Composites Part B 79 (2015) 351–358

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Defect detection in CFRP structures using pulsed thermographic data enhanced by penalized least squares methods

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ARTICLE INFO

Article history:
Received 28 December 2014
Received in revised form
22 March 2015
Accepted 29 April 2015
Available online 8 May 2015

Keywords:
A. Carbon fiber
D. Non-destructive testing
D. Thermal analysis
Pulsed thermography

ABSTRACT

Pulsed thermography (PT) is a widely used non-destructive testing (NDT) method for detecting defective regions in carbon fiber reinforced polymers (CFRP) structures. In order to improve the spatial and temporal resolution of thermographic data, thermographic signal reconstruction (TSR) is often adopted for data processing and analysis. However, TSR only performs data filtering along the time direction, while the spatial information is not exploited for noise reduction. In addition, TSR cannot handle the non-uniform backgrounds commonly existing in thermal images. To get around these problems, this paper extends the utilization of the penalized least squares methods to defect detection in CFRP structures. The experiment results show that, with the aid of penalized least squares, the defective regions in thermal images are characterized more clearly, while the signal-to-noise ratio (SNR) values are increased significantly.

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1. Introduction

Due to the high chemical stability, high mechanical strength and low density, carbon fiber reinforced polymers (CFRP) have been widely used in the areas where high strength-to-weight ratio and rigidity are required, including aerospace, automotive, wind turbines, civil engineering, etc. However, various types of defects may exist in CFRP structures, such as fiber breaks, voiding, cracking, delaminating and interfacial debonding. These defects are often invisible at the part surface, but have negative effects on the strength and stiffness of CFRP products. Therefore, defect detection in CFRP structures is critical to product performance and safety.

Generally, defect detection methods can be categorized as destructive and non-destructive. Due to the high cost of CFRP materials, non-destructive testing (NDT) methods including thermography [1–4], ultrasonic inspection [5–8], X-ray inspection [9–11], shearography [11,12], electronic speckle pattern interferometry [13,14], etc. are commonly applied. Among these methods, thermography is attractive for its low cost, easy operation and wide scanning scope.

Thermography is a surface radiation measurement technique, which uses infrared camera to measure surface temperature of target specimen and constructs thermal images for analysis. The thermographic NDT techniques can be divided into two categories: active thermography and passive thermography. The major difference between these two lies in the utilization of external energy source. In active thermography, an external energy source is required to produce a thermal contrast between the inspected parts and the surroundings. In contrast, no such external energy is supplied in passive thermography. As a result, active thermography are more robust to the influence of ambient temperature, and more widely used in defect detection of fiber reinforced polymers (FRP) [15,16].

In the past one or two decades, the use of pulsed thermography (PT), one of the most popular methods in active thermography, has increased dramatically for NDT of composite materials [17]. A major reason for this popularity is the quickness of the inspection relying on a thermal stimulation pulse [18]. In PT, the surface of a tested part is heated with a brief pulse of light usually from a high power source, e.g. photographic flashes. Then, the heat flux on the surface tends to diffuse into the material. The time-dependent surface temperature response is captured as a series of thermal images by an infrared camera connected to a computer. The temperature contrast between the defective and non-defective regions enables defect detection based on thermographic data.

However, thermal images usually involve significant measurement noise and non-uniform backgrounds caused by uneven heating. As a result, it is difficult to recognize the defective regions

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http://dx.doi.org/10.1016/j.compositesb.2015.04.049
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clearly by naked eyes. Hence, different types of thermographic image analysis methods have been proposed for signal enhancement, e.g. thermographic signal reconstruction (TSR) [19,20], differential absolute contrast (DAC) [21,22], pulsed phase thermography (PPT) [23,24], principal component thermography (PCT) [25], etc., where TSR is frequently used for its performance in data compressing and noise reduction. Based on the Fourier diffusion equation, TSR applies polynomial filters to eliminate the noise contained in thermographic data. In addition, TSR can also use derivatives to further improve its defect detection ability.

The major shortcomings of TSR are of the following two aspects. First, TSR only applies polynomial filters in time dimension to reduce noise, while the abundant spatial information contained in thermal images is not exploited. Therefore, the effectiveness of noise reduction is still not good enough. Especially, if time derivative is performed, the noise will be further amplified. Second, TSR cannot handle the non-uniform backgrounds well. To get around these problems, the statistical techniques of penalized least squares are adopted in this paper to better utilize the spatial information.

Originally proposed by Whittaker [26], penalized least squares smoothers have become promising methods in the field of chemical data analysis [27], the ideology of which is to divide a noisy series into two parts, i.e. the signal and the noise, by solving a penalized optimization problem. Recently, Zhang et al. proposed an iteratively reweighted procedure based on penalized least squares to correct the baseline contained in chemical signals [28]. The penalized least squares smoothers have following attractive properties. (1) The programming is easy, especially in a MATLAB environment. (2) The boundaries of the data can be treated well in an automatic way. (3) Penalized least squares handles missing data. (4) The smoothness of the reconstructed signal obtained from decomposition can be controlled by tuning a single parameter. (5) The algorithms are efficient.

Although with different dimensions, both thermographic data and chemical data consist of three critical elements: signals, backgrounds and noise. Inspired by such similarity, the penalized least squares methods are adopted in this paper to decompose the TSR-treated thermographic data and to extract the reconstructed images with least influence of non-uniform background and noise. By doing so, the defect detection efficiency of pulsed thermography can be significantly enhanced.

The paper is organized as follows. In Section 2, the principle of pulsed thermography is briefly introduced. Then, the methodologies are presented in Section 3, including TSR, noise reduction with penalized least squares, and non-uniform background elimination. In Section 4, the experiment results show the effectiveness of the proposed method comparing to the conventional TSR method. Finally, conclusions are given in the Section 5.

2. Pulsed thermography

The problem of heat diffusion through a solid specimen can be described by Fourier's law of heat diffusion:

$$\nabla^2 T - \frac{1}{\alpha}\frac{\partial T}{\partial t} = 0. \tag{1}$$

Here, ∇ is the three-dimensional del operator, T is the temperature in the specimen, t is the time index, $\alpha = k/(\rho c)$ is the material thermal diffusivity, k is thermal conductivity, ρ is the material density, and c is heat capacity. Under the circumstances of pulsed heating and thermal insulation, the one-dimensional solution of (1) in a semi-infinite homogeneous and isotropic solid can be expressed as follows [29].

$$T(z,t) = T_0 + \frac{Q}{e\sqrt{\pi t}}\exp\left(-\frac{z^2}{4\alpha t}\right), \tag{2}$$

where Q is the energy absorbed by the specimen surface, T_0 is the initial temperature, $e = \sqrt{k\rho c}$ is the effusivity, and $T(z,t)$ is the material temperature at depth z and time t. In pulsed thermography, only the temperature of specimen surface is measurable, i.e. $z = 0$. Accordingly, (2) can be simplified as:

$$T(t) = T_0 + \frac{Q}{e\sqrt{\pi t}}. \tag{3}$$

After pulsed heating, the thermal front travels through the specimen as time elapses, while the surface temperature decreases uniformly over time if there is no defect. On the contrary, subsurface discontinuities caused by defects lead to resistances to heat flow, resulting in certain temperature patterns at the surface. Consequently, the abnormalities can be identified by the temperature contrast between defective and non-defective regions. However, as discussed in the introduction section, the useful information in thermographic data often hides behind measurement noise and non-uniform backgrounds caused by uneven heating. Therefore, effective processing methods are necessary for thermographic data analysis.

3. Methodologies

To fully making use of both the temporal and spatial information in thermographic data analysis, the proposed method can be divided into two stages. In the first stage, the TSR algorithm is applied to the thermographic data, which reduces the noise using a time-directional filter. Then, in the second stage, penalized least squares algorithms are adopted to extract the reconstructed thermal images by further reducing noise and eliminating non-uniform backgrounds. In this stage, spatial information contained in each thermal image is utilized.

3.1. Thermographic signal reconstruction

TSR assumes that the decay pattern of the surface temperature profile of a non-defective pixel can be described by (3) whose logarithmic form is as follows:

$$\ln(\Delta T) = \ln\frac{Q}{e\sqrt{\pi}} - 0.5\ln(t), \tag{4}$$

where $\Delta T = T(t) - T_0$. Although (4) is concise, it is only an approximation of the solution for the 3-D Fourier diffusion equation. In practice, the profile of the logarithmic thermographic data may diverge from the ideal linear equation for several reasons, such as poor camera calibration, reflection artifacts, convection and so on. Thus, in TSR, a polynomial function with m degree is used to fit the relationship between $\ln(\Delta T)$ and $\ln(t)$, i.e.

$$\ln(\Delta T) = a_0 + a_1(\ln t) + a_2(\ln t)^2 + \ldots + a_m(\ln t)^m. \tag{5}$$

In a CFRP specimen, the thermal decay profiles belonging to intact regions behave approximately linear, while those of defective regions usually have different patterns. In order to make a good balance between data fitting and noise reduction, the value of m should be set properly. A too large value of m may cause overfitting, while a too small value may lead to model mismatch. Hence, it is suggested to set m as 4 or 5 [1]. In the following of this paper, the value of m is specified as 4. After acquiring the regression coefficients, the entire temperature profile can be compressed into

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