Numerical Approach for Characterization of Structural Steel Sample using Frequency Modulated Thermal Wave Imaging

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Abstract

This work demonstrates a finite element analysis based modeling and simulation study for finding out the defect detection capabilities of frequency modulated thermal wave imaging technique. A structural steel specimen with hidden subsurface slags and inclusions such as calcium fluoride, silicon dioxide and air of various sizes and shapes, is considered. Pulse compression based correlation processing scheme is adopted on the generated temporal temperature data and comparisons have been made with the conventional widely used frequency domain phase based approach.

Keywords: *Non-destructive testing; Phase analysis; Frequency modulated thermal wave imaging; Finite element analysis*

1. Introduction

Over the years, Thermal Wave Imaging (TWI) is intensively used for the characterization of various solid materials due to its inherent merits like non-destructive, non-contact, rapid and full-field inspection capabilities[1-5]. In active TWI approach, the test object is thermally stimulated to generate heat flow within it. The presence of defects within the material alters heat flow, causing thermal contrast over it, which can be monitored using infrared camera. Based on the shape of applied heat flux on to the test sample, these thermograhic methods are named either as Pulse (Pulsed Thermography (PT), Pulsed Phase Thermography (PPT), Step Thermography (ST)) or modulated thermographic methods (mono-frequency sinusoidal Lock-in Thermography (LT)) [6-11]. The requirement of high peak power heat sources in case of pulse based techniques and limited depth resolution in a single experimentation cycle in LT are the key issues. Further various research groups all over the world are working on modulated non-stationary transient thermographic techniques such as Frequency Modulated Thermal Wave Imaging (FMTWI), Digitized Frequency Modulated Thermal Wave Imaging (DFMTWI), Barker Coded Thermal Wave Imaging (BCTWI), Golay Coded Thermal Wave Imaging (GCTWI), etc. to overcome these constraints and also on various data processing schemes to improve test resolution and sensitivity [12-18].

This paper describes the application of Finite Element Analysis (FEA) approach for the assessment of a structural steel sample having defects of different shapes such as circular, square and triangular, using FMTWI. This method employs a pre-determined band of frequencies decided by sample thermal properties and its thickness. Hence the whole sample can be inspected in a single run using relatively moderate peak power heat sources in a limited span of time. In simulation, three types of inclusions are incorporated as defects of various shapes at a given depth inside the test sample. Further, in order to test the capabilities of FMTWI, frequency domain based phase and correlation based analysis schemes are carried out on the resultant temporal thermal response.

2. Theory

Heat flux incident onto the test sample generates thermal waves which propagate into the sample by diffusion. The presence of surface and sub-surface defects modify the heat flow, producing thermal gradients over the test sample. The resultant temperature response for a given incident heat flux can be obtained from 1D heat diffusion equation in the absence of any heat source and sink as follows [19]:

$$\frac{\partial^2 T(x,t)}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T(x,t)}{\partial t} \tag{1}$$

where $T(x,t)$ is the temperature at a given depth x at a time instant t and α is the thermal diffusivity of the sample being inspected. The thermal diffusion length for the temperature variations due to a linear frequency modulated heat flux incident onto a semi-infinite solid is expressed as follows:

$$\mu = \sqrt{\frac{\alpha}{\pi\left(f+\frac{Bt}{\tau}\right)}} \tag{2}$$

where f is the initial frequency, B is the bandwidth and τ is the total duration of excitation. The thermal diffusion length determines the decay of thermal wave as it penetrates through the material. The dependence of diffusion length on the slope of time frequency response (B/τ) of applied stimulus assures complete sample depth scanning.

The presence of subsurface defects can be identified either by conventional frequency domain based phase approach or recently proposed correlation coefficient based approach as shown in Fig.1 and 2 respectively.

2.1 Frequency Domain Phase Analysis

In this method, one-dimensional Fast Fourier Transform (FFT) is considered to compute the phase angle of captured temporal thermal profile of each pixel $f(t)$ (where t is the index in image sequence of length N) [20]:

$$F(u) = \frac{1}{N}\sum_{t=0}^{N-1} f(t)\, e^{\left[\frac{-j2\pi ut}{N}\right]} = R(u) + jI(u) \tag{3}$$

where $R(u)$ and $I(u)$ are the real and imaginary components of $F(u)$ respectively. Then the phase angle corresponding to different frequencies is determined using:

$$\emptyset\,(u) = tan^{-1}\left(\frac{I(u)}{R(u)}\right) \tag{4}$$

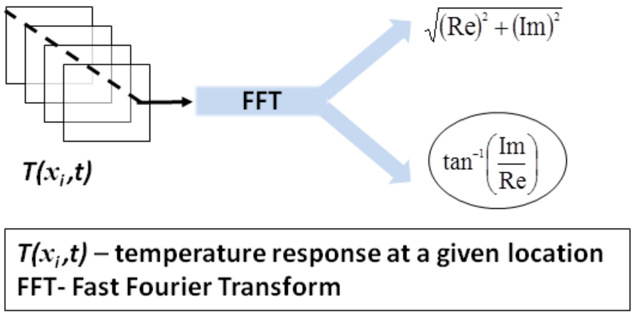


Fig.1 Data processing approach adopted for the construction of frequency domain based phasegrams

2.2 Correlation Coefficient Based Analysis

In this approach, data analysis is carried out to achieve pulse compression in order to reconstruct the correlation coefficient images of the captured temporal thermal sequence as follows [20]:

$$Correlation\ coefficient\ (CC) = IFFT\{T(x_r,\omega)^*\ T(x_i,\omega)\} \tag{5}$$

where $T(x_r,\omega)$ and $T(x_i,\omega)$ are the Fourier transforms of thermal profiles at reference location and at a given location respectively.

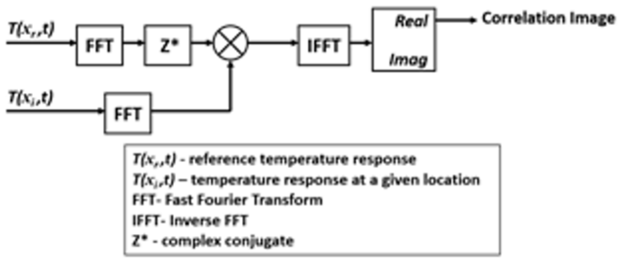


Fig.2 Data processing approach adopted for the construction of correlation coefficient based images

3. FEA Modeling

A FEA model has been developed using the heat transfer module in Comsol Multiphysics version 4.2. The details of the model and simulation parameters are given below.

<u>*Model Geometry*</u>
Numerical analysis is carried out on a structural steel sample of thickness 7 mm, of 100×110 mm lateral dimensions, containing circular, square and triangular shape defects located at a depth of 0.3 mm from the front surface of the sample. The defect thickness is 5.7 mm. The dimensional layout of the simulated sample is as shown in Fig.3. The first row containing all the three different shape defects is filled with air, whereas

second and third rows are filled with silicon dioxide and calcium fluoride respectively, to simulate artificial inclusion and slag.

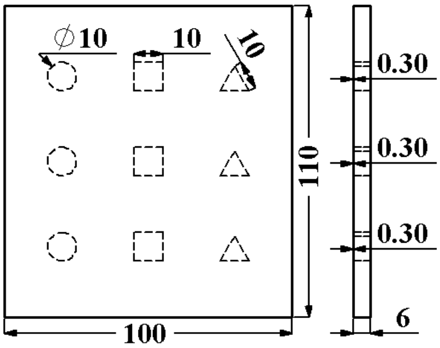


Fig.3 Schematic layout of simulated structural steel sample (all dimensions are in mm)

<u>*Sample Parameters and Mesh*</u>

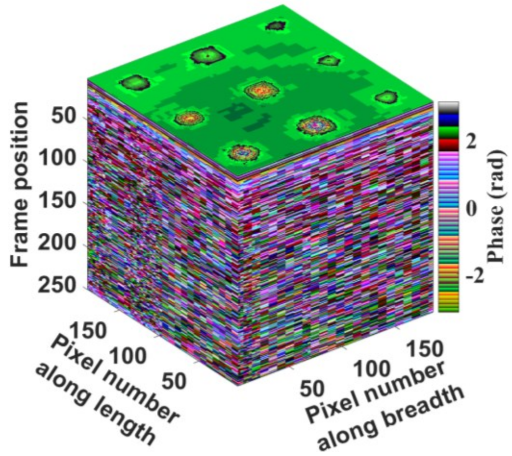
The model geometry is discretized with a finer mesh using 38133 tetrahedral elements. Table.1 summarizes the parameters used for the test sample.

Table.1 Parameters used for the test sample

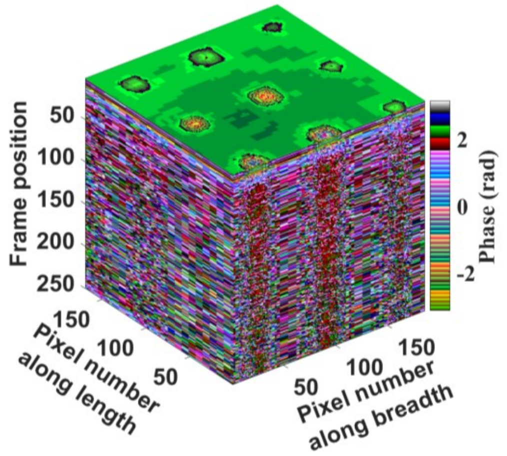
Material	**Thermal Conductivity** k **[*W*/(*m·K*)]**	**Heat Capacity** C_p **[*J*/(*Kg·K*)]**	**Density** ρ **[*Kg*/m^3]**
Structural steel	44.5	475	7850
Air	0.0258	1005.4	1.0215
Silicon dioxide	1.5	730	2650
Calcium Fluoride	9.71	854	3180

4. Numerical Results

The simulations are performed by imposing linear frequency modulated heat flux of 200 W/m^2 with frequency sweep of 0.01 to 0.11 Hz in a time span of 100 s. The temperature map over the sample is recorded at a frame rate of 20 Hz. The mean rise in temporal thermal profile of each pixel is removed by proper polynomial fit. The frequency domain phase and correlation information is then calculated from mean removed thermal data. Figure 4(a)-(d) show the depth scanning performance obtained from frequency domain phase images for four different cross–sectional views.



(a)



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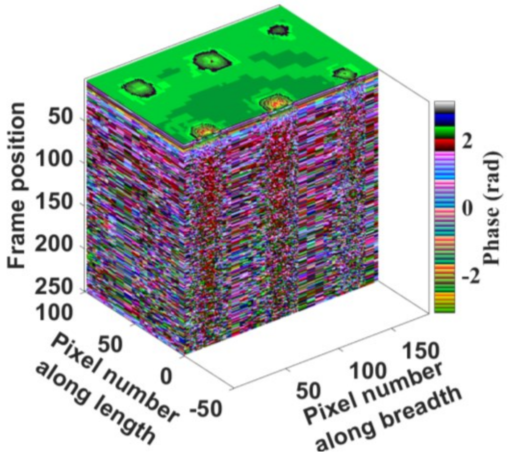

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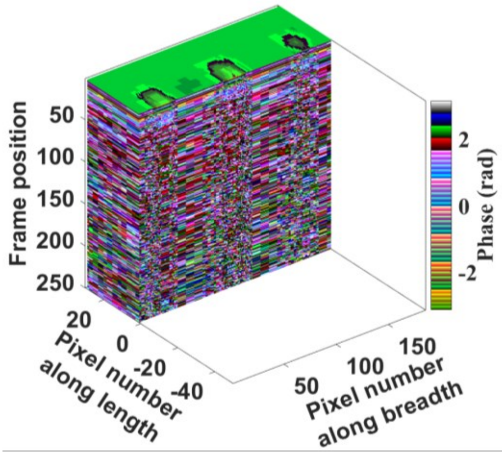
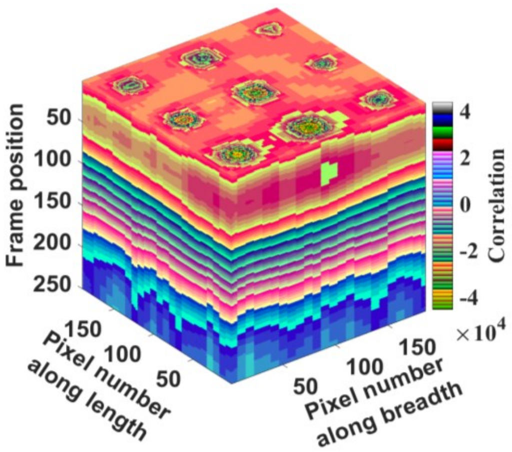
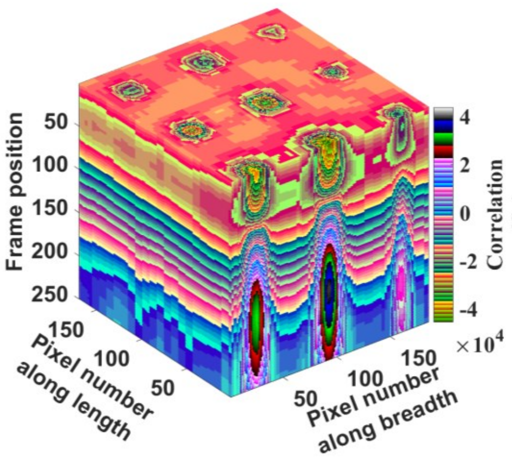


(d)

Fig.4 Depth scanning performance obtained from frequency domain phase analysis



(a)



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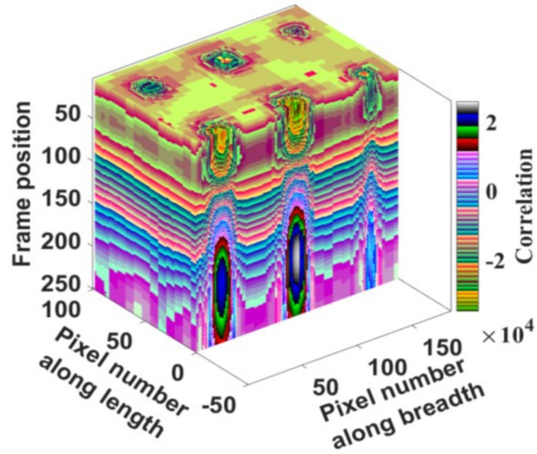
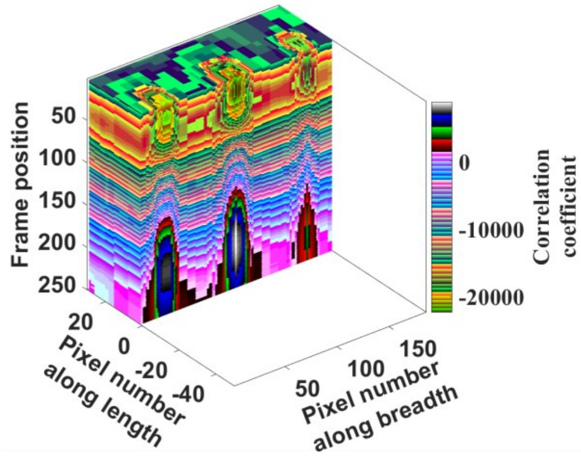


(c)



(d)

Fig.5 Depth scanning performance obtained from correlation coefficient images

whereas Figure 5(a)-(d) show the depth scanning performance obtained from correlation coefficient images for four different cross–sectional views.

The results demonstrate that correlation coefficient approach show better detectability for revealing sub-surface anomalies over the frequency domain phase images. The enhanced detection capabilities provided by correlation based processing scheme are due to its inherent potential capabilities like concentration of energy into a very narrow duration pulse and immunity to random noise.

5. Conclusions

This paper highlights the capabilities of correlation based approach for defect detection in structural steel sample. This method provides better detection capabilities than that of frequency domain based phase approach. This technique utilizes the merits of matched filter based pulse compression process which is immune to random noise makes this approach more robust than that of conventional frequency domain phase approach.

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