Data Fusion Based Enhanced Defect Detection for Quadratic Frequency Modulated Thermal Wave Imaging

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Abstract
Active thermography is an emerging nondestructive evaluation modality to inspect subsurface features of the stimulated test object using temporal temperature contrast over it. But captured thermal history may not explore all the subsurface anomalies due to non-uniform radiation, non-uniform emissivity and insufficient thermal contrast embedded in noise from deeper anomalies which demands the application of various signal and imaging processing techniques. But no single post processing method has been found to exhibit all the details with better contrast. Hence a modality to better explore all the details by embedding the details extract from various processing methods is to be investigated.

Data fusion facilitates us to embed the features obtained from various post processing modalities for anomaly detection and provides an enhanced defect detection capability in non-stationary thermal wave imaging. In order to obtain better subsurface details like location and size of defect, various post processed thermal features are merged using fusion techniques like wavelet and curvelet transform methods.

This paper proposes a curvelet based fusion methodology to combine the details obtained from various subsurface analysis approaches for quadratic frequency modulated thermal wave imaging through simulation carried over a CFRP sample and compares it with existing wavelet based fusion methodology using defect signal to noise ratio.

I INTRODUCTION

In recent years the materials made up of Carbon Fiber Reinforced Plastic (CFRP) [14] are used in aerospace, civil and mechanical industrial applications due to its peculiar properties like high strength and low weight etc. But anomalies present in these materials may cause severe damages while used in applications which demands rigorous evaluation. Infrared nondestructive testing is evolving as a reliable, non-contact and quick testing modality to cater the needs of these evaluation requirements. It uses the infrared portion of the spectrum to identify anomalies present in the material, in which a temperature variation over the tested object surface is recorded using an infrared camera. In active thermography the test object surface is excited by an external predefined stimulus which initiates progressive thermal waves very nearer to the surface due to temperature gradient. Further this temporal thermal response of the object is captured by an infrared camera [1, 9, 11].

Among various active thermographic techniques, in pulse thermography, a short duration and high peak power stimulation is imposed on the surface of the test sample and subsequent thermal response is captured using an infrared camera, whereas lock-in
thermography\[1,4\] make use of a low power, low frequency excitation and FFT phase based subsurface analysis. But use of high peak power sources in PT and repetitive experimentation in lock in thermography are to be substituted by a stimulation using low peak power sources and sweeping a band of frequencies in a single experimentation cycle using quadratic frequency modulated thermal wave imaging technique\[3\]. In order to extract surface details from the captured thermal history various processing approaches like FFT, Hilbert transform based phase analysis etc., are used to locate them and to estimate their parameters\[8, 10, 11\].

But subsurface anomalies will be exhibited at different instants corresponding to their depth and size in post processing, which may be misinterpreted in their exploration through analysis. This demands a modality to embed all these details in a single image for end user analysis and defect visualization. In order to cater these needs, recently a wavelet based data fusion modality has been introduced for IRNDT applications. This paper proposes a curvelet transform based fusion modality to embed the subsurface details intended for better defect edge extraction.

II. METHODOLOGY

In active thermography, the test object is energized by a modulated stimulus to generate corresponding diffusive thermal waves inside the object. The generated waves progress uniformly into the object and perturb their usual propagation at subsurface anomaly due to a change in thermo physical properties of the anomaly and contribute for a temperature contrast over the object surface. This temporal temperature map of the surface is recorded by an infrared imager and further analyzed using various post processing approaches.

FFT based phase based analysis is a frequency domain method which uses the frequency decomposition capability of Fast Fourier Transform (FFT) to generate the phasegram corresponding to a frequency for identification of defect location. Whereas 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 \[6, 8, 9,12\]. In this process, a reference profile is chosen from non-defective region, further normalized and cross correlation is performed between reference profiles and remaining pixels profiles. 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 \[6\]. The correlation contrast in correlation image is used to visualize the defects. In Hilbert phase based approach, multiple transforms that is Hilbert transform followed by Fourier transform, are applied over thermal profile of each pixel and ordinary cross correlation based pulse compression has obtained. Finally phase value has been calculated between Hilbert phase based PC to ordinary PC further time domain phase images are formed \[8, 6\].

One cannot guarantee that any single instant may give all the subsurface details of interest accurately, which demands the application of data fusion \[13\] for combining the details obtained from various instants of any post processing approach.

In order to get the better defect details, the present work highlights the curvelet transform based data fusion to embed the individual features as explained below\[7,15,16 17\].
1. The images which are to be fused are registered.
2. Curvelet transform is applied on both the processed images.
3. For the fusion of the curvelet transform of sub bands of both the images, maximum frequency fusion rule is applied.
4. On these fused sub bands inverse transform is applied.
5. The combined details of both the images can be visualized in a single image so that we can get more details and better defect edge information.

III. RESULTS AND DISCUSSION
In order to validate the proposed methodology, a numerical study has been carried over a CFRP specimen with dimensions 100×100×3mm containing nine flat bottom holes with a diameter of 20mm and defect depth varies from 0.2mm to 1.8mm. The front surface of the specimen is energized by a quadratic chirp with a heat flux of 2kw for duration of 100s, object response is captured at a frame rate of 20 Hz.
In order to extract fine subsurface details various processing methods like phase analysis, pulse compression and Hilbert phase are employed on captured thermal data. Curvelet transform is applied on each processing method which gives the coefficients of individual images which facilitated to fuse the coefficients so that better defect edge information of fused images are as shown in Fig.1

![Fig.1.](image_url)

**Fig.1.** a) Sample layout (all dimensions are in cm), b) FFTPhasegram, c) Hilbertphasegram and d) pulse compression.
Defect Detectability has been quantified by Signal to Noise Ratio (SNR) [10] as shown in table 1 given below:

\[
\text{SNR (db)} = \frac{\text{Mean of the defective region} - \text{Mean of the non defective region}}{\text{Standard deviation of non defective region}}
\]

<table>
<thead>
<tr>
<th>Post processing approach</th>
<th>SNR of Defects (in dB)</th>
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<tr>
<td></td>
<td>a</td>
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<td>Pulse compression</td>
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<td>Hilbert phase</td>
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<td>Phase</td>
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Table 1. SNR of defects

Fig 1(b): Result of FFT phasegram of defects a, b, c, d, e are clearly visible, remaining defects are not visible. Fig 1(c): Result of Hilbert phasegram of defects a, b, c, d, e, f, g are clearly visible and remaining defect holes are not visible. Fig 1(d): Result of Pulse compression of defects a, b, c, d, e, f, g, h, i are visible.

IV. CONCLUSION

By simulating the above three processing methods, we conclude that Pulse compression and Hilbert phase visualize even deeper and with smaller defects. These (Pulse compression and Hilbert phase) fused images are more clear when compared with FFT phase images by combining the details obtained from various subsurface analysis approaches for quadratic frequency modulated thermal wave imaging through simulation carried over a CFRP specimen.

ACKNOWLEDGMENTS

This work has been supported by University Grants Commission- India’s Research Award under grant number F.30-1/2014/RA-2014-16-GE-ANP–5573 and also supported by Science and Engineering Research Board, Department of Science and Technology, India under the grant no: SB/S3/EECE/0139/2013.
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