MODIFIED DIFFERENTIAL ABSOLUTE CONTRAST USING THERMAL QUADRUPOLES FOR THE NONDESTRUCTIVE TESTING OF FINITE THICKNESS SPECIMENS BY INFRARED THERMOGRAPHY

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Abstract

Infrared thermography is a nondestructive evaluation technique in which the specimen surface is thermally stimulated to produce a temperature difference between "sound" (free of defects) areas and eventual defective regions. It is well known that the thermographic methods based on the thermal contrast are strongly affected by non-uniform heating at the surface. Hence, thermal contrast-based results considerably depend on the chosen reference point. The differential absolute contrast (DAC) method was developed to eliminate the need of determining a reference point by defining the thermal contrast with respect to an "ideal" sound area. The DAC technique is based on the 1D solution of the Fourier diffusion equation for homogeneous and semi-infinite materials stimulated with a Dirac heat pulse. Although very useful at early times, this assumption considerably decreases DAC accuracy when the heat front approaches the sample rear face. We propose a modified DAC version by explicitly introducing the sample thickness using the thermal quadrupoles theory. We demonstrate that taking into account the sample thickness, the DAC validity range considerably extends for long times after excitation while preserving its performance for short times.

***Keywords**: Infrared thermography, thermal contrast, differentiated absolute contrast, thermal quadrupoles, nondestructive evaluation.*

1. Introduction

Thermal contrast is used in nondestructive evaluation (NDE) by infrared thermography to evaluate defect visibility, enhance image quality and ultimately for quantitative purposes. Several types of contrasts have been defined such as absolute contrast, running contrast, normalized contrast and standard contrast [1, 2]. All these contrast definitions require the use of the temperature in a sound area whose definition is a critical issue. In a wide sense, its locations are not precisely identified since it may not be known in advance where the defects are, if present at all. Only assumptions can be made about the sound areas. This is the main limitation that can complicate the application of thermal contrast methods. Moreover, it is well-known that defect quantification methods based on thermal contrast are strongly affected by non uniform heating. The differentiated absolute contrast (DAC) method was developed to perform a more convenient computation of the sound area temperature through the 1D solution of the Fourier equation for homogeneous and semi-infinite materials stimulated with a Dirac impulse [3]. This model however, does not include the sample thickness. Therefore the DAC accuracy decreases for long times after heating when the heat front reaches the sample face opposite to irradiation. In this article we propose a modified DAC version by explicitly introducing the sample thickness by means of the thermal quadrupoles theory [4]. We demonstrate that taking into account the sample thickness, the DAC validity range can be extended for long times after excitation while preserving its performance for short times.
This new DAC technique is tested with a carbon fiber reinforced plastic (CFRP) sample containing 25 Teflon® insertions to simulate delaminations of different sizes, depths and locations. Finally, the limitations of the corrected DAC are discussed.

1.1. DAC modification using thermal quadrupoles

A one layer slab, made out of homogeneous material, is characterized by its thickness e, its thermal diffusivity α and by its volumetric heat capacity ρC, with ρ being its mass density and C its heat capacity rate.
For a one-direction heat transfer the temperature profile inside the slab can be denoted by $T(x, t)$, where x is the coordinate perpendicular to the slab faces and t the time.
It is now assumed that the front face of the slab ($x = 0$), is excited by a Dirac heat pulse of total energy density Q (in Jm^{-2})

while its rear face ($x = e$) remains insulated [5]. The Laplace temperature for front heated face is given by:

$$\theta(p) = \frac{Q}{b} \coth \sqrt{\frac{pe^2}{\alpha}} \quad (1)$$

Where p is the Laplace variable and b is the thermal effusivity.
The following steps describe the deduction of the DAC corrected with thermal quadrupoles.
The temperature in the time domain at times t and t' ,where t' is a given value of time t ranging between the time of flash impulse and the time at which the first defect becomes visible, can be found by using the inverse Laplace transform:

$$T(t) = \frac{Q}{b} L^{-1} \left[\coth \sqrt{\frac{pe^2}{\alpha}} \right]_t \quad (2)$$

$$T(t') = \frac{Q}{b} L^{-1} \left[\coth \sqrt{\frac{pe^2}{\alpha}} \right]_{t'} \quad (3)$$

From Eq. 3 we can derive that

$$\frac{T(t')}{L^{-1} \left[\coth \sqrt{\frac{pe^2}{\alpha}} \right]_{t'}} = \frac{Q}{b} \quad (4)$$

Replacing Eq.4 in Eq.2 we get:

$$\frac{T(t)}{T(t')} = \frac{L^{-1} \left[\coth \sqrt{\frac{pe^2}{\alpha}} \right]_t}{L^{-1} \left[\coth \sqrt{\frac{pe^2}{\alpha}} \right]_{t'}} \quad (5)$$

$$\Delta T_{DAC_{CORR}} = T(t) - \frac{L^{-1} \left[\coth \sqrt{\frac{pe^2}{\alpha}} \right]_t}{L^{-1} \left[\coth \sqrt{\frac{pe^2}{\alpha}} \right]_{t'}} T(t') \quad (6)$$

The corrected DAC (Eq 6) explicitly contains the specimen thickness *e.*

2. Experimental validation of the modified DAC technique

The modified DAC method is tested with a 2 mm thick CFRP sample whose configuration is presented in Figure 1. The locations and geometry of the 25 Teflon® insertions are also indicated in this figure.

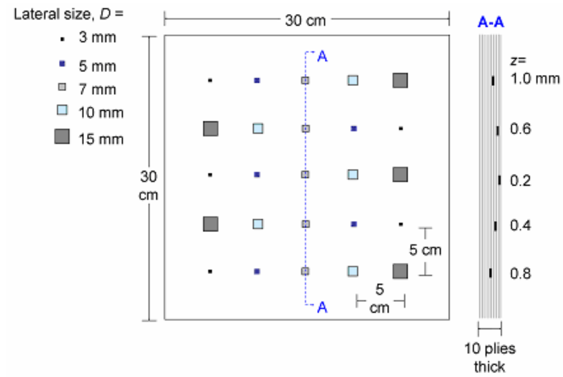

Figure 1. CFRP sample with Teflon insertions

The sampling frequency used to acquire the image sequence for this test is 39.45 Hz and the acquisition time is 6.80 s.
For this particular test, only one flash was used as heat source producing a strong non uniform heating pattern as seen in Figure 2.

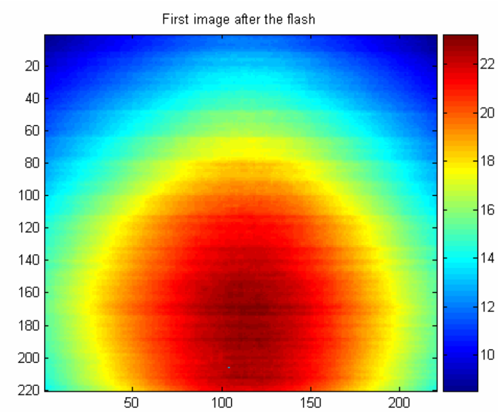

Figure 2. Non uniform heating pattern applied to the sample

The classical DAC technique was also applied to the sequence of images obtained from the CFRP sample and the maximum contrast image (*maxigram*) is used to compare the performance of classical DAC with the performance of modified DAC.

The maxigram obtained from classical DAC (Figure 3) only reveals 9 defects in the sample. Moreover, the observed DAC curves of defects with 15 mm side length (Figure 4) and the DAC curves of the sound area deviate from the 1D model for long times (t >3s) as expected.
On the other hand, the maxigram obtained from the modified DAC (Figure 5) reveals at least 19 defects in the sample and the thermal contrast curves (Figure 6) show that the validity range of the DAC method increases considerably for long times while preserving its performance for short times.

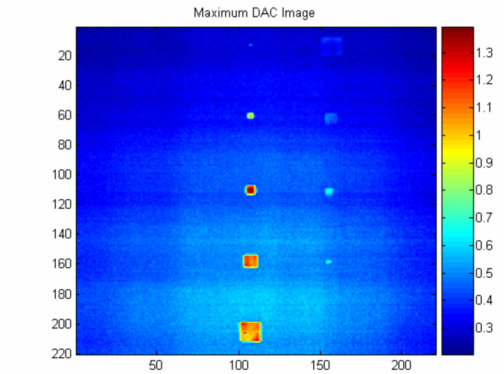

Figure 3. Maximum contrast image of DAC

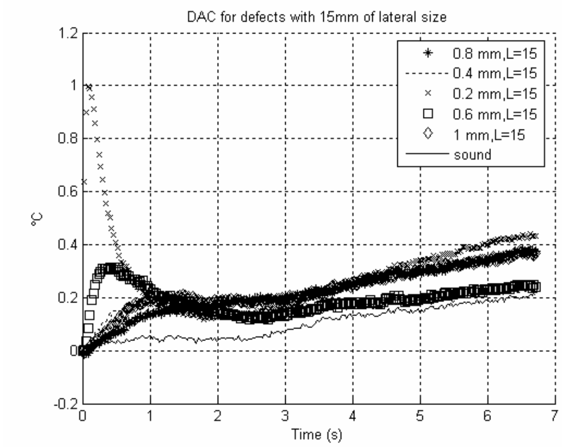

Figure 4. DAC curves for the five largest defects at different depths (15 mm in lateral size).

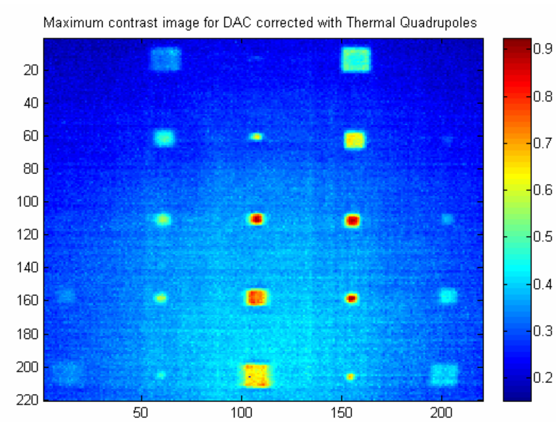

Figure 5.Maximum contrast image of corrected DAC

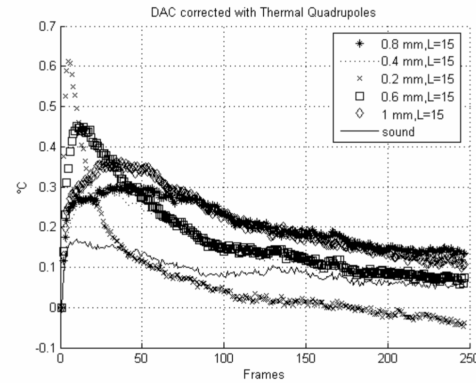

Figure 6 Modified DAC curves for the five largest defects at different depths (15 mm in lateral size).

For these tests, the value of α was $4.2\text{x}10^{-7}$ m^2/s and t' was 0.1012 s.

3. Limitations of the corrected DAC

This method is sensitive to the following parameters:

1. The material thermal diffusivity α;
2. The time before the first defect becomes visible t'; and
3. The initial time value for numerical inversion of the Laplace transform.

The sample front face temperature in the Laplace domain (Eq.1) depends on the material thermal diffusivity α and is affected by its variations as shown in Figures 7 and 8 where corrected DAC was applied using two different α values: α_1=4.1e-7 m^2/s, α_2= 4.5e-7 m^2/s.
On the other hand changes in t' have an impact on the shape of the thermal contrast curves. The longer t' the faster the curves go to zero and begin to take negative values. Moreover, the initial time value for the numerical inversion of Laplace transform also affects the curves shape. The Stehfest method algorithm was used for numerical inversion [6]. In this case, the time vector was defined as t = [1e-4 : 0.0272 : 6.8] s. Figure 9 shows the effect of changing the initial time value by 0.0272 s, in this case the performance at short times is not preserved.

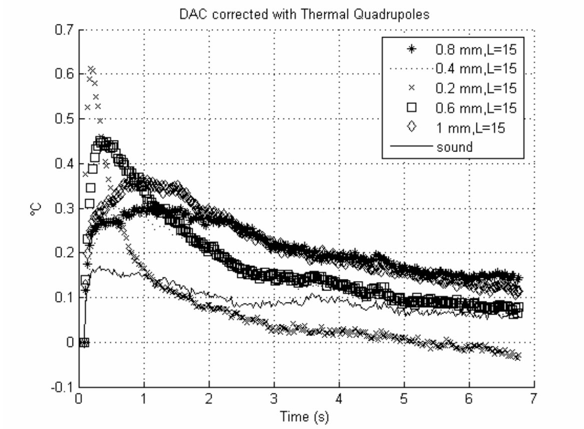

Figure 7
Curves of DAC corrected with thermal quadrupoles
$\alpha_1 = 4.1e\text{-}7\ m^2/s$

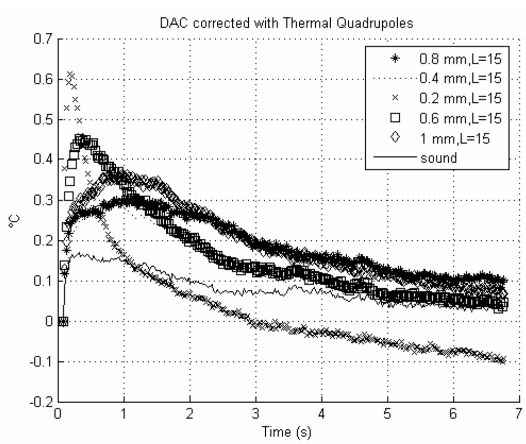

Figure 8
Curves of DAC corrected with thermal quadrupoles
$\alpha_2 = 4.5e\text{-}7\ m^2/s$

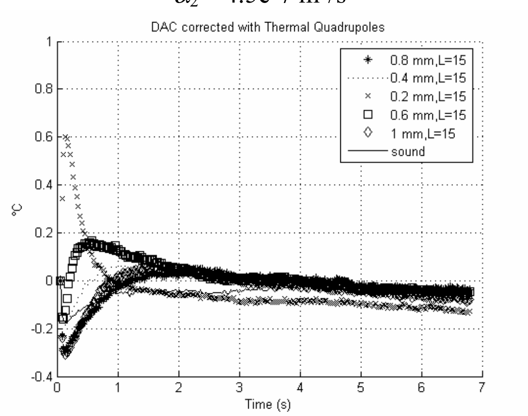

Figure 9
Curves of DAC corrected with thermal quadrupoles
Initial time value = 0.0272 s.

4. CONCLUSIONS

The proposed modified DAC technique was able to reveal more defects in the maximum contrast image than the classical DAC in an experiment strongly affected by non uniform heating. In addition, the modified DAC method conserves its validity for long times while preserving its performance for short times.

On the other hand, the modified DAC technique using thermal quadrupoles is sensitive to the thermal diffusivity of the tested material, *t'* and the initial time value used for the numerical inversion of Laplace transform.

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