Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/bbe

Review Article

The thermographic signal reconstruction method: A powerful tool for the enhancement of transient thermographic images

Daniel L. Balageas [a,*], *Jean-Michel Roche* [b], *François-Henri Leroy* [b], *Wei-Min Liu* [c], *Alexander M. Gorbach* [d]

[a] TREFLE Department, Institute of Mechanics and Engineering of Bordeaux, Bordeaux, France
[b] ONERA, Composite Materials and Structures Department, Châtillon, France
[c] Department of Computer Science and Information Engineering, National Chung Cheng University, Taiwan, ROC
[d] Infrared Imaging and Thermometry Unit, National Institute of Biomedical Imaging and Bioengineering, Bethesda, MD, USA

ARTICLE INFO

Article history:
Received 7 March 2014
Received in revised form
23 July 2014
Accepted 24 July 2014
Available online 7 August 2014

Keywords:
Stimulated thermography
Non-destructive evaluation
Experimental mechanics
Damage detection
Biomedicine
Thermographic signal reconstruction

ABSTRACT

Important progress occurred in pulse-stimulated thermography, in particular thanks to the TSR technique, a technique based on the decomposition of thermograms on a logarithmic polynomial basis and the use of the logarithmic derivatives to enhance the detection of defects in structures. Its fields of application begin to broaden to the characterization of transient internal heat sources in experimental mechanics and biomedicine. The TSR technique is presented, in particular the last developments leading to the production of a unique synthetic image. Two recent examples of applications in experimental mechanics and biomedicine, taken from literature, are described: in situ detection of damages in a composite material during mechanical tests and in vivo visualization of subcutaneous functional angioarchitecture in humans.

1. Introduction

Four decades of continuous research to improve the detection and the characterization of defects have made stimulated thermography, especially pulse thermography (PT), one of the most sophisticated and versatile thermal non-destructive evaluation (NDE) techniques [1–4]. The thermographic signal reconstruction (TSR) data processing technique is the most recent improvement which raises thermography to the level of the most established NDE techniques (ultrasonics, X-rays, liquid penetrant, magnetic particles and eddy currents). These developments, both on the thermographic equipments themselves and on the advanced data processing techniques, could

* *Corresponding author at*: TREFLE Department, Institute of Mechanics and Engineering of Bordeaux, Bordeaux, France.
E-mail addresses: daniel.balageas@wanadoo.fr, daniel.balageas@u-bordeaux1.fr (D.L. Balageas).

http://dx.doi.org/10.1016/j.bbe.2014.07.002

have an impact not only in the NDE field, but also in biomedicine. Although the ''structures'' observed in NDE remain less complex than those studied in the biomedical field, the progress made in NDE may indeed be useful for this field too.

Thus, the aim of this review paper is to illustrate the applicability of TSR to biomedicine and to point out the spectacular enhancements of the thermographic images obtained in this domain. Consequently, the paper does not claim to provide new and unpublished results to the reader, but it does propose a relevant selection of examples, based on recent pioneering works taken from three research fields, associated with structures of increasing complexity:

- *NDE field*: inspection of a laminate composite coupon;
- *experimental mechanics field*: in situ damage monitoring of woven composite samples under tensile loading;
- *biomedical field*: visualization of blood circulation in the forearm.

In the first case, simple but realistic artificial defects simulating delamination damage, are detected (Section 2); in the second case, matrix cracking and fibers/matrix decohesions are monitored as local thermal sources (Section 3); in the third case, the effects of an arterial occlusion is studied (Section 4).

2. Thermographic signal reconstruction technique: state-of-the-art

2.1. Theoretical bases

Originally developed for pulse thermography, the TSR processing technique consists in:

- the fitting of the experimental log–log plot thermogram by a logarithmic polynomial of degree n:

$$\log_{10}(\Delta T) = a_0 + a_1\log_{10}(t) + a_2[\log_{10}(t)]^2 + \cdots + a_n[\log_{10}(t)]^n \quad (1)$$

with ΔT the temperature increase as a function of time t (thermogram) for each pixel (i,j). This fitting replaces the full sequence of temperature rise images ΔT (i,j,t) by the series of ($n + 1$) images of the polynomial coefficients: $a_0(i,j), \ldots a_n(i,j)$, from which a full thermographic sequence can be rebuilt.

- the computation of the 1st and 2nd logarithmic derivatives of the thermograms, the derivation being achieved directly on the polynomial, with a limited increase of the temporal noise.

The fitting and derivations of the thermograms depend on the time domain considered. A time window has to be defined with the objective to consider the sole part of the thermograms influenced by the physical phenomena to characterize. The so-obtained defect images may have better signal-to noise ratio (SNR) and sharpness than the raw thermographic images.

The ''classic'' use of TSR consists in selecting the best derivative images associated with every given depth range, in order to either qualitatively detect the defects (Fig. 1), or quantitatively evaluate their depths from characteristic times. To that latter extent, it might be necessary to optimize the degree of the polynomial: it was empirically found that $n = 11$ was a satisfying degree for delamination-like defects [5,6].

More recently [5,6], it has been proposed to project the three best polynomial coefficient images in an RGB basis, in order to build a unique ''composite'' image of the defects. For delamination-like defects, the best detection was obtained for degree $n = 7$. The process can be fully automated, which would considerably simplify the NDE operations during manufacturing or maintenance industrial processes.

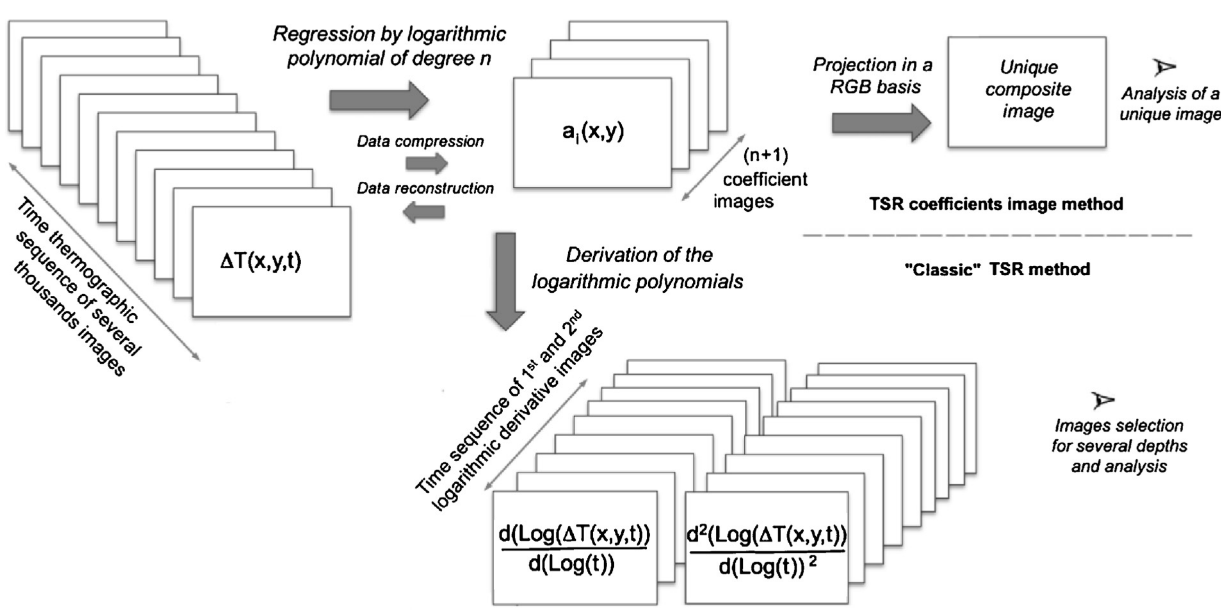

Fig. 1 – Defect detection by the TSR method.