Review of thermal-contrast-based signal processing techniques for the nondestructive testing and evaluation of materials by infrared thermography

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Abstract. Infrared thermography is a nondestructive and evaluation technique in which the surface of the inspected specimen is subjected to a thermal stimulation in order to produce a temperature difference between eventual surface or subsurface defects and non-defective zones. The classical signal processing techniques are based on thermal contrast computations, the simplest definition being the absolute contrast, defined as the arithmetic difference between a defective and a reference (defect-free) area. The absolute thermal contrast is affected by different problems such as emissivity variations, environmental reflections, non-uniform heating due to the energy source and surface shape. The impact of these problems can be considerably reduced through the normalization of the thermal contrast. Nevertheless, to carry out thermal contrast calculations, normalized or not, it is necessary to define a defect-free or sound area S_a, which is not always straightforward or possible to do. The differential absolute contrast (DAC) has been proposed to eliminate the need for a sound area definition. The idea is to calculate ideal sound areas for each and every surface point (pixel) based on the 1D solution of the Fourier equation for a semi-infinite plate stimulated on the surface by a Dirac pulse. This simplification is strictly valid only for homogeneous materials at early times, *i.e.* before the thermal front reaches the opposite side of the specimen and the 1D assumption does not hold anymore. The validity of the DAC approach can be extended for later times with the inclusion of the plate thickness L, explicitly in the solution. In this case, the Laplace transform can be used in combination with the thermal quadrupoles theory. Using this modified DAC algorithm, it is possible to estimate the depth, size and thermal properties of a defect. In this paper, we present a review of classical and recent thermal-contrast-based processing techniques and some of their applications.

1. Introduction

Pulsed thermography (PT) is a nondestructive evaluation (NDE) technique allowing the fast inspection of large surfaces. Data acquisition and processing is carried out as depicted in Fig. 1 and can be summarized as follows.

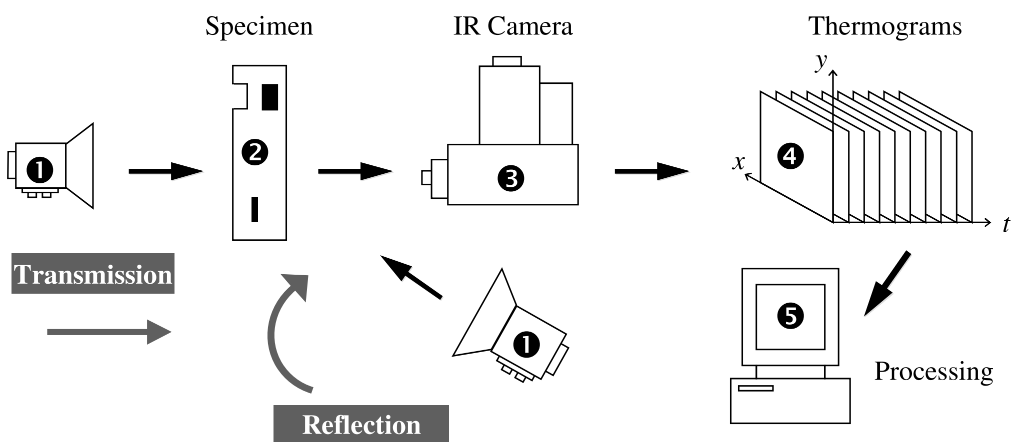


Fig. 1. Schematization of the data acquisition and processing by PT

First, the specimen surface is stimulated with a thermal pulse ❶ in either transmission or reflection mode depending on the application. The thermal cooling is monitored at the surface where defective zones will appear at higher or lower temperature with respect to non-defective zones on the surface, depending on the thermal properties of both, the material and the defect ❷. The thermal signatures are recorded using an infrared camera ❸. A thermal map of the surface or a *thermogram* is captured at regular time intervals. A 3D matrix is formed ❹, where *x* and *y* coordinates are the horizontal and vertical pixel positions respectively, and the *z* coordinate corresponds to time. The thermogram matrix is ready to be processed ❺.

Enhancement of the subtle IR signatures involves various techniques including, among many others: thermal contrast computation [1], pulsed phase thermography [2], principal component thermography [3], and thermographic signal reconstruction [4]. In this paper, we discuss the thermal contrast-based techniques from the classical approach to the most recent developments.

2. Classic Thermal Contrast

Various thermal contrast definitions exist [1], p. 198, but they all share the need to know a sound area S_a, *i.e.* a non-defective region within the field of view. For instance, the absolute thermal contrast $\Delta T(t)$ is defined as [1]:

$$\Delta T(t) = T_d(t) - T_{S_a}(t) \tag{1}$$

with $T(t)$ being the temperature at time *t*, $T_d(t)$ the temperature of a pixel (defective or not) or the average value of a group of pixels, and $T_{Sa}(t)$ the temperature at time *t* for the S_a. No defect can be detected at a particular *t* if $\Delta T(t)=0$.

Establishing this S_a is the main drawback of thermal contrast especially if automated analysis is needed or if nothing is known about the specimen. Even when defining a S_a is a straightforward, considerable variations on the results are observed when changing the location of S_a [4]. See for instance Fig. 2a, which shows the thermal contrast profiles (bottom) for the four different sound areas around a defect shown in the thermogram (top). Data comes from a CFRP specimen with Teflon® inserts having different depths and sizes. As can be seen, there are significant variations in thermal contrast profiles even though the selected sound areas are not far from each other. The spatial profile on top of Fig. 2a provides an indication of non-uniform heating, the right side of the specimen is at higher temperature (up to 3^oC) than the left.

Several quantitative methods based on the thermal contrast have been proposed [1], chap. 10. All rely on a sort of calibration either with a thermal model or with various specimens representative of unknown ones. For instance, one can compute defect depth *z* by extracting a few parameters on the thermal contrast curve such as the maximum contrast ΔT_{max} and its time of occurrence t_{max} [5]:

$$z = A \cdot t_{\max}^{1/2} \cdot \Delta T_{\max}^{h} \tag{2}$$

with parameters *A* and *h* obtained from the calibration process.

Similar empirical relationships have been proposed for thermal resistance *R*, which is proportional to defect thickness. Defect sizing is generally achieved by extracting the contour of the detected anomaly either at peak contrast slope, at peak maximum thermal contrast or as early as possible to avoid the lateral thermal diffusion (that tends to enlarge the size at peak contrast or slope). An iterative technique was also proposed and consists to extract the contour in each (contrast) image at full width half maximum (FWHM) amplitude. A plot of the size as function of the square root of the time is then established and the extrapolated line at time zero yield to a good estimation of defect size [6].

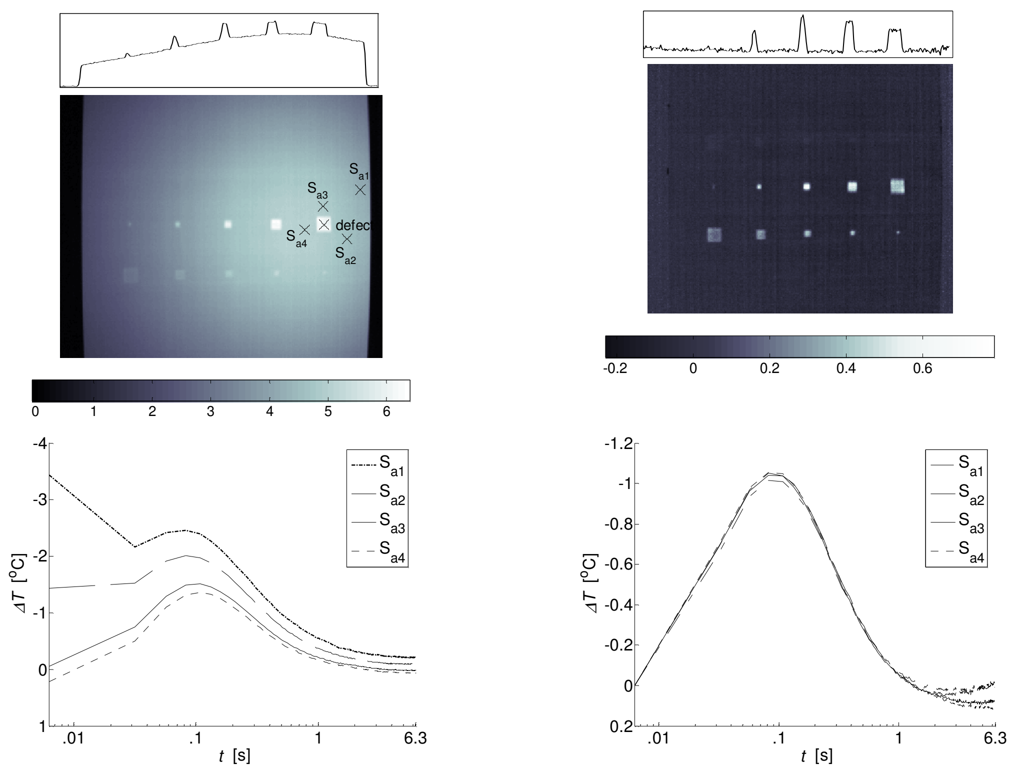
In spite of the popularity of classical thermal contrast, the inherent problems (non-uniform heating, emissivity variations and environmental reflections) and the need to specify a reference area, forced researchers to look for other alternatives. The differential absolute contrast is one of such techniques and is described in the nest paragraph.

3. Differential Absolute Contrast, DAC

Problem of S_a location was recently solved with the differential absolute contrast (DAC) [7]. This technique is based on Eq. (1) as the classical approach. However, instead of looking for a non-defective area somewhere in the thermogram, the S_a temperature at time t is computed locally assuming that on the first few images (at time t' in particular, see below)all points behave as a S_a [7]. The DAC method relies on the 1D solution of the Fourier diffusion equation for a Dirac pulse applied on the surface (z=0) of a semi-infinite body, which may be written as follows [8]:

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

where $T(t)$ is the temperature evolution, Q [J/m^2] is the injected energy at the surface, $e=(k\rho c_P)^{1/2}$ [m] is the thermal effusivity of the sample, with k [W/mK] being its thermal conductivity, ρ [kg/m^3] its density and c_P [J/kgK] its specific heat at constant pressure.



(a) (b)

Fig. 2. Spatial profiles (top), thermograms at t=209 ms (center), and thermal contrast profiles for 4 different S_a definitions (bottom); and (b) DAC result

The first step is to define *t'* as a given time value between the instant when the pulse has been launched t_0, and the precise moment when the first defective spot appears on the thermogram sequence, *i.e.* when there is enough contrast for the defect to be detected, t_1. At *t'*, there is no indication of the existence of a defective zone yet, therefore the local temperature for a S_a is exactly the same as for a defective area:

$$T_{S_a}(t') = T(t') = \frac{Q}{e\sqrt{\pi t'}} \quad \Rightarrow \quad \frac{Q}{e} = \sqrt{\pi t'} \cdot T(t') \tag{4}$$

From this result, T_{Sa} can be computed for every pixel at time *t*, and substituting this result into the absolute contrast definition, Eq. (1), it follows that:

$$\Delta T_{DAC} = T(t) - \sqrt{\frac{t'}{t}} \cdot T(t') \tag{5}$$

The solution provided by Eq. (3), diverges from the non-semi-infinite case as time elapses and as the plate thickness increases. Nevertheless, Eq. (5) provides a good approximation at early times even for the case of anisotropic materials as can be seen in Fig. 2b. The thermal contrast profiles in this case behave practically the same at the first instants. Discrepancies begin at later times when heat diffusion increases and the 1D model collapses. In addition, the DAC method was found particularly efficient to remove unwanted effects appearing in specimen, see for instance the spatial profile at the top of Fig. 2b, which do not show the non-uniform heating effect as in Fig. 2a. Originally, proper selection of *t'* required an iterative graphical procedure. An automated algorithm is now available [9]. Furthermore, a modified DAC algorithm has been proposed as well as described next.

4. Modified DAC technique

A new version of the DAC algorithm has been developed [10] based on the thermal quadrupoles theory [11] to extend the validity of DAC to later times. The model in this case was derived under the hypothesis of a plate of finite thickness under Dirac pulse stimulation. All the derivation is carried out in a transformed Laplace space by defining the temperature *T(z,t)* and the thermal density flux $\phi(z,t)$, and their corresponding Laplace transforms as $\theta(z,t)$ and $\Phi(z,t)$, respectively. It can be demonstrated that a solution of the problem is provided by [12] :

$$\begin{pmatrix}\theta_i \\ \Phi_i\end{pmatrix} = \mathrm{M}\begin{pmatrix}\theta_o \\ \Phi_o\end{pmatrix} \quad \text{with } \mathrm{M} = \begin{pmatrix}A & B \\ C & D\end{pmatrix} \text{ and } \begin{array}{l} A = D = \cosh(p^* L) \quad C = kp^* \sinh(p^* L) \\ B = \sinh(p^* L)/(kp^*) \quad p^* = \sqrt{p/\alpha} \end{array} \tag{6}$$

where *i* is the input and *o* the output.

Eq. (6) can be expressed as an equation system of the form:

$$\theta_i = A\theta_o + B\Phi_o \tag{7}$$

$$\Phi_i = C\theta_o + D\Phi_o$$

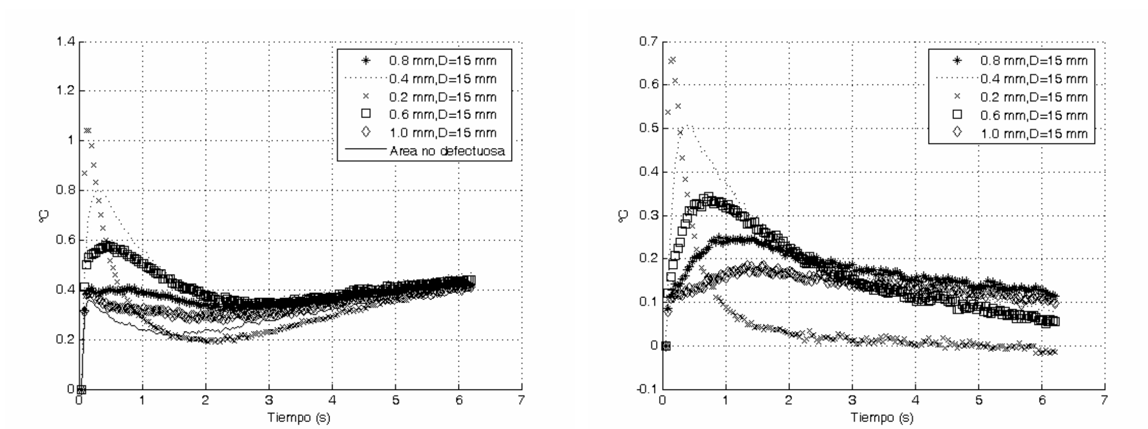
In the case of a plate with an isolated rear face: $\Phi_i = Q$ et $\Phi_o = 0$, the Laplace temperature is given by:

$$\theta_i = \frac{QA}{C} = \frac{Q \coth\sqrt{pL^2}}{b\sqrt{p}} \tag{8}$$

The Laplace inverse transform is used to derive a solution of the form [11]:

$$\Delta T_{DAC,\mathrm{mod}} = T_d(t) - \frac{\ell^{-1}\left(\coth\sqrt{\dfrac{pL^2}{\alpha}}\right)_t}{\ell^{-1}\left(\coth\sqrt{\dfrac{pL^2}{\alpha}}\right)_{t'}} \cdot T(t') \tag{9}$$

The solution includes the plate thickness L explicitly in the solution and do not depend on the delivered energy, extending in this way the validity of the DAC algorithm to later times as seen in Fig. 3 [11].



(a) (b)

Fig. 3. Spatial profiles (top), thermograms at t=209 ms (center), and thermal contrast profiles for 4 dif

Fig. 3a shows the DAC profiles for 5 subsurface defects at different depths from the same specimen as in Fig. 2, and Fig. 3b presents the modified DAC results for the same defective areas. The correction to the profiles can be observed at later times.

5. Conclusions

A review of thermal-based methods to process pulsed thermography data was presented herein. The classic contrast technique is the most popular and quantification is possible. However, it suffers from the need of specifying a sound area from, and from a variety of problems (non-uniform heating, environmental reflections and emissivity variations). These problems are significantly reduced with the development of the differential absolute contrast (DAC) approach. Moreover, there is no longer need to determine a reference area. The DAC technique however, works well only at early times, given that is been derived from a 1D solution of the Fourier's equation. The thermal quadrupoles theory is used to extend its validity to later times in a transformed Laplace space.

6. References

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