Eddy-Current Pulsed Thermography for the Detection of Impact Damage on CFRP

Abdoulaye Ba[1,*], Huu-Kien Bui[1], Gérard Berthiau[1], Qiuji Yi[2], Junzhen Zhu[2], Gui Yun Tian[2]

[1] Institute of Research in Electrical Energy of Nantes-Atlantiques (IREENA), University of Nantes, 44602, Saint-Nazaire Cedex, France
[2] School of Engineering, Newcastle University, Newcastle upon Tyne, United Kingdom;
*corresponding author, E-mail: abdoulaye.ba@univ-nantes.fr

Abstract

Carbon Fiber Reinforced Polymer (CFRP) materials are widely used in aerospace due to their low weight and high strength. Non-destructive Testing (NDT) Techniques become a necessity with increasing use of CFRP materials. Induction Thermography is a new NDT technique that can be exploited as a promising fast and global control. However, the detection of typical flaws in carbon composites such as delamination, fibers rupture and impact damages need to be further investigated in order to optimize the technique. Optimization can be done in the test configuration level and by the use an appropriate image processing technique. In this paper Eddy Current Pulse Compression Thermography (ECPuCT) is used to detect impact damages on CFRP materials. The Principal Component Analysis (PCA) based image processing technique is used to detect and visualize impact damage area from transient thermal images. Flaw detection results using experimental measures will be shown and discussed.

1. Introduction

Non-Destructive Testing techniques are employed to examine an object or material without impairing its future usefulness. Eddy Current Pulsed Thermography (ECPT)[1] and Eddy Current Pulse-Compression Thermography (ECPuCT)[2] are one of the NDT techniques which can be applied for the non-destructive testing of various kind of conductor work piece such as Carbon Fiber Reinforced Polymers (CFRP). In industries such as aerospace, CFRP materials are used due to their relatively high strengh to weight ratio compared to other conventional materials. Induction Thermography system combines two techniques : Eddy Current and Thermography. In Induction Thermography, the heat isn't limited to the sample surface, it can reach a certain depth according to the penetration depth of the electromagnetic wave into a conductive material. Induction Thermography focuses the heat on the defect area due to Eddy Current distorsion. This phenomenon increase the thermal contrast between the defective region and defect-free areas.

2. Theoretical background

Induction thermography is a technique that uses a camera to record and process thermal information from the surface of an equipment that radiate electromagnetic energy. Modeling a composite structure is a difficult task because laminates are very heterogeneous and anisotropic.
In a semi-infinite conducting material, eddy-current density in the depth direction reads :

$$J(z) = J_S * e^{-\frac{z}{\delta}} \qquad (1)$$

where z represents the depth and δ the skin depth which depends on the frequency, electrical conductivity and relative permeability. J_S represents the surface eddy-current. In ECPT, the distribution of Eddy-Current depends on parameters such as: frequency, lift-off, electrical conductivity, magnetic permeability, geometry of the specimen etc.
To simulate the thermographic inspection, a multi-scale model [3] using a three dimensionnal Finite Element Method (FEM) has been developped by using the commercial software Matlab. The well known $\mathbf{A}-\varphi$ formulation is used to solve the electromagnetic and thermal problem. The matrix form of the discrete $\mathbf{A}-\varphi$ formulation reads [4]:

$$\begin{aligned}(\boldsymbol{R}^t\boldsymbol{M}_{ff}^{1/\mu}\boldsymbol{R} + j\omega\boldsymbol{M}_{aa}^{[\sigma]})\boldsymbol{A} + j\omega\boldsymbol{M}_{aa}^{[\sigma]}\boldsymbol{G\varphi} \\ = \boldsymbol{R}\boldsymbol{M}_{aa}\boldsymbol{T}_a^s \\ j\omega\boldsymbol{G}^t\boldsymbol{M}_{aa}^{[\sigma]}\boldsymbol{A} + j\omega\boldsymbol{G}^t\boldsymbol{M}_{aa}^{[\sigma]}\boldsymbol{G\varphi} = 0\end{aligned} \qquad (2)$$

Where $\boldsymbol{R}$, $\boldsymbol{G}$ are respectively the discrete counterparts of ***rot***, and ***grad*** operators, t denotes the transpose operator. For the Themal part, the matrix is given by [4]:

$$\begin{aligned}(\boldsymbol{M}_{nn}^{[\rho c]} + \boldsymbol{G}^t\boldsymbol{M}_{ee}^{[\lambda]}\boldsymbol{G} + \boldsymbol{M}_{nn}^{[h]})\Delta\boldsymbol{T}_{n,i+1} \\ = \boldsymbol{M}_n^{[P]} + \boldsymbol{M}_{nn}^{[\rho c]}\Delta\boldsymbol{T}_{n,i}\end{aligned} \qquad (3)$$

With the electromagnetic and thermal problem of equations 2 and 3, we can respectively calculate the distribution of eddy current and the thermal distribution, in each layer of the composite plate. The equations 2 and 3 are used to simulate induction thermography system. The

numerical simulation can help in the design and development of ECPT techniques. It is conducted in order to unsderstand the experimental phenomena.
In this paper, experimental induction thermography testing will be carried out. The Principal Component Analysis is applied for ECPuCT thermal responses for quantitative analysis of a composite plate with impact damage of 18 J. The defect is evaluated by analyzing the heat distribution and patterns in thermal images. Principal Componant Analysis (PCA) based features extracted from the thermal response are used to detect impact damage in a CFRP specimen.

3. Principal Component Analysis (PCA)

The principal component analysis method is used to reduce data dimensions and extract main features. PCA is a multivariate statistical analysis method which transforms the Eddy Current Pulsed Thermography thermal data into uncorrelated eigenvectors or principal components (PCs) corresponding to the maximum variability within the data. In PCA method, each principal component is a linear combination of the original variables. In general, the first principal components carry most of the information regarding the original data. A detailed description of PCA method for defect evaluation can be found[5].

4. ECPuCT configuration

Fig.1 shows the ECPuCT configuration used for experimental studies. It contains four units, a signal generator, an excitation module with a coil, an infrared camera and a computer.

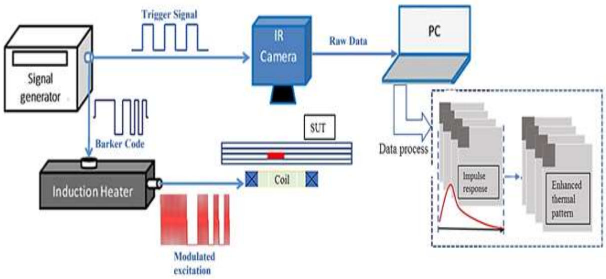

Fig.1: ECPuCT diagram [2]

A high frequency and high power signal generator provides high power currents for induction heating. Signal generator is used to send both the Barker code signal to the induction heating coil and a reference clock trigger signal to the infrared camera to acquire thermograms at 50 frames per second. The induction heater is a Cheltenham EasyHeat 224 with a maximum excitation power of 2.40 Kw, a current values of 400 A and an excitation frequency range of 150-400 kHz. An IR camera FLIR SC655 was used to record the thermal responses of the specimen. The camera has a resolution of 640×480 pixels at a frame rate of 50 Hz and a sensitivity of 7.5-14.0μm. The thermal video are transmitted to a PC for visualisation and post-processing.

5. Experimental studies

The test sample in this study is a CFRP material which was impacted by impact damage. The composite specimen has dimension of $300mm \times 300mm \times 37h_{ply}$ where h_{ply} is the thickness of a ply which is equal to $140\mu m$. Le layup sequence of the specimen si X/0/Xs where X is defined as: X = [0°/0°/135°/0°/45°/0°/45°/90°/135°/0°/135°/90°/45°/0°/45°/0°/135°/0°] and Xs denotes the symmetric layup sequence of X with respect to 0° ply.
In ECPuCT experiment, there are two phases: the heating phase and the cooling phase. The heating phase as duration of 13s and 30s for the cooling phase. The duration of the whole process of 43s is recorded by the thermal camera. The reflection mode is used in the experiment.

6. Results and discussion

Data obtained in the experiment is an 2150 frames sequence and the size of each frame is 90×400. The data can be regarded as a three-dimension matrix with two stages. The thermal data only provides temperature distribution on the surface of the sample. A further processing is required on the thermal videos in order to obtain quantitative information about the defects under inspection.
After calculating the impulse response, the PCA method is used to locate the defect. Fig. 2 shows the thermal distribution along the line A. This latter crosses the area of the defect.

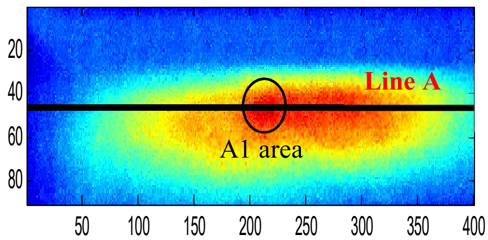

Fig.2: Thermal distribution along line A

From Fig. 2, we can expect that the thermal response on the area of the defect A1 be higher than surrounding area. The thermal responses of two pixels located in the area of the defect and near the defect are plotted in Fig.3.

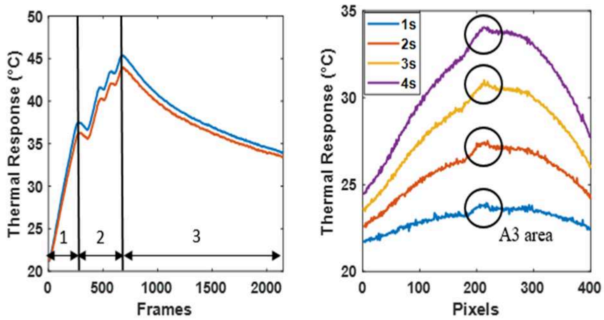

Fig.3: Thermal response of two pixels (Fig. a) and along line A (Fig. b)

Fig. 3.a shows the thermal response of two pixels in the defect area and near the defect. The blue curve is the pixel in the area of the defect and the red curve in the surrounding area. The heating stage and the cooling stage are observed. In the heating stage, the effects of the Barker code which is a bit length of 13 with a series of 1 or -1 appears. The temperature increase in this stage. In the cooling stage, the temperature decrease gradually. The maximum temperature recorded by the thermal camera is 45°C. This value is reached at the end of the heating stage.
Fig. 3.b shows the thermal responses along the impact damage A1 at respectively 1s, 2s, 3s and 4s. We can distinguish clearly the area of the impact damage from Fig. 3.a. The thermal lobes indicate the area of the defect. The lobes are due to low electrical conductivity in the area of the impact damage.
The thermal data of size $90 \times 400 \times 2150$ is used for PCA calculation. Here, $k = 90 \times 400$ pixels and $N = 2150$ frames are recorded by the thermal camera at a frame rate of 50Hz. N Principal components (PCs) with k elements are obtained with different eigenvalues. The first PCs for example 4, with a decent eigenvalue are selected. The corresponding output vector for each Principal component is converted into an image.
The fig. 4 shows the first PCs of the thermal data. The number of principal component is set to four. Thus, four column matrix are obtained through the PCA method. And finally, four images or Principal Components (PC

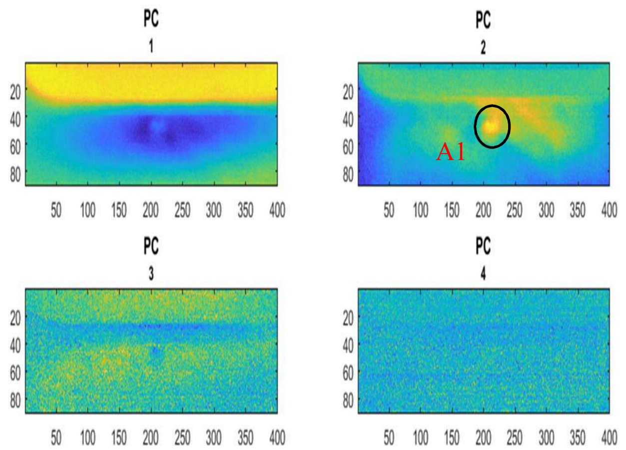

Fig.4: First PCs of PCA for the thermal sequences in heating phase

From the PCs images, it can be seen that the impact damage area A1 is revealed in the image reconstructed by the second principal component. The impact point is like a hot spot because of lower of the electrical conductivity in this area. The temperature at the impact area is higher than surrounding area caused by eddy current diversion around the area of the impact damage. Above the third principal component, the information useful for the detection of the impact area is limited. To sum up, PCA can enhance the abnormal region (A1) caused by defect (impact damage) and reduce the dimension of the data.

7. Conclusion

Experimental measurements have been conducted to investigate the performances of Eddy Current Pulse Compression Thermography applied to the detection of impact damage on CFRP sample. PCA has been applied to the thermal data in order to identify the impact location on the sample. The first PCs shows that the method PCA can be used to enhance the abnormal region caused by defect and to reduce the dimension of the thermal data recorded by the infrared camera.

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References

[1] H. K. Bui, G. Wasselynck, D. Trichet, and G. Berthiau, "Study on flaw detectability of NDT induction thermography technique for laminated CFRP composites," *Eur. Phys. J. Appl. Phys.*, vol. 73, no. 1, p. 10902, 2016.

[2] Q. Yi, G. Y. Tian, H. Malekmohammadi, J. Zhu, S. Laureti, and M. Ricci, "New features for delamination depth evaluation in carbon fiber reinforced plastic materials using eddy current pulse-compression thermography," *NDT&E Int.*, vol. 102, pp. 264–273, 2019.

[3] H. K. Bui, G. Wasselynck, D. Trichet, B. Ramdane, G. Berthiau, and J. Fouladgar, "3-D modeling of thermo inductive non destructive testing method applied to multilayer composite," *IEEE Trans. Magn.*, vol. 49, no. 5, pp. 1949–1952, 2013.

[4] H. K. Bui, G. Wasselynck, D. Trichet, and G. Berthiau, "Performance assessment of induction thermography technique applied to carbon-fiber-reinforced polymer material," *IEEE Trans. Magn.*, vol. 51, no. 3, 2015.

[5] L. Cheng and G. Y. Tian, "Transient thermal behavior of eddy-current pulsed thermography for nondestructive evaluation of composites," *IEEE Trans. Instrum. Meas.*, vol. 62, no. 5, pp. 1215–1222, 2013.