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Comparison of three thermographic post processing methods for the assessment of a repaired aluminum plate with composite patch

P. Daryabor, M.S. Safizadeh *

Department of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran

HIGHLIGHTS

- Investigation of the post processing effect on the step heating thermography result.
- Quantitative comparison of the TSR, PCA and PPT approaches performance.
- Application of the Infrared thermography for the repaired structure defects sizing.

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ABSTRACT

Composite patches are widely used to repair damaged metal structures, especially in aerospace industry. Perfect patch and bonding are necessary to achieve an effective repair. Various thermographic methods such as step heating thermography are commonly applied to inspect repaired structures. Since accurate determination of defect features are admirable, some techniques are used to process the thermal films. In this study, three common post processing techniques of thermography (namely, principle component analysis (PCA), pulse phase thermography (PPT) and thermal signal reconstruction (TSR)) have been utilized to inspect an aluminum plate repaired with carbon/epoxy patches. Several delaminations with various sizes and locations along with some disbond defects were artificially embedded in five samples of composite patches to experimentally investigate the performance of the three techniques for post-processing of the step heating thermography data. Furthermore, the outputs of the mentioned processing techniques were quantitatively compared to find the most effective one. Based on the comparison results, it was demonstrated that, TSR outputs leads to the more accurate defect sizing.

1. Introduction

In recent years, the need for the reliable and effective repair of damaged structures is growing in different industries. In order to have a reliable repair, it is necessary to assess the bonding and patch quality. Both delamination in patch and the disbond between patch and structure affect the integrity of the repair and the service life of the structure [1]. When such defects are detected, it is necessary to perform a defect assessment to identify their position and dimension. Currently, different thermographic techniques are considered as appropriate methods for characterization of the defects in repaired structures.

Infrared imaging of an object using an external heat source is called active thermography [2], which is widely used for assessment of various materials [3] such as composites [4]. In some studies [5–7], it has been demonstrated that the dimension and depth of defects can severely affect the detection in composite. Especially, defects within deeper layers in the composite are harder to be detected. Step heating thermography is among the active methods which have been previously used to characterize composite delaminations [8] and disbonds as well [9]. In this method, heating duration is longer than the pulse thermography and detection can be performed in both heating and cooling steps. Just like other active thermographic methods, application of step heating thermography to characterize some defects is associated with some limitations. For instance, non-uniform surface heating is mostly unavoidable in active thermographic methods, even when a flat surface has been inspected. As defect detection principle is based on temperature differences, non-uniform heating may produce confusion, especially for defect quantification. Lateral heat diffusion is also an inevitable problem in the thermographic inspection. The amount of lateral heat diffusion is basically related

* Corresponding author.
E-mail address: safizadeh@iust.ac.ir (M.S. Safizadeh).

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to the thermal properties of the material [10,11]. Additionally, the spatial resolution of the infrared camera and the timing-image capturing may cause some difficulties in defect characterization [12]. In the case of characterizing smaller and deeper defects, the mentioned limitations become more serious. For the repaired structures, it was observed that the accuracy of detection significantly decreases for defects which are not close to the surface [13] such as disbond [14,15].

The limitations reported in the literature can be decreased using an effective post processing technique, especially for deeper and smaller defects. Pulse phase thermography (PPT), principle component analysis (PCA) and thermal signal reconstruction (TSR) are commonly utilized for defect characterization [16]. Recently, applications of PPT and TSR for the enhancement of the glass/epoxy composite thermographic results have been compared, considering some rectangular bulks as the defects [17]. Based on the results, TSR exhibited a better performance in detecting this kind of defects, compared to PCA. In different researches, the limitations and benefits of PPT [18], PCA [19] and TSR [20] methodologies have been reported. The most important reported advantages and difficulties corresponding to the PPT, PCA and TSR have been listed in Table 1.

As it has been mentioned in Table 1, each processing technique has specific capabilities. Regarding the importance of accurate inspection of the repaired structures and the wide utilization of thermographic processing techniques in the assessment of composites, it seems necessary to clarify the ability of different post-processing techniques for the inspection of repaired structures. Therefore, in this research, the ability of PPT, PCA and TSR approaches for the enhancement of the thermographic outputs of an aluminum plate repaired with a carbon/epoxy patch have been quantitatively investigated. For this purpose, five patches containing delaminations and disbonds with different sizes and locations were inspected via step heating thermography. Then, the thermal films were processed with the three mentioned approaches According to the comparison of the defect sizes in the resulted images the most appropriate technique for the enhancement of thermographic results was determined. The basic theory of post processing techniques is briefly described in the subsequent paragraphs.

2. Post processing techniques

As stated, in order to properly characterize the defects, the thermal film recorded by the infrared camera should be processed by some algorithms, in most of which, the image data are processed on a pixel by pixel basis. Therefore, the time series of each pixel is separately evaluated. These time series represent the surface temperature variation of the material over time. Since thermal diffusion in the lateral direction could be neglected compared to the normal direction, one can consider the one-dimensional heat transfer equation for the thermography as shown in Eq. (1).

$$\frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{dT}{dt} \tag{1}$$

where T is the temperature and α is the thermal diffusivity of the material. t and z denote the time and the depth into the material, respectively. For an ideal impulsive heat flux, the response for a semi-infinite surface is

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

where e is the thermal effusivity of the material determined by the thermal conductivity, mass density and specific heat. Q is the quantity of energy absorbed by the surface. Since thermal imaging is only applicable to surface temperatures, Eq. (2) is evaluated at z = 0, resulting in the surface temperature presented by Eq. (3).

$$T_{Surf}(t) = T(0,t) = \frac{Q}{e\sqrt{\pi t}} \tag{3}$$

Eq. (3) provides a basis for the algorithms (PCA, PPT and TSR) utilized in this research.

2.1. Pulse phase thermography (PPT)

In PPT technique, which is based on the Fourier Transform, the pixel time series are transformed from time to the frequency domain using discrete Fourier transform as shown in Eq. (4).

$$F_n = \frac{1}{N}\sum_{k=0}^{N-1} T(k) e^{-\frac{2\pi i k n}{N}} = Re_n + iIm_n \tag{4}$$

Table 1
Limitations and advantages corresponding to the PPT, PCA and TSR approaches.

	Advantages	Limitations
PPT	• Effect of non-uniform heating is considerably minimized in PPT [21] • The phase image is less affected than raw thermal data by environmental reflections, emissivity variations, and surface geometry and orientation [22] • These phase characteristics are very attractive for qualitative inspections and quantitative characterization of materials [22] • PPT is an attractive tool for the inspection of complex shape specimens [10] • While using PPT, less attention is required on applying emissivity-enhancing treatments on the inspected specimen [10]	• PPT requires the examination of the whole sequence, or at least a part of it, to determine the most suitable image for defect detection [21] • The noise content is considerable, especially at high frequencies. A de-noising step is therefore often required [22] • Selection of the sampling and truncation parameters significantly affects defect characterization especially for deeper defects [22,10] • The Fourier transform operates through the use of sinusoidal basis functions, which may not be the best choice for representing transient signals such as temperature functions in pulse and step heating thermography [22]
PCA	• In PCA outputs, fixed pattern noise is removed [21] • Instead of relying on a basis functionm, PCA is an eigenvector-based transform that forms an orthonormal space [22] • The first two orthogonal functions of PCA output provide a remarkably thorough description of the significant spatial variations [23]	• PCA requires the examination of the whole sequence, or at least a part of it, to determine the most suitable image for defect detection [21] • PCA outputs are affected by non-uniform heating [22]
TSR	• The TSR method provides significant improvements in noise reduction and thus allowing the detection of deeper and smaller defects [11,24] • TSR reduces the temporal noise in the time history of each pixel [24] • TSR reduces the amount of blurring due to lateral diffusion [24] • One of the most important features of TSR is that it can be used to obtain time-derivative images, in which the detection sensitivity is increased and the effects of non-uniform heating and the background reflection are reduced [11,22]	• TSR is not able to remove the fixed pattern noise [25] • Selecting thermal image at a specific time to define local flaw boundaries is not so easy without temporal behavior of temperature [21] • When working with anisotropic materials, inappropriate selecting of coefficients number may results in higher residuals between fitted and experimental data [11] • Since TSR is derived from the 1D heat conduction equation, the fitting can be affected when considering longer times, when the lateral heat diffusion becomes predominant [11]