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A novel defect depth measurement method based on Nonlinear System Identification for pulsed thermographic inspection

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ABSTRACT

This paper introduces a new method to improve the reliability and confidence level of defect depth measurement based on pulsed thermographic inspection by addressing the over-fitting problem. Different with existing methods using a fixed model structure for all pixels, the proposed method adaptively detects the optimal model structure for each pixel thus targeting to achieve better model fitting while using less model terms. Results from numerical simulations and real experiments suggest that (a) the new method is able to measure defect depth more accurately without a pre-set model structure (error is usually within 1% when SNR > 32 dB) in comparison with existing methods, (b) the number of model terms should be 8 for signals with SNR$\in$[30 **dB**, 40 **dB**], 8–10 for SNR > 40 dB and 5–8 for SNR < 30 dB, and (c) a data length with at least 100 data points and 2–3 times of the characteristic time usually produces the best results.

1. Introduction

Over the last decade, pulsed thermography has gained increasing attention due to its rapid, robust, non-contact, non-invasive and in-expensive characteristics. It has been qualitatively and quantitatively applied to different classes of material to detect a variety of in-service degradations [1] such as corrosion in metals, impact damages and delamination in composites [2]. Quantitative characterisation by extracting degradation depth, size, shape and thermal properties has been proven to be effective in pulsed thermography [3–10].

Quantitative prediction of defect depth has been an important research topic over the past 20 years. Most of the proposed methods estimate the defect depth using a characteristic time. For the different methods based on thermal contrast in the normal time scale or logarithmic scale, the peak time of the first or second derivative of temperature curve is usually considered as the characteristic time. The Peak Temperature Contrast method (PTC) [11] calculated the thermal contrast between the defective/damaged region and an adjacent sound or non-defective region. Because of the 3D heat conduction effect, the temperature contrast first increases with time and then decreases [11]. The time at which the temperature difference rises to its maximum value is approximately proportional to the square of the defect depth, and the proportionality coefficient depends on the size of the defect. The smaller the size, the lower the maximum contrast and the

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shorter the peak contrast time is [12]. This dependence limits the applications of the PTC method. Peak Slope Time (PST) is corresponding to the peak time of the 1st derivative of thermal contrast. It was found that PST is also approximately proportional to the square of the defect depth and the proportionality coefficient does not depend on the defect size [13]. Krapez et al. [14] proposed to use an early detection of the contrast to recover defect depth that requires a pre-set threshold. Maldague [15] proposed to use the Discrete Fourier Transform (DFT) to calculate defect depth in the frequency domain. It was observed that deeper defects are visible at lower frequencies while shallower defects are detected at higher frequencies. A relationship between the frequency and depth was then studied. All above-mentioned methods require a reference point which is normally chosen from a sound area manually. There are several reports that tried to automatically obtain the reference. Ringermacher et al. [16] used the average temperature from the entire surface before flash as the reference. This works well only when the damaged region is small and the surface is uniformly illuminated. Pilla et al. [17] used the first several frames to calculate a reference temperature. However, sometimes automatic selection of the reference can be challenging, especially when the size of defect is large.

Recently some reference-free methods have been developed. Shepard et al. [18] suggested to use the peak time of the second derivative of temperature decay in the logarithmic scale to determine defect depth, which is also called Log Second Derivative (LSD) method. It is observed that the second derivative peak time t_{LSD} appears earlier than the Peak Slope Time t_{PST}, before it is affected by 3D conduction. This method is more accurate than the PST method described above. However, applying the second order differentiation of the temperature can be noisy. A polynomial function fitting of temperature decay was therefore proposed to address this problem, where the second derivative is calculated directly from the fitted model. In this case, fitting the curve on the exact location of the second derivative peak is very important [6]. Zeng et al. [19] proposed an Absolute Peak Slope Time (APST) method to predict the defect depth. A new time-dependent function is obtained by multiplying the original temperature decay with the square root of the corresponding time. The absolute peak slope time t_{APST} is defined as the peak time of the first derivative of this new function. It has been demonstrated that the square of the defect depth has a linear relation with t_{APST}. A polynomial model can also be used to fit the new time-dependent function and the first derivative can be calculated directly from the fitted model. All of the methods described are susceptible to signal noise that is typically large in thermography data because the fitted models are data-driven without considering the underlying physics-based models. Sun [6] introduced a method based on Least-Square Fitting (LSF) of a theoretical heat transfer model to the temperature decay for a direct determination of depth. This method also accounts for part of the 3D heat conduction effect and therefore is expected to be more reliable and robust when the 3D effect is significant. Although fitting based on physics-based models, where the model structure is known, reduces the sensitivity to noise, it requires the estimation of multiple unknown parameters simultaneously using optimisation techniques. This can be very time-consuming and requires advanced searching methods.

This paper proposes a Nonlinear System Identification (NSI) method to measure the defect depth in a more automatic and flexible manner. This paper is organised as follows. The proposed method is presented in Section 2. The results and discussions of the numerical simulations and the experimental example are presented in Section 3 while the conclusions are given in Section 4.

2. Nonlinear System Identification method

2.1. Theory

In pulsed thermographic inspection, the experimental setup of which is illustrated in Fig. 1(a), a short and high energy light pulse is projected onto the sample surface through one or two flash lamps. Heat conduction then takes place from the heated surface to the interior of the sample, leading to a continuous decrease of the surface temperature [6]. An infrared camera controlled by a PC captures the time-dependent response of the sample surface temperature. In areas of the sample surface above a defect (see point 2 in Fig. 1) the transient flow of heat from the surface into the sample bulk is wholly or partially obstructed, thus causing a temperature deviation from the sound areas (see point 1 in Fig. 1). The time when the temperature deviation occurs can be used to estimate the defect depth. The surface temperature due to a defect at depth L for a plate is given by [20,21].

$$\Delta \boldsymbol{T}(\boldsymbol{t}) = \frac{\boldsymbol{Q}}{\sqrt{\boldsymbol{\pi\rho ckt}}}\left[1 + 2\sum_{\boldsymbol{n}=1}^{\infty} \mathbf{exp}\left(-\frac{\boldsymbol{n}^2\boldsymbol{L}^2}{\boldsymbol{\alpha t}}\right)\right] \tag{1}$$

where $\Delta T(t)$ is the temperature variation of the surface at time t, Q is the pulse energy J, ρ is the material density (kg/m^3), c is the heat capacity (J/K kg), k is the thermal conductivity of the material (W/(K m)), and α is the thermal diffusivity (m^2/s). In order to obtain a specific characteristic time without a reference curve, Zeng et al. [19,22] proposed to first multiply both sides of Eq. (1) with $\sqrt{t}$, and define a new time-dependent function $f(t)$ as:

$$\boldsymbol{f}(\boldsymbol{t}) = \Delta \boldsymbol{T}(\boldsymbol{t}) \cdot \sqrt{\boldsymbol{t}} = \frac{\boldsymbol{Q}}{\boldsymbol{e}\sqrt{\boldsymbol{\pi}}}\left[1 + 2\sum_{\boldsymbol{n}=1}^{\infty} \mathbf{exp}\left(-\frac{\boldsymbol{n}^2\boldsymbol{L}^2}{\boldsymbol{\alpha t}}\right)\right] \tag{2}$$