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Inverse heat transfer approach for nondestructive estimation the size and depth of subsurface defects of CFRP composite using lock-in thermography

Gong Jinlong, Liu Junyan *, Wang Fei, Wang Yang *

State Key Laboratory of Robotics and System (HIT), Harbin 150001, PR China
School of Mechatronics Engineering, Harbin Institute of Technology, Harbin 150001, PR China

HIGHLIGHTS

- A CFRP laminate with the artificial FBHs is tested using lock-in thermography.
- An inverse thermal wave problem approach is used for estimation of the size and depth of the subsurface defect.
- The estimated errors of the size and depth of the given defects are less than 5% and 4%.

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ABSTRACT

An inverse heat transfer approach is developed to characterize the size and depth of subsurface defects in CFRP composite materials through the reconstruction phase profile of lock-in thermography (LIT) obtained by finite element simulation. This work mainly focuses on the application of hybrid method that integrates simulation annealing algorithm (SA) and Nelder–Mead simplex search method (NM) for determination of the sizes and depths of subsurface defects within the CFRP laminate materials. For this purpose, an 808 nm laser is used for imposing a modulated heat excitation on the CFRP laminate specimen, and the thermal images are collected using an infrared camera. The hybrid method is employed to find the optimal solutions of the objective or cost function constructed by phase profile of LIT between an experimental configuration and numerical solution for a CFRP specimen. The experimental results show that the size and depth of subsurface defects are effectively obtained through inverse solving the constructed objective or cost function by the hybrid method. The estimated maximum errors for the size and depth are less than 5% and 4% for given subsurface defects by the proposed method, respectively.

1. Introduction

To improve the production quality has brought about the development of techniques or methods that supported by advances in computing and material sciences, allow the existed internal irregularities in materials to be detected without any effects on their physical integrity and subsequent performance. These evaluation techniques are known as Nondestructive Tests and Evaluation (NDT&E). Among the advanced NDT&E techniques employed nowadays, infrared thermography has led to most attention, and represented one of the promising methods for the detection of structures and materials using the principle that all bodies emit infrared radiation with the absolute temperature above 0 K [1–3]. It is well known that infrared thermography (IRT) as an NDT&E method includes two categories, passive thermography and active thermography, and active thermography has also been widely applied as NDT&E technique in practice, external stimulation of material is induced to produce an internal heat flux. Subsurface defect will affect the heat diffusion and produce the corresponding thermal contrast on the surface, which can be tested. IRT allows the detection and characterization of internal defects by analyzing alterations or contrasts in the thermal pattern of the sample surface [4–6]. Active thermography has become much attention in NDT&E techniques. Among the several active infrared imaging methods, pulsed thermography (PT) and continuous thermal-wave imaging (i.e. Lock-in thermography) have been widely used for NDT&E. In PT, a short-duration high peak power

* Corresponding authors at: School of Mechatronics Engineering, Harbin Institute of Technology, Harbin 150001, PR China. Tel.: +86 451 8640 3257; fax: +86 451 8640 2755 (L. Junyan). Tel.: +86 451 8641 4557; fax: +86 451 8640 2755 (W. Yang).
E-mail addresses: ljywlj@hit.edu.cn (L. Junyan), wyyh@hit.edu.cn (W. Yang).

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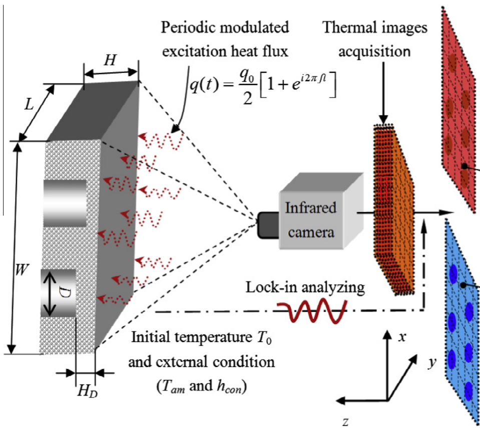

Fig. 1. The procedure of LIT for NDT&E.

is imposed on the surface of the sample, and the temporal temperature of the sample surface is monitored by an infrared camera, therefore, PT is also called the transient infrared thermography (TIRT) [7–9]. The surface temperature gradients on the specimen help to localize the subsurface defect in material using PT. However, the surface temperature gradients depend not only on subsurface defects, but also on local variations of emissivity as well as non-uniform heating. Lock-in thermography (LIT) which uses a modulation heat excitation to the sample has been successfully employed for NDT&E of composite material, and LIT phase image has the advantage of being less sensitive to the local variations of illumination or surface emissivity [10,11]. LIT also has been widely used to measure the thermal diffusivity of solid samples. Pradère [12] et al., proposed a modulated laser excitation method to measure the thermal diffusivity of single carbon and ceramic fibers at very high temperature by lock-in analysis. However, this is only suitable for the determination of thermal diffusivity along fiber for a very thin film based on one-dimensional heat conduction equation. There exists a difficulty to directly measure the thermal properties of CFRP layer from 2D or 3D heat transfer problem.

Although the detection efficiency of IRT technique has increased due to improvement performance of the equipment and the contribution provided by computers, but, defect characterization methods still represent an important and broad field of investigation. With respect to this regard, neural approach has been employed for defect detection in the analysis of thermographic images [13,14], and inverse heat transfer approaches constitute reliable techniques to determine thermal physical properties associated with the detected defects. Hanke [15] and Rodríguez and de Paulo Nicolau [16] have described to solve the inverse problem for the estimation of thermal conductivity and depth of hidden defects by the conjugate gradient method (CGM) of minimization procedure by infrared images reconstruction.

In this work, a hybrid method which integrates simulation annealing algorithm (SA) into Nelder–Mead simplex search method (NM) was developed to search the optimal solution of the inverse heat transfer problem during LIT inspection process. The direct problem of LIT inspection was solved by numerical finite element method (FEM), and experimental investigation has been carried out to verify the feasibility of the inverse heat transfer approach to characterize the size and depth of subsurface defects within the unidirectional lay-up CFRP laminate using LIT approach.

2. Direct formulation

2.1. The proposed thermal NDT model of LIT

The thermal model used to predict the heat transfer during a non-destructive test by LIT inspection, consists of imposing a periodic modulated excitation heat flux on a unidirectional lay-up CFRP sample with artificial flat-bottom holes (FBHs), (with dimensions $L \times W \times H$, the lay-up is form of $[(\pm 45°)_{50}]$, each layer thickness is about 0.2 mm). During the imposed periodic modulated excitation heat flux on the sample surface, the sample surface is monitored using an infrared camera, a series of thermal images are recorded in the duration of periodic modulated excitation heat flux imposing. Through lock-in correlation operation between the oscillation component of surface temperature (thermal-wave signal) and periodic modulated excitation heat flux (reference signal), the amplitude and phase images of thermal-wave signals are formed, and this is shown in Fig. 1.

During LIT inspection, the CFRP sample surface has been imposed a periodic modulated excitation heat flux, with respect to its surrounding, leading to transfer heat by conduction within the material and by convection between its surface and the ambient environment. The excitation heat flux is given by [11],

$$q(t) = \frac{q_0}{2}(1 + e^{i\omega t}) \equiv q_{tem} + q_{osc}(t) \tag{1.a}$$

$$q_{tem} = \frac{q_0}{2}; \quad q_{osc}(t) = \frac{q_0}{2}e^{i\omega t} \tag{1.b}$$

where, $q(t)$, q_0 represent the modulated excitation heat flux and the peak heat flux, respectively, q_{tem}, $q_{osc}(t)$ denote the temporal and oscillation components of the incident heat flux, and f is the modulated frequency.

From Fig. 1, the thermal conductivities k_x, k_y, and k_z of the unidirectional fiber lay-up of CFRP laminate (laying up $[(\pm 45°)_{50}]$) are related to the thermal conductivities $k_{//}$ (parallel to the fiber) and $k_\perp$ (perpendicular to the fiber), and they can be expressed as [17],

$$k_x = k_{//}\cos^2\theta + k_\perp \sin^2\theta \tag{2.a}$$

$$k_y = k_\perp \cos^2\theta + k_{//}\sin^2\theta \tag{2.b}$$

$$k_z = k_\perp \tag{2.c}$$

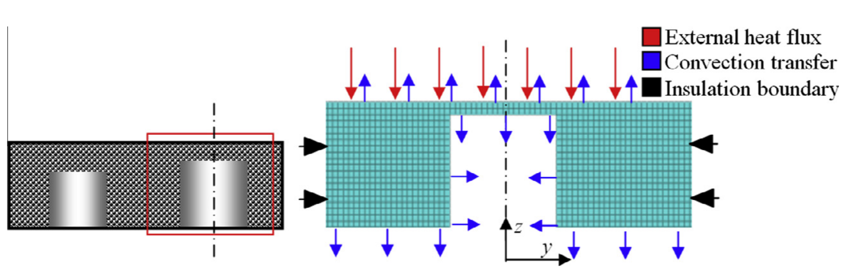

Fig. 2. Two-dimensional structure of CFRP specimen and finite element model.