Quantitative evaluation of delamination depth in CFRP based on pulse compression eddy current pulse thermography

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Abstract. The growing application of composites material in aerospace leads to the urgent need of non-destructive testing and evaluation (NDT&E) of fatal defects such as impact damage and delamination in these materials. Eddy Current Pulsed Thermography (ECPT) is an emerging NDT technique capable of detecting such defects (e.g. impact damage and delamination). However, the characterization of delamination within a CFRP specimen is difficult to be accomplished by a single pulse excitation due to the challenging extraction of thermal diffusion in multi-layered structures. To cope with this problem, this paper combines the use of Eddy Current(EC) stimulus and barker coded modulated pulse compression technique for enhancing the delamination characterization ability for CFRP. Based on the estimated impulse response obtained by exploiting the PuC algorithm, delamination area is located by thermal pattern enhanced method based on K-PCA(kernel principal component analysis) techniques. Crossing point feature is extracted between defective area and non-defective area impulse response. Results show that delamination can be detected with depths from 0.46mm to 2.30mm and the proposed feature crossing point has a monotonic relationship with delamination depth.

Keywords: Pulse Compression, Eddy Current Pulsed Thermography, Quantitative evaluation, CFRP, Delamination depth

1. Introduction

The use of CFRP materials have become increasingly popular among conventional engineered materials due to their extraordinary mechanical and thermal properties, such as high strength-to-weight ratio, corrosion resistance, improved fatigue performance and low coefficient of thermal expansion [1]. Delamination is one of the most common defects for composite materials, which might arise either during the manufacturing process or during their onin-service life, e.g. during the standard life-time of aircraft components. A promising NDT technique to detect delamination in CFRP is the Active Thermography (AT) [2, 3]. Being a non-contact method with the capability of inspecting a large area of the Sample Under Test (SUT). In AT, the desired thermal contrast is achieved by applying an external heating stimulus over the SUT [4] by mans of various illumination sources [5]. SUT’s illuminated surface heats up and then diffuses into the sample. Among the AT techniques, one of the extensively applied AT technique is ECPT. Based on the nature of EC
technique, and since CFRP exhibits low electrical conductivity, in ECPT the stimulation is volumetric [6, 7]. Hence, ECPT is not influenced by the surface conditions of the SUT [8]. However, despite the progresses made on both evaluating the so-called barely invisible impact damage (BVID) [9] and visualizing delamination [6] by means of ECPT, the quantitative evaluation of delamination depth is still challenging. In fact, the complex structure of CFRP i.e. layered structure, anisotropic conductivity and different fiber direction, results in non-uniform thermal distribution, thus hampering the faithful quantitative evaluation of delamination depth from thermal response.

The PuC algorithm outputs a good estimate of impulse response that is close in both characteristics and quality to that obtainable from PT. In PuCT, the heat source emission is commonly modulated either by a frequency-modulated “Chirp” signal [10], or by a phase-modulated signal [11], e.g. Barker code. These coded excitations have a unique feature: their bandwidth B and their time duration T are uncorrelated. As a consequence, the frequency content of the coded signal can be tailored to suit the investigation of a given sample, while T can be increased almost arbitrarily to achieve the desired SNR [12]. Although PuCT is now a quite established technique that shows premises promises for maximising the SNR even when low power heat sources are employed, very few attempts are reported in literature to extend this approach to ECPT [13, 14].

Fig.1 shows the block diagram of the processing steps accomplished on the raw data. A man-made CFRP delamination sample was excited by a Barker-modulated induction heating stimulus and the raw thermal data are acquired. Then, a denoising algorithm is applied pixelwise to the raw data, as well as a non-linear fitting algorithm to remove the step-heating contribution [11]. PuC is then performed by convolving the detrended data with the so-called ‘matched filter’, so as to retrieve the impulse response h(t) pixelwise. A thermal pattern enhancement method is then applied over the h(t)’s to visualize and locate each delamination. A new feature extraction algorithm based on analysing the time delay of h(t) resulting from pixels area onto delamination buried at different depths into the sample is also proposed to conduct a quantitative study of delamination depth.

This paper is organized as follows: Section 2 presents the theoretical background of ECPT; the basic theory of PuC and the methodology of impulse response based thermal enhanced pattern technique. Section 3 provides details about the Barker code, the ECPuCT experimental setup and the benchmark delaminated sample. Section 4 shows how to perform PuC correctly and highlights the analysis of various extracted thermal pattern by the proposed technique. A Quantitative study of depth information of delamination by the proposed feature is also included (Depth QNDE). Conclusion will be made in Section 5.

![Fig 1 Block diagram of the processing steps](image-url)

2. Theoretical background of eddy current pulse compression thermography

2.1 Theory of eddy current simulated volumetric heating in CFRP

The theory of ECPT on ferromagnetic material has been addressed in previous researches [15-17]. The principle of ECPT for CFRP, is different from that of ferromagnetic materials, concerning both the heating mode and the thermal wave diffusion pattern. According to electromagnetic wave penetration depth equation (Eq.(1)), the penetration depth $\delta$ has a monotonic decreasing relationship with increasing current frequency:
where \( f_{\text{carrier}} \) is the frequency of the excitation current [Hz], \( \sigma \) is electrical conductivity [S·m\(^{-1}\)], and \( \mu \) is magnetic permeability [H·m\(^{-1}\)]. In general, for CFRP the bulk conductivity \( \sigma \) value is in the order of 15000 S/m and it is non-magnetic [18]. Considering \( f_{\text{carrier}} = 300 \) kHz, the corresponding penetration depth is 7.50 mm while for the same value of \( f_{\text{carrier}} \), the penetration depth in steel (\( \sigma = 9.93 \times 10^6 \) S/m, \( \mu = 3.77 \times 10^{-4} \) H/m) is equal to 29.08 \( \mu \)m, which is significantly smaller than one obtained for CFRP. Thus, since the thickness of the CFRP sample is lower than corresponding value of \( \delta \), the heating mode is volumetric. The unique advantage of volumetric heating compared to the surface heating scenarios (e.g. flash thermography) comes from the direct interaction between the buried defect and the induced eddy current field. Overall, the heating pattern of EC excitation in transmission arrangement can be considered as follows: firstly, the whole specimen is heated up by induced eddy current by Joule’s effect. Then, the defected area is heated more than the sound areas at the same depth.

2.2 Pulse compression basic theory

The working principle of the PuC technique is sketched in Fig.3. Given a coded excitation \( s(t) \) of duration \( T \) and bandwidth \( B \), and another signal \( \Psi(t) \), which is the so-called matched filter, such that their convolution “\(*\)” approximates the Dirac's Delta function \( \delta(t) \) as:

\[
s(t) * \Psi(t) = \delta(t) \approx \delta(t)
\]  

If Eq.(4) holds, then an estimate \( \hat{h}(t) \) of the \( h(t) \) is obtained by convolving the recorded output signal \( y(t) \) with the matched filter \( \Psi(t) \). The process is mathematically showed below for a single pixel of the acquired thermograms, in the presence of an Additive-White-Gaussian-Noise \( e(t) \), which is uncorrelated with \( \Psi(t) \). By convolving the output signal \( y(t) \) with the matched filter \( \Psi(t) \), the impulse response can be obtained as:

\[
\hat{h}(t) = y(t) * \Psi(t) = h(t) * s(t) * \Psi(t) + e(t) * \Psi(t) = h(t) * \delta(t) + \hat{e}(t) \approx h(t) + \hat{e}(t)
\]  

The main advantages of PuC over pulsed excitation is that an estimate of the impulse response can be achieved at end of the procedure, while delivering energy to the system over an extended time. In this way, it is possible to provide more energy, and hence to increase the SNR and detectability of eddy current thermography system.

![Fig 3 Comparison between pulse excitation and coded excitation](image-url)
2.3 Thermal pattern enhancement techniques based on impulse response and feature extraction

To gain insight on how K-PCA has been applied here for enhancing ECPuCT data, the implementation of the enhancement method is schematically depicted in Fig.4 and mathematically introduced here below. Considering the calculated impulse response \( \tilde{h} \)'s retrieved pixelwise by exploiting the procedure described in Eq.(5) being reshaped as:

\[
[\tilde{h}^1, \tilde{h}^2, ..., \tilde{h}^N_xN_y, \tilde{h}^N_xN_y-1, \tilde{h}^N_y]
\]  
(6)

where, \( N_x \) and \( N_y \) are the number of x and y pixel of the acquired IR thermograms. Thus, the reshaped data can be recognized as a matrix having dimension of \( Q \times N_xN_y \), where \( Q \) denotes the number of frames recorded by the IR camera, i.e. \( T_h \times FPS \), where FPS stands for the acquired Frames Per Second. By using the kernel method, the impulse response is projected to kernel space \( \phi \), thus obtaining the kernel matrix \( K(i, j) \) as:

\[
K(i, j) = \frac{1}{M} \sum_{i=1}^{M} \left( \phi(\tilde{h}_i) - \frac{1}{M} \sum_{j=1}^{M} \phi(\tilde{h}_j) \right) \left( \phi(\tilde{h}_i) - \frac{1}{M} \sum_{j=1}^{M} \phi(\tilde{h}_j) \right)^T
\]  
(7)

where \( M \) is equal to \( N_xN_y \) and \( \phi \) is Gaussian kernel function, defined as Eq.(8):

\[
\phi(\tilde{h}_i, \tilde{h}_j) = \exp\left(\frac{\|\tilde{h}_i - \tilde{h}_j\|^2}{2\sigma^2}\right)
\]  
(8)

The kernel matrix \( K(i, j) \) of Eq.(7), can be simply named as \( K \). The eigenvector \( \alpha_i \) of \( K \) can be obtained as:

\[
\lambda_i\alpha_i = K\alpha_i
\]  
(9)

Based on the obtained eigenvector \( \alpha_i \), the enhanced thermal pattern can be projected as:

\[
H_{\text{enhanced}} = [\alpha_1, ..., \alpha_T] H_{\text{original}}^T
\]  
(10)

where \( H_{\text{enhanced}} \) contains different extracted thermal patterns.

![Fig 4 Diagram of feature extraction](image)

3. Experiment setup

3.1 Eddy current pulse compression thermography setup

The ECPuCT system diagram is illustrated in Fig.5. Signal generator is used to send both the BC modulating signal to the induction heating coil and a reference clock trigger to the IR camera to acquire thermograms at 50 FPS. A Cheltenham Easyheat 224 Induction heating unit is used for coil excitation with a maximum excitation power and current values of 2.4 kW and 400 A respectively with tuneable \( f_{\text{carrier}} \) from 150 to 400 kHz. For the reported experimental results, values of excitation current \( I \) equal to 40 A and \( f_{\text{carrier}} \) of 240 kHz were selected to avoid eventual damage on the CFRP sample due to the long excitation time using BC signal. IR camera was the FLIR SC655, equipped with an un-cooled microbolometer detector array with the resolution of 640 \( \times \) 480 pixels, the spectral range of 7.5 - 14.0 \( \mu \)m and NETD < 30 mK. The IR camera records the surface temperature.
distribution of the 13 s BC as well as additional 30 seconds cooling period. Finally, captured thermal videos were transmitted to a PC for visualization and postprocessing, including signal pre-process, pulse compression, thermal pattern enhancement and quantitative depth evaluation.

3.2 Sample under test
The CFRP sample was realized by MDP company (Terni, Italy) [11]. The CFRP laminate sample contained twelve plies of carbon fibre fabric with an areal density of 0.2 g/m². Its lateral dimensions were 240 mm×200 mm for an overall thickness of ~2.80 mm which is shown in Fig 6. The fibres orientations were 0° and 90° and the matrix was an Epoxy Resin RIM 935. The artificial delamination were realized by inserting thin square pieces of Teflon tape having lateral dimensions of 20 mm×20 mm and thickness equal to 75 μm between the plies. Nine artificial defects were inserted at increasing depths: the shallower was placed under the 2nd ply at a depth d~0.46 mm (defect #1), the deepest (defect #9) under the 10th ply at a depth of d~2.3 mm.

4. Results and analysis
4.1 Defect location based on pattern enhancement method
The impulse response $\tilde{h}(t)$ is a sequence of 1500 frames. However, when it comes to visualize the delamination, most of the frames contribute little to the defect location. To solve this problem, the kernel method described in Sec.2.3 is applied to find and learn the mutual relation of impulse response in individual pixels. Thus, the pixelwise-retrieved $\tilde{h}(t)$’s are embedded into a suitable high-dimensional feature space through Gaussian kernel function. In addition, the kernel method is also an efficient way to imply the nonlinear characteristics of the raw data. Fig. 7 shows the extracted thermal pattern from BC raw data (threshold). It is noted that first thermal pattern summarizes the overall heating phenomena during experiment because the heating is conducted on one side of rectangular coil, which generates linear
heating. The sensitivity of pattern 1 for visualizing defect is heavily reduced for increased delamination depth. This is because pattern 1 contains most of information about heating pattern, which might cover up the faithful defect information. It is observed that patterns 2 and 3 obtain opposite profile for delamination. Pattern 2 generally presents the delamination in lower contrast while pattern 3 shows higher contrast compared to the surrounding area. This is because the eigenvectors extracted were supposed to be orthogonal with each other in kernel space $\phi$. The indicated relationship between pattern 2 and pattern 3 can enhance the detectability in delamination area through logic operation. In fig 8, it is shown that defect SNR is reduced after D5, where the square shape of delamination profile cannot be identified. However, the delaminated area can still be characterized by fibre structure in 0° and 90° from D6~D9 since induced eddy currents are parallel to 0° and 90°, which have the largest electrical conductivity and thermal conductivity in SUT thus generating abnormal thermal wave with diffusion length $\mu$ longer than the delamination depth $d$.

To conclude, artificial delamination in CFRP has been demonstrated to exhibit different patterns by kernel method. In the following section, the impulse response retrieved at the most abnormal pixels area are investigated for quantitative study.

4.2 Quantitative analysis

As discussed in Section 4.1, the delamination ranging from 0.46mm to 2.30 mm of depth can be visualized by thermal pattern enhanced method based on the impulse response. Moreover, to determine the delamination depth, the phase contrast between defected and non-defected areas can be exploited, by comparison of the obtained impulse responses based on
PT theory [19]. Each defected area and non-defected area is formed by five lines of data in the centre of higher contrast and lower contrast based on enhanced pattern.

It can be noted the defective area is cooling slower due to the thermal diffusivity, which means the material ability to exchange heat with its surroundings has become worse with the increase in depth. The deeper the delamination, the worse is the ability to exchange heat with non-defective area. Results showed in Fig.9 demonstrates that the impulse response amplitude is less sensitive than the phase change of crossing point of defective and non-defective area. Thus, it is observed that the position of the first crossing point of impulse responses of defected and non-defected areas has a monotonic relationship with delamination depth, as shown in Fig.9 and Fig.10. This can be served as an excellent feature to quantify the delamination depth. From Fig.10, it can be noted that the feature based on the crossing point value follows a linear trend if three defects in a row over the SUT are considered, e.g. D1-D3 or D6-D9, which is due to the actual linear coil used in this experiment. In fact, the experimental condition can be considered the same if defects are on the same line. Better results could be possibly obtained by achieving a more uniform heating through optimizing coil shape.

However, after defect 6, the crossing pattern of defected area and non-defected area has been disturbed by noise, (see Fig.9(c)). Moreover, extra crossing points observed in D7, continuing equal value of defected and non-defected areas in D8 and initial disturbed crossing point in D9 are caused by the low SNR of original signal. Thus, despite the effectiveness of the denoised approach applied in this work, the clear information of defect is still challenging to be extracted in D7~D9.

Fig.11 shows the fitted curve for the depth versus time instant of the first crossing point of defective and non-defective areas acquired on 5 different lines. Based on the fitting curve, there is still a crossing point value between defective area and non-defective area when the depth is zero, i.e. surface defect. Considering the crossing point feature is influenced by defect’s depth and the electrical and thermal properties, when depth is zero, this feature can only be related to defect’s electrical and thermal properties, which can be useful to derive these properties. Moreover, judging by error bar in Fig. 11(a) and from the selected data distribution in Fig.11(b), the deviation generated by the selected position is acceptable.

To conclude, monotonic relationship between crossing points of retrieved impulse responses illustrates that depth evaluation of delamination in CFRP can be conducted by calculating the phase change of defected and non-defected areas.
Fig 9 mean value of selected impulse response at: (a) D1/D2/D3, (b) D3/D4/D5, (c) D7/D8/D9

Fig 10 Monotonic relationship of delamination depth (D1-D9) and crossing point

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<th>Line 3</th>
<th>Line 4</th>
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Fig 11 Acquired crossing points of 5 lines of data versus delamination depth: (a) fitting curve, (b) specific data for D1–D9
5. Conclusion

In this paper, proposed feature based on ECPuCT for CFRP delamination evaluation is investigated. The main contribution of this work includes:

1) The feasibility of Barker code modulated eddy current pulse stimulation on CFRP is experimentally investigated. Results show that delamination can be detected with depth from 0.46 mm to 2.30 mm using ECPuCT approach.

2) Quantitative evaluation of depth information of different delamination is made based on proposed feature which is the crossing point of the impulse response acquired from selected abnormal pixel. The proposed feature has monotonic relationship with delamination depth.

Reference


