerospace industries for composite structural bonding. A drywall scraper was used to evenly distribute the adhesive on adherend bonding area to ensure a uniform adhesive bond thickness. The dimensions of the lap joint specimens were measured after the specimens were assembled to keep the artificial defects in place. The specimens were cured at room temperature for 7 days. The thickness of the adhesively bonded specimens was
measured after curing to calculate the average thickness of the adhesive layer and to determine the level of variation due to the manual process.

### 2.2 PULSED PHASE AND MODULATED THERMOGRAPHY

The experimental setup used for pulsed phase thermography (PPT) and modulated thermography (MT) is shown in Figure 2.7. In the pulsed phase thermography experiments, a function generator (Tektronics AFG3021B) was used to provide a 5V square pulse signal to the IR power module (IR Power control 330 US). The IR power module amplified the input pulse signal to power two Hedler halogen lamps, which were used as the heat source in the experiment. Each of these halogen lamps can supply 850W output power at the 5V input signal [23]. These two halogen lamps were positioned at a 17.65° angle and 0.84 m away from the front surface of the specimen. Specimen surface thermal data were acquired using a Cedip 560M, a mid-wave infrared thermal camera with a spectral response range of 3.6 to 4.9 μm through an Indium Antimonide (InSb) detector. The resolution of the thermal images was 640 pixels x 512 pixels, at a frame rate of 50 Hz. This IR camera was positioned 0.68 m away from the specimen, and perpendicular to the plane of the sample. In the experiments for double lap joint specimens, the distance between the infrared camera and specimens was increased by 0.13 m to capture all overlapping regions in a single frame.

Starting at the heating period, thermal images of the surface were captured from the infrared camera until 120 seconds after the thermal loaded ended, using Altair software with a 50 Hz sampling frequency. Next, the saved thermal data was converted to ASIC format files for further processing in MATLAB. To reduce this conversion effort, a previous NCSU
program [23] was modified and implemented in MATLAB to decrease the computational time by automatically reducing the data to the region of interest and subsampling and combining individual data frames together. The open source MATLAB program IRVIEW, was then used to calculate the phase delay angles for each pixel in the temperature profile. To help calculate and plot the average phase delay angle, contrast, and blind frequency based on the phase delay angle data, a program was implemented in MATLAB.

The modulated thermography experiments used the same experimental setup as that of the PPT, with one exception. Instead of the function generator, an arbitrary function generator (Agilent 33500B Waveform Generator) was used to provide the input signal to the IR power module. The modulated thermal waves for the single and double lap joint specimens were designed based on the blind frequency of pulsed phase thermography. These waveforms were calculated and represented as vectors in MATLAB. A MATLAB program was used to convert these vectors to ARB format files, which were then downloaded to the arbitrary function generator and provided the input signal to the IR power module.
Figure 2.1 Dimensions of (a) single and (b) double lap joint specimens.
Figure 2.2 Carbon fiber reinforced polymer laminate fabrication layup schematic.

Figure 2.3 Cutting CFRP laminates for lap joint fabrication.
Figure 2.4 Locations of artificial defects in (a) single and (b) double lap joint specimens.
Figure 2.5 Position of artificial defects in single lap joint specimen.

Figure 2.6 Adherends of double lap joint specimen.
Figure 2.7 Pulsed phase thermography and modulated thermography (a) experimental set-up (b) schematic.
CHAPTER 3 MODULATED THERMOGRAPHY OF SINGLE LAP JOINT SPECIMENS

This chapter describes the application of MT to single lap joint specimens. Polytetrafluoroethylene (Teflon) tapes were inserted at different adherend-adhesive interfaces to simulate manufacturing defects in adhesive bonds. The use of Teflon tape to simulate the manufacturing defects was a conservative approach towards defect detection as Teflon has a thermal diffusivity near that of CFRP. As a first step, PPT imaging of the single lap joint specimens was performed for benchmark data. Then the frequency information of the PPT inspection was used to design potential modulated thermal waves for the modulated thermography inspection to improve the visualization contrast of the artificial defects in adhesive bond. Finally, imaging via these modulated thermal waves was applied to the single lap joint specimens.

3.1 SPECIMEN QUALITY

Four single lap joint specimens were fabricated, labeled A, B, C, and D. While thermography imaging identifies inconsistencies in the adhesive layers due to voids or other defects, significant thickness variations across the specimen can also create artificial phase contrast differences. Therefore, prior to the application of adhesive layer, the thickness of every adherend was measured using a micrometer, to inspect the manufacturing quality of the CFRP adherends. As shown in Figure 3.1, the measurements were taken 15 mm away from edges, towards the center of the CFRP laminates. The measurement results are shown in
Table 3.1. Due to the manual alignment of the laminate in the hotpress, the average thickness of each CFRP adherends varied from 1.70 mm to 1.99 mm. It was later determined that specimen B contained large air voids in the adhesive layer and was not suitable as a test specimen, therefore results for this specimen are not presented in this chapter.

After complete fabrication of the single lap joints and full cure, the bonded joint thicknesses were measured using a micrometer. As shown in Figure 3.2, the measurements were again taken 15 mm away from the lengthwise edges, towards the center of each specimen. The results from these measurements are shown in Figure 3.2 and Table 3.2; the origin of each plot in Figure 3.2 was set at the left edge of top adherend of each specimen. Though the thickness of the single lap joint specimens varied along the longitudinal direction, as shown in Figure 3.2, the thickness of the specimens in the transverse direction was relatively uniform. The maximum percentage difference between the top and bottom thickness measurements was 4.8% (Table 3.2).

On the top surface of Specimens A and C (as shown in Figure 3.1), some bonding adhesive was accidentally applied to these surfaces during the fabrication process. These zones were likely to corrupt the phase angle data around this region due and possibly create phantom defects due to the increase of specimen thickness. In practical applications, these surfaces could be sanded prior to imaging.
3.2 PPT INSPECTION ON SINGLE LAP JOINT SPECIMENS

3.2.1 THERMAL MEASUREMENTS

Based on previous research [24], a square heat pulse of 7 seconds and a truncation window of 30 seconds were used for the PPT inspections of the single lap joint specimens. Shin [24] showed that these heating parameters provided sufficient energy and reliable defect detection for single lap joints specimens. The specimen surface temperature was measured and recorded during the heating and cooling period of the PPT inspections, acquired using the infrared camera and Altair software. Each specimen was imaged from both sides using the same parameters (arbitrarily labeled as side 1 and side 2). Figure 3.3(a) shows the average temperature of the front surface of Specimen A from side 2 in the bonded region, during the heating and cooling periods. Figures 3.3 (b), (c), and (d) show the surface temperature distribution of Specimen A from side 2, taken at 1 second before the maximum overall temperature, immediately after the heating period, and after 30 seconds of cooling respectively.

Figure 3.3 highlights the noise inherent when using temperature data without processing to phase data. A significant non-uniform heating phenomenon was observed at the center of the sample in Figure 3.3 (b) and (c). The temperature difference between the center area and the region near edges of the specimen varied from 3°C to 5°C. Due to the difference between the thermal properties of carbon fiber threads and epoxy matrix, and the twill formation between tows and picks in the CFRP adherends, the diagonal rib of the twill weave appears at a negative 45° angle in the temperature data in these regions. Figure 3.2 (d) was
acquired at 30 seconds after the maximum temperature of the specimen was achieved. The temperature difference between the maximum pixel and minimum pixel was less than 2.5°C across the specimen surface. Also, due to the non-uniform heating and low contrast between the non-defective area and defective areas, it is very difficult to visualize the defects in the thermal images (i.e. using pulse thermography).

### 3.2.2 PHASE ANGLE CALCULATION AND DEFECT DETECTION

Phase angles of each pixel in the thermal profile of each single lap joint specimen were calculated using the MATLAB open source software, IR-View. Examples of these phase images are shown in Figure 3.4. The locations of the Teflon tape inserts are marked in some images using red dashed boxes. This phase data was acquired by subsampling the surface thermal image frames to a 5 Hz sampling rate during the first 30 seconds of the cooling, which corresponds to a total of 150 frames. The effect of non-uniform heating was significantly decreased in these phase images, as shown in Figure 3.4.

A significant effect of the weave pattern in the CFRP adherends was observed in the phase images of PPT inspection on Specimen A side 2 and Specimen D side 1, seen in Figure 3.4 (a) and (c) respectively. The diagonal ribs of the twill weave were shown at a negative 45°. In Figure 3.4 (b), the phase images of PPT inspections on Specimen C side 2, the weave pattern was shown in 0° and 90°. In Figure 3.4 (d), the phase images of PPT inspections for Specimen D side 2, the weave pattern was not detected and shown on the phase image.

As shown in Figure 2.4 (a) and Figure 3.1, one deep artificial defect and one shallow defect were inserted in each single lap joint specimen. The artificial defects resulted in
different phase delay angles in these phase images, ranging from 0.41 rads to 0.44 rads. The phase delay angle is the difference in average phase over the defect and the average phase over a region without defects. Notice the shallow defect and deep defect lead to approximately the same phase delay angles in the PPT inspection for Specimen A side 2 and Specimen D side 1, as shown in Figure 3.4 (a) and (c). The shallow defect and deep defect shown on Figure 3.4 (b) and (d) lead to different phase delay angles on each phase image. The phase delay angle of the defective regions was potentially influenced by many factors, such as the defect depth, location (i.e. at the center of specimen, near the edges of the specimen), CFRP adherend thickness, and adhesive bond thickness.

In Figure 3.4 (b), two high phase delay zones on the upper left and bottom right corner were observed, which resemble voids that were visible from the edge of the specimen. Photographs of these voids are shown in Figure 3.5. These two edge voids were formed during the manufacturing process due to the shrinkage of the adhesive during the curing period. Also, notice the triangular high phase delay region in the upper middle part of the specimen C, which was a possible manufacturing defect formed during the fabrication process, not visible from the outer edges. This extrapolation was proved later, when Specimen C was cut into 3 pieces in lengthwise direction after all imaging was completed. The cross section of Specimen C showed a large air gap inside the adhesive bond layer, as shown in Figure 3.5 (c) and (d). At the same axial location as the triangular high phase delay region, there was a small ellipsoidal low phase delay zone, centered approximately at the pixel locations (275, 260) (Figure 3.4 (b)). This zone is caused by the adhesive spot on the specimen surface (Figure 3.4 (b)).
Except the phase image for Specimen C side 2, all the phase images show high phase delay regions near the upper and lower edges of the specimen along the lengthwise direction and low phase delay regions near the left and right edges of the specimen along the widthwise direction. As shown in Figure 3.4 (b), the phase image on Specimen C side 2 shows only an ellipsoidal low phase delay zone near the right edge of the specimen along the lengthwise direction.

In conclusion, the PPT imaging was able to identify both the Teflon inserts and voids unintentionally created during the adhesive bonding process of the lap joint. However, the contrast between the defects and the surrounding region was not always high, and was often strongly influenced by the specimen boundaries. There is therefore a need to improve the imaging contrast and remove external influences such as the surface weave pattern and the boundaries in the phase contrast images. This was the goal of modifying the thermal input (MT) to better focus on frequencies that highlight defects specifically in the adhesive bond layer. The following sections describe both the design of these input thermal waves and the resulting thermography measurements using them.

3.3 MODULATED THERMOGRAPHY

3.3.1 MODULATED THERMAL WAVE DESIGN

Knowing that the target area for inspection in this work is the adhesive layer, the goal of modulated thermography was to focus the thermal energy only the region of interest. In the ideal case, this region would be approximately the frequency region between the blind
frequency of the lower and upper adhesive edges. The ideal modulated thermal wave is shifted slightly to lower frequencies that this range so that the lower adhesive edge can be fully imaged, as shown in Figure 3.6 (a). This ideal frequency range was tested in this section. Figure 3.6 (b) shows an approximation to this frequency range, simply by summing waves with frequencies throughout this range, which would be easier to implement. Finally, Figure 3.6 (c) shows the same approximation with only three frequency components, which was also implemented in this work, before the ideal case was implemented.

In order to determine the specific frequency component range for potential modulated thermal waves, the average phase delay angle for the artificial defective areas and non-defective area were calculated for every frequency in the phasegram profile, as shown in Figure 3.7. The phase contrasts between these two artificial inserts and sound area were plotted in Figure 3.8. For the left (deep) and right (shallow) defect on the phasegram of Specimen A side 2, the corresponding blind frequencies were approximately 0.7 Hz and 1.3 Hz respectively.

Since the calculated phase contrast data contained significant measurement noise (typical for PPT data), the MATLAB Curve Fitting tool was employed to fit curves to the two set of data, as shown in Figure 3.8. In addition, a threshold was set representing the noise level, at which the phase contrast is assumed to be zero. As the threshold value was merely estimated, it was adjusted slightly to maximize the distance between two intersections of threshold and fitting curves, to determine the frequency components for potential modulated thermal waves. The detail of intersections between the fitting curves and applied threshold are shown in Figure 3.9. The lowest frequency component for this specimen was 0.5 Hz,
which was the biggest number within 0.1 Hz on the left side of the intersection between the threshold and deep defect contrast data fitting curve. The thermal wave with a frequency of 0.5 Hz was used to detect the defects at the deeper adherend-adhesive interface. The highest frequency component was 1.2 Hz, which was the closest number within 0.1 Hz to the intersection between the shallow defect fitting curve and the threshold. A 1.2 Hz thermal wave was used to detect the defects at the shallower adherend-adhesive interface. The third frequency chosen was 0.9 Hz, which was the mid-point of the two other frequencies. A thermal wave with a frequency of 0.9 Hz was used to detect the defects between the shallow and deep adherend-adhesive interface. The applied modulated wave was the summation of three sinusoidal waves with frequencies of 0.5 Hz, 0.9 Hz and 1.2 Hz. The modulated wave amplitude was normalized and multiplied by 5V, in order to match the output range of the function generator, as shown in Figure 3.10.

3.3.2 VALIDATION OF DESIGNED MODULATED WAVE

An Arbitrary Wave Generator was used to convert 1 cycle (10 seconds) of the designed modulated wave to a 0 - 5V signal, which was used as the input signal for the IR power module to power the halogen lamps. The temperature data acquisition followed the same procedures as detailed in section 3.2.2, with the surface thermal images subsampled to a 5 Hz sampling rate and processed during the first 30 seconds in the cooling period, for a total of 150 frames. IR-View was used to generate the phase images for the modulated thermography test.
Figure 3.11 shows the phase image from the modulated thermography inspection of Specimen A, side 2. Both shallow and deep defects in the specimen were clearly detected. The phase delay angle of the shallow defect (on the right side) was 0.02 rads higher than the phase angle resulted by deep defect. The effect of the weave pattern and the top and bottom edges was significantly decreased on the phase gram. However, compared with the PPT inspection of Specimen A, side 2 (Figure 3.4 (a)), a new defective zone appears at the lower right corner, which has a same phase delay angle with the phase delay angle of the right artificial defect. Also, the low phase delay regions caused by the left and right edges of the specimen were not decreased.

The designed modulated thermal wave was validated by modulated thermography inspections of Specimens C and D. The designed modulated thermal wave was applied to heat the Specimen C side 2 and both sides of Specimen D, followed by the same data acquisition and processing procedures. The generated phase images from the modulated thermography inspection of Specimen C and D are shown in Figure 3.12.

For Specimen C, side 2 (Figure 3.12 (a)), the modulated thermography technique was able to significantly increase the contrast between the right defect (deep defect) and its surrounding area, compared with the phase image generated from the PPT inspection. All the defects in the bond layer of Specimen C, including the artificial defects (Teflon inserts) and manufacturing defects (upper left and bottom right visible voids, non-visible triangular void) were detectable on the modulated thermography phasegram.

For Specimen D, side 1, both the left (deep) and right (shallow) defects were emphasized, appearing with the same phase delay angle at $f = 0.0333$ Hz, as shown in Figure
3.12 (b). On the phase image at $f = 0.0666$ Hz (Figure 3.12 (c)), both the shallow and deep defects in Specimen D resulted in a larger phase delay angle than that in Figure 3.12 (d). In the phase images for modulated thermography inspection of Specimen D, the shallower defect was detected to be larger than the deep defect, although they were both the same size.

For inspection of Specimen D, side 2, the modulated thermography improved the detection of the right (shallow) defect; the size and shape of the right defect can be determined from the phasegram at $f = 0.0333$Hz. However, most area of the left part of the specimen is detected as a defective zone, which is shown as a high phase delay zone. These parts were recognized as non-defective zones in the PPT inspection of Specimen D, side 2.

In all these modulated thermography tests, the effect of the weave pattern and the adhesive spot on the top of the specimen was decreased, which proves that the modulated thermography was able to focus the detection to the adhesive bond region, while the objects at other depths (i.e. the surface twill weave pattern) were neglected in the phasegram.

### 3.3.3 Optimal Modulated Thermal Wave

Based on the positive results of the simplified modulated thermal wave with three distinct frequencies, the experiments were repeated with the optimal modulated thermal wave, containing all of the frequency range of interest. Since a 0.5 Hz thermal wave was able to detect the deeper artificial defects in the single lap joint specimens and a 1.2 Hz thermal wave was able to detect the shallow artificial defects, an integration of thermal waves within the frequency range of 0.5 Hz to 1.2 Hz was applied. The optimal waveform, shown in
Figure 3.13 (b), was calculated through the inverse Fourier transform of this frequency range in the frequency domain (Figure 3.13 (a)).

However, there were two obstacles to applying the optimal modulated thermal wave of Figure 3.13 to the specimens. First, due to the large range of frequencies, the signal did not have a finite period, therefore the thermal wave had to be artificially truncated after an arbitrary amount of time. Truncated heating periods of 12.94 s and 22.07 s were set for different trial thermal waves, as these matched those tested with the PPT system. Secondly, physically applying the optimal input signal to the IR power module did not produce the designed thermal wave on the specimen. When the IR Power module input signal was less than approximately 1 V, the halogen lamps did not have sufficient input current to illuminate. Therefore the portion of the thermal wave beyond approximately 9 s was not applied. The optimal modulated thermal wave was therefore modified for different trials. Four different potential optimal modulated thermal waves were designed and tested, as shown in Figure 3.14.

The phase images of modulated thermography inspections for single lap joint specimens using these modulated thermal waves are shown in Figure 3.15. In all the phase images generated from modulated thermography inspections, the artificial defects in the specimens were not visualized on these phase images. However, the weave patterns of the CFRP adherends and the surface adhesive were clearly shown on all the phase images. The triangular void in Specimen C, located in the adhesive region, was not shown in the corresponding phase images; Figure 3.15 (c) and (d). These results indicate that the inspection highlighted surface effects, while reducing the contrast of the defects in the
adhesive bond region, the opposite of the intended output. It is not clear why this effect was observed. One potential reason could be nonlinear thermal wave propagation effects in the material or interactions between the different frequency components, which were accentuated during the rapidly changing input wave (not at a single frequency). These results should be investigated in further studies. However, in this project, the optimal modulated thermal wave was not applied to the double lap joint specimens, as improved visualization of the internal defects was not expected.

3.3.4 THERMAL ENERGY COST OF THERMOGRAPHY INSPECTION

The IR power module linearly amplified the 0 – 5 V input signal to power the halogen lamps, so the output energy of the two halogen lamps were proportional to the input signal. Since the total power of the two halogen lamps were 1700W, the output thermal energy of an arbitrary input signal can be calculated using the equation (3.1).

\[ E = \int_{0}^{\infty} \frac{1700 \, W}{5 \, V} \times I(t) \, dt \]  

(3.1)

where \( I(t) \) is the input signal of the IR power module. The output thermal energy of different type of input signals was shown in Figure 3.16. Compared with the PPT inspections, the use of modulated thermography can significantly decrease the thermal energy cost.
Table 3.1 Measured CFRP adherend thicknesses. A1 and A2 refer to the two separate laminates used to make the single lap joint specimen A.

<table>
<thead>
<tr>
<th>CFRP Laminate</th>
<th>Average Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>1.90 mm</td>
</tr>
<tr>
<td>A2</td>
<td>1.71 mm</td>
</tr>
<tr>
<td>C1</td>
<td>1.94 mm</td>
</tr>
<tr>
<td>C2</td>
<td>1.87 mm</td>
</tr>
<tr>
<td>D1</td>
<td>1.71 mm</td>
</tr>
<tr>
<td>D2</td>
<td>1.72 mm</td>
</tr>
</tbody>
</table>

Table 3.2 Single lap joint specimen average thicknesses. The maximum percentage bond line thickness variation is reported in the transverse direction.

<table>
<thead>
<tr>
<th>Single Lap Joint Specimen</th>
<th>Specimen Average Thickness</th>
<th>Specimen Bond Line Average Thickness</th>
<th>Maximum Percentage Bond Line Thickness Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3.852 mm</td>
<td>0.245 mm</td>
<td>4.80%</td>
</tr>
<tr>
<td>C</td>
<td>4.142 mm</td>
<td>0.337 mm</td>
<td>3.27%</td>
</tr>
<tr>
<td>D</td>
<td>3.702 mm</td>
<td>0.270 mm</td>
<td>1.29%</td>
</tr>
</tbody>
</table>

Table 3.3 Energy of different type of thermal waves for thermography inspection (modulated thermal wave data from Figure 3.10).

<table>
<thead>
<tr>
<th>Type of Thermal Wave</th>
<th>Energy Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>12s Square Heat Pulse</td>
<td>11.9 kJ</td>
</tr>
<tr>
<td>Modulated Thermal Wave</td>
<td>8.50 kJ</td>
</tr>
</tbody>
</table>
Figure 3.1 CFRP adherend and Teflon tape thickness measurement points (marked with triangles and circles).
Figure 3.2 Thickness measurements of single lap joint specimens: (a) measurement points on Specimen A; (b) Specimen A thickness data; (c) measurement points on Specimen C; (d) Specimen C thickness data; (e) measurement points on Specimen D; (f) Specimen D thickness data.
Figure 3.3 Thermal data and images for Specimen A from side 2: (a) change of average surface temperature during the pulse phase thermography inspection; (b) thermal image at 1 second before maximum overall temperature; (c) thermal image immediately after heating period; (d) thermal image after 30 seconds of cooling.
Figure 3.4 Phase images of PPT inspections (at $f = 0.0333$ Hz, $f_s = 5$ Hz, $N = 150$, $w(t) = 30$ s): (a) Specimen A, side 2; (b) Specimen C, side 2; (c) Specimen D, side 1; (d) Specimen D, side 2. Images chosen that best highlight both defects.
Figure 3.5 Visible defects on out edge of Specimen C: (a) upper left corner; (b) lower right corner (from side 2); (c) air gap in adhesive bond; (c) detailed image of gap in adhesive bond. Lengths are in μm.
Figure 3.6 (a) Ideal modulated thermal wave; (b) discrete frequency component approximation; (c) three frequency component wave.

Figure 3.7 Phase profile for the two defects and the sound area (data from Specimen A2).
Figure 3.8 Phase contrast profile reconstructed from data in Figure 3.7.

Figure 3.9 Close up of threshold region of data in Figure 3.8.
Figure 3.10 Modulated thermal wave in (a) time domain and (b) frequency domain.
Figure 3.11 Phase image of modulated thermography for Specimen A from side 2 (at $f = 0.0333$ Hz, $f_s = 5$ Hz, $N = 150$, $w(t) = 30$ s).
Figure 3.12 Phasegram of modulated thermography ($f_s = 5 \text{ Hz, } N = 150, w(t) = 30 \text{ s}$): (a) Specimen C, side 2 ($f = 0.0333 \text{ Hz}$); (b) Specimen D, side 1 ($f = 0.0333 \text{ Hz}$); (c) Specimen D, side 1 ($f = 0.0666 \text{ Hz}$); (d) Specimen D, side 2 ($f = 0.0333 \text{ Hz}$).
Figure 3.13 Optimal modulated wave in (a) frequency domain and (b) time domain.
Figure 3.14 Optimal modulated thermography inspection input signals: (a) truncated modulated thermal wave A with duration 13 s; (b) truncated modulated thermal wave B with duration 22 s; (c) optimal envelope modulated thermal wave C; (d) optimal envelope modulated thermal wave D with extended initial heating.
Figure 3.15 Phase images of modulated thermography inspection \( f = 0.0333 \text{ Hz}, f_s = 5 \text{ Hz}, N = 150, w(t) = 30 \text{ s} \) on single lap joint specimens: (a) optimal thermal wave A, Specimen A, side 2; (b) optimal thermal wave B, Specimen A, side 2; (c) optimal thermal wave A, Specimen C, side 2; (d) optimal modulated thermal wave B, Specimen C, side 2; (e) optimal modulated thermal wave C, Specimen A, side 2; (f) optimal modulated thermal wave D, Specimen A, side 2.
(e)

(f)
Figure 3.16 Thermal energy cost of different thermal waves (modulated thermal wave data from Figure 3.10).
CHAPTER 4 DOUBLE LAP JOINT SPECIMENS

The double lap joint is a second kind of aerospace structural lap joint, shown in Figure 4.1. The manufacturing method previously described for single lap joint specimens was used to fabricate two similar double lap joint specimens, labeled E and F. Artificial defects of Teflon tape were also inserted at different adhesive bonds in the double lap joint specimens. Prior to designing the modulated thermal waves, the optimal heating period and truncation window of PPT inspection for double lap joint specimens was determined based on experiments. The potential modulated thermal waves were designed based on the frequency information of PPT inspection with the optimal heating period and truncation window. Modulated thermography was finally performed on both sides of the double lap joint specimens, to image the artificial defects across multiple interfaces and perform deeper detection.

4.1 SPECIMEN QUALITY

Prior to assembling the double lap joints, the thickness of the CFRP adherends was measured using a micrometer, in the same manner as for the single lap joint specimens. The measurements were taken along the edges of each adherend, 15 mm away from edges toward the center of each adherend. The calculated average thickness of each CFRP laminate adherends are shown in Table 4.1. The thickness of the double lap joint specimens was also measured after the full curing cycle, as shown in Figure 4.2. The calculated average thickness of each specimen and adhesive bond were shown in Table 4.2. As shown in Figure 4.2 (b),
the difference between the maximum and minimum specimen thickness was about 0.4 mm. However, the adhesive layer thickness was relatively uniform in the width wise direction (Table 4.2), the maximum percentage difference between the top and bottom thickness at the same width wise direction measurement was 2.01%.

4. 2 PPT INSPECTION ON DOUBLE LAP JOINT SPECIMENS

4.2.1 INITIAL TESTING

The average thickness of the double lap joint specimens was approximately 5.8 mm, which is about 150% of the thickness of the single lap joint specimens. Therefore the optimum heating period for PPT on the double lap joint specimens was estimated to be 150% of the heating of PPT inspection for single lap joint specimens, approximately 12 seconds. This length should ensure the heat saturation through the entire double lap joint specimen.

In order to examine the double lap joint specimen manufacturing quality and generate benchmark phase images, PPT imaging with 12 seconds heating period was performed on both sides of the double lap joint specimens. The average surface temperature of Specimen E during the heating and cooling period are plotted in Figure 4.3 (a). Due to the effect of non-uniform heating and surface variations, the maximum temperature difference between two points on the surface of Specimen E surface is 9.02 ℃. After a 30 second cooling period, as shown in Figure 4.3 (c), the effect of non-uniform heating was significantly decreased and the maximum temperature difference across the specimen surface was decreased to 0.81 ℃. The specimen surface temperature then decreased slowly until the whole specimen reached
room temperature. The effects are similar to those seen in the previous experiments on single lap joint specimens.

The phase images resulting from the PPT inspection for the double lap joint specimens are shown in Figure 4.4. These phase images were selected from the phasegram sequences to maximize the phase contrast between the artificial defects and the sound areas. The black dots on the phase images were used to indicate the direction of each specimen. The actual locations of the deep artificial defects and shallow defects are marked by the red dashed box and blue dashed box respectively.

The shallow (right) defects were clearly imaged in these phase images, as shown in Figure 4.4. The phase delay angles in the shallow defects were higher than the phase delay angle caused by the sound area. In Figure 4.4 (a) and (b), the deeper (left) defect was not detected, though a high phase delay region was shown in the middle of the left part of each phase image. In Figure 4.4 (c), the regions near the right edge and left edge of Specimen F presented higher phase delay angles than the middle part of the Specimen F. Both the shallow defect (blue dashed box) and deep defect (red dashed box) were masked by these two high phase delay angle regions. It is difficult to determine the size and shape of the artificial defects from these phase images. A high phase delay region was also observed on the right half of the phase image of PPT imaging from Specimen F side 2 (Figure 4.4 (d)). This high phase delay region indicated the location of the shallow defect (blue dashed box). However, the size of the high phase delay region was much larger than the actual size of the shallow defect. These phase images from the PPT initial testing of the double lap joint specimens also clearly present the surface weave pattern of the CFRP laminates.
Based on the results of these initial tests, Specimen E was chosen to design and compare the modulated thermal waves for MT inspection. This decision was primarily because the shallow defects in Specimen E side 1 and side 2 were able to be identified and sized on the phase images. Specimen F was then used for validation of the designed modulated thermal waves.

4.2.2 OPTIMAL PPT TRUNCATION WINDOW AND HEATING PERIOD

Prior to designing the modulated thermal waves, the optimal truncation and heating period of pulsed phase thermography for the double lap joint specimen was further refined. Because the 12 second heating period was a rough estimate based on prior experience, this choice may not provide sufficient energy for the heat saturation of double lap joints. Based on the PPT inspections with a 12 second heating period for Specimen E, 5 different truncation windows were used to generate phase images, as shown in Figure 4.5. In Figure 4.5 (a) and (b), it was observed that the right half of the phase image presented a higher phase delay angle than the left half, due to the effect of two CFRP adherend in the middle of the double lap joint specimens. This effect was not observed as strongly in the other images of Figure 4.5. It was determined that the 30 second truncation can maximize the phase contrast, and present an accurate detection for the shallow artificial defects in Specimen E, from side 1.

In order to obtain the optimal PPT heating period for the double lap joint specimens, additional pulsed phase thermography experiments with different heating periods (ranging from 10 seconds to 20 seconds, at intervals of 2 seconds) were conducted on both sides of
Specimen E. All these experiments use a 30 second truncation to calculate the phasegram profile. Phase images generated from PPT inspection of Specimen E side 1 and side 2 were shown in Figures 4.6 and 4.7 respectively. Based on the known defective areas and sound areas, the phase contrast between the artificial defective zones and sound zone were calculated for these PPT inspections with the different heating periods, as shown in Figures 4.8 and 4.9.

Three criteria were considered when choosing the optimal heating period for the double lap joint specimens: 1. whether the phasegram obtained from the PPT inspections with particular heating periods provided a clear detection on the artificial inserts (i.e. shape, size); 2. whether the phase images were significantly influenced by other factors (i.e. edges of the specimens); and 3. the effect of noise on the phase contrast data (shown in Figures 4.8 and 4.9).

As shown in Figure 4.6 and Figure 4.7, all the PPT inspections were able to image the shallow defects in the specimens onto the phase image. Compared to all these phase images generated from different heating periods, the phase images of the PPT inspection with a 20 second heating period provided the most accurate detection on the location and sizing of the shallow defects.

It was observed that phase contrast data was covered by noise at all frequencies. Comparing all the phase contrast plots, the relatively shorter heating period (i.e. 10 seconds) or longer heating periods (i.e. 20 seconds) were less affected by the noise, with the phase contrast data distributed in a narrow range. Due to the fact that the 20 second heating period PPT inspections for both sides of Specimen E provided high quality detection for artificial
defects and were less affected by noise, 20 seconds were considered to be an optimal heating period for the PPT inspections for double lap joints.

In conclusion, the 20 second heating period and 30 second truncation window were the optimal parameters for the PPT imaging of double lap joint specimens. The frequency and phase information of PPT imaging of Specimen E from side 1 (Figure 4.6 (f)) were then used to design the modulated thermal waves.

It was also noticed that two kinds of weave patterns were observed in Figures 4.6 (d), (e), and (f). These different patterns were probably caused by two the different CFRP adherend orientations assembled in the middle of the double lap joint specimens. Also, the gaps in the middle of double lap joint specimens were not visualized in these phase images, due to their small width and the fact that they were filled with adhesive.

4.3 MODULATED THERMOGRAPHY INSPECTION OF DOUBLE LAP JOINTS

4.3.1 DESIGN OF MODULATED THERMAL WAVE

In order to determine the component frequency range for potential thermal waves, the phase contrast between the artificial inserts and sound area were calculated for every frequency in the phasegram profile (Figure 4.10). The phase value of shallow defective region was calculated by averaging the phase values in the pixels located in the shallow defective zone, which was defined by the blue dashed box in Figure 4.6 (f). Similarly, the phase value of the deep defective region and sound area were calculated by averaging the
phase values in the pixels located in the deep defective region and sound area, which were defined by the blue dashed box and green dashed boxes respectively. The phase contrast data for the shallow defect was the difference between the phase value of shallow defective region and the phase value of sound area. The phase contrast data for deep defect was calculated in a similar way.

In order to decrease the effect of noise on the phase contrast data, the MATLAB Curve Fitting tool was used to smooth the data. Three different thresholds, 0.01 rads, 0.015 rads, and 0.02 rads, were set to determine the frequency components for potential modulated waves, as shown in Figure 4.10. Figure 4.11 shows the detail of the intersections between the fitting curves and thresholds.

These three frequency components were determined following the same principles stated in section 3.3.1. By using a threshold of 0.01 rads, three frequency components, 0.8 Hz, 1.0 Hz, and 1.1 Hz, were applied to form a modulated thermal wave. The lowest frequency component, 0.8 Hz, was applied to detect the deeper defect behind the middle CFRP laminates. The thermal wave with the highest frequency component, 1.1 Hz, was used to detect the shallow defect in the specimen. 1.0 Hz is approximately the mid-point of 1.1 Hz and 0.8 Hz. The modulated thermal wave was formed by three individual sinusoidal waves (Figure 4.12(a)). Based on a threshold of 0.015 rads, another three frequency components, 0.45 Hz, 0.6 Hz, and 0.75 Hz were also chosen to form another potential modulated thermal wave. Similarly, the frequency components 0.2 Hz, 0.4 Hz, and 0.5 Hz were derived from the threshold of 0.02 rads. The designed modulated thermal waves are shown in Figure 4.12. Since a single lower frequency thermal wave was able to detect defects at deeper depths, the
modulated thermal wave formed by the lower frequency components were expected to detected deeper defects. The corresponding heating period of these three modulated thermal waves are 10 seconds, 6.667 seconds, and 10 seconds, which were set to be the heating period of modulated thermography inspection with these potential modulated thermal waves.

4.3.2 VALIDATION OF THE POTENTIAL MODULATED THERMAL WAVES

The modulated thermal waves shown in Figure 4.12 were applied to inspections on both sides of Specimen E. The phase images with maximized phase contrast are shown in Figure 4.13. Though the different thermal waves resulted in different quality phase images; these entire three thermal waves were able to provide a clear and detectable phase image for the shallow (right) artificial defect from side 1. For the phase images generated from side 2, the shallow (right) defect was imaged on the phasegram, however, the high phase delay zone indicated a larger defective area than the actual size of the Teflon tape insert.

From side 1, the middle part of the left half of Specimen E presented a phase delay angle which is higher than that of the sound area and lower than that of the artificial defective area (Figure 4.13 (a), (b) and (c)). This high phase delay zone was located on the right side of the deep (right) defect. On the other hand, Figures 4.13 (b) and (c) were significantly influenced by the upper edge of the Specimen E; the region near the upper edge were shown with a phase delay angle as high as the phase delay angle caused by the shallow (right) defect. Compared with Figures 4.13 (a) and (b), Figure 4.13 (c) provided a more accurate detection of the artificial defects with less effect of the weave pattern. But Figure 4.12 (c)
was affected by the lower edge of the specimen; a narrow strip high phase delay zone was shown near the left half of the bottom edge.

Specimen E was then flipped horizontally and inspected by modulated thermography using these three thermal waves, as shown in Figures 4.13 (d), (e), and (f). All of these three phase images presented a same shape high phase delay angle zone on the right half of the phase images. The shallow defect was indicated by these high phase delay angle regions, but the exact location of the artificial defect was not able to be determined from the phase images. Because this high phase delay region was much larger than the actual size of the artificial defect.

Two modulated thermal waves (shown in Figure 4.12 (a) and (b)) were then applied in the modulated thermography inspections of Specimen F. The phase images of the modulated thermography inspections of Specimen F from side 1 and side 2 were shown in Figure 4.14. Compared with the benchmark PPT phase images of specimen F (Figure 4.4 (c) and (d)), the modulated thermography imaging using the thermal wave showed in Figure 4.12 (a) was able to improve the contrast of the shallow defect (Figure 4.14 (a) and (c) blue dashed box). As shown in Figure 4.14 (a) the upper left corner of Specimen F side 1 was presented with higher phase delay angle than any other regions in this phase image. In the benchmark phase image (Figure 4.4 (c)), the same region of the Specimen F was also detected as a high phase delay zone.

Both the shallow and deep defects were not imaged on the phase images (Figures 4.14 (b) and (d)) generated from the modulated thermography imaging using the thermal wave shown in Figure 4.12 (b). This zone was proven to be an unintentionally created air
bubble. In Figure 4.14 (b), although a high phase delay angle region was shown on the right part of the phase image, it is not the artificial (deep) defect. The deep artificial defect was located at the left side of this high phase delay region. In Figure 4.14 (d), the left half of the phase image was shown with a high phase delay angle, and the weave pattern was clearly imaged. At the same time, the artificial defects were not detected on the phase image.

In conclusion, both the PPT and modulated thermography were not able to detect the deep defects in the double lap joints specimens. However, the modulated thermography provided a higher contrast than PPT for the shallow defects.

4.3.3 INDEPENDENT MICRO-CT IMAGING OF DOUBLE LAP JOINT SPECIMENT

Finally, micro-CT scanning (micro-computed-tomography) was also performed for Specimen F to provide an independent measurement and two slices from these scans are shown in Figure 4.15. Micro-CT is much more computationally and experimentally intensive and is therefore not suitable for rapid inspection of composite structures. However it can provide higher resolution, benchmark data for comparison with the thermography data of this work.

An air bubble was clearly showed in Figure 4.15 (a) at the top left part of the specimen, which was also detected by the modulated thermography inspection as shown in Figure 4.14 (a). The detection of this air bubble in the adhesive bond proved that the modulated thermography was able to detect manufacturing defects in the adhesive bond. There were several small air bubbles existing in the adhesive bond, as shown in the middle
Figure 4.15 (a) and in the right half of Figure 4.15 (b). Due to their small size, these air bubbles were not visible on the thermography phase images.

4.3.4 THERMAL ENERGY COST OF MODULATED THERMOGRAPHY

The output thermal energy of different type of input signals was again calculated using equation (3.1) (Figure 4.16). Compared with PPT inspection, the use of modulated thermography can significantly decrease the thermal energy cost. The maximum energy cost of the modulated thermography inspections for the double lap joint specimens was 8.5 kJ, while the minimum energy of the PPT inspections was 20.4 kJ. Therefore the MT inspection represented a 58% decrease in thermal energy supplied to the specimens. While the MT inspection did not improve the defect visualization as hoped for these experiments, the possibility exists that putting more thermal energy into the MT inspection may still result in an improved defect visualization for the same thermal cost. More thermal energy could be put into the specimen by increasing the periods of the thermal wave input into the specimen.
Table 4.1 Measured CFRP adherend thicknesses. (a), (b), (c), and (d) refer to the four separate laminates used to make the double lap joint specimen as depicted in Figure 4.1.

<table>
<thead>
<tr>
<th>CFRP Laminate</th>
<th>Average Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen E adherend (a)</td>
<td>1.78 mm</td>
</tr>
<tr>
<td>Specimen E adherend (b)</td>
<td>1.70 mm</td>
</tr>
<tr>
<td>Specimen E adherend (c)</td>
<td>1.63 mm</td>
</tr>
<tr>
<td>Specimen E adherend (d)</td>
<td>1.79 mm</td>
</tr>
<tr>
<td>Specimen F adherend (a)</td>
<td>1.68 mm</td>
</tr>
<tr>
<td>Specimen F adherend (b)</td>
<td>1.83 mm</td>
</tr>
<tr>
<td>Specimen F adherend (c)</td>
<td>1.82 mm</td>
</tr>
<tr>
<td>Specimen F adherend (d)</td>
<td>1.78 mm</td>
</tr>
</tbody>
</table>

Table 4.2 Double lap joint specimen average thicknesses. The maximum percentage bond line thickness variation is reported in the transverse direction.

<table>
<thead>
<tr>
<th>Double Lap Joint Specimen</th>
<th>Specimen Average Thickness</th>
<th>Specimen Bond Line Average Thickness</th>
<th>Maximum Percentage Bond Line Thickness Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>5.972 mm</td>
<td>0.367 mm</td>
<td>2.01%</td>
</tr>
<tr>
<td>F</td>
<td>5.728 mm</td>
<td>0.221 mm</td>
<td>1.28%</td>
</tr>
</tbody>
</table>

Table 4.3 Energy of different type of thermal waves for thermography inspection. Modulated thermal wave (a), (b), and (c) refer to the modulated thermal waves shown in Figure 4.12.

<table>
<thead>
<tr>
<th>Type of Thermal Wave</th>
<th>Energy Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>12s Square Heat Pulse</td>
<td>20.4 kJ</td>
</tr>
<tr>
<td>20s Square Heat Pulse</td>
<td>34.0 kJ</td>
</tr>
<tr>
<td>Modulated Thermal Wave (a)</td>
<td>8.50 kJ</td>
</tr>
<tr>
<td>Modulated Thermal Wave (b)</td>
<td>5.67 kJ</td>
</tr>
<tr>
<td>Modulated Thermal Wave (c)</td>
<td>8.50 kJ</td>
</tr>
</tbody>
</table>
Figure 4.1 Double lap joint specimen side view.
Figure 4.2 Thickness measurements of double lap joint specimens: (a) measurement points on Specimen E; (b) Specimen E thickness data; (c) measurement points on Specimen F; (d) Specimen F thickness data.
Figure 4.3 Thermal data and images for Specimen E from side 1: (a) change of average surface temperature during the pulse phase thermography inspection; (b) surface temperature immediately after heating period; (c) thermal image after 30 seconds of cooling.
Figure 4.4 Phase images of PPT inspection for double lap joint specimens with 12 s heating period ($f = 0.0333 \text{ Hz}, f_s = 5 \text{ Hz}, N = 150, w(t) = 30 \text{ s}$):  (a) Specimen E, side 1; (b) Specimen E, side 2; (c) Specimen F, side 1; (d) Specimen F, side 2. Images chosen that best highlight both defects.
Figure 4.5 Phase images of PPT inspections for Specimen E side 1 with different truncation windows ($f = 0.0333$ Hz, $f_s = 5$ Hz, $N = 150$): $w(t) = (a) 30$ s (b) 35 s (c) 40 s (d) 45s (e) 50 s.
Figure 4.6 Phase images of PPT inspections for Specimen E side 1 with different heating periods ($f = 0.0333$ Hz, $fs = 5$ Hz, $N = 150$, $w(t) = 30$ s):
(a) 10 s (b) 12 s (c) 14 s (d) 16 s (e) 18 s (f) 20 s.
Figure 4.7 Phase images of PPT inspections for Specimen E side 2 with different heating periods ($f = 0.0333$ Hz, $f_s = 5$ Hz, $N = 150$, $w(t) = 30$ s): (a) 10 s (b) 12 s (c) 14 s (d) 16 s (e) 18 s (f) 20 s.
(e)

(f)
Figure 4.8 Phase contrast between artificial defective zones and non-defective zone for different heating periods (data from Figure 4.6, Specimen E, side 1): (a) 10 s (b) 12 s (c) 14 s (d) 16 s (e) 18 s (f) 20 s. Curve fits to data are also shown.
(c)

(d)
Figure 4.9 Phase contrast between artificial defective zones and non-defective zone for different heating periods (data from Figure 4.7, Specimen E, side 2): (a) 10 s; (b) 12 s; (c) 14 s; (d) 16 s; (e) 18 s; (f) 20 s. Curve fits to data are also shown.
Figure 4.10 Phase contrast profile (data from Figure 4.6 (f) and Figure 4.8 (f)) with different thresholds: (a) 0.01 rads; (b) 0.015 rads; (c) 0.02 rads.
Figure 4.11 Close up of threshold region of data in Figure 10: (a) 0.01 rads; (b) 0.015 rads; (c) 0.02 rads.
Figure 4.12 Modulated thermal wave designed based on different thresholds: (a) 0.01 rads; (b) 0.015 rads; (c) 0.02 rads.
Figure 4.13 Phase images of modulated thermography ($f = 0.0333$ Hz, $f_s = 5$ Hz, $N = 150$, $w(t) = 30$ s) for Specimen E from: (a) side 1, thermal wave from Figure 4.12 (a); (b) side 1, thermal wave from Figure 4.12 (b); (c) side 1, thermal wave from Figure 4.12 (c); (d) side 2, thermal wave from Figure 4.12 (a); (e) side 2, thermal wave from Figure 4.12 (b); (f) side 2, thermal wave from Figure 4.12 (c).
Figure 4.14 Phase images of modulated thermography ($f = 0.0333$ Hz, $f_s = 5$ Hz, $N = 150$, $w(t) = 30$ s) for Specimen F from: (a) side 1, thermal wave from Figure 4.12 (a); (b) side 1, thermal wave from Figure 4.12 (b); (c) side 1, thermal wave from Figure 4.12 (a); (d) side 2, thermal wave from Figure 4.12 (b).
Figure 4.15 Micro-CT scan images for Specimen F at depth in adhesive layer closest to (a) side 1 and (b) side 2.
Figure 4.16 Thermal energy cost of different thermal waves (modulated thermal wave data from Figure 4.12).
CHAPTER 5 CONCLUSIONS

This research study was conducted to improve the detection of manufacturing defects in adhesively bonded lap joint structures. The goal is to concentrate the detection and imaging of the defects within the adhesive bond, while ignoring defects at other depths. In previous research, quantitative methods were used to detect artificial defects and fatigue loading damage within adhesive bond, however, the detection was affected by many factors (i.e. phase delay angle variations, noise, adhesive bond thickness variations). Specifically in this study, the thermal input waves were amplitude modulated to select frequency components that highlight defects in the adhesive layer. Based on blind frequency results from a previous study, a threshold filtering method was used to select the frequency components for creating modulated thermal waves.

The initial experiments for single lap joint specimens confirmed that PPT can detect the artificial defect and manufacturing defects at adhesive bond. Establishing a threshold value from the noise level in the phasegram profile of PPT inspection provided the frequency components to form a modulated thermal wave. An optimal modulated thermal wave was designed and several modifications to this wave, that could be physically implemented, were tested. In addition, a simplified optimal thermal wave based on only three frequency components was implemented and tested. For the case of this three frequency wave, the artificial defects were directly imaged and highlighted on the phase images of the modulated thermography inspections. Also, noticeable manufacturing flaws (a void in the adhesive bond and two edge voids) in a single lap joint specimen were detected using modulated thermography. Compared with PPT results, the modulated thermography enhanced the
contrast of the phase images and highlighted the defects. The results with the optimal thermal wave were less successful, presumably due to the complexity of the wave and its interaction with the material system.

Double lap joint specimens were then tested to simulate a more complex structure in an airframe with multiple adhesive interfaces. Initial tests indicated that PPT can only detect shallow artificial defects. The artificial defects in the deeper adhesive layer were not visible on the phase images. The frequency information obtained from PPT inspection after optimizing the thermal imaging parameters for the double lap joint specimens provided more reliable data for designing the modulated thermal waves. Three modulated thermal waves with different frequency components were designed for inspection of the double lap joint specimens based on three different threshold values. These three different modulated thermal waves can highlight the characteristics of the adhesive bond at different depths, depending on their frequency components and heating periods. Modulated thermography can also enhance the contrast of shallow defects and an unintentionally created void in the adhesive bond. Compared with the PPT inspections for the double lap joint specimens, the modulated thermography improved the detection of artificial defects, though the artificial defects in the deeper adhesive layer still could not be detected. Different specimen characteristics highlighted by different modulated thermal waves indicated the importance of properly choosing frequency components for creating the modulated thermal waves. Finally, calculating the thermal energy cost of modulated thermal waves and heat pulses proved the economy of modulated thermography.
The experiments confirmed that modulated thermography not only can detect the manufacturing defects, but also can concentrate the thermal energy on particular depth and focus on adhesive bonds. It has the ability to provide high contrast detection phase images for CFRP adhesively bonded lap joints.
REFERENCES


