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Low energy impact damage detection in CFRP using eddy current pulsed thermography

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ABSTRACT

The carbon fiber reinforced polymer (CFRP) is widely used in aircraft and wind turbine blades because of their high strength and low weight. The CFRP is sensitive to impact damage and detecting damages in CFRP is important for ensuring the structural safety. This study is conducted to detect impact damages using eddy current pulsed thermography (ECPT). The impact damages were artificially produced by impact energies of 4 J, 6 J, 8 J and 10 J, respectively. The structural impact damages lead to non-uniform distribution of eddy current in CFRP excited by coil with high frequency alternating current. The eddy current can be represented by heat distribution according to Joule's law. And the damages also influence the transmission of heat in the CFRP. The change of heat is represented by surface temperature recorded in the form of thermal image sequence by IR camera. Then defects are evaluated by analyzing the heat distribution and patterns in thermal images. In addition, due to the 4 J energy is low, the damage size of the CFRP is small and cannot be observed directly from the original thermal images. In order to distinguish the small defects, a multi-resolution statistical analysis method, employing the wavelet transform combined with principal component analysis (PCA), is used to extract the defective characteristics of impact damage. Through this method, the information of thermal images has been improved to distinguish defects and the detectability of impact energy producing damage are also discussed.

1. Introduction

The carbon fiber reinforced polymer (CFRP) composite can be defined as a combination of two or more materials with different ways. It is widely used in aircraft and wind turbine blades due to their superior characteristics of high strength and low weight [1]. However, the damages of CFRP induced by impact loading [2] significantly impact structural performance, which is a critical issue for defect detection and characterization. Non-destructive detection and evaluation (NDT&E) techniques [3] are widely used for structural integrity assessment during both manufacturing process and in-service operation of CFRP composite components. In previous studies, several NDT&E techniques such as eddy current [4,5], X-ray [6], acoustic emission and microwave have been employed to evaluate CFRP damages. Ultrasonic testing [7,8] can detect interior defects of materials. But this method is difficult to identify shallow surface breaking defects due to its blind detection area. The microwave [9,10] methods have high sensitivity for dielectric materials, but it is only for surface defects. However, the impact damages in CFRP include both surface and interior defects. Even there are no distinct defects on the surface under low energy impact, interior micro-defects including plastic deformation may be also induced. Consequently, the integration of multiple NDT&E techniques is increasingly developed to improve detectability of defects.

Eddy current pulsed thermography (ECPT), an emerging integrated NDT&E technique, combines both advantages of pulsed eddy current and thermography. The major advantages of thermography over other techniques is the potential of rapid inspection of a large area within a short time [11]. Through integration of thermography and pulsed eddy current, it enhances the detectability of defects [12]. In ECPT, varied excitation direction can be used to investigate different layers for composite materials. It has been successfully applied to detect cracks with different penetration depths in metallic materials [13,14], and cracks, impact damage and delamination of CFRP [15–17]. Principal component analysis [16] and thermal images processing of optical flow algorithms [17] are applied for ECPT thermal responses for quantitative analysis of a set of composite samples from our EU partner with impact tests of 2 J, 4 J, 6 J, 8 J, 10 J and 12 J. Only impact damages

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higher than 4 J are detected. This paper will investigate whether low energy impact damage detection can be detected using ECPT and different signal processing algorithms.

Based on the ECPT, thermal image sequences which can be used to identify defective areas are captured and recorded by infrared camera. The structural characteristics of CFRP specimens are represented by heat distribution in thermal images and the transient thermal image in different time contains different physical effects [18]. So thermal images processing methods are pivotal to extract features of defects. At present, the PCA [19–21], ICA [22], Fourier transform [23] and wavelet transform [24] techniques have been applied in thermal image analysis for defect identification. Marinetti, et al. [25], compared the efficiency of PCA to thermographic feature extraction by considering the initial sequence as either a set of images or a set of temporal profiles. He, et al. [26], proposed Tucker decomposition based signal reconstruction to detect and evaluate the impact damage of CFRP. Yang et al. [27], used wavelet transform to analyze the best thermal image which was selected having the greatest high frequency wavelet energy. The eddy current accumulation area induced by defect can be observed visually by thermal imaging. But the improper selection of thermal images and image processing algorithms will influence the defect identification and NDT&E performance of ECPT.

In this work, a new method combining PCA and wavelet transform is proposed to process thermal image sequences of ECPT for impact damages evaluation of CFRP. And a critical challenge for detecting small defects induced by 4 J low energy impact is discussed with ECPT experiments. Wavelet transform is effective in time, frequency and spatial analysis. It is useful to detect the weak information based on the multi-resolution analysis. But it is not suitable for processing large amounts of data. The PCA method can reduce the dimensionality of datasets and transform the original measured data into new uncorrelated variables. It can improve the ability of detecting the deep defects and micro defects. Integration of PCA and wavelet transform have optimal time-spatial scale feature and make up each other effectively to strengthen the detectability of small impact damage.

The rest of paper is organized as follows. The methodology including physical principle of ECPT and integrated thermal images processing approach with wavelet transform and PCA are described in Section 2. The experiments and result analysis with comparison are presented in Section 3. Finally, the conclusion is derived in Section 4.

2. Methodology

2.1. The physical mechanism of ECPT

For conductive materials, the coil with high frequency alternating current will induce eddy current on its surface or depth. The eddy current attenuation aggravates with increasing depth. The depth of the infiltration of eddy current is called the skin depth. The formula is expressed as:

$$\delta = \frac{1}{\sqrt{\pi\mu\sigma f}} \tag{1}$$

where the f is the frequency of excitation current, σ is the electrical conductivity of materials, μ is the magnetic permeability of material.

According to Joule's law, part of the eddy current will convert into heat energy from electrical energy. The generated heat Q are in direct proportion to eddy current density J_s and electric field density E, as follow:

$$Q = \frac{1}{\sigma}|J_s|^2 = \frac{1}{\sigma}|\sigma E|^2 \tag{2}$$

The generated Joule heat will spread inside the material. The propagation equation is as follows:

$$\rho C_P \frac{\partial T(z,t)}{\partial t} - \nabla(k\nabla T(z,t)) = Q \tag{3}$$

In the above formula, z is the distance from the surface. $T(z,t)$ represents the temperature of position z at time t. The ρ, C_P and k denote respectively density, thermal capacity and thermal conductivity of material.

The system diagram of ECPT in transparent mode is shown in Fig. 1. The computer is used to control the system and receives the data from the IR camera. When the function generator gets a command from the computer, it makes the induction heater and IR camera work synchronously. The induction heater makes the coil flux high frequency alternating current, which induces eddy current in the sample. When the induced eddy current encounter a discontinuity in the sample, they are forced to divert, leading to regions of increased and decreased eddy current density. According to formula (2) and (3), the sample has been heated by the eddy current and the heat will spread inside the sample. For the crack case, eddy current diversion results in eddy current density increasing at the crack bottom or tips, where higher Joule heat is achieved. Thus, the defect can be identified from a characteristic heat distribution. After the period of eddy current heating, the defect also affects the heat diffusion in the cooling stage. The heat distribution in whole process is recorded by IR camera in the form of thermal images. Then the thermal image sequence containing valuable information is transmitted to computer for further analysis.

The thermal image sequence obtained from IR camera is represented by mathematical model as follow:

$$M(n) = \begin{bmatrix} Y_{1,1}(n) & \cdots & Y_{1,320}(n) \\ \vdots & \ddots & \vdots \\ Y_{256,1}(n) & \cdots & Y_{256,320}(n) \end{bmatrix}, \quad n = 1,2,\ldots,N \tag{4}$$

In the formula (4), $M(n)$ is the n_{th} frame thermal image. $Y_{i,j}(n)$ represents the temperature in the position of row i and column j in n_{th} frame image. The N is the total frame number and n is between 1 and N.

2.2. Feature extraction algorithm

The wavelet transform is a multi-scale analysis and has good localization performance in both time domain and frequency domain to extract effective information from images. Through the wavelet transform, an image has decomposed according to wavelet bases. The bases of two dimensional wavelet transform are shown as follow:

$$\varphi(x,y) = \varphi(x)\varphi(y), \tag{5}$$

$$\psi^1(x,y) = \varphi(x)\psi(y), \tag{6}$$

$$\psi^2(x,y) = \psi(x)\varphi(y) \tag{7}$$

$$\psi^3(x,y) = \psi(x)\psi(y) \tag{8}$$

In the above formula, $\varphi(x)$ is the scaling function of one dimensional wavelet transform and $\psi(y)$ is the mother wavelet function relatively.

At every level of transformation, an image is decomposed to four sub-images with the same size. The size of sub-images is a quarter of the original image. Using the interval of two times sampling the inner product of the original image and a wavelet basis, a