Three-Dimensional Pulse Compression for Infrared Nondestructive Testing

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***Abstract*—This letter proposes an optimal nondestructive subsurface defect detection method to investigate the capabilities of the infrared thermography through a finite-element analysis-based model. A finite-element analysis (FEA) software was used to generate models and analysis was carried out using MATLAB software. Pulse compression approach has been introduced for subsurface defect detection and its advantages and limitations are compared with existing phase approach-based thermography. Investigations has been carried out on a simulated plain carbon steel specimen with a flat bottom hole defects at various depths of different diameters is introduced. Comparison has been made with the conventional phase-based techniques.**

***Index Terms*—Chirp excitation, infrared thermography, nondestructive testing, pulse compression, thermal waves.**

I. INTRODUCTION

INFRARED nondestructive evaluation (IRNDE) involves mapping of surface temperatures as heat flows through a test sample, with the aim of detecting surface and subsurface features (voids, disbands, cracks, etc.). It is a fast, whole field, and noncontact method for defect detection [1]–[4]. Since most solids conduct heat, IRNDE has the potential for wide use in defect detection in a variety of materials such as metals, semiconductors, and composites. IRNDE can be broadly categorized into active and passive approaches [1]. The passive approach is usually performed by measuring the natural temperature difference between the ambient and the material or structure to be inspected. The limitation of the passive approach is its general inability to detect defects lying deep inside the test sample, for which it does not provide sufficient temperature contrast over defect and nondefective regions. In order to reveal these deep defects with a high contrast, active thermography is used. Active approach, on the other hand, requires application of an external energy as stimulus on to the material to be inspected. Presently, two different approaches of active thermal nondestructive techniques are predominantly in use: pulsed thermography (PT) [3]–[5] and modulated lock-in thermography (LT) [2]. In PT, the examined material is warmed up (cool perturbations can also be used) with a short duration high peak power pulse (usually with optical flash lamps), and the thermal response is recorded. The resultant sequence of infrared images recorded by an IR camera indicates defects in the material at different depths. In practice, this technique requires high peak power heat sources and has the inherent drawback of being sensitive to surface emissivity variations and nonuniform heating on the surface of test sample. In contrast to pulsed thermography, LT is based on thermal waves generated inside the specimen under study [2]. Mono-frequency sinusoidal thermal excitation at a given excitation frequency, introduces highly attenuated, dispersive thermal waves of the same frequency inside the test specimen. The excitation frequency in LT is chosen depending on the sample thermal characteristics and its geometrical dimensions. Smaller is the frequency of the thermal waves, lowers the velocity in the test specimen and deeper is the penetration into the test specimen. From the obtained image sequence, in the stationary regime of heat cycle, information about the phase, and magnitude of the reflected thermal wave is derived. Phase angle images have several advantages over magnitude images, including those of being less sensitive to local variations of illumination of heat sources, radiation reflected on the object surface and variations of surface emissivity on the sample. Further, phase images are capable of probing deeper defects compared to the magnitude images. Since in a single run there is limited depth resolution of the lock-in thermography due to fixed driving frequency of the excited heat sources (fixed wavelength in side the test sample), therefore, in order to get good resolution for various defects at different depths inside the test specimen it is necessary to repeat LT with different excitation frequencies [6], [7]. Maldague proposed a technique called pulsed phase thermography (PPT), which has some of the advantages of both conventional PT and modulated LT. The experimental procedure for PPT is similar to PT, but extraction of various frequency components from the obtained infrared image sequence is performed by Fourier transform (FT) on each pixel of the thermogram sequence. The phase images obtained from the FT in PPT provides all the merits of the phase images obtained in LT, (i.e., less sensitive to surface in-homogeneous emissivity and illumination variations). Theoretically, the short duration excitation pulse in PPT does launch a large number of frequency components into the test sample, but the higher order frequency components may not have sufficient energy to cause a thermal wave to propagate deep into the sample. In order to detect deeper subsurface defects in test sample, PT and PPT needs high peak power heat sources, which however may damage the surface of the test sample.

In order to overcome these limitations of LT and PPT, this letter presents a finite-element analysis-based frequency modulated thermal wave imaging (FMTWI) [7] in order to send a desired band of frequencies, with significant magnitude, into the test sample in a one run. Comparison has been made with the most widely used conventional phase image approach to the recently proposed 3-D pulse compression approach.

II. RESULTS AND DISCUSSIONS

In order to find the depth resolution capability of the proposed frequency modulated thermal wave imaging (FMTWI)

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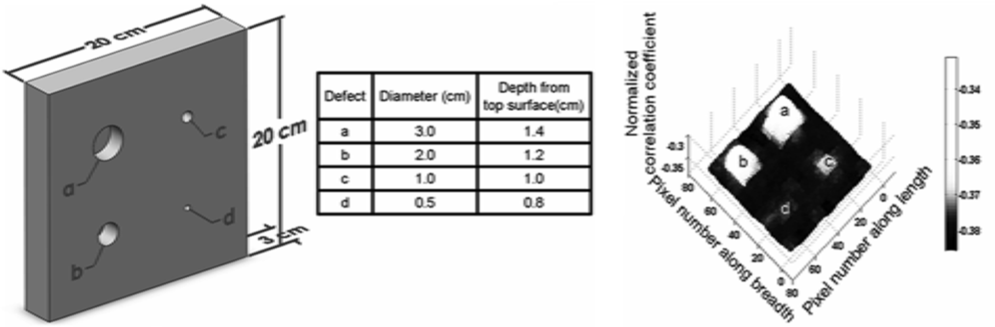


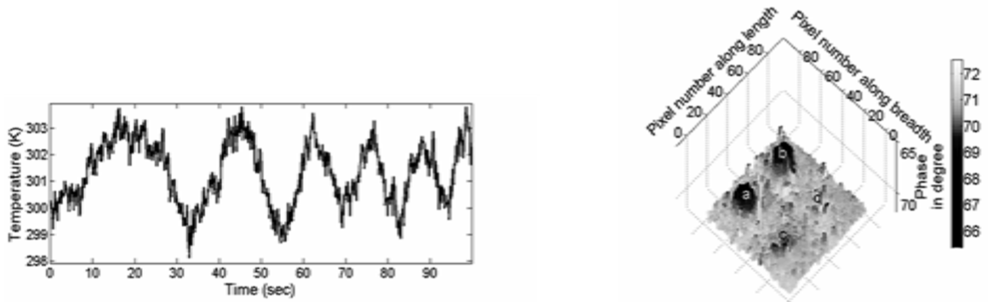
Defect	Diameter (cm)	Depth from top surface(cm)
a	3.0	1.4
b	2.0	1.2
c	1.0	1.0
d	0.5	0.8

Rear view of the simulated sample

Fig. 1(a)

Image obtained from correlation approach

Fig. 1(c)



Temporal temperature distribution over the sample surface for the given linear frequency modulated heat flux (0.01Hz to 0.1Hz with the noise level of -6db)

Fig. 1(b)

Image obtained from phase approach at 0.05 Hz

Fig. 1(d)

Fig. 1. Shows (a) the schematic of the simulated sample, (b) temporal temperature response over nondefective reference region of the sample, (c) correlated compressed image, and (d) phase image obtained at 0.05 Hz frequency for a given frequency modulated incident heat flux.

technique, finite-element-based simulations were carried out on plain carbon steel sample using SolidWorks software. The sample contains four circular flat bottom holes located at different depths from the top surface, as shown in Fig. 1(a). A linear frequency modulated (sine chirp) temperature distribution on the sample surface, as shown in Fig. 1(b), which is obtained from the linear frequency modulated heat flux (sine chirp) of 100 s duration, with its frequency varying from 0.01 to 0.1 Hz, is imposed on the sample surface with an additive white Gaussian noise of $-6\ \mathrm{db}$. It may be noted that simulations were carried out for only one linear chirp excitation cycle and sequence of images are generated from the simulated data at a sampling interval of 0.1 s.

Temperature profiles over the sample surface are extracted for the given active heating. In this study, the transient temperature response over the sample [Fig. 1(a)] at a given location over the nondefective region has been considered as the reference. Correlations of the temperature responses at different locations over the sample surface with respect to the chosen reference (nondefective region over the sample) were obtained.

Fig. 1(c) shows the group delayed (6 s) pulse compressed image obtained by correlation approach. Correlation peaks in Fig. 1(c) clearly illustrate the capability to detect deeper defects in the simulated sample [Fig. 1(a)] with enough depth resolution.

Extraction of phases of the various frequency components in FMTWI is performed with the 1-D fast Fourier transform on each pixel of the thermogram sequence using MATLAB. The same process is repeated for all the pixels in the field-of-view, in order to obtain the phase images for various frequency components, form the generated image sequence. Fig. 1(d) shows the phase image obtained for a frequency of 0.05 Hz.

It is clear from Fig. 1(c) and (d), the phase contrast over the defects are not very clear, whereas the compressed images clearly preserve the contrast over all the defects even at a signal-to-noise ratio (SNR) of $-6\ \mathrm{db}$. This shows the capability of the pulse compression approach over the phase approach for subsurface defect detection for nondestructive characterization.

III. CONCLUSION

This letter proposes a novel simulation approach to thermal nondestructive testing for the detection of subsurface defects. The group delayed temporal temperature responses over the sample surface for all the spatial pixels are correlated to obtain a 3-D pulse compression, to improve the detection capability over the conventional phase approach even in noisy conditions.

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