engineering proceedings

Proceeding Paper

Defect Identification in Thermographic Nondestructive Testing under Cyclic Heating Using SVD Thermo-Component Analysis †

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† Presented at the 17th International Workshop on Advanced Infrared Technology and Applications, Venice, Italy, 10–13 September 2023.

Abstract: This study applied SVD (singular value decomposition) thermo-component analysis to defect detection using active infrared thermography. SVD decomposes time-series thermal image data into a temperature time-series waveform (PC) and a relative-value distribution image with a PC waveform (EOF image). It is possible to clarify the physical meaning of the EOF image based on the analysis of the PC waveform. The optimal EOF image that coincides with the characteristic thermal variation image due to the effect of defects can be selected.

Keywords: nondestructive inspection; active infrared thermography; multivariate analysis; singular value decomposition

Citation: Oiso, S.; Shiozawa, D.; Ogawa, Y.; Sakagami, T. Defect Identification in Thermographic Nondestructive Testing under Cyclic Heating Using SVD Thermo-Component Analysis. *Eng. Proc.* **2023**, *51*, 42. https://doi.org/10.3390/engproc2023051042

Academic Editors: Gianluca Cadelano, Giovanni Ferrarini and Davide Moroni

Published: 12 December 2023

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1. Introduction

Active infrared thermography [1] is one of the nondestructive inspection methods for detecting defects inside structures. This method observes the propagation process of thermal energy given to a measurement object externally using a lamp, heater, and ultrasonic wave. When heat is applied from the surface to the component with an internal defect, a time variation in temperature distribution is observed on the surface because the defect prevents heat conduction in the internal direction. Since this temperature change is small, image analysis methods that emphasize the detection of the temperature change are applied. Maldague and Marinetti [2] proposed a method for extracting defects in flash-heated active thermography based on the phase of temperature variation obtained via FFT. Rajic [3] proposed PCT (principal component thermography) based on principal component analysis to extract temperature variations due to defects in flash-heated active thermography, and showed that PCT has excellent noise reduction effects by extracting characteristic temperature distribution variations. Uchida et al. [4] showed that, in thermoelastic stress analysis (TSA), the load signal and stress distribution can be simultaneously extracted from thermoelastic temperature fluctuations observed in a loaded measurement object using SVD (singular value decomposition), without the need for a reference signal input from another measurement device. This method (SVD thermo-component analysis) is suitable for in situ measurements because it does not require a reference signal, and by decomposing each principal component into various temperature fluctuations it has the potential to reduce noise and extract various phenomena other than the dominant loading frequency.

The flash heating and FFT or PCT technique extracts the temperature change in the out-of-plane heat conduction from the surface to the interior due to the influence of internal defects. The temperature change including the effect of defects appears in principal components with large singular values, such as the first or second principal component. The principal components smaller than the second principal component include not only the out-of-plane heat conduction but also the temperature change in the in-plane heat conduction. The use of multiple principal components is expected to improve defect detectability by increasing the information that can be obtained about the defect. The analysis of cyclic heating and cooling processes facilitates a consideration of the physical significance of each principal component. In this paper, SVD thermo-component analysis is applied to the temperature change under cyclic heating, and the decomposition behavior of the temperature fluctuation is studied via SVD thermo-component analysis and the defect detectability is examined.

2. Principle of SVD Thermo-Component Analysis

$\varphi(p,t)$ is the time series of a thermal image obtained via infrared thermography. $P = (x, y)$ is the pixel position of the thermal image. Let us define a $P \times N$ observation matrix φ^*. The rows are the rearranged pixel positions and the columns are the corresponding times. P is the total number of pixels in the image and N is the total number of frames. The SVD of the observation matrix φ^* is given by

$$\begin{aligned}\varphi^*(p,\ t) = U\Sigma V = [u_1\ u_2\ \cdots\ u_N]\begin{bmatrix}\sigma_1 & \cdots & 0\\ \vdots & \ddots & \vdots\\ 0 & \cdots & \sigma_N\\ 0 & \cdots & 0\end{bmatrix}\begin{bmatrix}v_1^T\\ v_2^T\\ \vdots\\ v_N^T\end{bmatrix}\\ = u_1(p)\sigma_1 v_1^T(t) + u_2(p)\sigma_2 v_2^T(t) + \ldots + u_N(p)\sigma_N v_N^T(t)\end{aligned} \tag{1}$$

SVD decomposes the time series of a thermal image to the right singular vector $v_i(t)$ (PC waveform) and the left singular vector $u_i(p)$ (EOF image), which is an intensity distribution per pixel relative to the $v_i(t)$ waveform. The singular values σ_i are the contributions of the decomposed temperature change $\boldsymbol{u}_i(p)\ \boldsymbol{v}_i^{\boldsymbol{T}}(t)$. In TSA, temperature change is observed on the surface subjected to periodic load based on the thermoelastic effect.

$$\Delta\sigma = -k\Delta T \tag{2}$$

$\Delta\sigma$ is the principal stress range, k is the thermoelastic coefficient, ΔT is the temperature change range. Since temperature changes appear mainly in response to the load signal, the PC waveform is the load signal and EOF is the stress distribution of the load signal. The thermal time-series data obtained via infrared thermography are decomposed into PC waveforms and EOFs using SVD, and the various waveforms and their components are analyzed, which is called SVD thermo-component analysis. In the active thermography method using cyclic thermal loads, the surface temperature distribution and its changes include differences in thermal conduction properties due to inside defects. It is considered that SVD thermo-component analysis extracts and emphasizes the temperature changes and distributions affected by defects from the measurement results.

3. Experimental Method

This study used a flat-bottom hole specimen with eight artificial defects of 10 mm in diameter introduced into a 10 mm thick SUS304 steel plate, as shown in Figure 1. The surface opposite the hole opening was measured with an infrared camera in simulation of the detection of the thickness reduction (remaining thickness R). Heating was performed from the side opposite the infrared camera using halogen lamps. Four halogen lamps were used to provide a periodical thermal load by controlling the emission time of the lamps with a solid-state relay. The heating cycle was defined as one cycle of 2.0 s for the lamp emission time and 2.0 s for the lamp off time, and time-series data for five cycles were acquired via infrared thermography (FLIR SC7500). The SVD thermo-component analysis was performed on the time-series data of each defect trimmed to a size of 30 mm square.

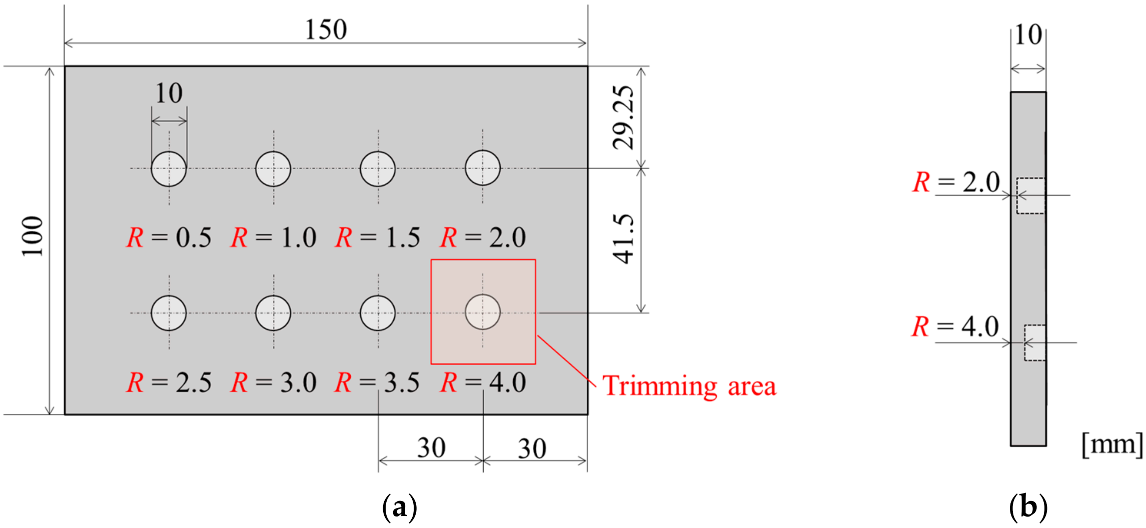

Figure 1. Flat-bottom hole specimen employed in this study: (**a**) illustration of the specimen of the side for infrared temperature measurement; (**b**) illustration of cross-section of (**a**).

4. Result and Discussion

Figure 2 shows the results of the SVD thermo-component analysis for an artificial defect with a residual thickness of 4.0 mm at the trimming area of the square surrounded by the red solid line in Figure 1a. The PC1 waveform shows a monotonic temperature increase and the values of EOF1 are all positive and their range is small. It is considered that the component that monotonically increases the temperature of the specimen while undergoing cyclic heating is extracted. The values of EOF1 are large at the center where the plate thickness is thin, and this indicates that temperature increase in PC1 is large.

The PC2 waveform shows mainly an increase in temperature, with a small periodic temperature decrease. The EOF2 shows positive values at the center and negative values at the periphery. Equation (1) indicates that the negative EOF has the opposite temperature change to the positive EOF. In other words, the EOF2 indicates a temperature rise at the center, while it decreases at the periphery. It is considered that the temperature rise in the thinned area is larger than that in the surrounding area because the thermal load is applied to the back of the surface, and that in-plane heat diffusion occurs from the high-temperature part of the thinned area to the surrounding area when the heat source is turned off.

EOF3 is a noise component of the thermographic equipment because of its random temperature waveform and distribution. The PC4 waveform shows periodic fluctuations corresponding to the periodic heating of the halogen lamp; EOF4 shows a distribution of values close to the diameter of the defect's hole. These trends were similar for defects of different residual thickness. The small heat capacity in the thinning area indicates that large cyclic temperature changes occur compared to the surrounding area. Negative values around the wall thinning are considered to indicate heat conduction from the hot wall thinning area to the surrounding area.

It was found from the results of SVD thermo-component analysis that SVD separates the monotonic temperature rise and the periodic temperature change from measurement data, and the difference in heat capacity at the wall thinning is easily detected as a periodic fluctuation component.

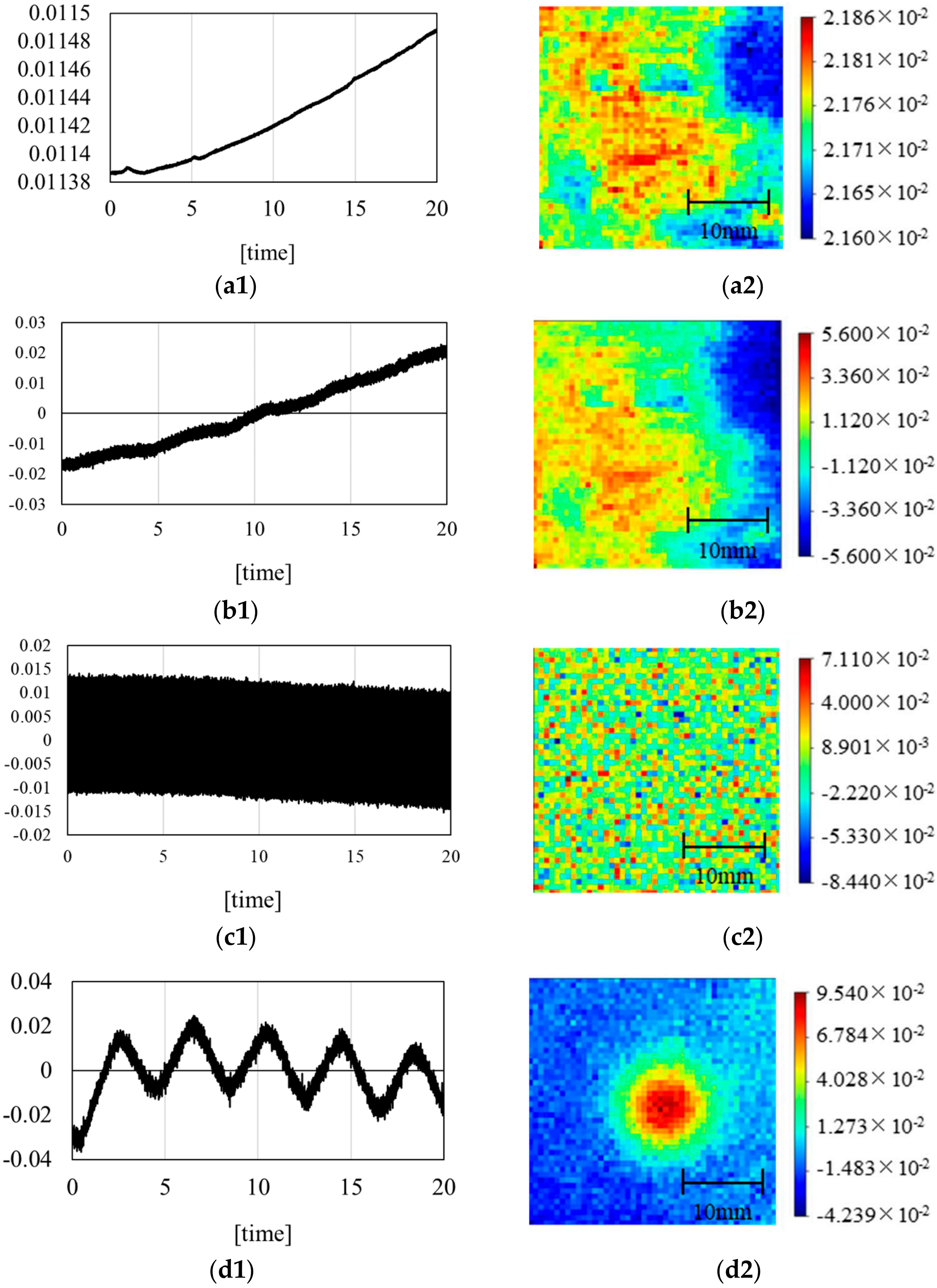

Figure 2. Results of the SVD thermo-component analysis of thickness R = 4.0 mm: (**a1**) PC1, (**b1**) PC2, (**c1**) PC3, and (**d1**) PC4 time-series temperature variation waveform; (**a2**) EOF1, (**b2**) EOF2, (**c2**) EOF3, and (**d2**) EOF4 images of the relative value distribution image with PC waveform.

5. Conclusions

To improve the accuracy of defect detection using active infrared thermography, this study applied SVD thermo-component analysis to time series of thermal image data observed when an object was subjected to a periodic thermal load. The active infrared thermography with periodical thermal load was performed on specimens with introduced artificial defects of different thicknesses. It was found that artificial defects can be detected by selecting the optimal EOF image based on the interpretation of the PC waveform corresponding to the periodical thermal load.

Author Contributions: Author Contributions: The work presented in this paper is a collaboration between all authors. S.O. and Y.O. acquired and processed the experimental data. D.S. and T.S. analyses and contributed to writing the paper. The manuscript has been discussed by all the authors. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by JST, PRESTO Grant Number JPMJPR2095, Japan.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

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