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Probability density function estimation of a temperature field obtained by pulsed radiometric defectoscopy

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ABSTRACT

This paper presents testing of subsurface defects by Pulsed Radiometric Defectoscopy (PRD) techniques. Such techniques rely on transient infrared radiation from the sample heated by the short duration flux initiated by flesh. Response function is derivated by experimental measurement with infrared camera FLIR SC 620. Experimental results are considered for the samples with controlled designed defects. For illustration, PRD techniques analysis was applied to detect subsurface defects in the aluminum samples. The time history of the surface temperature after the absorption of a short light pulse is used to obtain information about the subsurface structure and the thermophysical properties of the material. For the obtained values of the temperature difference (measurand), which is the random quantity, it is necessary to determine the probability density function (PDF). Namely, PDF estimation of the temperature difference has been done using a Monte Carlo method and a modified least-squares method. Knowledge of the PDF for the output quantity is needed to determine a coverage interval.

1. Introduction

The Pulsed Radiometric Defectoscopy (PRD) method has attracted interest in different applications since it was first presented in 1961 [1]. In papers [2–4], this method has different names, e.g. impulse radiometry, pulsed video thermography, and it was developed by theoretical approach in detail analysis of infrared (IR) signals and its reflection from the sample to IR detector. Implementation of IR equipment of 80 s, with possibilities to be employed for Pulse Videothermography (PVT) techniques, has been described in [2,5]. Approval for PVT method for detection of defects or cracks beyond the surface is the basic advantage of this method.

The basic concept of method is to measure small temperature differences, detected on the surface by radiation emitted from the frontside of the samples. This radiation is caused by flashing with flux from the opposite side. Backside of samples has defects which transform emitted radiation in the form of small temperature differences recognised by IR camera. Physical parameters such as thermal diffusivity, reflections from surface, heat capacity and thermal conductivity can be obtained after pulse by analyzing images of modern IR cameras.

For the obtained values of the temperature difference (measurand), which is a random quantity, it is necessary to determine the probability density function (PDF). Consequently, PDF estimation of the temperature difference has been done using a Monte Carlo method and a modified least-squares method [6].

This paper presents the pulsed radiometric defectoscopy technique application for determination of the thermal

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NDE, i.e. measurement of the temperature difference. Section 2 gives theoretical basis of the PRD techniques method. The experimental method set up is given in Section 3. Section 4 presents the experimental results. The choice of probability density function (PDF) for two input quantities (temperatures) is presented in Section 5.1. In Section 5.2 evaluation of probability density function for the temperature difference (output quantity) is demonstrated. The conclusion is given in Section 6.

2. Theoretical basis of the method

Basic physical principle of PRD method is conversion of absorbed electromagnetic energy, generated by the light pulse on the surface into the heat. This generated heat energy is conducted through the wall, thickness changing absorbing surface radiance depends on structure in the wall thickness. Heat conduction along the wall thickness is considered by one-dimensional temperature model (1D model) [5]. Optimizing the pulse to provide efficient heat transparence through the surface and sample wall thickness, without overheating, is an important condition for evaluating the temperature inside the sample. Transversal-mode pulse is changing over the depth of the sample with Gaussian distribution whose wavelength is much larger than the sample thickness. Under these conditions general solution of Fouriers equation [7], can be approximated with one-dimensional temperature field. In this equation radiated heat E_0 penetrates through the sample depth and injected heat density above the defects will make an inhomogenous field distribution of scene radiance. The layer above the defect will have temperature T_2, and its time profile is shown in Fig. 1 (dashed curve). In addition, the layer behind the defect will have temperature T_1, and its time profile is shown by full curve (Fig. 1). According to reference temperature profiles, solutions behind and above defects, where sample has full thickness, are given by Eqs. (1) and (2), respectively:

$$T_1 = \frac{E_0}{\rho C\sqrt{\pi a t}} \exp\left(-\frac{x^2}{4at}\right) \tag{1}$$

$$T_2 = \frac{E_0}{\rho C x_1}\left[1 + 2\sum_{n=1}^{\infty} \exp\left(-n^2\pi^2 F_0\right)\right] \tag{2}$$

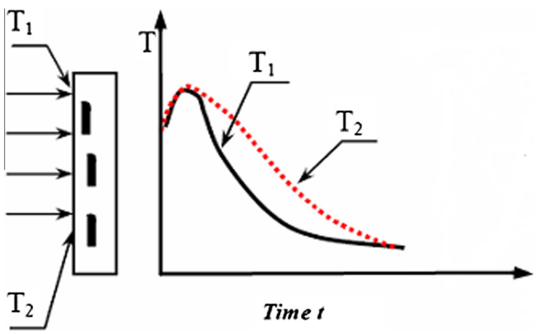

Fig. 1. Temperature decay in time on the sample surface.

That value can be measured with suitable IR sensor.

The inspection of surface evaluated by thermal differences that appear above defects can approximately give empirical estimations of threshold sensitivities analyzed by IR images. Measuring temperature with IR cameras, such as FLIR SC 620, provides high scene resolution in new applications. Accuracy of measuring temperature this way requires the knowledge of thermal diffusion process through the material and thermophysical properties of observed sample [5]. High sensitive IR sensor is able to detect all spots on the surface that have described heterogenic heat conduction.

If there is heat conduction, measured temperature difference is shown as thermal radiation flux equivalent to the current signal on IR detector and expressed by the following equation [7,8]:

$$I = \frac{\varepsilon_b(\lambda, T)A}{e^{\frac{B}{T}} - C} \tag{3}$$

where I is the IR camera output signal (thermal value) that corresponds to thermal radiation flux equivalent to some grey body, $\varepsilon_b(\lambda, T)$ is emissivity coefficient of grey body, T is corresponding analog temperature of grey body, A, B and C are calibration constants that can be determined experimentally. Excitation is luminous pulse variable in time and it causes non-steady heat effect over the depth of sample.

In the case of equilibrium with environmental temperature, radiance of scene indicates homogenous emissivity of inspected surface. This theoretical basis [2], is improving by continuous exploitation using new types of IR sensors. Their temperature resolutions became more sensitive than 0.04 °C (e.g. FLIR SC 620). This feature resulted in capability to capture very short thermal pulses [4] and excitations of radiance differences on the sample surface [8]. The mathematical model of one-dimensional heat conduction cannot completely describe radiance on the surface above the defects. It is approved by many experiments [8], where defects width and shape disturb one-dimensional model of heat conduction due to lateral heat conduction and distribution. That is the reason why limited defects cannot be treated only by depth, but also by its shape and its width.

3. Experimental method setup

The experimental setup consists of a photographic flesh light source – PF1, a test sample – TS 13 and the IR camera – FLIR SC 620 presented in Fig. 2 [4]. These elements are kept in the ambient temperature. For heating surface of the sample, photographic flash YASHICA CS-250AF was used, as pulsed source. IR radiated energy was recorded with IR camera and transferred to personal computer.

Aluminum sample with periodical structure of the grooves (simulated defects) was used. Structure of the sample is shown in Fig. 3a and b. The number of defects was six (Fig. 3a). All defects were equally spaced and of equal dimensions. Consequently, displacement of the defect from the top surface of sample is marked with d, width and depth of the defect with W and z, respectively (Fig. 3b). Thickness of the sample is marked with L, and it was kept