Detecting Non-Stationary Thermal Wave Imaging through Orthonormal Projection Transforms

Badugu Suresh

Koneru Lakshmaiah Education Foundation, Vadedeswram, Guntur, AP, India,

Pin code:522302. suresh.nitr@gmail.com

Abstract.

Recent past witnessed the introduction of a few nonstationary thermal wave imaging modalities to overcome the shortfalls of conventional thermographic methods. Quadratic frequency modulated thermal wave imaging (QFMTWI) is one of these techniques which imposes a continuous frequency sweep containing more energy with low frequency thermal waves in a single experimentation cycle to facilitate entire depth probing of the test object, unlike its linear frequency counterpart.

In order to extract fine subsurface features in this modality, the temporal thermal history of the stimulated object is captured using an infrared imager and post processing methods like phase analysis or pulse compression etc., have been carried out. But all these existing post processing methods are based on Fourier transform which provides limited frequency resolution based on the number of captured thermograms and their capturing rate. This inadequate frequency resolution subsequently limits the depth resolution capability of this modality and required to be enhanced.a proposed a method Orthonormal projection which give better performance than other post processing methods. Performance of Orthonormal projection based approach is demonstrated by considering defect detection, signal to noise ratio (SNR).

Keywords: Quadratic frequency modulated thermal wave imaging, Orthonormal projection**,** Pulse compression, Hilbert Phase, Signal to noise ratio and Full width at half maxima.

1.Introduction

In recent years the usage of carbon fiber plastic materials increased in aerospace, civil and mechanical industries due to it's peculiar properties compared to other materials. But anomalies present in the materials causes severe damage in their service time which are produced in the manufacturing time. To prevent damages with these anomalies a monitoring of the object is necessary, for this Infrared Non-destructive testing makes an easy way due to its non-contact whole field non-destructive method of evaluation. It uses the infrared spectrum to identify the inhomogeneities 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 in the form of light, the incident optical energy initiates thermal waves very nearer to the surface due to diffusion process, generated thermal waves travel to back end of the object. in this process the object dissipates energy to the surroundings and to reach equilibrium. The total temporal and thermal response of the object is captured by infrared camera. Among various available IRNDT methods pulse thermography and continuous wave thermography are popular, in PT a short time high peak power stimulations are used further the thermal response is recorded by camera.

To overcome above two limitations R. Mulaveesala and group recently introduced nonstationary thermal wave imaging methods, In these non-stationary imaging methods a low power, low frequency and a suitable band of frequencies are employed to energize the test object in a single experimentation cycle. LFMTWI uses a chirp like stimulation where as in DLFMTWI uses a digitized version of LFMTWI by probing more harmonics compared to its analog version. It gives a better depth resolution than LFM. The recently introduced Quadratic frequency modulated thermal wave imaging (QFMTWI) with the support of feature separation processing method for the defect identification.

2.Methodology

In IRNDT the test object is energized by a modulated stimulus, this incident energy initiates thermal waves nearer to the surface which will further propagate into interiors of the object to reach equilibrium. The anomalies present in the object gives an abnormal behavior to conduction process; it results in a temperature contrast over the surface at defect location compared to non-defective region. This total temporal thermal response recorded by infrared camera and anomalies are extracted by processing the captured temperature history.

In the captured data, thermal history is embedded with the experimental noise, non-uniform radiation and non-uniform emissivity which hides the defect signature. In order to extract fine defect details, various signal processing methods are used. Prior to the application of processing methods the captured thermal data is necessary to remove a response corresponding to offset in excitation to get dynamic responses according to proposed excitation using a linear fitting procedure.

2.1 Phase Analysis:

It is a frequency domain method, employing fast Fourier transform (FFT) for frequency unscrambling. Fast Fourier transform applied over mean removed thermal profile of each pixel and phase values to each frequency component is calculated, phase images are formed by arranging phase values of corresponding frequency component into its respective pixel position. The constructed phase images exhibits phase contrast due to phase delay contributed from thermal waves of anomalies at different depths. The frequency corresponding to the phase image exhibiting the defects can be determined 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.

2.2 Hilbert phase:

It is a multi-transform method, in which a reference profile is selected from pixel’s profile, further Hilbert transform has applied over it next fast Fourier transform has been employed over remaining pixel profiles and complex conjugate of it is calculated. Then inverse FFT is calculated over multiplication of referenced Hilbert transform profile and calculated complex conjugate profiles.

$$Q_1 = IFFT\left[\{FFT\left(Hilb(T_r)\right)\}*\{FFT(T)\}\right] \text{...............(3)}$$

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

$$Q_2 = IFFT\left[\{FFT\left(T_r\right)\}*\{FFT(T)\}\right] \text{...............(4)}$$

Finally, the time domain phase will be obtained using

$$\theta = \tan^{-1}\left(\frac{Q_1}{Q_2}\right)$$

Time domain phase images are formed by arranging above phase values in to their respective locations.

2.3 Pulse Compression:

Pulse compression is a time domain analysis, it uses group delay in the thermal profile to discriminate defective and non-defective regions. In the first stage a mean removed thermal profile is selected as a reference profile from the region of non-defective pixels. Cross correlation has been carried out between reference profile and to the remaining pixel profiles results in a data of normalized correlation coefficient sequence, further correlation images are formed by arranging the resultant coefficient sequence. Delayed instants are kept into their respective spatial location. The correlation images exhibit correlation contrast due to the dependency on delay and attenuation of the defective profiles.

2.4 Orthonormal projection transform.

Orthonormal projection transform is a powerful dimensionality reduction method the algorithm used in this technique is Gram Schmidt. In this method dimensionality reduction can be done by linear transformation of original data from original vector space to a lower dimensional subspace. The method finds an orthonormal basis vector set from the given data using the below Gram Schmidt process.

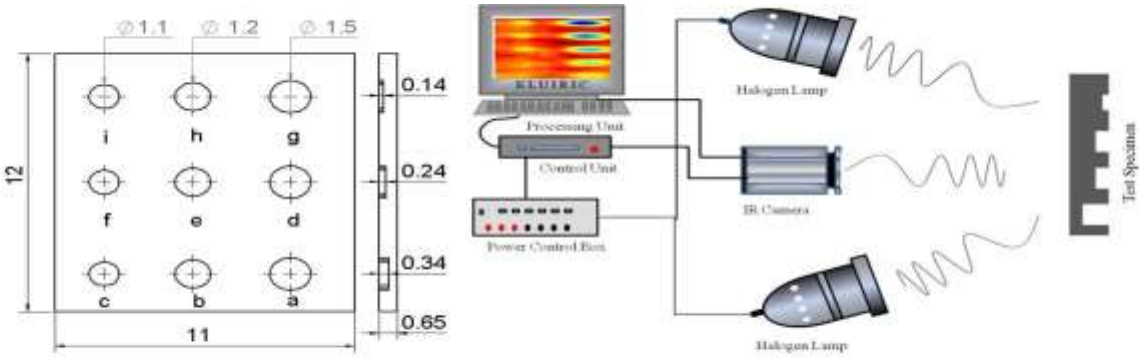
$$V_1 = \frac{T_1[n]}{\|T_1[n]\|} \quad and \quad V_2 = T_2[n] - \left(V_1^T T_2[n]\right)V_1$$

Where T represents the thermal profile of the corresponding pixel, this process is repeated with all remaining pixel profiles.

In this method the original three dimensional captured data is converted in to two dimensional data, by arranging spatial variations occurred in column wise and temporal variations occurred in row wise and mean value across each row of the matrix is subtracted. An orthonormal set is generated using Gram Schmidt method from the converted two-dimensional matrix. Further the original data is projected onto derived basis vectors which give random projection component along column wise. Finally the desired thermal contrast component is chosen from set of components.

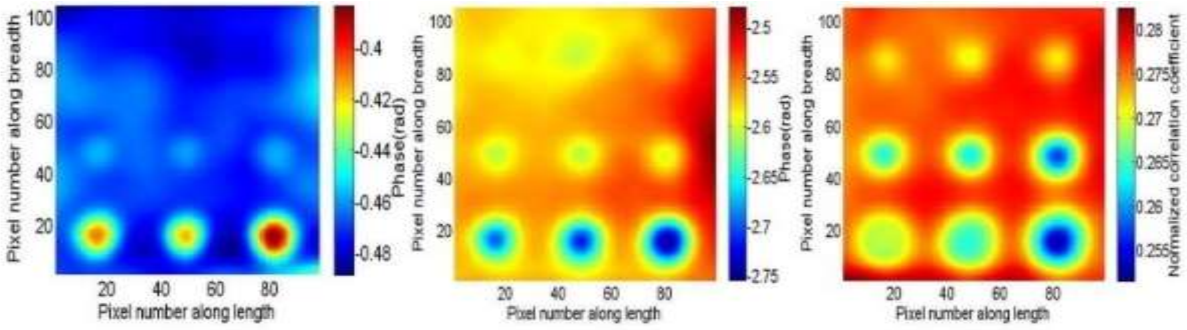
3.Results and Discussion

In order to validate the proposed methodology experimentation has carried out over CFRP sample containing flat bottom holes which varies with different size and depth. The object front surface is illuminated by Barker coded stimulation with a heat flux of 2 KW for duration of 140 seconds. The object thermal response is captured by Flir camera.



a b

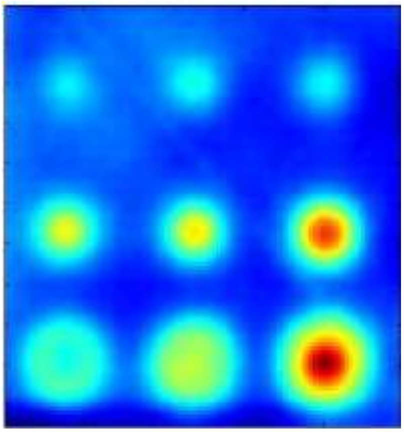
Fig 1.a. Sample layout (Fig dimensions are in cm) 1.b. Experimental setup for active thermpgraphy



a b c

Fig.2.ProcessedresultsofCFRPSample

a. Phase analysis b. Hilbert phase and c. Correlation based images.



d) Random projection image

To extract fine subsurface defect details, captured thermal data has processed by phase, correlation, Hilbert phase and Orthonormal projection transform methods, in Fig 2. A phase image obtained at 0.02 hz exhibits well defect details of larger diameter only where as in Fig 2. a

And 2.b pulse compression images gives better details of smaller and deeper defects also due to it's concentration of energy and noise minimization property. In Fig 2.d orthonormal projection images gives better details of all defects irrespective of their size and depth of anomaly. From Fig.6 It clearly shows the depth resolution capability of QFMTWI supported by orthonormal random projections

The detectability of these processing methods was compared using signal-to-noise ratios (SNR) of the defects computed from below equation

$$\text{SNR}=20\log\left(\frac{\text{mean of the defective area-mean of non defective area}}{\text{standard deviation of the non defective area}}\right)\text{dB}$$

From SNR shows that the orthonormal projection approaches outperforms conventional methods by exhibiting enhanced defect detectability with better signal to noise ratio.

Defect	**Actual defect size (in cm)**	**Estimated Size (in cm)**					
		FFT phase	**% of Error**	**Hilbert phase**	**% of Error**	**Orthonormal projection**	**% of Error**
a	1.5	1.38		1.39		1.52	
b	1.2	1.08		1.06		1.21	
c	1.1	1.05		1.01		1.09	

Table 1 Comparison of full width at half maxima of defects of first column for FFT phase, Hilbert phase and Orthonormal projection

4.Conclusions

To extract fine subsurface features in QFMTWI, the temporal thermal history of the stimulated object is captured using an infrared imager. Existing post-processing methods, such as phase analysis or pulse compression, have been applied, but they predominantly rely on Fourier transform, leading to limited frequency resolution based on the number of captured thermograms and their capturing rate..

References

1. D P Almond and S K Lau, ‘Defect sizing by transient thermography. I. An analytical treatment,’ J. Phys. D: Appl. Phys. vol.27, pp.1063, 1994.
2. Busse G, Wu D and Karpen W, ‘Thermal wave imaging with phase sensitive modulated thermography,’ J. Appl. Phys, vol.71 (8), pp. 3962– 3965, 1992.
3. Ghali V S and Mulaveesala R, ‘Quadratic frequency modulated thermal wave imaging for non-destructive testing’, Prog. Electromagn.Res M, vol. 26, pp. 11–22, 2012.
4. Tabatabaei, N, Mandelis A, and Amaechi B T,‘Thermophotonic : an emissivity-normalized modality with advantages over phase lock-in thermography,’ Appl. Phys. Lett., vol.98, pp. 163706, 2011.
5. Tabatabaei N and Mandelis A,‘Thermal coherence tomography usingmatch filter binary phase coded diffusion waves,’ Phys. Rev. Lett, vol.107, p. 165901, 2011.

6. V S Ghali and R Mulaveesala, 'Quadratic frequencymodulated thermal wave imaging for non-destructive testing' Progress in Electromagnetics Research M, Vol 26, pp 11-22, 2012
7. N. Rajik, "Principal component thermography for flaw contrast enhancement and flaw depth characterisation in composite structures," Composite Structures, 58 (2002) 521-528
8. V.S Ghali, B Suresh and A Hemanth,"Data fusion for enhanced defect Detectability in non-stationary thermal wave imaging " IEEE sensors,2015, 15(12)pp6761-6762.
9. Sk. Subhani .B Suresh and V.S.Ghali "Orthonormal projection approach for depth-resolvable subsurface analysis in non-stationary thermal wave imaging" Infrared Imaging ,Insight ,Vol 58 ,No 1, January 2016.
10. Ghali V S, Nataraj J and Mulaveesala R, 'Three dimensional Pulse compression for infrared thermal wave imaging,' IEEE Sensors, vol.9(7), pp. 832-833, 2009
11. Marineeti S ,Grinzato E, Bison P G, and Salvetti O, 'Statistical analysis of IR thermographic sequences by PCA,' Infrared Physics & Technology, vol.46, pp. 85–91, 2004.
12. Arora. V, Juned, A. Siddiqui, Mulaveesala R, and Amarnath M, 'Pulse compression approach to non-stationary infrared thermal wave imaging for non-destructive testing of carbon fibre reinforced polymers,' IEEE Sensors Journal, vol. 15, pp.663-664, 2015.
13. V.S Ghali,Bsuresh and A hemanth,"Data fusion for enhanced defect Detectability in non stationary thermal wave imaging " IEEE sensors, 2015, 15(12)pp6761-6762.
14. B Suresh, SK Subhani, A Vijayalakshmi, VH Vardhan, VS Ghali "Chirp Z transform based enhanced frequency resolution for depth resolvable non stationary thermal wave imaging,"Rev.Sci.Instr.,88(1), 014901,(2017).
15. B.Suresh,Sk. Subhani,V.S.Ghali and R.Mulaveesala"Subsurface details fusion for anomaly detection in non stationary thermal wave imaging", Insight, 59(10),2017.
16. Sk. Subhani .B Suresh and V.S.Ghali "Orthogonal projection approach for depth-resolvable subsurface analysis in non-stationary thermal wave imaging" Infrared Imaging Insight ,Vol 58 ,No 1, January 2016.