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THE THERMOGRAPHIC SIGNAL RECONSTRUCTION METHOD: A POWERFUL TOOL FOR THE ENHANCEMENT OF TRANSIENT THERMOGRAPHIC IMAGES

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I. 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 [1,2]. 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 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 Consequently, the paper does not claim to provide new and unpublished results to the reader, but it does propose a relevant selection of examples, based on recent pioneering works taken from three research fields, associated with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 II); in the second case, matrix cracking and fibers/matrix decohesions are

monitored as local thermal sources (Section III); in the third case, the effects of an arterial occlusion is studied (Section IV).

II. THERMOGRAPHIC SIGNAL RECONSTRUCTION TECHNIQUE: STATE-OF-THE-ART

II.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 :

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

with T 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

$T(i,j,t)$ by the series of $(n+1)$ images of the polynomial coefficients: $a_0(i,j)$, ..., $a_n(i,j)$, 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 (Figure 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.

II.2. Illustration for pulse-heating thermography NDE

For illustration purpose, a 5.25 mm-thick carbon-epoxy plate containing 80 μm -thick Teflon® inserts of various sizes, embedded at different depths during the fabrication (see Figure 2a), was pulse-heated by two Elinchrom flash lamps delivering a pulse of total energy 6 kJ in 4 ms. The temperature distribution (320×256 pixels) is recorded during 60 s

at 200 Hz, with an integration time of 230 μ s, by a CEDIP Jade LWIR (7.7 mm – 9.3 mm) camera.

Figure 2b displays typical thermograms taken from sound and defective zones (the center of the largest and shallowest defect #1-1). As mentioned in Section II.1, a time window for the TSR application has to be selected: in the present case, the time window must start a few instants before the appearance of the first contrast generated by a defect and last long enough to contain all the contrasts, at least partially.

The classic TSR method is used to select the best images of the two logarithmic derivatives (Fig. 3), based on the criterion of the number of detected defects. The process is time-consuming and tedious since it requires to observe the full sequences which may count several hundreds or thousands images. However, the enhancement achieved with the logarithmic derivation is unquestionable, as illustrated by Figure 4.

The recently developed TSR-based technique is applied to the three coefficient images presented in the first column of Figure 5 (coefficients of ranks 5, 6 and 7). The “composite” color image (Fig. 5left-bottom image), in addition to provide valuable information as far as defect detection is concerned, also reveals a correlation between the colors and the relative depths of the defects, which might be used to produce a full thermal depth-scans, similar to ultrasound scans [7].

Figure 5 also compares this method to other well-known methods, sometimes used for defect imaging: Principal Component Thermography (PCT) [8,9], Pulse Phase Thermography (PPT) [10,12] and High-Order Statistics (HOS) [11]. A visual comparison of the key-processed images (first three rows of Figure 5) shows that the TSR coefficient images are always the most valuable (based on the number of detected defects). The composite RGB images elaborated from the triplets of these images show a higher color contrast, a better sensitivity of the colors to the defect depths and a lower noise in the sound zone by disappearance of the patterns due to the structure of the composites (plies of various orientations). The existence of redundant information in the triplets appears by the presence of grey tones mixed with the colors (PPT composite image). This is particularly noticeable for the HOS composite image which is almost in grey tones. This once again demonstrates the richness of the information contained in the TSR coefficient composite image.

II.3. Extension to other transient thermal regimes used for NDE

Although no theory has been published on this topic, the TSR method can be applied to other transient thermal regimes such as step-heating, square-shaped heating, long pulses, ... Figure 6 displays coefficient and logarithmic derivatives images resulting from the application of a step-heating excitation to the coupon described in Section II.2. The quality of these images is comparable to that resulting from the application of the pulse heating.

The work of Dumoulin *et al.* [12] on the application of TSR to a square-shaped heating, with exploitation of the relaxation phase, should also be mentioned. In this case, fitting polynomials of degree 5 were used for the coefficient images. As for the whole square-shaped heating sequence, the best fitting required higher degrees up to 13 or 14.

These examples show that the logarithmic polynomials constitute an efficient basis on which to project the thermograms of transient thermal regimes.

Furthermore, the presence of a defect or any interface can be considered equivalent to an internal thermal source or a thermal well when monitoring the surface temperature. Inversely, internal thermal sources or wells produce a distortion of the temperature distribution on the monitored surface, which is similar to the one created by a defect. Consequently, the TSR approach, designed for NDE, might also be relevant for the inspection of structures presenting internal non-stationary heat sources or wells: this is what the following sections intend to illustrate, based on two recently published examples taken from experimental mechanics and biomedicine.

III. EXAMPLE OF APPLICATION IN THE EXPERIMENTAL MECHANICS FIELD

The present example of application of the TSR method to experimental mechanics is taken from [13]. Passive infrared thermography is used during mechanical testing for an in situ damage monitoring of a 2D glass-epoxy woven composite samples. A 2 mm thick, 20 mm wide and 180 mm long specimen is submitted to five successive tensile loadings, from 0 to 120 MPa, as described in Figure 7a. Each loading is monitored by the infrared camera (already described in Section II.2) and considered as an independent test. The acquisition rate was 200 Hz since the persistence of the thermal signature associated to the damage creation is short. This monitoring is essential since the damage detection during the plateaus using active thermography is ineffective due to the orientation of the generated cracks (perpendicular to the surface).

For each test, the thermal images are normalized by the first recorded image. For a given tensile loading, no additional damage is detected between 0 MPa and the previously reached plateau level (Kaiser effect). Therefore, the analysis is based only on the final part of the loadings, corresponding to stress levels higher than the ones reached by the previous plateaus.

The review of the whole sequence of thermal images for damage detection and location is a time-consuming work because it requires to examine more than one thousand images for each loading. This is precisely when the TSR-coefficient image approach might become useful. The procedure was thus applied to the normalized thermograms. The degree of the polynomials is 7 and the selected coefficient image is the higher rank coefficient, a_7 . This image has been chosen because it contains all the thermal events that occurred during the loading. The data compression reached with TSR is quite impressive.

Obviously, due to the shape of the thermograms, the logarithmic polynomial regressions are quite poor (Fig. 8). However, this is not a problem since the analysis only aims at differentiating a damaged zone from a sound zone. From this point of view, the results are satisfactory.

By this experiment, the extension of the method, initially developed for active thermography in which transient heat fields are created by external heat sources, to passive thermal monitoring of structures in which heat sources are internal to the material, is then validated. Such results are now paving the way to applications in new research fields such as mechanics and biomedicine.

IV. EXAMPLE OF APPLICATION IN THE BIOMEDICAL FIELD

Infrared thermography can be used for the visualization of the vessels underlying the skin. This is crucial for the assessment of peripheral vascular diseases, skin reconstruction surgery, wound and ulcer management, or for the study of the muscular function.

Using mechanical stimulations, active thermography can assess vascular structures up to a depth of 10 mm below the skin surface. Two types of stimulation have been explored:

- modulation at low frequencies (15 and 30 mHz) of the blood pressure in the arm using a compression cuff, and lock-in thermography imaging of the forearm [15] or the back-hand vascular tree [16]. In the first case, both amplitude and phase images were obtained; in the second case, the stimulation was optimized by using a sawtooth modulation at 30 mHz and the data processing consisted in a discrete Fourier transform leading to amplitude images, in particular at the frequency of the modulation.
- complete arterial occlusion using an inflatable cuff and time-resolved analysis of the thermal images of the forearm after the end of the occlusion [17–18]. In that case, the stimulation is a step-shape type and the duration of the analyzed thermogram (50 s) corresponds to a "f = 20 mHz" frequency domain.

The TSR method is applicable to the second type of stimulation.

It was shown by Liu *et al.* [17] that patterns characteristics to microvascular (MV) perforator vessels, conduit vessels, as well as skin areas without infrared detectable vessels (SWV), can be discernible by complete arterial occlusion in human forearm during 5 min. These authors tried to reduce the duration of the ischemia by monitoring the transient evolution of temperature following occlusions of less than 5 min (down to 1 min). To avoid losing sensitivity in the angioarchitecture map, they enhanced the contrast between MV and SWV by the use of the TSR method. The short-wave (3–5 μm) infrared camera used had a NETD of 15 mK, a 320x256 px matrix, encoded on 14 bits. The procedure was the following: the camera records the forearm skin temperature at a frame rate of 2 Hz during the full duration of the experiment: 25 minutes (3,000 images). The experiment counts three successive periods: i) Base Line (BL) period of 10 min, the subject being at rest before the occlusion; ii) arterial OCclusion (OC) period of 5 min; iii) Post-Occlusion (PO) period.

The application of TSR method to the present configuration must take into account the following differences:

- in NDE situation, the energy input is uniform, controllable and coming from the outside; here, the energy is endogenous, variable and depends on many parameters linked to the structure itself.

- in NDE, the flux of energy and the temperature field are mainly 1-D; here, multiple heat sources exist, embedded at different depths, creating heat waves of different directions.
- for the perforator vessels and only for the first moments following the end of the occlusion, the thermal regime is of the step-heating type.
- in NDE situation, the thermal properties of the structure are uniform (or almost uniform), and known, so that quantitative evaluation of the defect depths is possible; here, due to the complexity of the structure, it is impossible.

To adapt the method to these experimental conditions, only the first 50 s of the PO period are considered for the application of the TSR procedure: fitting by a logarithmic polynomial of degree 5, followed by a derivation of the fitted thermogram. It should be noted that in [18], the derivation is a classic one, not a logarithmic derivation, but both approaches have been tested and led to similar images. Furthermore, the fitting is applied to the temperature time-evolution and not to its change since the baseline temperature in human varies all the time making the reference temperature difficult to be determined

A sequence of 100 derivatives images is then obtained. The image with the best signal-to-noise ratio between MV and SWV is chosen. The enhancement of the image quality is spectacular and makes the MV pattern clearly visible, as illustrated by Figure 9 with images taken from [18]. The quality of the images after TSR treatment is so improved that it is possible to identify the elements of the angioarchitecture of the forearm and to follow the time-evolution of the reperfusion in the different regions of interest during the PO period. Moreover, the responsiveness of different vascular regions of human skin under occlusion tests of different durations can be quantified, by calculation of a temperature-derived reactive hyperemia index (RHI_T), taken as the maximum of the 1st-order derivative within the first 50 seconds after the occlusion.

V. CONCLUSION

After a brief theoretical recall on the TSR processing technique, the present paper shows the relevance of such an approach to any type of transient thermal regimes caused by external or embedded heat sources. The most recent developments aiming at compressing the information in a unique image have been presented.

For the NDE applications, domain for which the method has originally been elaborated, the comparisons of the logarithmic derivative method, and more recently the polynomial coefficient method, to well-established methods such as Principal Component Analysis, Pulse Phase Thermography and High Order Statistics, have shown that the TSR approach always leads to results at least as good as the best ones of the other methods. More quantitative comparisons are to be done to precisely assess the gain in image quality, obtained with TSR.

The application of the method to experimental mechanics, and more precisely to the monitoring of a composite material under damaging loading, has been presented as an intermediate case from the viewpoint of the monitored structure complexity, between NDE

and biomedicine. The point of using TSR, even though a more accurate fitting of the thermograms could be reached with other techniques (splines, wavelets, ...), is unquestionable given the considerable data compression it allows: the opportunity to synthesize data from a whole mechanical loading experiment in one, unique, image really is valuable.

Finally, the applicability of TSR to biomedical imaging has been shown. Since such studies are very recent, only one example was given. The main results of this pioneering study underline the spectacular enhancement of the quality of the obtained thermographic images, which opens encouraging perspectives.

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Figure 1.
Defect detection by the TSR method

Figure 3.

Best observation times for defect imaging, using the 1st (*on the left*) and 2nd (*on the right*) logarithmic derivatives (research of the highest SNR of the absolute contrast between the center of the defects and a mean sound zone). The sign of the contrast is indicated. Defect images obtained for the best two contrasts are also given for each defect.

Figure 4.

Crude thermograms: best thermal image at time 7.5 s (a). 1st logarithmic derivative at time 3.5 s (b) and 2nd logarithmic derivative at time 2.3 s (c).

Figure 5.

Comparison of the present method to other data processing techniques producing defect images. (a) First three top lines: grey level images (256 bits) of individual component; (b) bottom line: RGB projection of these components. *Remark: if printed in grey tones, RGB images are not comparable to monomial images and seem of inferior quality.*

Figure 6.

Images obtained by the TSR method applied to step-heating thermography. (a) crude temperature increase image, (b) image of the a_3 coefficient of the polynomial of degree 5, (c) first logarithmic derivative, (d) second logarithmic derivative.

Figure 7.

Tensile mechanical test of a composite material consisting in a series of 5 loadings alternated with plateaus at increasing stress levels. First step: record of the crude thermographic images during the loadings. Second step: fit of the thermograms by logarithmic polynomials of degree 7 and data compression by recording the sole a_7 TSR-coefficient image of each loading.

Figure 8. Regression by a logarithmic polynomial of degree 7, for a sound zone (left), and a damaged zone (right). Taken from [12].

Figure 9.

Top row: Best raw images (a) MV pattern with the highest contrast (0.313) appeared at 27 s after 1-min occlusion; (b) MV pattern with the highest contrast (0.461) appeared at 21.5 s after 4-min occlusion; (c) MV pattern with the highest contrast (0.386) appeared at 31.5 s after 5-min occlusion. *Middle row:* Best TSR processed images: (a) MV pattern with the highest contrast of 0.613 appeared 4 s after 1-min occlusion; (b) MV pattern with the highest contrast of 0.729 appeared 3 s after 4-min occlusion; (c) MV pattern with the highest contrast of 0.814 appeared 8 s after 5-min occlusion. *Bottom row:* RHI_T maps derived from (a) 1-min occlusion experiment; (b) 4-min occlusion experiment; and (c) 5-min occlusion experiment. Images taken from [17].