Signal Reconstruction and Feature Extraction of Pulsed Eddy Current Thermography for Aerospace Composites

Yunze HE 1,2, Guiyun TIAN 2, Mengchun PAN 1,2, Dixiang CHEN 1, Feilu LUO 1
1 College of Mechatronics and Automation; National University of Defense Technology; Changsha 410073, P. R. China; hejicker@163.com
2 School of Electrical, Electronic and Computer Engineering, Newcastle University; Newcastle upon Tyne, NE1 7RU, United Kingdom; g.y.tian@ncl.ac.uk

Abstract
Pulsed eddy current (PEC) stimulated thermography is proposed as a powerful non-destructive evaluation (NDE) technique, allowing the operator to observe the heating developed from the eddy current distribution in a structure using infrared imaging, detecting defects over a relatively wide area within a short time. Some defects (impact, delamination, disbond or crack) commonly occur in aerospace composite components, such as carbon fibre reinforced plastic (CFRP), which can lead to safety issues. For the defects on the surface and near-surface, early detection has been proposed previously. For the sub-surface or deep hidden defects like delamination, the raw data is invalid because of the severe lateral heat diffusion. Tucker decomposition is proposed combining PEC stimulated thermography to detect and evaluate the defects in composites. In the proposed signal reconstruction (SR) approach, several hundred frames of raw data (3D tensor) representing the time history are processed.

Keywords: Pulsed eddy current stimulated thermography, tucker decomposition, aerospace composites, signal reconstruction, imaging process.

1. Introduction

To inspect defects over a large area and at large lift-off, integration of thermography and other non-destructive evaluation (NDE) approaches have been investigated, e.g. flash thermography [1, 2], vibro thermography, sonic thermography [3], laser thermography [4], and pulsed eddy current (PEC) thermography or induction thermography [5]. PEC thermography, combining PEC and thermography, has its own advantages: high spatial resolution, high sensitivity, both assessing electrical and thermal properties [6]. The pulsed eddy current (PEC) technique is an important advance over conventional eddy current methods, which uses the pulse as the excitation and usually processes the response in time-domain. It can be applied to both magnetic and non-magnetic metals. There is no requirement for surface preparation or cleaning and no couplant is needed unlike ultrasonic based techniques. Finally, with the help of thermography, this method can rapidly inspect a large area. Many PEC thermography applications have been applied to metallic materials for crack detection [7], crack/notch detection for carbon fibre reinforced plastic (CFRP) [8]. The early detection based on the heat diffusion is proposed to evaluate the corrosion, especially corrosion under coating [9].

In some cases, the maximum temperature difference between a defect and the surrounding intact areas decreases, often to level comparable to the noise level of the infrared (IR) camera, and is not detectable in the raw camera data. Therefore, the signal reconstruction (SR) method provides a significant degree of improvement in terms of sensitivity, reduction of blurring and depth range compared to contrast analysis. Principal component analysis (PCA), independent component analysis (ICA and other SR methods are usually used in thermography [2, 10, 11],
where the first and second derivative are used to calculate the local wall thickness or flaw depth [12].

Considering the 3D raw data in PEC thermography, our contribution in this work is to:
1. Apply tucker tensor decomposition to reconstruct the thermography data and PEC scanning data;
2. Detect and evaluate the impact and delamination in aerospace composite material through the proposed methods.

The paper is organised as follows: After introduction of the research background in section 1, section 2 reports the methods using tucker decomposition; section 3 presents the PEC thermography system and experimental studies; section 4 completes conclusion.

2. Methods

2.1 Data analysis in PEC thermography

The data PEC thermography is a 3D tensor (3-dimensional array), as shown in Figure 1. The $m \times n$ means the pixels of camera and $p$ denotes the number of frame. At every pixel point, the time response $T-t$ is a vector. The $T$ at one time is a $m \times n$ array.

![Figure 1. PEC thermography data](image)

2.2 Tucker decompositions

The class of Tucker models was proposed in 1963 in psychometrics [13] as the extensions of ordinary two-mode PCA to multimode equivalents. The three-way Tucker3 model [14] with $(P, Q, R)$ components in the 1st, 2nd and 3rd mode may be formulated as in Eq. (1)

$$X_{gi} = \sum_{p=1}^{P} \sum_{q=1}^{Q} \sum_{r=1}^{R} a_{pq} b_{qr} c_{tr} g_{pqr} + e_{gi}$$

In the case of orthonormal component, matrices $A(I \times P)$, $B(J \times Q)$ and $C(K \times R)$, the three-way array $g(P \times Q \times R)$ reflects the importance of the interaction between factors. Thus, the squared element, $g_{pqr}^2$, reflects the explained variation by the combination of factor $p$ from the first mode, factor $q$ from the second mode and factor $r$ in the third mode.

The N-way Toolbox for MATLAB is a freely available collection of functions and algorithms for modelling multi-way data sets by a range of multi-linear models, such as tucker models [15]. In the N-way Toolbox, the Tucker algorithms have been implemented with an empirical scheme for determining the most efficient method for estimating the components in each of the modes.
3. Results

3.1 Experimental set-up

The PEC thermography system used in the tests is shown in Fig. 2. The excitation sub-system is based around a commercial induction heating system, with a maximum excitation power of 2.4 kW, a maximum current of 400 A<sub>RMS</sub> and an excitation frequency range of 150 kHz - 400 kHz. The FLIR SC7500 IR camera is chosen for the work, which is a cooled camera with a 320 x 256 array of 1.5 - 5 μm InSb detectors. The camera has a sensitivity of <20 mK and a maximum full frame rate of 383 Hz. The 383 Hz frame rate provides one frame every 2.6 ms, thus nearly eight frames are generated within our minimum test period.

![Figure 2. Experimental set-up](image)

3.2 Impact damage

Figure 3 shows the impact damage on a CFRP sample. Figure 4 shows the images of reverse of the impact point after tucker decomposition. On the 1st PC image, the impact point can be easily observed as a hot spot because the electrical conductivity is decreased at the impact point [16], which leads to eddy current diversion in this area, increasing the eddy current density. Therefore, the temperature at the impact point is higher than surrounding area. The crack can also been seen on the 2nd PC image. On the 4th PC image, the delamination can be found around the impact damage. This illustrates that impact can cause delamination when the impact energy is large enough.

![Figure 3. Impact damage on a CFRP sample](image)
3.3 Delamination

Figure 5 shows the delamination damage in the CFRP sample. The 15 mm-diameter delaminations with varied depths are manufactured in samples.

Figure 6 shows the images of delamination area after tucker decomposition. Heat diffusion is a space and time dependent process in the CFRP samples. The heat not only transfers to the surface of sample but also transfers to the surrounding area. If the defect is deep, the temperature change on the surface is small. On Figure 6 (a)-(c), the delamination cannot be observed. However, the delamination area can be seen on the tucker 4th PC. Although the energy of 4th PC is small, it contains valuable information relating to defects.
4. Conclusions and further work

The work shows the performance of tucker decomposition in PEC thermography. It has been applied to carry out 3D PCA analysis on the transient PEC response to identify both impact and delamination damage on composite components. Further work involves the application of tucker decomposition to other scanning techniques, such as PEC scanning or ultrasonic C-scans. In the PEC scanning, $m \times n$ in Figure 1 means the scanning position [17] and $p$ denotes the time response.

Acknowledgements

Mr. He would like to thank the China Scholarship Council for sponsoring his visiting study to Newcastle University, Ministry of Education for Scholarship Award for Excellent Doctoral Student (No.: JY20101).

References


