NDT&E International 87 (2017) 60–67

Contents lists available at ScienceDirect

NDT&E International

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

Non-uniformity correction and sound zone detection in pulse thermographic nondestructive evaluation

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ARTICLE INFO

Keywords:
Pulse thermography
Non-uniform heating
Vignetting
Nondestructive evaluation
Sound zone

ABSTRACT

An important requirement in the thermographic nondestructive evaluation is the identification of actual sound zone or the base line with which the defective areas are compared to determine the actual temperature contrast and the corresponding defect severity. In a part under inspection, the actual sound zone is not known a priori and various approximations have been used in the past to serve as this unknown base line. Determination of actual sound zone in a defective test object is still a challenge. A related issue before the identification of this base line pixel is in the elimination of non-uniformity in the temperature distribution across the specimen surface which is unrelated to the actual defects. This spurious contrast is often introduced by the limitations of the instrumentation or the test procedure and it has to be eliminated before pixels in the sound zone can be located. This paper presents an automated procedure for simultaneously eliminating spurious contrast and locating sound zone pixels, directly from experimental data in a thermographic nondestructive evaluation. Location of actual sound zone pixels facilitates accurate thermal contrast computations, extraction of thermal properties such as break time and thermal diffusivity. In addition, based on the actual sound zone temperature profile it is possible to normalize experimental thermographic results in such a way that they can be directly correlated with results from numerical simulations.

1. Introduction

Pulse thermographic nondestructive evaluation (TNDE) method is emerging as a fast and economical tool for inspecting wide areas of structural members and detecting near surface defects [1]. In TNDE the part that is examined is subjected to a short pulse of heat energy from xenon lamps. As the heat from the surface diffuses in the thickness direction, the surface temperature gradually decreases. Subsurface defects change the rate of this diffusion, causing the surface above the defects to remain relatively warm compared to defect free regions or the so-called 'sound zones'. TNDE technique depends on the temperature contrast between defective zones and a representative sound zone, at different instants during the cooling period, to detect and quantify defects. Contrast measurement was improved by researchers through thermal image enhancements such as absolute contrast, normalized contrast, running contrast, and standard contrast [2]. Among them standard contrast being the most widely used approach. Sound zone's temperature profile, i.e., variation of temperature versus time, serves as the baseline or reference profile for quantifying defects. In this temperature profile, the time taken for the surface temperature to reach the equilibrium temperature is defined to be the break time (see [3]). Break time is useful in determining the diffusivity of the material. Also, knowing sound zone is helpful in estimating thermal diffusivity of the material. However, for a structure that is being inspected in the field, reliably locating a representative sound zone is difficult. This difficulty arises from the non-uniform temperature variation, unrelated to defects, introduced by extraneous factors such as limitations of the instrument and/or test procedure. This spurious contrast has to be eliminated before sound zone pixels can be located.

Researchers have developed several approaches for overcoming the effect of spurious contrast [1]. Pilla et al. [4] developed a procedure for calculating the thermal contrast by approximating the temperature profile of sound zone for a given surface called Differential Absolute Contrast (DAC). The DAC method uses the Fourier heat conduction law to generate ideal sound zone data for each point on the surface. The method first identifies a point from the segment of the $\ln(\Delta T)$ versus $\ln(t)$ graph that is yet to be disturbed by the presence of defect. A line with a negative 0.5 slope is drawn from this point, in accordance with Fourier heat conduction law for a semi-infinite solid to represent the temperature profile of a representative sound zone at this location. The difference between such extrapolated virtual sound zone's temperature

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http://dx.doi.org/10.1016/j.ndteint.2017.01.006
Received 30 May 2016; Received in revised form 7 January 2017; Accepted 11 January 2017
Available online 19 January 2017
0963-8695/

profile and the experimentally determined temperature profile for the same location on the surface is defined as DAC.

Since the DAC method had difficulties in characterizing deeper defects, a correction was applied for a specimen of finite thickness to determine the thermal contrast called modified Differential Absolute Contrast (mDAC) [5–7]. In both DAC and mDAC methods, the contrast is determined for each point by comparing the experimental temperature profile for the defect with the theoretical defect free temperature profile at the same point. In these approaches, the effect of non-uniform heating across the specimen surface is automatically compensated, if the non-uniformity remains constant for all frames. However, in reality the spurious non-uniformity keeps varying from frame to frame as the specimen cools down and such variations introduce errors in the contrast obtained through this method. These two topics are discussed in a recent comprehensive review of pulse thermography by Balageas [8]. He points out the successes and limitations of various approaches and indicates the current needs.

Shepard et al. [9] developed the self-referencing thermography which eliminates the need for a representative sound zone. A similar method is also described by Omar et al. [10]. In this approach, a set of neighborhood pixels are selected and the temperature evolution of each pixel is compared with the average value of the total neighborhood pixels selected to find the defects. The effectiveness of this procedure depends on the size and the location of the neighborhood pixels selected.

The thermographic signal reconstruction (TSR) method is another widely used method introduced by Shepard et al. [11]. This method relies on the reconstructed data using a polynomial curve fit for the $\ln(\Delta T)$ versus $\ln(t)$ graphs and their derivatives to identify defects. Spurious contrasts are automatically eliminated in the derivative images. However, for quantifying the depth of the defect in TSR method for a material of unknown diffusivity, sound zone profile is needed. Because the break time and equilibrium temperature could only be estimated, if the sound zone temperature profile is known. Sripragash and Sundaresan [12] recently presented a normalization procedure that renders the thermographic temperature profiles independent of material properties and instrumentation settings. In the normalized format, experimental results can be readily compared with numerically generated thermographic results. Further, defect depths can also be easily obtained as a fraction of plate thickness from normalized plots. The determination of sound zone temperature profile is essential for this normalization procedure.

This paper presents (i) a new approach for determining the sound zone temperature profile based entirely on the measured data and (ii) a means of removing spurious non-uniformity in temperature distribution across the specimen surface. We start with an illustration of removing spurious contrast in defect free specimens. Since this procedure cannot be directly applied to specimens with defects, additional signal processing steps needed are described. Finally, the procedure for identifying the representative temperature profile of a sound zone pixel is described. Results from the successful application of this approach are presented for a steel specimen with flat bottom holes and two carbon fiber reinforced polymer laminates with embedded defects and fatigue damage.

2. Experimental setup

The experimental setup consists of a commercial pulse thermography equipment, Thermoscope II with a FLIR SC5000 IR camera having 320 × 256 of maximum resolution, two symmetrically placed Xeon flash lamps, and a 7 in×9 in rectangular enclosure or hood that supports the camera and flash lamps. This hood also surrounds the surface of the part that is being evaluated. The results reported in this paper were obtained from two sets of specimen. First set of specimens were free of defects and were used to illustrate and model the spurious contrast. They include a steel and an aluminum plates of uniform thickness of 0.5 in, and a 0.1 in thick quasi-isotropic carbon/epoxy laminate with $[0,45,90,135]_s$ layup. The second set of specimen was used to develop and validate the procedures, for determining the sound zone, presented in this paper. Three different specimens were used for this purpose. The first one is a 12 in × 12 in × 0.5 in steel specimen with flat bottom holes shown in Fig. 1a. The second specimen is a 11.5 in × 11.5 in × 0.092 in square composite plate having $[0,90]_{8s}$ layup and Teflon inserts as shown in Fig. 1b. The third specimen is a 3 in × 10 in × 0.7 in rectangular composite specimen $[0/60/-60/60/0]_s$ with a central circular hole shown in Fig. 1c, with a gauge length of 6.5 in, subjected to 135, 000 tension–tension fatigue loading that resulted in limited damages around the circular hole and edges. Based on preliminary studies the frame rate of the IR camera was selected as 60 Hz and according to ASTM E-2582 the duration of thermographic record was selected to be more than twice the break time of the respective specimen [13].

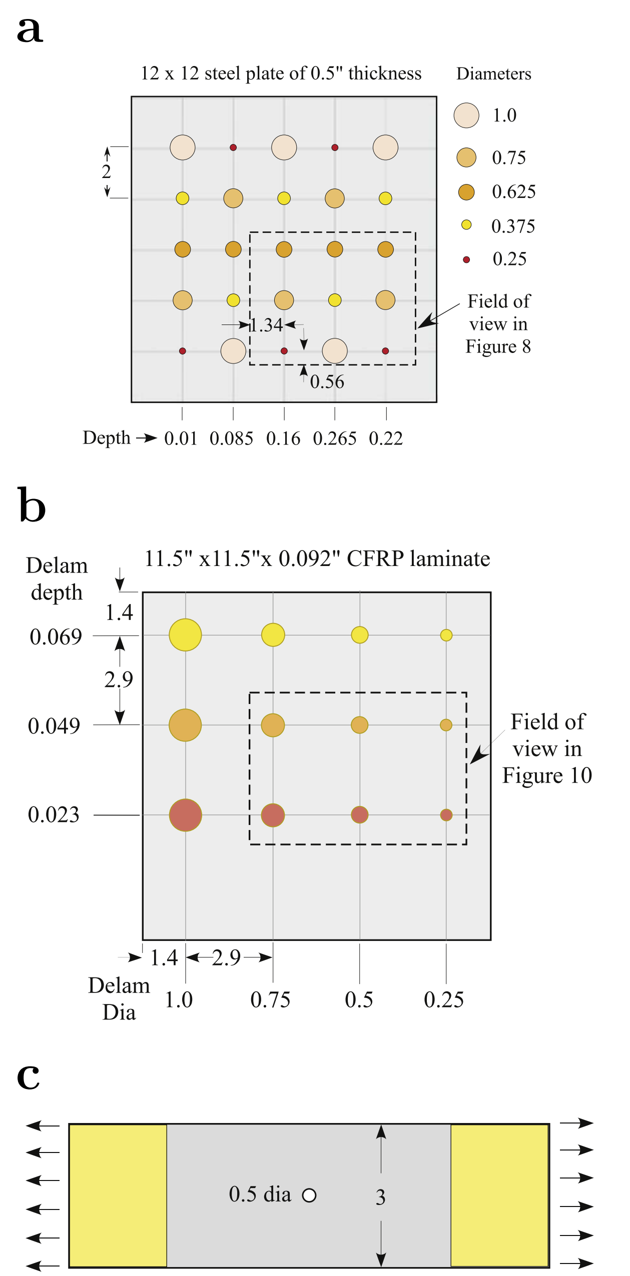

Fig. 1. (a) Steel plate with flat bottom holes. (b) Carbon/epoxy specimen with Teflon inserts to simulate delaminations. (c) Carbon/epoxy specimen with central circular hole subjected to fatigue loading (all dimensions are in inches).