ADVANCES IN QUADRATIC FREQUENCY MODULATED THERMAL WAVE IMAGING

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ABSTRACT

Subsurface analysis using thermal waves is gaining interest due to its whole field, non-contact and non invasive testing modality. Recent past witnessed a tremendous improvement in application of various non stationary stimulation mechanisms and processing modalities intended to enhance depth resolution of subsurface anomalies. Usually in realistic objects, anomalies exist at different depths demands stimulations consisting of a set of frequencies and further high resolution processing modalities. Quadratic frequency modulated thermal wave imaging, is one of those stimulation mechanisms cater to theses needs by providing a preselected band of frequencies and facilitates the detection of anomalies with enhanced depth probing due to more energy with low frequencies in addition to depth resolution. This contribution highlights various processing mechanisms used for defect detection and quantitative sizing analysis in this proposed methodology.

INTRODUCTION

Infrared non destructive testing(IRNDT) use of the radiation emitted by a test object in infrared range of the electromagnetic spectrum for surface and subsurface analysis without impairing its future usefulness. It is a non-contact and whole field modality employing various analysis procedures for extracting details from temperature contrast map captured by an infrared imager. There are two modes in this modality. Among them, in the first one called passive thermography, a natural temperature variation over the object surface is monitored by IR camera and the captured data is directly used for analysis. But deeper details may not be properly extracted and quantitative analysis is also difficult with this method. Where as in the second approach, called active thermography, an external stimulus used to energize the object and temporal thermal history will be captured by IR camera, and further analyzed with the intent of defect detection.

Among various active thermographic methods, in Pulse thermography (PT) the test sample is energized by a short duration and high peak power stimulation and the subsequent thermal history is recorded and analyzed. Analysis of this raw data suffers from non uniform radiation and non uniform emissivity[1,2].

In Lock in thermography(LT) has some advantages over PT, as it imposes a continuous mono frequency[3,4] sinusoidal stimulation to the object surface, which further initiate a similar thermal wave into the test sample. It is proved from state of art that phase analysis for this data provided better analysis than any other approach. Pulse phase thermography(PPT), introduced by Maldague[5], grabbed the features of simples stimulation of PT and phase approach accompanied with frequency decomposition capability added additional flavor to thermographic analysis. But in realistic objects defects may exists at different depths and demands the repetition of experiment by varying frequency.

In Linear Frequency modulated thermal wave imaging(FMTWI), introduced by Mulaveesala etal.[6,7,8], a continuous frequency sweep of stimulation is imposed on to the object surface in a single experimentation cycle. This method overcomes the draw backs of both pulse and lock in thermography, which gives better depth resolution. Where as in Quadratic frequency modulated thermal wave imaging (QFMTWI) favors larger depth probing than it's linear frequency counterpart due to the high energy probed with low frequency portion.

PROCESSING METHODOLOGIES

In Infrared non destructive testing, the test sample surface is exposed to a modulated stimulus which initiates similar thermal waves over a very thin layer nearer to the surface. These will further propagate into the interiors of the object due to diffusion wave propagation and creates a temperature contrast over the object surface due to the subsurface anomalies. In order to extract fine subsurface details, the captured thermal history is processed by various processing methods. This contribution compares phase analysis, pulse compression, Principal component analysis(PCA) and Hilbert phase processing methods to a simulated mild steel sample with the intent for defect detection using recently introduced quadratic frequency modulated thermal wave imaging.

Phase analysis

It is a frequency domain method, employing fast fourier transform(FFT) for frequency unscrambling. The original raw data contains mean raised temperature value in each temporal thermal profile. In order to perform phase analysis the mean raised temperature value has removed by using a linear fitting procedure from all thermal profiles. Further fast Fourier transform applied over thermal profile each pixel and phase values to each frequency component is calculated, phase images are formed by arranging phase values of corresponding frequency component in to its respective pixel position. The constructed phase images exhibits phase contrast due to a differential phase delay contributed from thermal wave reflection from discontinuities at different depths, which is grabbed from phase difference. The frequency corresponding to the phase image is exhibiting the defects is estimated by $f = \frac{F_s n}{N}$

F_s=Sampling frequency or Capturing rate.

N=Total number of the samples in thermal profile.

n=Number of the phase image.

Pulse compression

Pulse compression is a time domain method of analysis, in which a data of each pixel from captured thermograms is arranged in a sequence called thermal profile of that pixel. In this process, a reference profile is chosen from non-defective region, further normalized cross correlation is performed between reference profile to remaining pixels profiles[9-12]. Further these profiles were rearranged so that the normalized correlation coefficients of all the pixels at a delayed instant are kept in their respective spatial locations to form correlation image at a delayed instant. The correlation contrast in correlation image is used to visualize the defects.

PCA

PCA extracts the underlying information from raw thermal data by projecting on to orthogonal basis vectors. it separates the thermal features like non uniform radiation, thermal contrast and noise from the original raw data, these components are coming on the basis of direction of maximum variance in the data [13,14].

Thermal data is in three dimensional i.e N_r by N_c by N_t to apply PCA original three dimensional data is converted to two dimensional data matrix 'D' which can be done by arranging temporal variations along row wise and spatial variations along column wise i.e. each row as image, the data matrix has dimensions as N_t by (N_r *N_c) . The covariance (or) scattering matrix is constructed by subtracting the mean value across each row vector of 'D' from it

$$S = (D - D_{mean}) * (D - D_{mean})^T$$

In order to get Eigen vectors SVD is employed on scattering matrix 'S' which gives three matrices the dimension of scattering matrix is 'N_t ' by 'N_t'

$$[Y_1 \Lambda Y_2] = SVD(S)$$

The matrix Y_1 is an orthogonal matrix , Λ is a diagonal matrix , Y_2 is a orthogonal matrix and transpose of Y_1. in order to get the principal components original data is projected on to orthogonal basis function 'Y_1' which gives Pc's along row wise further each principal component is rearranged as two dimensional Principal component image

Hilbert Phase: It is a multi transform method, in the first stage a reference profile is selected from view and Hilbert transform is applied over it next a fourier transform has been applied over remaining pixel profiles and a conjugate is calculated. Referenced Hilbert transform profile is multiplied by calculated conjugate profiles and inverse fourier transform is calculated

$$\mathrm{T_1 = IFFT}\left[\left\{\mathrm{FFT(Hilb(p_r))}\right\}^* \left\{\mathrm{FFT(p)}\right\}\right],$$

where ' * 'represents complex conjugate.

In the next stage cross correlation between reference thermal profile and temporal thermal profiles of all the pixels in view has been obtained as given by

$$\mathrm{T_2 = IFFT}\left[\left\{\mathrm{FFT(p_r)}\right\}^* \left\{\mathrm{FFT(p)}\right\}\right]$$

Further time domain phase will be obtained from

$$\theta = \tan^{-1}\left(\frac{\mathrm{T_1}}{\mathrm{T_2}}\right)$$

Time domain phase image has been obtained from the above relation and arranged in respective locations.

RESULTS AND DISCUSSION

In order to test the applicability of proposed method a simulation based analysis has been carried over mildsteel sample containing flat bottom holes as shown in fig.1, in Comsol 4.3b and a quadratic frequency stimulation has been employed over object surface with imposed heat flux of 1KWwith a frequency sweep from 0.01 hz to 0.1 hz. A thermal response of the test object is captured at a frame rate of 0.1 seconds in duration of 100 seconds. In order to extract fine subsurface details various processing methods like phase analysis, pulse compression, principal component analysis and Hilbert phase are employed on simulated data.

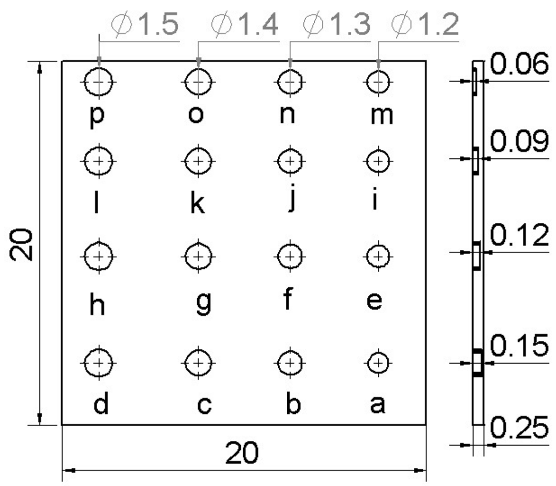


Fig.1. Sample layout of simulated mild steel specimen with embedded flat bottom holes.

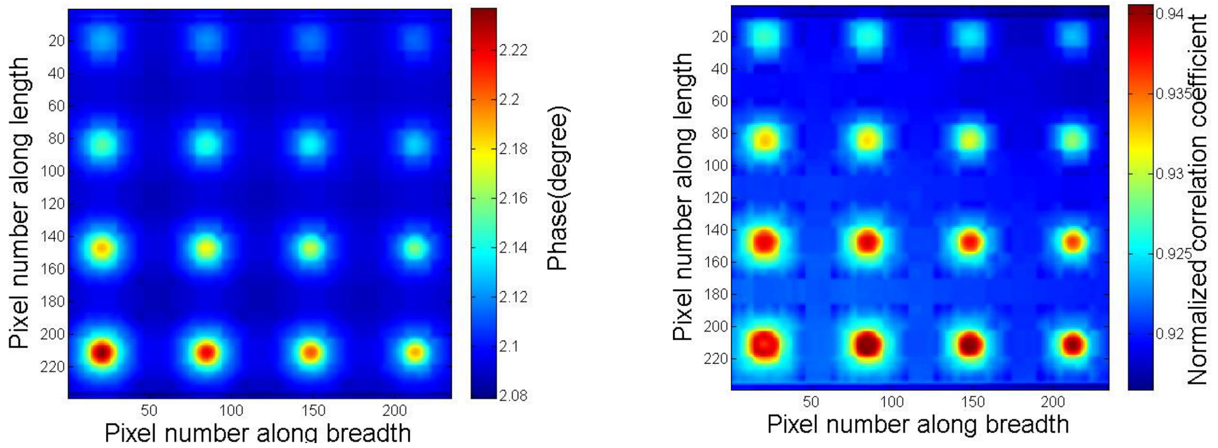
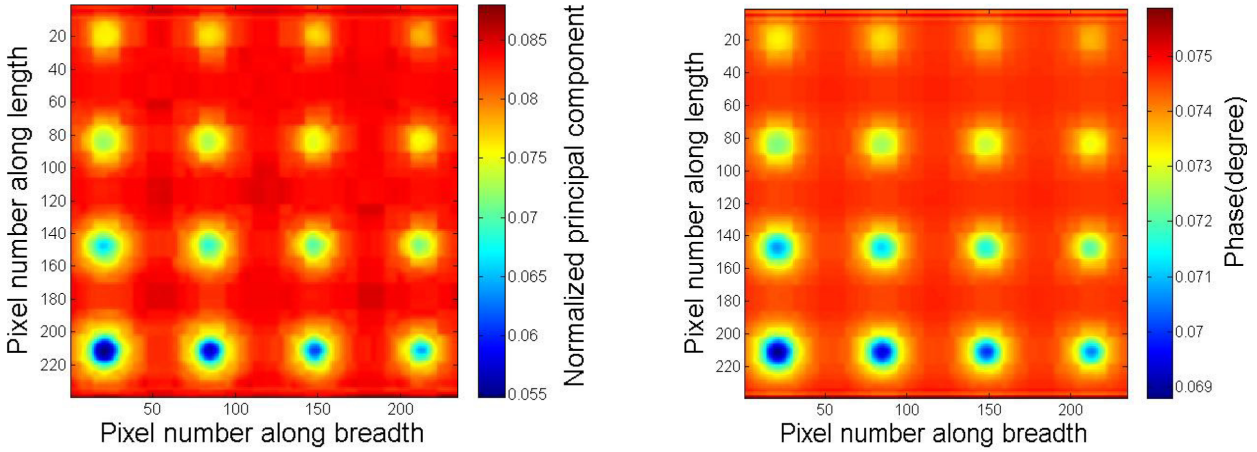


Fig2. a) Phase image at 0.002 Hz b) Correlation image at 4.5 s



c) 9th Principal component d) Hilbert phase at 15 s

It is observed from Fig 2 that pulse compression analysis is perfuming better than other methodologies and provides better detection for small and deeper defects compared as to other due to its energy concentrating capability and the sizing of defects to bottom row of defects are calculated using full width at half maxima and result is listed in below table1

Table1: Sizing of defects

Defect	Radius of the defect (in cm)			
	Phase	PC	PCA	Hilbert phase
d	1.23	1.4	1.43	1.56
c	1.3293	1.38	1.1976	1.52
b	1.4771	1.23	1.222	1.43
a	1.4678	1.18	1.15	1.23

CONCLUSION

A comparative study of various contemporary processing approaches for defect detection and sizing estimation, have been tested on QFMTWI using a simulation based analysis carried over a mild steel specimen and observed that pulse compression approaches is better performing than other techniques.

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