

# Inspection of Defects in CFRP Based on Principal Components



Md M Pasha, G V Subbarao, B Suresh, S Tabassum

**Abstract:** Recent advances in thermal non-destructive testing (TNDT) witnessed improved defect detection capabilities in various fields. Active thermography enables fast and easy inspection of products made of composites. A number of post processing techniques are being developed with an aim to enhance the subsurface defects from the thermographic data. This paper explores the idea of applying principal component analysis (PCA) to thermal wave imaging for possible enhancement of subsurface defects in carbon fibre reinforced plastic (CFRP) material. The experimentation is carried over CFRP sample using quadrature frequency modulated thermal wave imaging (QFMTWI) excitation scheme and results are compared with conventional phase based methods. The results demonstrate the potential of this approach for detecting subsurface defects in CFRP.

**Keywords:** PCA, QFMTWI, Subsurface defects, Thermal wave imaging.

## I. INTRODUCTION

In recent years the demand for fibre reinforced plastics is considerably increased due to its properties such as light in weight, good strength and high immunity against corrosion. Various application areas such as automobiles, aerospace and civil are extensively using these materials due to these properties. But manufacturing defects in the form of voids and delaminates severely effects the efficiency of the material and therefore they limit the usefulness of the material. In order to overcome this careful and complete evaluation of these materials is required. TNDT maps the temperature on the surface of a test sample with an aim to explore the defects lying underneath [1] - [3]. As many solids have the property of conducting heat, TNDT can be used effectively in different materials like metals, semiconductors and composites for defect detection. Among different implementations of TNDT Infrared non-destructive evaluation (IRNDE) has been accepted widely for evaluation of materials without effecting their physical properties and further in-service applications. IRNDE has two approaches namely active thermography and passive

thermography. Passive thermography in the absence of external stimulation maps the difference in temperature between ambient and material to be tested. The drawback of this approach is that it cannot provide temperature contrast over the defective and non-defective regions and also it cannot highlight defects lying deeper inside the material. In order to counter this active thermography is introduced. In this approach external stimulation is used to energize the test sample so that considerable temperature contrast is achieved over the sample which leads to detection of subsurface defects. Various active thermography techniques on the basis of excitation are Pulse thermography (PT) [3], [4], Lock in thermography (LT) [5], Pulse phase thermography (PPT) [6]. On the other hand based on non-stationary thermal excitation variants of Frequency modulated thermal wave imaging (FMTWI) are introduced to detect subsurface defects [7], [8]. Every technique has its own advantages and disadvantages, and based on the application and thermal properties of the material to be inspected choice of the technique depends. Continuous wave thermography like LT and FMTWI was introduced to overcome the drawback of requirement of high peak power excitation sources in PT and PPT. Even though LT requires low peak power sources due to its mono frequency operation defects lying at various depths cannot be resolved in a single experimentation cycle. FMTWI overcomes this drawback by exciting a band of frequencies on to the test sample in a single run. In our work continuous wave Quadratic FMTWI [9] approach of excitation is used to energize the test sample. For continuous wave thermography phase analysis of the recorded thermal response is most widely used technique for subsurface defect detection. In phase based analysis fast Fourier transform (FFT) of the thermal response is used to obtain phase images. But in FMTWI approach as wideband non stationary excitation is used, sinusoidal basis functions contained in FFT may not be suitable for resolving defects. To overcome this, an alternative basis functions based on singular value decomposition (SVD) called principal component analysis (PCA) [10] – [12] is used in our present work. The results are compared FFT phase and Hilbert phase (HP) [14] approaches.

## II. THEORY

In active thermography as the excitation is imposed on to the test sample the heat from the source produces a thermal wave which travels into the test sample and as a result of which a time varying temperature distribution is observed on the sample surface. Defects present in the test sample effects the flow of heat and therefore thermal contrast is observed over the test sample.

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The one dimensional heat transfer equation to study this thermal response is [13]:

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

where  $\alpha = k/\rho c$  is the thermal diffusion coefficient of the material,  $k$  is the thermal conductivity,  $\rho$  is the density and  $c$  is the specific heat and  $T$  is the instantaneous temperature on the surface at a given spatial location  $x$  at time  $t$ . On solving the above equation for a semi-infinite solid for the boundary conditions  $x = 0, \varphi(t)$  surface temperature varying with  $t$  and  $x \rightarrow \infty T =$  ambient temperature) and for initial conditions  $T(x, t = 0) = 0$ , instantaneous temperature is obtained as:

$$T(x,t) = \frac{2}{\sqrt{\pi}} \int_{x/2\sqrt{\alpha t}}^{\infty} \varphi(t - \frac{x^2}{4\alpha\mu^2}) e^{-\mu^2} d\mu \quad (2)$$

For excitation using optical sources an offset is added to the proposed continuous wave. Therefore the excitation can be treated as a combination of a step and quadratic frequency modulated excitation. Hence the temperature evolution on the sample's surface can be considered as the response due to both the excitations considered independently. Temperature response due to static part is given by:

$$T_s(x,t) = \frac{Q_0}{k} ((\alpha t/\pi)^{0.5} \exp(-x^2/4\alpha t) - \frac{x}{2} \operatorname{erfc}(\frac{x}{2(\alpha t)^{0.5}})) \quad (3)$$

where  $Q_0$  is the peak heat flux.

Temperature evolution due to quadratic frequency thermal wave is:

$$T_d(x,t) = \frac{Q_0}{k\sigma} \left( \frac{\cosh \sigma(L-x)}{\sinh \sigma L} \right) \exp(i(w_0 + bt^2)t) \quad (4)$$

where  $L$  is the thickness of the sample,

$\sigma = \sqrt{\frac{1}{\alpha} (\frac{i+1}{2} (w_0 + 3bt^2))}$ ,  $w_0$  is the initial frequency of the quadratic chirp and  $b$  is the sweep rate. The total temperature evolution due to both the excitations is

$$T(x,t) = T_s(x,t) + T_d(x,t) \quad (5)$$

The thermal wave diffusing inside the material is attenuated as it progresses through the material. The thermal diffusion length  $\mu_{qfm}$  (the depth at which the energy of wave decays to  $1/e$  times of its surface value) due to quadratic frequency modulated thermal wave is given by:

$$\mu_{qfm} = \sqrt{\frac{2\alpha}{(w_0 + 3bt^2)}} \quad (6)$$

Here, the second term in the denominator is the modulation factor, which indicates the rate at which frequency changes with time for a quadratic frequency modulated signal. The dependence of diffusion length on bandwidth helps to scan complete depth of the sample using applicable frequency range in a single experimentation cycle. The thermal wavelength ( $\lambda$ ) which is related to diffusion length  $\mu_{qfm}$  for the case of frequency modulated thermal wave imaging is given by:

$$\lambda = 2\pi\mu_{qfm} = 2\pi \sqrt{\frac{2\alpha}{(w_0 + 3bt^2)}} \quad (7)$$

As the thermal wavelength depends on the frequency of the induced frequency modulated heat stimulus, it leads to detection of defects located at different depths.

### III. PCA BASED THERMOGRAPHY

Even though in continuous wave thermography PPT is

used extensively the frame which highlights the defects has to be searched locally from huge thermal data. Therefore there is a necessity to compress the data and limit the search window for defect detection. PCA [12] is a popular tool which can be computed via SVD for concentrating low dimensional information contained in a high dimensional data and also to concentrate maximum variance into as less dimension as possible. This feature extraction and compression property of PCA is used in numerous engineering applications.

The thermal response from the test sample is captured using an IR camera at fixed frame rate which gives a three dimensional thermal image set. Therefore the inter-frame redundancy in thermal data is very high. The degree of compression depends on the fact that how much redundant data can be removed. Each of the orthogonal basis function derived by the PCA is based on the statistical properties of the data and therefore it has excellent energy compaction and de-correlation property. The property of de-correlation together with maximum variability makes PCA based analysis suitable for defect detection from the thermal data. Therefore using PCA we can efficiently transform the three dimensional thermal image set to compress and extract the information related to subsurface defects.

Let  $K$ -frame three dimensional thermal sequence consisting of images of size  $W \times H$  is represented by  $f_k(x, y)$ ,  $1 \leq x \leq W$ ,  $1 \leq y \leq H$  and  $1 \leq k \leq K$ . Consider a vector  $X_k$  which is obtained by row or column stacking of image  $f_k(x, y)$ . Therefore

$$X_k = [f_k(1,1), f_k(1,2) \dots f_k(1,W), f_k(2,1), f_k(2,2) \dots f_k(2,W) \dots f_k(H,1) \dots f_k(H,W)]^T \quad (8)$$

Where  $1 \leq k \leq K$

$X_k$  is arranged such that spatial variations occur in rows and time variations occur in columns. Mean and covariance vector of  $X_k$  can be obtained as

$$\mathbf{m}_f = E\{X\} = \frac{1}{K} \sum_{k=1}^K X_k \quad (9)$$

$$\mathbf{C}_f = E\{(X - \mathbf{m}_f)(X - \mathbf{m}_f)^T\} \approx \frac{1}{K} \sum_{k=1}^K X_k X_k^T - \mathbf{m}_f \mathbf{m}_f^T \quad (10)$$

where  $\mathbf{m}_f$  is a vector consisting of  $WH$  elements and  $\mathbf{C}_f$  is  $WH$  order square matrix. The eigen values  $\lambda_k$  ( $k = 1, 2, \dots, K$ ) of the covariance matrix  $\mathbf{C}_f$  are arranged in descending order and corresponding eigen vectors are  $\mathbf{a}_k = [a_{k1}, a_{k2}, a_{k3}, \dots, a_{kWH}]^T$ , then orthogonal transformation matrix  $\mathbf{A}$  is obtained by arranging eigen vector corresponding to highest eigen value in first row, eigen vector corresponding to second highest eigen value in second row and so on. The vector  $X_k$  is centralized by removing mean  $\mathbf{m}_f$  from each of its column such that

$$\bar{X} = X - \mathbf{m}_f \quad (11)$$

Therefore principal component analysis can be done by

$$Y = (\mathbf{A})^T \bar{X} \quad (12)$$

The above result can also be obtained by computing singular value decomposition (SVD) to matrix  $X$ . Since PCA maximizes the variance in the data set first few principal components contain as much variability in the data as possible.

In thermography applications as the external heat stimulation propagates through the surface of the test sample it causes temperature variations at the defective locations compared to the non-defective locations. This causes variations in the pixels at the defective locations when compared to pixels at the non-defective locations.

Thus PCA can be used as efficient tool to extract information about defects in the materials. And also dimensionality reduction property of PCA achieves compression of the thermal response data and eliminates the need to inspect all the processed thermal images for defect detection.

The following procedure is implemented for detection of defects from the thermal response data using PCA approach.

- Convert three dimensional thermal data of dimension  $W \times H \times K$  to two dimensional data  $X$  of dimension  $WH \times K$  by row or column stacking using Eq. (8)
- Compute mean vector  $m_f = E\{X\}$  and covariance vector  $C_f = E\{(X - m_f)(X - m_f)^T\}$ .
- Form orthogonal transformation matrix  $A$  by arranging eigenvectors of covariance matrix  $C_f$  row wise according to decreasing order of eigen values  $\lambda_k$ .
- Centralize  $X$  by removing mean from each of its column using  $\bar{X} = X - m_f$ .
- Principal component analysis is done by projecting  $\bar{X}$  on to transformation matrix  $A$  i.e  $Y = (A)^T \bar{X}$
- For inspection of defects convert two dimensional matrix  $Y$  to three dimensional matrix  $W \times H \times K$  by rearranging each column of  $Y$  to form an image.
- First three images of rearranged data are extracted and used for inspection of defects in the test sample.

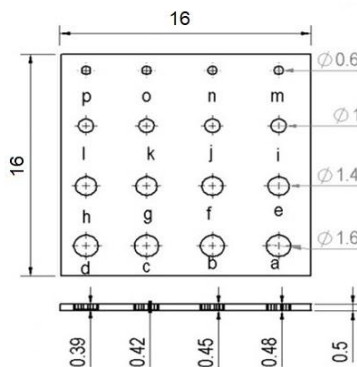


Fig. 1 Layout of the CFRP sample

#### IV. TEST SAMPLE AND EXPERIMENTATION

To test the capability of PCA based approach for defect detection experiment is conducted on a CFRP sample containing flat bottom holes. The layout of the test sample is shown in the Fig. 1. It contains 16 flat bottom holes drilled at various sizes and depths to show the defect detection capability. To conduct the experiment a linear frequency modulated excitation is generated from the control unit of the imaging system for 100 seconds duration in the frequency range of 0.1 Hz to 0.01 Hz and CFRP sample is energized with a set of halogen lamps of 1 kW each. The experimental setup is as shown in the Fig. 2. The thermal response over the sample is acquired using a FLIR infrared

camera at a rate of 25 frames per second for 100 seconds duration. Therefore 2500 frames are captured by infrared camera. From the captured thermal response mean rise in temperature due to active heating is removed by fitting the thermal data to a linear fitting routine. This mean removed thermal response is processed using PCA and Phase based approach and performance is compared. PCA based approach is applied to three dimensional thermal response captured by infrared camera as described in previous section. The processed data matrix  $Y$  is converted to three dimensional data and first three images are inspected for defect detection. In phase based approach thermal profile at each pixel of the thermal response is extracted and FFT phase and Hilbert phase [14] methods are applied. And then phase image sequence is extracted and inspected for defects.

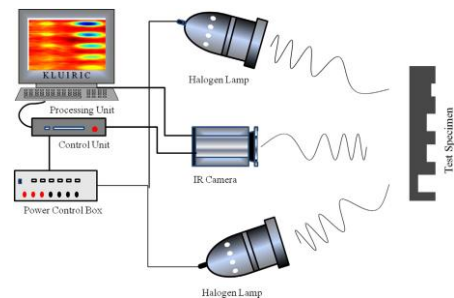


Fig. 2 Experimental Setup

#### V. RESULTS

As PCA maximizes the variance in the data first three images are sufficient for defect detection analysis. This leads to compression of the data and narrows the search region for defect inspection. Where as in phase approach the complete image sequence is extracted and frame highlighting the defects need to be searched.

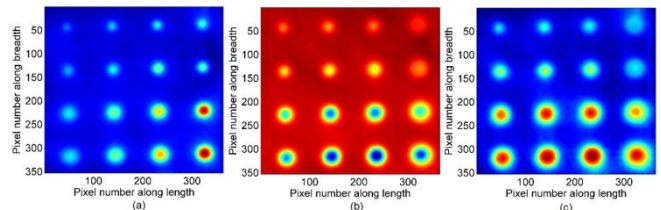


Fig. 3 (a) Phase image at 0.02 Hz (b) Hilbert Phase image at 0.02 Hz (c) PCA processed image at frame No. 2

Fig. 3 shows FFT phase image, Hilbert phase image and processed image using PCA approach. It can be seen that image using PCA approach has better contrast over FFT and Hilbert phase images. It can also be seen that second image in the sequence Fig. 4 shows first three images obtained using PCA approach.

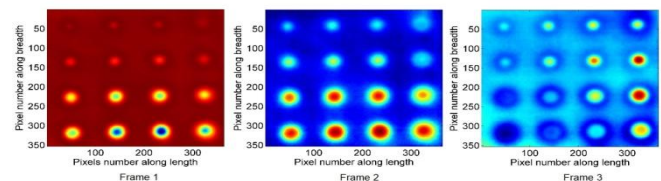


Fig. 4 First three frames of processed thermal response using PCA approach

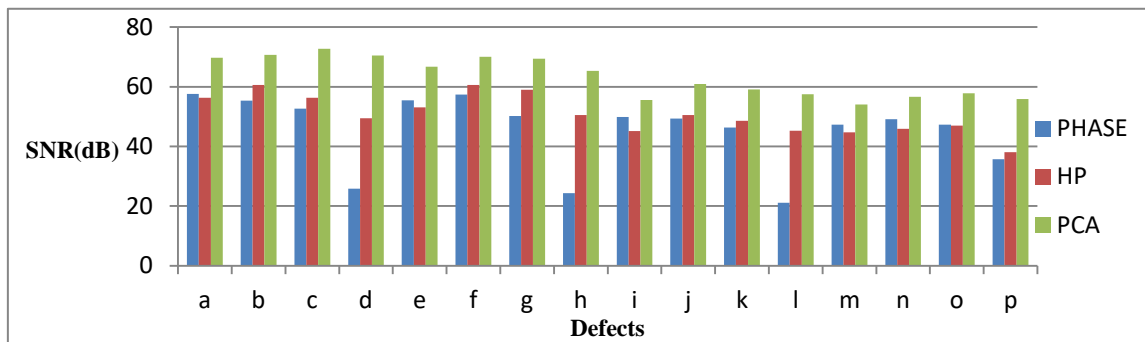
**SNR Comparison**

SNRs of the defects are calculated to assess the quality of PCA and Phase based approaches for defect inspection. The SNR at a defect location is computed by

$$SNR = 20 * \log_{10} \left( \frac{M_d - M_{nd}}{\sigma_{nd}} \right)$$

(13)

where  $M_d$  and  $M_{nd}$  are the mean of the defective and non-defective regions and  $\sigma_{nd}$  is the standard deviation of the non-defective area. Fig. 5 shows



**Fig. 5 SNRs comparison of defects**

SNR comparison between chosen image from Raw thermal data highlighting defects, PCA and Phase approach methods.

**VI. CONCLUSION**

In this paper PCA based approach is used to process the thermal response data obtained by conducting experiment on CFRP sample. Comparisons are made with FFT phase and Hilbert phase approaches and SNRs of the defects are computed. The results show that PCA approach has the better defect detection capability and it also compresses the thermal response data.

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