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RECENT ADVANCES IN SUBSURFACE ANALYSIS WITH QUADRATIC FREQUENCY MODULATED THERMAL WAVE IMAGING

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ABSTRACT

Thermal wave imaging makes use of thermal response over the stimulated surface for detection of anomalies underneath the surface of the test object which requires the deployment of various post processing approaches to extract fine subsurface details. These subsurface details appear at various moments depending on their depth and size. Extraction of these fair details with low axial and temporal resolutions provided by thermal imagers against various noises is a criterion of importance in thermal wave imaging. Capability of non stationary thermal wave imaging to explore the subsurface details within a single experimentation at low powers resulting in gaining the interest in using it motivated the recent research to incorporate various new processing modalities intended to extract fine details along with this stimulation mechanism. This paper highlights the application of various post processing modalities to extract subsurface details using experimentation carried over a glass fiber reinforced plastic specimen with embedded Teflon inserts to simulate de-lamination like defects encountered with composites.

Keywords: *Glass Fiber Reinforced Plastic (GFRP), Principal Component Analysis (PCA), Thermal Wave Imaging, Chirp*

1. INTRODUCTION

From last few decades the usage of thermal NDT & E methods[1] increased tremendously for the evaluation of a variety of materials like carbon or glass fiber reinforced polymers, semiconductors and metals. Among various available NDT methods infrared non - destructive testing method is named after its utility as a versatile technique due to its ease of experimentation, quickest examination and non contact whole field method of evaluation. It is employed in a numerous applications like aerospace, electronic and mechanical fields. Infrared non destructive testing (IRNDT) uses temperature map of the object surface to find the inhomogeneity inside the material. This modality of exploring infrared originated temperature evolution of test object successfully ensured its use in the extraction of hidden subsurface details either from its inherent thermal response or after stimulation by external agency. Later processes known as active thermography has been researched and practiced for quantitative and qualitative analysis all over the world for subsurface analysis of a variety materials from metals to composites[2]. In this active method, an external heat stimulus is imposed over the test specimen and subsequent temporal and thermal history from the specimen’s surface recorded by an infrared camera further various post processing methods are used to find out fine subsurface details.

Among various active thermographic methods, pulse thermography(PT) gained popularity due to its simplicity and quickest subsurface exploration feasibility[3,4]. But large peak power requirement to investigate the test object, non uniform radiation and non uniform emissivity limits its applicability in addition it is also not recommended for testing of thick objects due to minimum absorbance of incident power within a fraction of second. Introduced by Maldague, FFT based phase analysis along with this pulsed stimulation enhanced its depth probing capability and become popular as pulsed phase thermography (PPT). Various post processing modalities were further developed to facilitate the enhanced defect detectability using this pulsed thermographic testing modality, one of the oldest methods accepted since a few decades. Proposed by Busse etal.,[4] to overcome the problem with high peak powers, a low power and low frequency sinusoidal stimulation for longer duration is provided to the test sample in lock-in thermography(LT). Further either an amplitude based or phase based analysis using four bucket method was used to extract fine subsurface details[4]. Being capable to give more depth information and free from non uniform radiation and emissivity problems, later approach is preferred in most of the applications. This steady state analysis requires more time for experimentation and suffers from blind frequency problems associated with defects existing at different depths in a realistic object. Subsurface information corresponding to various depths will be obtained by repetitive experimentation with different frequencies makes this process more tedious.In order to overcome the limitations of these conventional methods like high peak powers with PT and repetitive experimentation with LT, Mulaveesala etal., imposed[5,6] a stimulation containing a continuous sweep of a suitable band of frequencies onto the test object and used various post processing approaches over corresponding thermal response to further explore fine subsurface details. Along with these advantages and to further increase the incident power as well as bandwidth, a digital frequency counterpart of FMTWI named as digitized FMTWI(DFMTWI) has been introduced by Mulaveesala etal., They also introduced various other coded stimulation mechanisms to facilitate pulse compression based post processing and broken the barrier of aspect ratio limits of conventional thermographic methods.

This paper introduces a novel post processing methodology based on principal component analysis for enhanced defect detection using recently introduced quadratic frequency modulated thermal wave imaging (QFMTWI) with the experimentation carried over a glass fiber reinforced polymers containing Teflon patches of different sizes and compares it with other contemporary post processing methods[7-10].

2. THEORY OF QFMTWI

In active thermal wave imaging, a preselected simulation according to the testing modality will be imposed on to the surface of the object which creates a corresponding thermal perturbation over a thin layer of the object surface. It further propagates into the interiors of the object as diffusive thermal waves. These propagating thermal waves after encountered by anomalies will undergo a change in their propagation due to thermo physical property variation at these locations and create a temperature contrast over the surface and further captured by an infrared imager. This temperature evolution over the surface due to propagating thermal waves generated by the proposed method will be done by solving one dimensional heat equation for a homogeneous isotropic and semi infinite media as given by [11-14]

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

Where ‘α’ is the diffusion coefficient, T(x ,t) is the surface temperature at the location at time ‘t’ corresponding to depth of the defect ‘x.’ thickness of the object is ‘L,’ stimulated with a chirp heat flux of magnitude‘Q0’ on the front surface of specimen, with initial frequency ‘a’ and sweep rate ‘b,’ using the boundary conditions resulting in a temperature in Laplacian domain as

$$T(x,s)=Q(s).e^{-\sigma x}/k\sigma \qquad \ldots\ldots\ldots\ldots(2)$$

Where thermal diffusion length corresponding to the stimulation is obtained as $\sigma=\sqrt{s/\alpha}$. It is clear from this relation that the frequency variation corresponds to an appropriate change in diffusion length and used to scan the complete thickness of the test object.

3. PROCESSING OF THERMAL RESPONSE

Thermal wave imaging includes a few experimentation and processing steps to evaluate object for subsurface integrity as explained using Fig.1. Before experimentation, to avoid problems with surface emissivity and absorptivity of the test object, its surface (specimen) is coated with black. Further this prepared specimen is stimulated by an optical or suitable stimulation to create a thermal perturbation inside the object and corresponding temporal thermal response is captured by an infrared imager[15-21].

This captured thermal response contain very feeble temperature contrast corresponding to subsurface anomalies embedded in experimentation bounded noise and may not be clearly exhibited from this unprocessed data. In order to visualize fine subsurface details by applying various signal processing approaches, the data from the captured video using IR camera can be formulated into a one dimensional signal as shown in Fig.2.a and preprocessed to obtain the dynamic thermal response using a polynomial mean removal procedure and further Correlation, FFT and PCA based approaches will be employed on this mean removed thermal profiles corresponding to each pixel and rearranged to form a resultant image cube as shown in Fig.2.b.

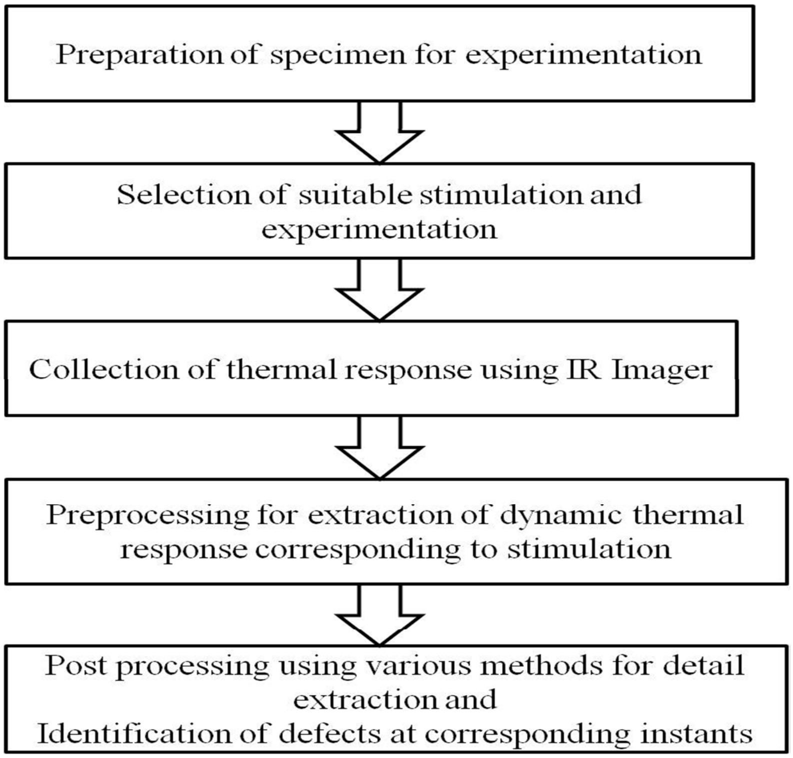


Figure 1. Fig.1. Flow chart of thermal wave imaging process

These resultant images at different instants will exhibit defects corresponding to their depths and used to identify subsurface features.

Phase analysis

In this method fast Fourier transform is employed over the mean removed profiles of each location and phase delay corresponding each pixel at a particular frequency is relocated into a phasegram. Further phase values have been determined at each frequency component, finally phasegrams are constructed by locating the obtained phase values of particular frequency in to their respective spatial positions. Due to differential phase delay possessed by thermal profiles of anomalies at different depths, phase images exhibits a phase contrast which can be used to identify the defect signatures [7-10].

$$f = \frac{F_s n}{N} \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

The frequency of the phase image can be calculated using above relation where [22]

Fs = sampling frequency.
n = number of the phase image.
N = total no of samples.

Pulse compression

Pulse compression is a time domain method of analysis, in which it enhances the defect detection capability by minimizing the noise component and concentrating whole supplied energy in its main peak. An offset response from all pixel profiles has been removed. Firstly a reference profile is selected from the non defective location, with this reference profile a cross correlation has been carried out over remaining pixel profiles in view which further results in a normalized correlation coefficient. This coefficient data has been rearranged in their respective spatial location corresponding to their delay value. The thermal profiles of different depths of defects possess different delay and attenuation hence the constructed correlation image exhibits correlation contrast which discriminates anomalies from sound surface regions [22-24].

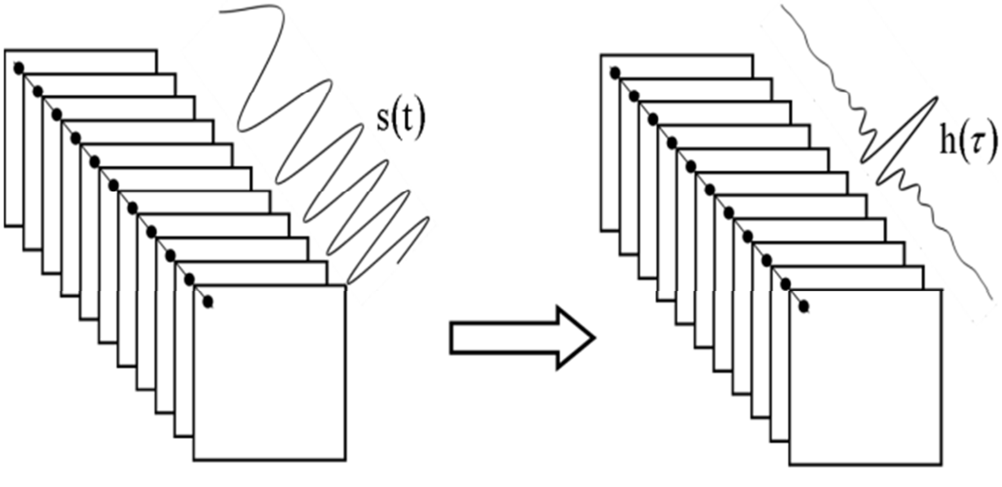


Fig.2 a) Thermal data *b) Correlation processed data*

Principal component analysis

Principal component analysis (PCA) [27-28] can be defined as dimensionality reduction method by projecting the given data on to least principal subspace, which gives variance in the projected data in a descending manner.

The captured data is in 3D for performing principal component analysis, a prior work on raw data is required for the application of singular value decomposition, i.e the original captured 3D data into a two dimensional matrix 'A' in such a way that the by arranging the time variations in row wise and the spatial variations along column wise[27-28].

$$S = (A - A_{mean})(A - A_{mean})^T \text{.............}(4)$$
$$[Y_1\ Y_2\ Y_3] = SVD(s)\text{...........................}(5)$$

To implement PCA, a covariance matrix for the above 2D matrix 'A' is constructed by multiplying the mean removal matrix and its transpose. Now this scatter matrix is convenient for performing singular value decomposition. After applying SVD to the scatter matrix it decomposes 'S' in to three matrices which are Eigen vector matrix Y1, diagonal matrix Y2 and transpose of Eigen vector matrix Y3.The time variations have been obtained as columns in Eigen vector matrix 'Y1 ' and the Eigen values as diagonal elements in diagonal matrix 'Y2 ' and spatial variations as columns in third matrix 'Y3'. The principal components are determined by multiplying each column of Eigen vector matrix with original data matrix. Finally principal component images are reconstructed from principal component matrix.

4. RESULTS AND DISCUSSION

In order to test the applicability of proposed method experimentation has been carried out over glass fiber reinforced polymer containing Teflon patches with different depths and sizes as shown in Fig 4.a. A chirped stimulation of frequency sweep from 0.01 Hz to 0.1 Hz as controlled by NI control interface to modulate the optical output from the halogen lamps of 1KW each is provided to the front surface of the specimen and thermal response is captured with a frame rate of 25 Hz using Flir IR camera. The captured three dimensional response has been processed by phase, pulse compression and principal component analysis.

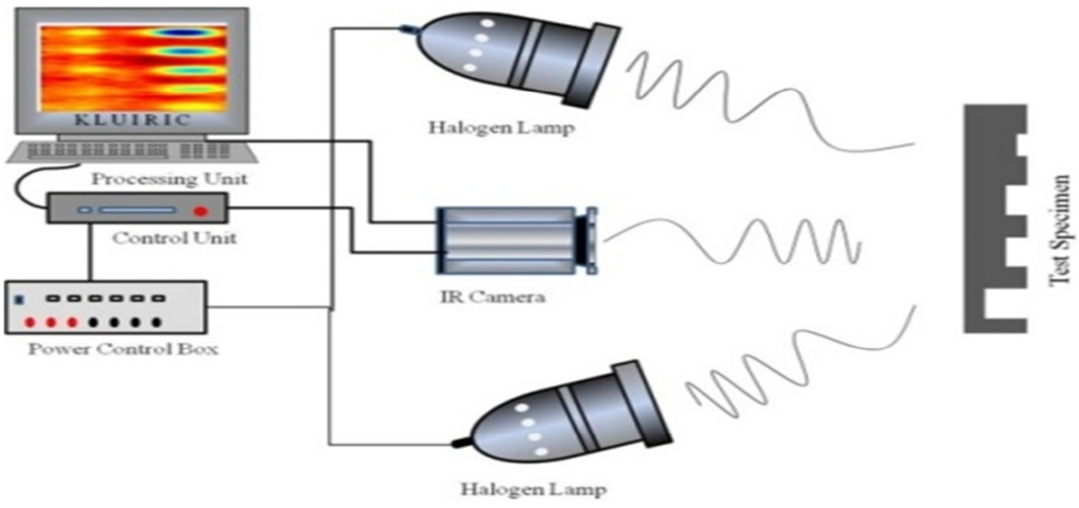


Fig.3. Experimental setup for active thermograph

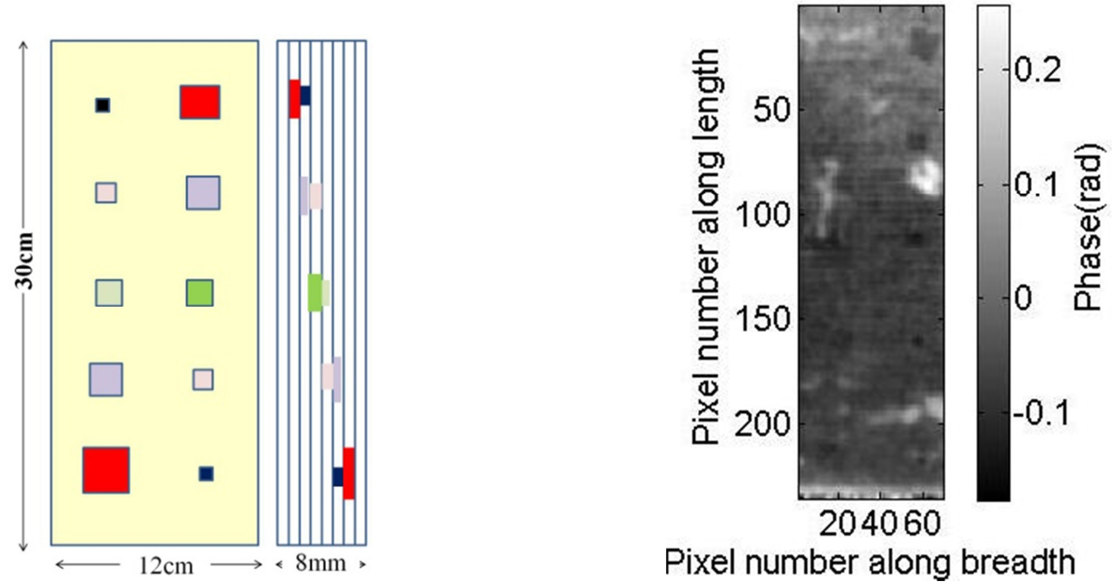
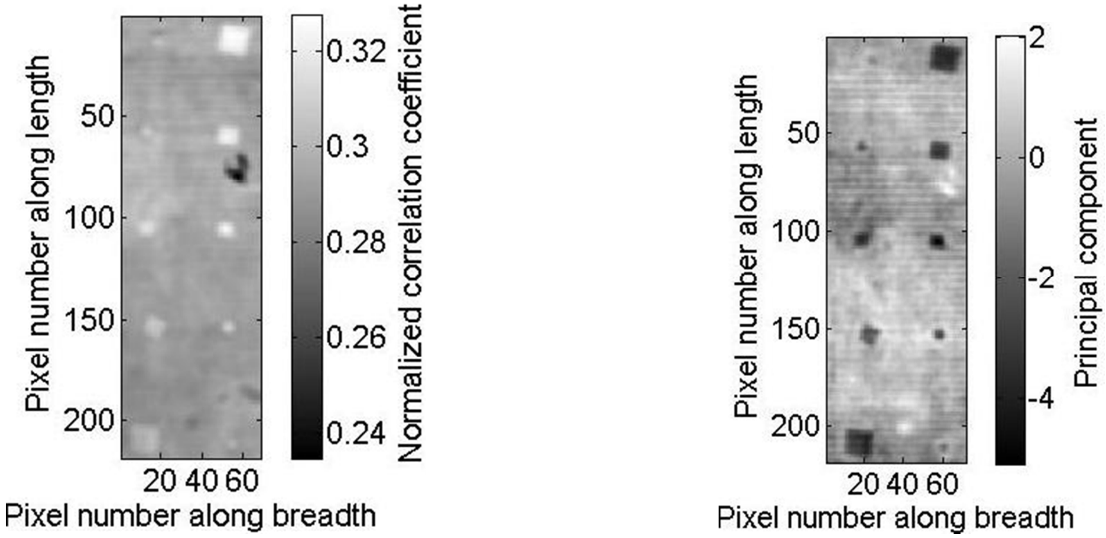


Fig.4. a) Layout of the experimental GFRP Specimen b *) Phase image at 0.02 hz.*



c) Correlation image at4.5s.

d) 2nd Principal component.

Fig.4.b represents the phase image obtained at 0.02hz. It is observed that it is exhibiting a good contrast with shallowest (1st column) defects only, fig.4.c. correlation image gives better thermal contrast to all the defects (2nd column also) compared to phase image due to minimization of noise component and concentration of whole energy property. Whereas fig4.d.2nd principal component exhibits good thermal contrast for all the defects irrespective of their size and depth this attribute is because of separating noise component fully from thermal data set.

Detectability among these approaches has been quantified using signal to noise ratio (SNR) given by

$$\text{SNR (db)} = \frac{\text{Mean of the defective region- Mean of the non defective region}}{\text{Standard deviation of non defective region}} \quad ...(6)$$

TABLE 1: Signal To Noise Ratio Defects

Defect	a	b	c	d	e	f	g	h	i	j
Phase	22	16	-13	-34	-8	30	-50	8	-26	-9
Correlation	32	26	30	3	14	6	15	31	16	32
PCA	46	46	41	18	3	28	33	43	24	34

Table.1 explores the comparative capabilities of various processing approaches in visualizing defects. It has been observed that the correlation based approach is visualizing more defects than phase analysis and exhibiting feeble contrast than PCA due to its noise removal capability at that principal component.

5. CONCLUSION

A novel feature separation approach based on principal component analysis is employed on frequency modulated thermal wave imaging modality. Proposed feature separation based approach for QFMTWI outperformed the conventional state of art techniques as assured from quantitative estimations using defect signal to noise ratio.

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