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Thermal Wave Image Processing for Characterization of Subsurface of Flaws in Materials

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Abstract

Infrared images resulting from back-scattered thermal waves in composite materials are corrupted by instrument noise and sample heat-spread function. This paper demonstrates that homomorphic deconvolution and "demultiplication" result in enhanced image quality for characterization of subsurface flaws in Kevlar and graphics composites. The choice of processing depends on the material characteristics and the extent of noise in the original image.

1. Introduction

Thermal-wave infrared imaging has been gaining widespread acceptance as a fast and effective technique for noncontact, nondestructive evaluation of a variety of materials. When a controlled heat pulse of flux Q is applied to the surface of a specimen, the resulting thermal wave propagates by diffusion in accordance with the equation

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$$k \nabla^2 T + Q = \rho C dT/dt \quad (1)$$

where T is the surface temperature, Q is the heat absorbed in the sample per unit volume per unit time, and k, C and ρ are respectively the thermal conductivity, specific heat and density of the sample. The presence of subsurface nonuniformities such as disbonds and cracks affects the diffusion rate and thereby causes a localized rise or fall in surface temperature. Because of wave propagation, the change in surface temperature (relative to that in the uniform, nondefect region of the sample) occurs after a delay which depends on the depth and type of nonuniformity. By recording the surface temperature in image format at the instant

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when there is maximum difference in temperature between the defect region and the uniform region, the type and size of flaw can be characterized with enhanced contrast sensitivity [1]. Due to (a) poor sensitivity of imagers, (b) nonuniformity of heat source, and (c) instrumentation noise, however, measurement resolution for subsurface flaws is highly degraded. This paper describes processing techniques used to enhance image quality for measuring flaws in Kevlar and graphic composites.

2. Infrared Image Acquisition

One of the widely used techniques of thermal wave imaging for nondestructive evaluation employs a flash lamp for applying uniform heat over a short duration (≈ 5 ms) on the front surface of a sample, and an infrared (IR) video camera to detect surface radiation [2] as shown in Fig. 1. A real-time digital image acquisition system with a frame grabber captures the IR images in a computer. The timing electronics provides signals to (a) trigger the flash lamp and (b) initiate image capture. For samples with low thermal conductivity, it has been experimentally observed that contrast surface temperature occurs after a long delay (about 16 s for Kevlar, and 500 ms for graphite for subsurface holes that are on the order of 1.5 mm deep) from the time of triggering the flash lamp. In addition to the peak (data) image frame obtained during heating, a second (background) frame of image is captured long after the application of heat pulse. The timing circuit generates the trigger for the flash lamp and enables data and background image captures at user selected intervals. The background frame, which corresponds to cooling of the sample, provides reference image. The image resulting from subtracting the background image from the data image provides better contrast for the surface temperature difference of the sample. To reduce noise further, the cycle of triggering and capturing a pair of images is repeated many times

Fig. 1. Block diagram of photothermal imaging system

The final averaged image represents relative temperature difference between uniform and nonuniform regions of the sample. Hence near-surface defects, which cause higher temperature rises, are clearly visible. Figure 2 shows the averaged (contrast-enhanced) image of a sample of Kevlar of 4.8 mm thick with intentional subsurface holes. The holes have a diameter of 6.1 mm and are at depths as given in Fig. 2. Ten pairs of images were taken each after about 16 s and 60 s from the instant of triggering a pair of flash lamps with a total energy of 3200 J. As seen in the figure holes which are farther from the surface are not readily detected. While contrast enhancement by system calibration has been investigated in [3,4], the present work shows minimization of the distortion caused by the nonideal spectral response of the optical system and the heat-spread function of the sample.

(a) averaged imaged

(b) Line profile along left side holes

Fig. 2. Averaged image of a Kevlar sample and a line profile along deeper subsurface holes

3. Modeling and Processing of the Observed Image

3.1 Convolution Model: An approximate solution to Eq. (1) [5,6] shows that the temperature difference $y(m,n)$ between the defect and the nondefect regions at a point (m,n) on the surface is the result of convolution of the heat-spread function $h(m,n)$ of the imaging system and the scattering function $r(m,n)$ (defect shape function) of the specimen at the defect location as

$$y(m,n) = h(m,n)**r(m,n)$$

(2)

To recover the image due to defect scattering and resulting surface temperature differential, Crowther, et.al., [4] proposed deconvolution of the contrast image using Fourier division.

Apart from the problem of frequency nulls, Fourier division requires the evaluation of the sample heat-spread function, which may not be available in all cases. If the heat-spread function is assumed essentially low-pass relative to the scattering function, then $r(m,n)$ may be recovered using homomorphic deconvolution [6]. The results of deconvolution of the image in Fig. 2 is shown by the line profiles in Fig. 3 along the same pair of coordinates as in Fig. 2 using a second order low-pass Butterworth filter with two different cutoff frequencies. As is evident these profiles better indicate the presence of the deepest hole (at 1.5 mm depth from the top surface) relative to the neighboring shallow holes. Clearly, in the absence of the known characteristics of the imaging system, deconvolution using different low-pass filters needs to be performed to enhance the image quality of the scattering function.

(a) Cut-off frequency = 100

(b) Cut-off frequency = 150

Fig. 3. Line profile along the same line as in Fig. 2, after deconvolution with a cut-off frequency of (a) 100, (b) 150. Image size is 512 x 512.

3.2 Multiplication Model: Instead of the convolution model, the detected gray level intensity, $y(m,n)$, of the IR image at any instant may be considered as the product of source excitation, $s(m,n)$, and localized thermal emission, $r(m,n)$, given by

$$y(m,n) = s(m,n).r(m,n) \quad (3)$$

This model, which is similar to optical illumination-reflection model, appears more appropriate for the flash lamp source and high emissivity by materials. With typically low spatial frequencies for the source, the excitation component may be minimized from the observed image by "demultiplication". Recovery of $r(m,n)$ by demultiplication is performed by homomorphic filtering, i.e., by high-pass filtering the logarithm of the observed image intensity $y(m,n)$.

The above recovery process was tested on a sample of graphite composite with six holes at different depths. Instead of contrast enhancement by repetitive averaging of pairs of peak data and background images, a single image was acquired after a delay of 2 s. To prevent overheating of the sample a single flash lamp was used at a power of about 1600 J. Because of the positioning of the

lamp more heat was applied near the bottom right hand side of the sample. The original image and a line profile along the three holes on the left are shown in Fig. 4. Due to nonuniform heating the bottom hole, which is at a depth of 1.5 mm, is not distinguishable from the surrounding uniform region.

To enhance the image contrast for bringing out the bottom hole, homomorphic filtering using a fourth-order high-pass Butterworth filter with a cut-off of 10 samples was applied. The result of the image after smoothing and the line profile along the same line as in Fig. 4 are shown in Fig. 5. The presence of the bottom hole is clearly detected in this profile. Deconvolution, on the other hand, did not show significant improvement over the original image.

Fig. 5. Line profile of image in Fig. 4 after demultiplication

4. Discussion and Conclusion

Based on the results presented it is observed that random system noise in the IR image of a Kevlar specimen is minimized by conventional averaging of repetitive images. Further image enhancement for the detection of deep subsurface defects is achieved by homomorphic low-pass filtering. Since the evaluation of imaging system response which is required for homomographic filtering may not be feasible in all cases, empirical homomorphic deconvolution as applied here is preferable in practical situations. In the case of a single-shot image of graphite sample, the illumination-reflection model appears more appropriate. In this model the removal of the source function by high-pass filtering also reduces the effect of nonuniform heating. Hence the choice of the model and the processing to obtain an enhanced image depend on the material characteristics and the amount of noise in the original image.

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