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Automatic seeded region growing for thermography debonding detection of CFRP

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ABSTRACT

The carbon fiber reinforced polymer (CFRP) has been widely used in aerospace, automobile and sports industries. In laminated composite materials, cyclic stresses and impact will cause internal defects such as delamination and debonding. In order to guarantee internal quality and safety, optical pulsed thermography (OPT) nondestructive testing has been used to detect the internal defects. However, current OPT methods cannot efficiently tackle the influence from uneven illumination, and the resolution enhancement of the defects detection remains as a critical challenge. In this paper, a hybrid of thermographic signal reconstruction (TSR) and automatic seeded region growing (ASRG) algorithm is proposed to deal with the thermography processing of CFRP. The proposed method has the capability to significantly minimize uneven illumination and enhance the detection rate. In addition, it has the capacity to automate segmentation of defects. It also overcomes the crux issues of seeded region growing (SRG) which can automatically select the growth of image, seed points and thresholds. The probability of detection (POD) has been derived to measure the detection results and this is coupled with comparison studies to verify the efficacy of the proposed method.

1. Introduction

The CFRP has advantages of extremely high specific strength and modulus, good fatigue resistance and low expansion coefficient [1]. In recent years, it has become an important and indispensable structural material in aerospace, petroleum chemical industry, wind turbine blades and etc. In laminated composite materials, repeated cyclic stresses and impact will cause quality problems, such as delamination, debonding, crack and impact defects [2]. Therefore, non-destructive testing and evaluation (NDT&E) techniques have been used for inner defects detection and structural integrity assessment of composite material [3].

At present, different NDT technology has been used to assess the internal quality of CFRP such as shearography [4], eddy current, ultrasonic C scanning, acoustic emission, infrared thermography (IRT) and etc. Specially, IRT has been applied to evaluate composite structure, such as diagnostic material characterization [5] due to its advantages of fast, non-contact, non-polluting. Sfarra et al. [6] inspected the impacted laminates by using IRT, near-infrared reflectography (NIR) and ultraviolet (UV). Excitation source of IRT includes hot air, flash, laser, ultrasonic, and terahertz spectroscopy etc. They are used to motivate the sample for generating a thermal contrast between the defect area and the background. Chulkov et al. [7] have compared different optical source for NDT, such as Xenon flash lamps, halogen lamps and LED. Optical pulse thermography (OPT) is commonly applied as an active heating method for IRT in various damage detections on both surface and internal position of the material.

Thermal images processed by using the OPT system have the issues of edge blur, uneven heating and low resolution. In order to ameliorate the above issues, different feature extraction algorithms are used. Maldague [8,9] proposed pulsed phase thermography (PPT) which combines simultaneously advantages of both pulse thermography (PT) and modulated infrared thermography. It has been shown to be able to detect deeper defect and reduce noise. Galmicheand et al. [10] combined PPT technology with the Wavelet transform which allows for simultaneously analysis time and frequency information. Principal component analysis (PCA) is a well-known technique of multivariate linear data analysis. Rajic [11] applied PCA to thermal imaging data to

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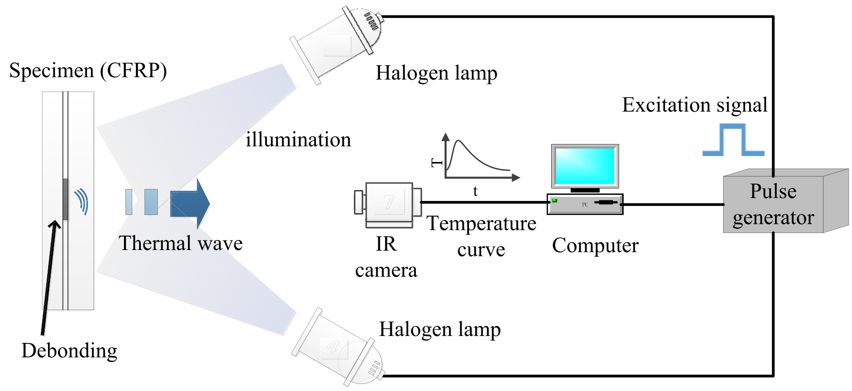

Fig. 1. Diagram of OPT system.

enhance the detectability of singular pattern. Kim et al. [12] proposed PCA mixture model to simplify the model order selection. Tao et al. [13] employed the wavelet transform and combined with PCA to distinguish the small impact defects. The optical flow (OF) method tracked the heat flow across thermography sequence [14], which can estimate the relevant physical parameters of CFRP, such as the heat diffusion and decay constants. Thermographic signal reconstruction (TSR) method has been widely used for defect enhancement of OPT [15]. Balageas et al. [16] used the decomposition of thermograms on a logarithmic polynomial and its derivatives to enhance of transient thermographic images and the defect information. Shepard et al. [17] has proposed separation method to remove temporal and spatial non-uniformity noise components in the image sequence to significantly reduce undesirable blurring effects. Partial least squares thermography (PLST) is introduced to pulsed thermography data for reducing the background noise through the reduction of the non-uniform heating effect [18]. Hajrya et al. [19] used independent component analysis (ICA) to structural health monitoring (SHM). ICA [20] was compared on thermography features extraction by considering the initial sequence as either a set of images or a set of temporal profiles. Mulaveesala et al. [21] proposed non-stationary thermal wave imaging (NSTWI) technique and it is an indispensable approach for the inspection and evaluation of various materials.

Image segmentation plays a vital role in image analysis and defect identification. It is the process of clustering defective pixels into a number of regions that are not overlapped according to the characteristics of gray scale, color, texture or shape [22]. The existing image segmentation methods are divided into the following categories: threshold-based method, region-based method, edge-based method and model based methods. Wang et al. [23] proposed the self-adaption threshold segmentation after top-hat transformation with double structure elements, which could effectively restrain background and noisy points. The problem of the threshold based technique is that it will ignore the spatial information of the pixel values. Hence, this method is inefficient for images that blur at object boundaries or for multiple image component segmentation [24]. Jin et al. [25] proposed an adaptive fuzzy clustering algorithm based on multi-threshold (AFCMT) to obtain the satisfied infrared image segmentation in complex environments. Edge based segmentation combined with other post processing were used for pedestrian and aircraft infrared image detection [26,27]. Shunyong et al. proposed Otsu and genetic algorithm for infrared image segmentation [28]. Seeded region growing (SRG) artificially selects several pixels in the image as seeds, and appends adjacent pixels that satisfied with the threshold to seed region until achieve the termination conditions. This technique is attractive for medical image segmentation in the seed selection procedure [29]. Ikonomakis et al. [30] combined seeded region growing and merging algorithm to segment grey scale and color images. The position and size of the debonding defects are extracted by using image segmentation.

In order to enhance the detection resolution of small and deeper defects, this paper combines the automatic seeded region growing (ASRG) and TSR to detect debonding of CFRP by using OPT. Particularly, the novel method proposes the strategy of automatically selecting pretreatment image, seeds and growth threshold according to the characteristics of the thermal image. In reviewing the current defect detection methods, it is necessary to objectively quantify the defect and enhance the detectability. The probability of detection (POD) has been used to validate the accuracy of detection in fatigue cracks of an aircraft wing and flat bottom holes of aluminum foam specimens [31,32]. In this paper, the POD is used for validation. The experimental platform and the man-made debonding specimens of the CFRP have been conducted to confirm the stability and validity of the proposed method.

The remaining portion of this paper is organized as follows. Firstly, the mechanism of OPT and the proposed defects detection method are introduced in Section II. Section III discusses the detectability assessment. Experiment and result analysis are presented in Section IV. Finally, the conclusion and further work are outlined in Section V.

2. Methodology

2.1. Mechanism of OPT

Optical pulsed thermography (OPT) has been extensively used as a large area rapid inspection technology for composite structures. It is based on the study of heat transfer occurred during pulse heating and cooling. The duration of the pulse excitation varies according to the thickness and the thermal performances (i.e. thermal conductivity, thermal diffusivity) of the material. During the cooling process, for a homogeneous material the surface temperature decreases uniformly. However, the presence of an internal debonding alters the diffusion rate while the defect location can be identified by observing the difference from the surface temperature. In order to clearly interpret the composition of OPT system and the physics characteristics of defect, Fig. 1 shows a diagram of the OPT system (in reflection mode) by using halogen lamps as excitation source. A pulse generator is used to generate the excitation signal, and the IR camera starts recording both the spatial and the transient response of temperature on the sample. The data is derived from the halogen-excited infrared thermography system, which are commonly used for the Optical Pulsed Thermography NDT in composite materials [7,33].

In the OPT system, the physical properties of the surface temperature change with time and space which can be expressed in Eqn. (1). The flawless regions are assumed to be a one-dimensional heat conduction in anisotropic infinite solid plate. If the instantaneous heating is injected to one side, the variation curve of the surface temperature can be obtained by the Fourier diffusion equation, namely: