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Improving defect visibility in square pulse thermography of metallic components using correlation analysis

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ABSTRACT

Infrared (IR) thermography has gained wide applications as an important non-destructive testing (NDT) technique. Improving defect visibility is critical to achieving an accurate detection result through IR thermography. In this study, we propose a novel approach to improving defect visibility in square pulse thermography (SPT) of metallic components. In the proposed approach, the correlation function of contrast (CFC) is defined for the first time. Based on the theories of heat conduction and of correlation analysis, the differences of CFC between defects and sound regions are determined. We found that the peak lag time of the CFC is an effective feature for discriminating defects and sound regions in SPT. A new image is then constructed using the peak lag time of the CFC to improve defect visibility. To verify the efficiency of the proposed approach, an experiment was conducted on a steel specimen, and the principle component analysis (PCA) and the presented approach were compared. The results show that through the proposed approach, defects in metallic components can be indicated more clearly and detected more accurately.

1. Introduction

Non-destructive testing (NDT) is an important technique for guaranteeing the qualities of components in a mechanical system. One kind of NDT method, infrared (IR) thermography, has been successfully applied to detect various defects in metallic and non-metallic components [1–5]. When implementing IR thermography, defect visibility depends on many factors, such as the size of the defect, the heating intensity and the performance of the IR thermal imager [6]. Meanwhile, intensive noise in the raw thermograms seriously weakens defect visibility [7,8]. As a result, improving defect visibility has always been a crucial issue for IR thermography.

Several signal processing techniques have been widely applied to improve defect visibility in IR thermography, including discrete Fourier transform (DFT) [9,10], thermographic signal reconstruction (TSR) [11,12], prominent component analysis (PCA) [13] and partial least square thermography (PLST) [14–16]. Through employing DFT, defects become more distinct in the phase image constructed in the frequency domain. TSR implements polynomial fitting on thermal data. The first or the second time derivatives of the fitted data construct new images in which defect indications are significantly enhanced. PCA processing can diminish redundancy and noise in the captured data. The second prominent component image can indicate the existence of defects in a clearer manner than raw thermograms can. PLST is a relatively new technique that employs partial least square regression (PLSR) to process captured thermal data. The first PLS component has been determined to

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represent the effect of non-uniform heating. Through subtracting this first component, visibility of defects can be distinctly improved in the constructed image. Besides these widely used techniques, some other approaches have also been proposed to improve the defect visibility [17,18]. Through these algorithms, some disturbances from non-uniform heating, inhomogeneous surface emissivity and random testing noise can be diminished to some extent, which is very useful for enhancing the contrast indications of defects. Each of these methods shows feasibility to improve defect visibility in thermal images in certain cases. However, some defects still remain ambiguous after processing due to factors such as the small dimensions of defects, the severe non-uniform heating phenomenon, or poor performance of the thermal imager. Consequently, improving defect visibility is still a challenge in IR thermography.

The potential of correlation analysis for improving defect visibility in IR thermography has been of growing interest in recent years. The correlation function between the temperature evolution of each pixel and the excited signal has been investigated in both lock-in thermography and inductive thermography. The new methods induced have been termed thermal-wave radar [19,20] and pulsed inductive thermal wave radar thermography [21], respectively. In [22], a correlation function between the temperature evolution measured in a real test and that calculated by an analytical model was studied in pulsed thermography. The maximum of this correlation function was used to construct an enhanced image. Besides the correlation function, a correlation coefficient was also applied to thermal data processing in IR thermography. The correlation coefficient between the temperature evolution of each pixel and that of a manually chosen reference pixel was employed to construct an image called a correlogram [23–25].

The present paper aims to further explore the potential of the correlation function to improve defect visibility in square pulse thermography (SPT), a kind of IR thermography. Although SPT is not as popular as pulsed thermography, it is still an alternative method of detecting deep defects and limiting the maximum temperature on the detected surface [26]. Unlike existing correlation-analysis-based methods in IR thermography, the proposed method performs correlation analysis on thermal contrast evolution rather than on temperature evolution. We define the correlation function of contrast (CFC) and determine the differences in the CFC between defects and sound regions. We also find that the peak lag time of CFC is an effective indicator for distinguishing defects and sound regions in SPT. A SPT experiment was conducted on a steel plate. The efficiency of the proposed approach was verified based on the experimental thermal data through comparison with the PCA method.

2. Methodology

In the present study, features of thermal contrast of defects in SPT are analyzed based on heat conduction theory. In a real test, these features are easily covered by noise. CFC is defined to detect these features of defects from heavily noisy signals. To indicate defects directly, a characteristic parameter of the calculated CFCs is further used to construct a new image in which the defect visibility is improved.

2.1. Features of thermal contrast in SPT

In IR thermography, thermal contrast is a common indicator for describing a defect. It is defined as the thermal difference between a defect and a sound region. To investigate the thermal contrast of a defect in SPT, the temperature evolution of each pixel should first be analyzed. The one-dimensional heat conduction model, in which the transverse heat conduction is ignored, has been commonly employed to determine the temperature variation in IR thermography [27–31]. By solving the one-dimensional heat conduction equation for SPT, the temperature evolution of a sound region (T_S) and that of a defect (T_D) during the heating period can be respectively described as follows [32]:

$$T_s(t) = T_0 + \frac{2q}{e}\frac{\sqrt{t}}{\sqrt{\pi}}\left[1 + 2\sqrt{\pi}\sum_{m=1}^{\infty} ierfc\left(\frac{mL_s}{\sqrt{kt}}\right)\right] \tag{1}$$

$$T_d(t) = T_0 + \frac{2q}{e}\frac{\sqrt{t}}{\sqrt{\pi}}\left[1 + 2\sqrt{\pi}\sum_{m=1}^{\infty} ierfc\left(\frac{mL_d}{\sqrt{kt}}\right)\right] \tag{2}$$

where *ierfc* is the integral of the complementary error function *erfc*, T_0 is the initial temperature of the sample before heating, q is the heating intensity injected into the specimen, L_s is the thickness of the sample, L_d is the residual thickness of the material at the defect region, e is the thermal effusivity and k is the thermal diffusivity of the material.

Based on the temperature evolution of a defect and a sound region determined by Eqs. (1) and (2), we can calculate the thermal contrast evolution for a defect through

$$C_d(n) = T_d(n) - T_s(n) = \frac{2q\sqrt{nt_s}}{e}\sum_{m=1}^{\infty} 2\left[ierfc\left(\frac{mL_d}{\sqrt{knt_s}}\right) - ierfc\left(\frac{mL_s}{\sqrt{knt_s}}\right)\right] \tag{3}$$

where $n = 1, 2, \ldots, N$, N is the length of the captured thermogram sequence, $T_d(n)$ is the temperature evolution of a defect, $T_s(n)$ is the temperature evolution of a referenced sound region and t_s is the time interval between two sequential thermograms.