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Qualitative Subsurface Analysis in Quadratic Frequency Modulated Thermal Wave Imaging

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ABSTRACT

From the Past decades Non Stationary Thermal Wave Imaging (NSTWI) is enlarging as reliable eminent technology to examine various materials like Reinforced polymers and coatings used in industrial applications like aerospace, mechanical, civil appliances etc. Testing of these materials prior to usage is a challenging task which makes use of Non Destructive Testing& Evaluation(NDT&E) techniques. Present article uses a chirped Quadratic Frequency Modulated Thermal Wave Imaging (QFMTWI) to test underneath the Carbon Fiber Reinforced Polymer (CFRP) specimen. Further various post processing methods are used to visualize the subsurface details. Signal to Noise Ratio (SNR) is used as a performance metric to evaluate the performance of various post processing approaches.

Key words: InfraRed Thermography (IRT), Quadratic Frequency Modulated Thermal Wave Imaging (QFMTWI), Non Destructive Testing & Evaluation (NDT & E), Carbon Fiber Inforced Polymer (CFRPP), Pulse Compression (PC), Principal Component Analysis (PCA), Random (Orthonormal) Projection Transform (RPT), Signal to Noise Ratio (SNR).

1. INTRODUCTION

Various manufacturing defects like voids, cracks and delaminations may occur during the preparation of polymers, these defects may damage the material and reduces its permanence. So a thorough inspection of these materials is required before using them in industries, Infrared Thermography (IRT) is growing as such an inspection technique in Non Destructive Testing and Evaluation (NDT&E) due to its noncontact, whole field, non-invasive, attributes. Several methods are developed in IRT to facilitate the industrialization; Infrared Thermography (IRT) is carried in passive and active modes [1].

In Passive thermography, temperature mapping of specimen to be tested is carried under the atmospheric temperature conditions, which may not give the thermal contrast on defective and non-defective regions predominantly for deeper defects. In order to disclose the defects at deeper depths with increased thermal contrast an Active Thermography (AT) is used. On the other hand active thermography makes use of external optical heat stimulus to test the specimen.

Depending on the optical stimulation AT is further divided into Pulse Thermography (PT) [2-3], Pulse Phase Thermography (PPT) [6-8], Lock-in Thermography (LT) [4-5], and Non Stationary Thermal Wave Imaging (NSTWI) [9-14]. From the past decades various researchers rigorously modelled and simulated different approaches to introduce new techniques to refine the limitations of existing techniques.

PT uses high peak power, short duration pulse signal as a heat stimulus to the test sample, which causes a non-uniform radiation and non-uniform emissivity on the surface of material being tested as a result misinterpretation of defects is perceived. Even though various signal and image processing techniques are used to reduce non uniform radiation and emissivity, but still requirement of a high peak power is a main drawback of PT [2, 3].

LT is a wave imaging i.e., a continuous low power mono frequency sinusoidal signal is used as a heat stimulus unlike PT, which reduces the non-uniform heating and emissivity on the surface of the test sample. The Mono frequency of the heat stimulus restricts the penetration of thermal waves which results in fixed resolution. A repetitive experimentation is necessary for specimens with different defects at different depths, which is not recommended [4, 5].

PPT has some advantages of both PT and LT, though the experimental set up and heat stimulus for PPT is similar to PT, it uses Fourier transform based phase analysis for extraction of subsurface details which is similar to LT and still the large power source requirement is a major limitation [6-8]. A NSTWI overcomes the limitations of the conventional techniques like PT, LT and PTT which uses a required band of frequencies which overcomes the repetitive experimentation unlike LT with a suitable (preferably low) magnitude unlike PT and PPT as a heat stimulus [9-14].

QFMTWI [7] uses a quadratic upsweep of band of frequencies for a limited duration with low peak power which results in better depth resolution in a single experimentation. Present work uses QFMTWI based numerical simulation carried on a CFRP test specimen. Later different signal processing approaches like FFT Phase, PC, PCA and RPT [15-19] are applied on the recorded thermal history to distinguish the fine details of the underneath the specimen. Further SNRs are calculated to compare the defect detection proficiency with the conventional state of art techniques.

2. THEORY OF THERMAL WAVES

2.1 QFMTWI

A quadratic chirped heat stimulus is given to the front side of the test specimen provides thereafter an equivalent heat waves on the surface of the specimen which further penetrates into the specimen. These penetrated thermal waves are bounce back either from extremities or from back holes and develops a thermal contrast over the surface of the test specimen which discriminates anomalies or sound area and it can be obtained by solving the one dimensional heat equation [1]

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

Where α is the thermal diffusivity coefficient, 'T' is the instantaneous temperature at a time t and x is the depth. Let us assume that the test sample is of thickness 'L', by solving the boundary conditions [14]

$$\left.\frac{\partial T}{\partial t}\right|_{x=0} = Q_0 e^{-j2\pi(at+bt^3)} \tag{2}$$

$$\left.\frac{\partial T}{\partial t}\right|_{x=L} = 0 \tag{3}$$

Where Q_o is the optical heat flux magnitude, 'a' is the initial frequency, 'b' is the sweep rate and 'k' is the thermal conductivity. The thermal response obtained by solving the above boundary conditions in Laplace domain is

$$T(x,s) = \frac{Q(s)e^{-\sigma x}}{k\sigma} \tag{4}$$

2.2 Processing and Subsurface Analysis

The recorded thermal data contains both dynamic and static data; this static response is not useful for subsurface analysis. So we need to pre-process the raw thermal data before applying post processing modalities like FFT Phase, Pulse Compression, Principal Component Analysis and Random Projection Transform to get the dynamic response related to the applied optical stimulus in order to detect the defects.

2.2.1 Phase analysis

Phase analysis is the conventional technique to extract the underneath details of the specimen. Fast fourier transform is implemented on the dynamic thermal data to remove the non uniform heating and emissivity problems. All the phase profiles are arranged in a view to construct the phasegrams containing the phase delay between the defect and sound area and is given by [9-16]

$$F(\omega) = \sum_{n=0}^{N-1} f(n)e^{j\omega n} = \sum_{n=0}^{N-1} \mathrm{Re}\big(F(n\omega)\big) + \mathrm{Im}\big(F(n\omega)\big) \tag{5}$$

Where, Re and Im are real and imaginary parts of nth component of thermal response in frequency domain. The corresponding phase at any frequency can be given by [5-7]

$$\phi(n) = \tan^{-1}\left(\frac{\mathrm{Im}(F(n\omega))}{\mathrm{Re}(F(n\omega))}\right) \tag{6}$$

2.2.2 Correlation based time analysis

Correlation based analysis is performed in time domain for the each profile of preprocessed thermal data by correlating with the sound area as the reference profile. It employs on the time delayed coefficients to differentiate the defective and sound regions.

The same procedure is done for all profiles and the normalized correlation coefficient is obtained and arranged in order to view the correlated image [17-24].

$$G(\tau) = \int_{-\infty}^{\infty} h(t)\, s(\tau+t)dt \tag{7}$$

2.2.3 Principal component analysis

The main purpose of proposing principal component analysis (PCA) is to represent the pre-processed thermal data into an orthogonal basis vectors with maximum variance. These orthogonal basis vectors are collected from experimental or simulated data. By using automatic or physical projection of respective Eigen vectors (L<<N, N is length of thermal response) on the maximized variance generates the dimensionally reduced thermal data with fine subsurface details [25, 28].

2.2.4 Orthonormal projection transform

The orthonormal project transform produces orthonormal random vectors based on the Gram-Schmidt's algorithm and later thermal profiles of the recorded thermal response are imposed on them in order to get the normalized random projection coefficients [29, 30].

In this method initially the recorded 3 dimensional thermal response is converted to 2 dimensional matrix by arranging different pixel values of a thermogram. It generates the random vector in the orthonormal basis by extracting:

$$v_1 = \frac{f_1[n]}{\left\|f_1[n]\right\|} \text{ and } v_2 = f_2[n] - \left(v_1^T f_2[n]\right) V_1 \tag{8}$$

3. EXPERIMENTATION

In addition to examine the proposed methodology a numerical based simulation is carried on CFRP specimen exited by QFM heat flux on the experimental side of the test specimen in COMSOL Multiphysics Software.

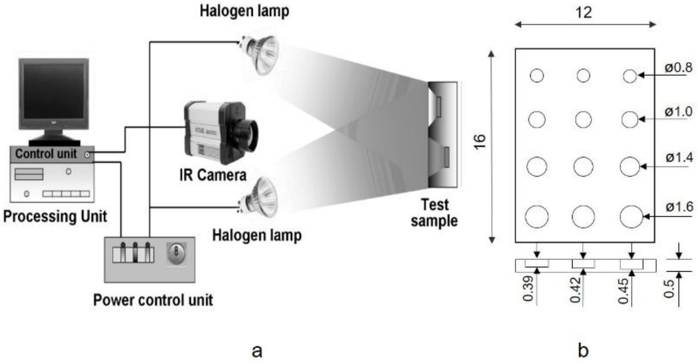

Figure 1 a. Experimental Schematic of Active Thermography and b. Experimental Layout of Specimen (all dimensions in cm).

The simulation is done for 100 seconds using quadratic frequency thermal waves for a band of frequencies from 0.01Hz to 0.1Hz using a set of halogen lamps each of 1kW as shown in the above figure 1.a [14]. The simulated CFRP test specimen is of 16cm long, 12cm width and 0.5 cm thickness with flat bottom holes of radius 1.6cm, 1.4cm, 1cm and 0.8cm at a depths 0.39cm, 0.42cm and 0.45cm respectively as shown in fig1.b.

The response form the test specimen is captured using infrared camera with a resolution of 320x240 at 25 frames per second. The captured thermal response of the test specimen is further processed using several signal processing techniques to extract fine details of the underneath the sample.

4. RESULTS AND DISCUSSION

Various post processing techniques like FFT phase, PC, PCA and RPT are employed over the captured thermal response and the corresponding results are shown in the fig 2.

Fig 2.a shows the FFT phasegram at 0.012Hz, 2.b shows the correlation image at 16.88 sec 2.c shows the 1^{st} PCA and 2.d shows the 55^{th} random projection component.

From the fig 2.d it is observed that 55^{th} RPT image gives better defect detection compared to all the other conventional post processing approaches.

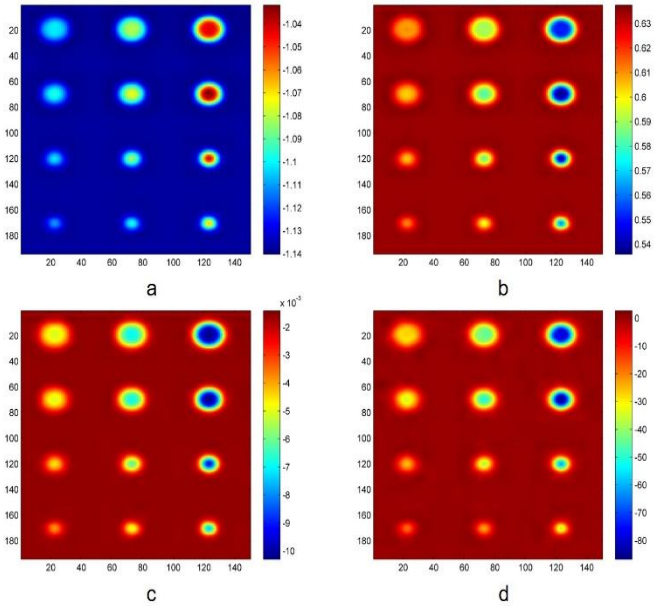

Figure 2 a. FFT phasegram at 0.012Hz, b. Pulse compression image at 16.88sec, c. 1st principal component image and d. 55th random projection component.

The defect detectability of these approaches were compared by calculating the performance metric Signal to Noise Ratio (SNR) for each defect using the following equation.

$$SNR(dB) = 20\log\left(\frac{\mu_{Defective} - \mu_{Sound}}{\sigma_{Sound}}\right) \qquad (10)$$

SNR is defined as the ratio between the difference between the mean of defective and sound area to the standard deviation of the sound area. The following figure 3 shows the comparison graph of SNRs for all post processing approaches. From this it is clear that SNR of RPT image gives the good SNR compared to other approaches.

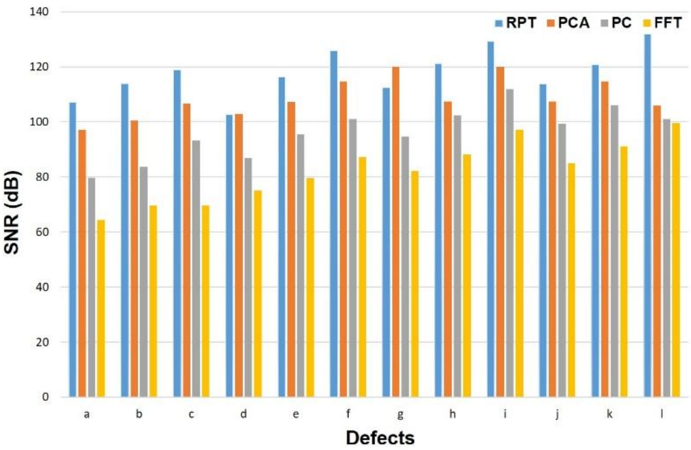

Figure 3: Comparison of SNRs of CFRP sample for various post processing approaches

5. CONCLUSION

The depth scanning and defect detectability of the QFMTWI is explored using RPT based processing technique. The suitability of RPT for identification of defects using QFMTWI is verified numerically in COMSOL Multiphysics. SNRs are compared for all processing methodologies to conclude that random projection based approach provides good signal to noise ratio.

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