Research Article

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Use of line laser scanning thermography for the defect detection and evaluation of composite material

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Abstract: The line laser scanning thermography was applied for the defect detection and evaluation of composite material in this work, which was carried out by the following procedures. First, a novel contrast enhancement method by homomorphic technology was proposed and validated by a case study. Then, a specimen containing 12 prefabricated defects was detected using line laser scanning thermography and the obtained thermal image sequence and changeable temperature were analyzed. Finally, the defect area was obtained via such thermal image processing as contrast enhancement based on the proposed method, threshold segmentation and quantitative evaluation. The obtained results show that the composite material defects with a depth of less than 4 mm can be detected using line laser scanning thermography but that with a depth of less than 3 mm can be evaluated quantitatively with a small error less than 10%.

Keywords: line laser scanning thermography, composite material, defect detection, quantitative evaluation

1 Introduction

Composite materials, acting as an important structural material, have been widely used in the field of aerospace, such as airplane, missile, rocket, etc., due to the advantages of excellent specific strength, specific stiffness, fatigue resistance, and corrosion resistance [1]. However, the composite materials are sensitive to such mechanical loads as impact load and fatigue load, which may lead to defects in the materials and dramatically affect the performance of the composite materials [2,3]. Therefore, it is vital to explore the effective detection method.

In recent years, infrared thermography, benefited from the rapid development of infrared camera and computer processing capability, has become a promising detection technology to evaluate the structure with the advantages of non-contact, high speed, visible results, etc. [4–6]. According to the different thermal excitation sources, infrared thermography is composed of pulse infrared thermography [7], ultrasonic infrared thermography [8], eddy infrared thermography [9], and laser scanning infrared thermography [10], among which the laser scanning infrared thermography uses high power laser to detect the structure with the advantages of high controllability, high accuracy, and great light uniformity.

Laser scanning infrared thermography system mainly consists of exciting source, scanning control system, and data acquisition system, as shown in Figure 1. Different from the pulse infrared thermography mechanism that can simplify a one-dimensional heat conduction problem, the laser scanning infrared thermography mechanism is a multi-dimensional heat conduction problem, because it uses high power laser to scan the structure, resulting in heat conduction in vertical direction and in transverse direction along the structure.

For the laser scanning infrared thermography mechanism, Carslaw et al. [11] proposed a surface temperature calculation model excited by continuous laser point/line heat source, but the model did not consider the cooling process after laser excitation. To solve this problem, Ready [12] proposed the laser Gaussian heat source and obtained the temperature field model in time domain. On this basis, Li et al. [13] assumed the adiabatic structural boundary and developed the finite difference model of temperature field under the laser scanning excitation. The obtained temperature curve was in great agreement with the 3D analytical curve. Afterwards, Li et al. [14]...
proposed a mirror point heat source diffusion model to solve the problem of crack detection. However, in the mirror heat source method, defect interface was assumed to be an adiabatic interface, as a result, the thermal wave was fully reflected at the interface without considering the transmission of thermal wave. To solve this problem, Jiang and Chen [15] considered the reflection and transmission of thermal wave at the defect interface and analyzed the changeable temperature of double-layer structure in laser scanning infrared thermography. The obtained results showed that when the laser scanning reached a certain speed, the temperature distribution on the sample surface conformed to that obtained by the one-dimensional heat conduction calculated model. Afterwards, some scholars used laser scanning infrared thermography to detect material defect. In 2011, Burrows et al. [16] used laser scanning infrared thermography to effectively detect crack defects in aluminum and stainless steel materials, which validated the effectiveness of the laser scanning infrared thermography technology for the crack defect detection. Chung et al. [17] built a portable line laser scanning infrared thermography nondestructive testing system with the detection efficiency of 0.254 m/s, which realized the impact damage detection of armored ceramic panel. In 2015, An et al. [18] used laser scanning infrared thermography technology to detect cracks in semiconductor wafers. The obtained results showed that the technology could detect cracks with the width of 28–54 µm. Shi et al. [19] compared the scanning point laser technology and the scanning line laser technology, and proposed an efficient detection strategy, i.e., the line laser was first applied to coarse scan to improve the detection efficiency and then the point laser was applied to refine scan in the defect area to improve the detection accuracy, to detect the surface crack defect of thermal barrier coating with the width of 9.5 µm. In 2016, Skala et al. [20] used pulsed infrared thermography and laser scanning infrared thermography to detect the pollutants of protective glass and analyzed the advantages and disadvantages of the two infrared thermography technologies. The obtained results showed that the better thermal image sequence with higher thermal image contrast can be obtained using laser scanning infrared thermography. In 2018, Jiang et al. [21] realized the coating defects detection using laser scanning infrared thermography with accurate defect location and high measurement accuracy and discussed the application of this technology in nondestructive testing. Aiming to the curvature thermal barrier coatings, Jiao et al. [22] realized the reconstruction of de-bonding defects based on laser scanning infrared thermography. Meanwhile, Wang et al. [23] proposed a detection algorithm based on the comparison of adjacent thermal signals to realize the high-precision detection of surface cracks in materials with low thermal conductivity using laser scanning infrared thermography.

The available literature showed that the laser scanning infrared thermography technology, acting as a great potential nondestructive testing technology, could effectively detect the crack, de-bonding, and impact damage in materials such as semiconductor wafer, ceramics, glass, coating etc., with the advantages of high thermal image quality and great detection accuracy. Therefore, this work attempts to apply the line laser scanning infrared thermography technology for the defect detection and evaluation of composite materials. To this end, a novel contrast enhancement method based on homomorphic technology is proposed to process the initial thermal image. On this basis, the defects are evaluated quantitatively. The proposed method is validated by a specimen with prefabricated defects. This work is of importance because it provides an alternative non-destructive method for the composite materials.
2 The novel contrast enhancement method by homomorphic technology

The purpose of contrast enhancement is to enhance the texture information of the defect area, to highlight the defect edge, and to enlarge the pixel difference between the defect area and the background area. At present, contrast enhancement methods mainly include gray transformation method and histogram adjustment method, which can effectively enhance the contrast. However, the noise in the thermal images is amplified with these methods, resulting in the drowning of defect information. On this account, it is necessary to explore a new contrast enhancement method for the thermal image with defect.

In fact, defect information and background information in the thermal image correspond to the different frequency domain information, i.e., the medium and high frequency information represent the defect texture and defect edge information, while the low frequency information represent the background area in the thermal image. The homomorphic technology, as a special nonlinear filtering technology, is very suitable for contrast enhancement due to the advantages of enhancing high-frequency information and weakening low-frequency information. Thus, a contrast enhancement method by homomorphic technology is proposed to enhance the thermal image contrast.

2.1 Contrast enhancement procedure

The essence of homomorphic technology is to perform the nonlinear transformation for the thermal image, as a result, the non-additive factors that constitute the image become additive to facilitate the contrast enhancement processing in the frequency domain. The contrast enhancement procedure based on homomorphic technology can be summarized as shown in Figure 2.

Generally, a thermal image \( f(x, y) \) can be expressed as

\[
 f(x, y) = i(x, y) \cdot r(x, y), \tag{1}
\]

where \( i(x, y) \) is the incident component, \( 0 < i(x, y) < \infty \), and mainly represents low-frequency information such as background area in thermal image, \( r(x, y) \) is the reflection component, \( 0 < r(x, y) < 1 \), and mainly represents the high-frequency information such as defect texture and edges in thermal image and “ \( \cdot \) ” is the point multiplication operation.

![Figure 2: The contrast enhancement procedure based on homomorphic technology.](image-url)

Due to the point multiplication operation between \( i(x, y) \) and \( r(x, y) \), the equation (1) is processed with logarithmic operation to transform the point multiplication operation into the additive operation to facilitate the subsequent operations in the frequency domain.

\[
 \ln f(x, y) = \ln i(x, y) + \ln r(x, y). \tag{2}
\]

In order to convert equation (2) to the frequency domain for operations, processing the equation (2) with Fourier transform yields,

\[
 Z_{\ln}(u, v) = F[\ln f(x, y)] = F[\ln i(x, y) + \ln r(x, y)] = I_{\ln}(u, v) + R_{\ln}(u, v), \tag{3}
\]

where \( Z_{\ln}(u, v) \) is the spectrum function of thermal image, \( I_{\ln}(u, v) \) is the low-frequency component, and \( R_{\ln}(u, v) \) is the high-frequency component.

In order to enhance the thermal image contrast, a homomorphic transfer function, \( H(u, v) \), is introduced and multiplied with the \( Z_{\ln}(u, v) \) in the frequency domain as shown in equation (4).

\[
 G_{\ln}(u, v) = H(u, v) \cdot Z_{\ln}(u, v) = H(u, v) \cdot I_{\ln}(u, v) + H(u, v) \cdot R_{\ln}(u, v) \tag{4}
\]

where \( G_{\ln}(u, v) \) is the spectrum function of thermal image after contrast enhancement, \( H(u, v) \) is the homomorphic transfer function with the function of enhancing the high-frequency component and weakening the low-frequency component. According to equation (4), the low-frequency component that represents background area in the thermal image is weakened and the high-frequency component that represents defect texture and edges in the thermal image is enhanced. As a result, the thermal image contrast between the defect area and background area is enhanced.

Subsequently, in order to obtain the thermal image after contrast enhancement, the equation (4) representing spectrum function is needed to be processed with inverse Fourier transform, which can convert equation (4) to the spatial domain, as shown in equation (5).
Finally, processing equation (5) with an exponential operation yields,

\[ g(x, y) = e^{\ln g(x, y)} = g_f(x, y) \cdot g_i(x, y), \]

where \( g(x, y) \) represents the thermal image after contrast enhancement.

From the above processing procedures, it is found that the key to implement the contrast enhancement of thermal image is to design an appropriate \( H(u, v) \). As mentioned before, the purpose of contrast enhancement is to enhance the texture information of the defect area, and to highlight the defect edge, i.e., enhance the high-frequency component. On this account, in combination with enhancing the high-frequency component and weakening the low-frequency component, an adaptive homomorphic transfer function is designed based on the traditional Gaussian filter in this work, as shown in equation (7).

\[
H(u, v) = (H_H - H_L) \left\{ 1 - \exp \left\{ -\left( \frac{D(u, v)}{D_0} \right)^2 \right\} \right\} + H_L, \tag{7}
\]

where \( H_H \) is the high-frequency gain, which is used for enhancing the high-frequency component, \( H_L \) is the low-frequency gain, which is used for weakening the low-frequency component, and \( D(u, v) \) is the distance between the pixel point \((u, v)\) and filter center \((u_0, v_0)\). As for a general thermal image with \( M \times N \), the filter center is located at \((M/2, N/2)\) after the image was processed with Fourier transform, i.e., the express of \( D(u, v) \) is shown as follows.

\[
D(u, v) = \left( u - \frac{M}{2} \right)^2 + \left( v - \frac{N}{2} \right)^2. \tag{8}
\]

\( D_0 \) is the cut-off frequency. In order to highlight the adaptive ability of \( H(u, v) \), the value of \( D_0 \) is dependent on the characteristics of the thermal image itself.

### 2.2 Case study for the validation of the proposed method

To validate the efficiency of the proposed contrast enhancement method based on the homomorphic technology, an image enhancement investigation is performed by a thermal image containing defect information, as shown in Figure 3 and the adaptive homomorphic transfer function is applied for the image. The obtained result is shown in Figure 4. It can be observed that both the brightness of the central vertically symmetrical intermediate frequency component and that of the surrounding symmetrical high frequency component in the thermal image after processing are brighter than that in the original thermal image. Moreover, the pixel value of defect area in the processed thermal image is larger than that in the original thermal image which indicates that the defect area as well as its edge is enhanced.

To evaluate the proposed method in this work, root mean square contrast is introduced. The root mean square contrast is acquired by equation (9). The corresponding results are listed in Table 1.

\[
C_n = \sqrt{\frac{1}{m \times n} \sum_{I_{m,n}} (I(x, y) - \mu_{I_{m,n}})^2}
\]

\[
\mu_{I_{m,n}} = \frac{1}{m \times n} \sum_{I_{m,n}} I(x, y),
\]

where \( I_{m,n} \) is the thermal image, \( m \) and \( n \) are the width and length of the image, respectively, and \( I(x, y) \) is the pixel.
value of point \((x, y)\), \(\mu_{max}\) is the mean value of the image, and \(C_\sigma\) is the root mean square contrast.

As shown in Table 1, the value of \(C_\sigma\) of the processed image is 41.5302, larger than that of the original image, which proves the validity of the method proposed in this work.

### 3 Experiment investigation

#### 3.1 Materials and equipment

The specimen studied in this work is made of carbon fiber polymer matrix composite with a size of \(150\, \text{mm} \times 100\, \text{mm} \times 4\, \text{mm}\). Some circular hole defects are prefabricated and numbered from 1#–12# on the back of the specimen, as shown in Figure 5. The 5 defects in the first row are numbered 1#–5# with the diameter, \(D\), of 15 mm and the depth, \(Ah\), of 1, 2, 3, 4, and 5 mm, respectively. The 4 defects in the second row are numbered 6#–9# with the diameter, \(D\), of 20 mm and the depth, \(Ah\), of 2, 3, 4, and 5 mm, respectively. The 3 defects in the third row are numbered 10#–12# with the diameter, \(D\), of 30 mm and the depth, \(Ah\), of 1, 3, and 5 mm, respectively.

As shown in Figure 6, the line laser scanning thermography detection device with the type of LaScan-S300 is made of detection platform, laser scanning stimulation source, and computer processing system. The detection platform is used for placing the specimen and the laser scanning stimulation source is used for stimulating the specimen with a scanning power of 240 W and the scanning speed range of 0–50 mm/s. The computer processing
system is used for controlling the stimulated parameters and processing the thermal images.

The infrared camera, acting as the thermal image capture device, is integrated with the laser scanning stimulation source, which can detect the temperature range of −20 to 120°C with a sensitivity of 0.05 at 30°C, resolution of 320 × 240 pixels, data capture rate of 50 frames per second, and spatial resolution of 1.36 mrad.

For the sake of improving the laser absorption rate of the specimen and removing the problems affecting the detection effect caused by uneven heating or laser reflection, black paint is sprayed uniformly on the surface of the specimen.

3.2 Experiment results and analyzing

In this section, the analysis of detection result is carried out which includes thermal image sequence analysis and surface temperature analysis to investigate the detectability of line scanning thermography for the defects in composite material.

The detection results are shown in Figure 7.

It can be observed from Figure 7 that initially the laser source starts to stimulate the specimen, as a result, the heat of linear laser beam accumulates at the surface of the specimen and the defects do not yet appear. At 2.26 s, the defects at first row have been scanned. At this moment, the defect 1# appears clearly but other deeper defects (2#–4#) do not appear due to the low thermal conductivity of carbon fiber polymer matrix composite. At 3.56 s, the defects at second row have been scanned. With the heat conduction along the thickness direction, the defect 2# at the first row can be gradually observed at this moment, but the defects 3# and 4# are still not apparent. Moreover, the defect 6# in the second row appears but the deeper defects (7#–9#) do not appear. Similarly, as the laser scanning and heat conduction proceeded, most defects are apparent at 8.42 s. Afterwards, as time passed by, the available defect contours become blurred due to the heat dissipation.

Additionally, we can find that the linear laser scanning thermography is different from the pulse thermography. The specimen surface is not excited at the same time, as a result, all the defects cannot appear simultaneously in a thermal image, i.e., there exists a delay effect in the thermal image sequence. Therefore, in order to obtain an intuitive detection result, the thermal image is processed by a delay correction algorithm [24] that is integrated with the computer processing system and the corresponding result is shown in Figure 8.

From Figure 8, we can find that the brightness of the thermal spots that represent the defects gradually decrease, even become blurred with the decrease in the defect size and the increase in the defect depth. In detail, the thermal spot corresponding to the defect 10# is the brightest due to its largest D of 30 mm and minimum Δh of 1 mm, while the defects 5#, 9#, and 12# are not apparent during the whole detection process due to too much Δh of 5 mm, which indicates that the laser scanning thermography can detect the shallow defect, specifically, the defects with Δh of less than 4 mm may be detected, while that with the Δh larger than 5 mm may not be detected using line laser scanning thermography.

For the purpose of directly characterizing the effects of defect size and defect depth on the detection results, the surface temperature difference, ΔT, with the D and Δh is extracted as shown in Figures 9 and 10.

Figure 9 shows the ΔT corresponding to the defects 1#, 2#, and 3# and Figure 10 shows the ΔT corresponding to the defects 3#, 7#, and 11#. From Figures 9 and 10, we can find that that maximum ΔT gradually decreases with the decrease in the defect size and the increase in the defect depth. In detail, as known from Figure 9, with the increase in Δh from 1 to 3 mm, the maximum ΔT decreases from 7 to 0.4°C. As known from Figure 10, with the decrease in D from 30 to 15 mm, the maximum ΔT decreases from 1.2 to 0.4°C, which indicates that the shallow defects with large size are more likely to be detected.
using line laser scanning thermography, consistent with the results obtained by the analysis of Figures 7 and 8.

3.3 Contrast enhancement and quantitative evaluation

In this section, the quantitative evaluation of the defects is carried out. In fact, the thermal image obtained by the infrared camera has some problems of low contrast due to the fixed pattern noise, environmental disturbance, etc. On this account, the thermal image should be enhanced and segmented to facilitate the defect area calculation. Thus, the quantitative evaluation is carried out with the following three steps.

Step 1, contrast enhancement procedure.
The thermal image is enhanced based on the proposed method in Section 2 and the obtained result is shown in Figure 11.

Step 2, image segmentation procedure.

Figure 7: The thermal image sequence of specimen detected by laser scanning thermography. (a) $t = 1.4$ s; (b) $t = 2.26$ s; (c) $t = 3.56$ s; (d) $t = 5.08$ s; (e) $t = 6.14$ s; (f) $t = 8.42$ s; (g) $t = 10.68$ s; and (h) $t = 12.9$ s.
The thermal image after enhancement processing is segmented based on the threshold segmentation method and the obtained result is shown in Figure 12.

Step 3, defect area calculation.

After thermal image segmentation, the binary image is obtained. The white zone with the pixel value of 1 represents defect zone and the black zone with the pixel value of 0 represents the sound zone. We therefore utilize the number of pixels to represent the defect zone and sound zone, i.e., the defect area and the sound area can be obtained by counting the number of 1 and 0, respectively. Thus, the defect area in the thermal image can be calculated by equation (10).

\[ S_1 = \sum_1. \]  

(10)

And the actual defect area in the specimen can be obtained by equation (11).
In equations (10) and (11), $S_1$ and $S_0$ are the defect area and sound area in the thermal image, respectively. $S_a$ and $S_s$ are the specimen area and the actual defect area in the specimen, respectively.

The defect evaluation is carried out via the above three steps and the corresponding results are obtained as shown in Table 2 and Figure 13. We can find that the depth of the defect has a direct effect on the defect evaluation accuracy, i.e., the shallow defect is easier to evaluate than the deep defect. In detail, the defects 5#, 9#, and 12# with the $\Delta h$ of 5 mm are not evaluated and the defects 4# and 8# with the $\Delta h$ of 4 mm are evaluated with a large error, while the defects 1# and 10# with $\Delta h$ of 1 mm, defects 2# and 6# with $\Delta h$ of 2 mm, defects 3#, 7#, and 11# are evaluated with a small error less than 10%, which indicates that the defect with the $\Delta h$ less than 3 mm can be evaluated with a small error less than 10% using line laser scanning thermography, while that with the $\Delta h$ large than 3 mm are not evaluated.

### 4 Conclusion

In this work, the line laser scanning thermography is applied for the defect detection and evaluation of composite material. To this goal, a contrast enhancement method based on homomorphic technology is proposed to enhance the thermal image contrast. On this basis, a specimen containing prefabricated defects is detected and the quantitative evaluation of the defects is carried out. The obtained results are listed as follows.

1. The proposed method to enhance the thermal image contrast is validated as an effectively contrast enhancement method, because it can improve the value of the root mean square contrast.
2. The detection capability and evaluation capability of line laser scanning thermography for the defects of composite material are understood preliminarily. In detail, the defects with $\Delta h$ less than 4 mm can be detected using line laser scanning thermography but that with $\Delta h$ less than 3 mm can be evaluated quantitatively with a small error.

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#### Author contributions:
Yin Li: writing – original draft writing and methodology analysis; Yuan-jia Song: project administration; Zheng-wei Yang: data analysis; Xing-yu Xie: experiment.

#### Conflict of interest:
We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, “Use of line laser scanning thermography for the defect detection and evaluation of composite material.”
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