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Bartlett Windowed Quadratic Frequency Modulated Thermal Wave Imaging

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ABSTRACT

Quadratic frequency modulated thermal wave imaging (QFMTWI) is gaining interest for active infrared non-destructive testing due to its depth resolution capability. Spectral reshaping of obtained thermal response through multiplying with a Gaussian window is gaining interest to study the variations of thermal response and in time and frequency domain. In present article, an analysis on the performance of Bartlett window on thermal response obtained from a carbon fiber reinforced polymer specimen excited by quadratic frequency modulated heat flux. The analysis is carried out by applying various post processing techniques on raw and windowed thermal response and Signal to noise ratio is taken as performance metric for comparison of results.

Key words : Quadratic frequency modulated thermal wave imaging, Bartlett window, CFRP, Spectral reshaping, Pulse compression, PCA, Random projection transform.

1. INTRODUCTION

Infrared thermography or infrared non-destructive testing is proved to be a reliable non-destructive testing and evaluation technique due to its non-contact, non-invasive, safe and whole field investigation capabilities. Active and Passive thermography are two streams of IRNDT in which the thermal variations of the object analyzed at ambient thermal conditions in passive thermography and an external stimulus is provided to the object and the corresponding thermal response is analyzed in active thermography (AT) [1]. Effect of heat radiation and heat transfer has been analyzed in various domains [26, 27].Over variety of stimulation mechanisms available in AT, non-stationary thermal wave imaging (NSTWI) [5, 6] techniques overcome the limitations associated with conventional Pulsed stimulus in PT [2], periodic stimulus in LIT [3] and Fourier transform based phase analysis employed in pulsed thermography named PPT [4]. NSTWI techniques viz., linear frequency modulated or quadratic frequency modulated thermal wave imaging techniques uses a band of low frequencies to modulate the moderate peak power heat sources such that the imposed stimulus generates temperature over the surface which further diffuse into subsurface layers. The presence of any subsurface anomaly creates the thermal contrast over the surface due to reflected thermal waves which can be captured through a thermal camera and further post processed for qualitative and quantitative analysis of defect detection. Further, various post processing methodologies have been proposed to quantitatively and qualitatively assess the subsurface defects and provide depth resolution [7-12]. Defect depth quantification based on pulse compression and CZT based techniques for FMTWI is theoretically proven in [8, 9]. Spectral reshaping in non-stationary thermal wave imaging is a new emerging area of interest in which the thermal response is multiplied by a window. Spectral reshaping is achieved by multiplying a signal or some part of the signal with a window. A typical Gaussian window is applied to the thermal response of FMTWI proposed [13-16], still the spectral reshaping remains as a pre-processing step. To avail the detectability of subsurface defects, FFT phase and pulse compression based post processing methodologies have been employed over spectrally reshaped thermal response. For in-detail visualization of defects, various image processing [19, 20] techniques have been employed on obtained thermograms [21]. Further, machine learning [22-24] based processing modalities employed for defect detection in QFMTWI [25].

The present article mainly focused on the effects of spectral reshaping of thermal response from FMTWI system for a CFRP sample by employing Bartlett Window [17, 18]. Further, an analysis on the thermal response for visualization of deeper defects with better thermal contrast through FFT phase, pulse compression, principle component analysis and random projection transform based post processing techniques has been carried out. The performance of these windows on FMTWI is compared using performance metric such as defect signal to noise ratio. From the observations, it is concluded that Kaiser windowed FMTWI gives better results compared to Gaussian windowed FMTWI.

The article organized as follows, a brief introduction to FMTWI, Bartlett windowed FMTWI along with different post processing techniques is presented in section II. Section III deals with the numerical simulation and methodology of post processing, section IV gives an in detail discussion over obtained attained results and finally the article concluded in section V.

2. THEORY

2.1 BW_QFMTWI

Contemporary pulse, lock-in stimulations have limitations like high peak power and mono frequency, repeated experimentation. Overcoming those limitations, a suitable band of frequencies, using QFMTWI with low power stimulus provides better depth scanning [6]. The schematic of QFMTWI is shown in fig 1.a. The objects under test were applied with a chirped optical stimulation with an initial frequency ‘a’ and chirp rate of ‘b’, using a set of halogen lamps. The diffusive one dimension thermal wave which represents the heat energy absorbed by thin layer and propagates into object is given by

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

Where T is temperature, x is depth and t is time and α=k/ρc is thermal diffusivity of specimen under test, k is the thermal conductivity, ρ is the density and c is the specific heat. By applied stimulation of heat flux at the top surface, the equation solved under boundary conditions is

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

And an adiabatic heat flow at bottom end for a planar object of thickness ‘L’ is given by

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

Obtained thermal response by the above solution in Laplacian domain is given by [5]

$$T(x,\mathrm{t}) = Q_0 e^{-x/\mu}[\cos(k) + j\sin(k)]$$
$$k = 2\pi(at + \frac{bt^2}{2T}) - x/\mu \qquad (4)$$

Where Q0 is the intensity of heat flux, x is the depth of the defect and the thermal diffusion length of FM is given by $\mu = \sqrt{\frac{\alpha}{\pi(a + bt/T)}}$ since T is the experimentation duration and α is thermal diffusivity derived from thermal properties of material. Now, this temporal thermal response is multiplied by a Bartlett (Triangular window) [15]. A typical Bartlett window is mathematically represented by

$$w(n) = 1 - \left|\frac{n - \frac{N}{2}}{\frac{L}{2}}\right|, \quad 0 \le n \le N \qquad (5)$$

Where, n is the discrete sample of the signal, L and N are length of the signal or window. Further the windowed thermal response is processed with different post processing schemes.

2.2 Post Processing Techniques

2.2.1 FFT Phase

A general post processing scheme in all thermographic inspection methodologies is Fast Fourier transform based phase analysis since phase is more immune to non-uniformities in the thermal radiation than compared to magnitude based analysis. In phase analysis, each windowed thermal profile is processed with a Fast Fourier transform and corresponding phase values are extracted as given below

$$F(\omega) = FFT\left(f(n)\right) = \sum_{n=0}^{N-1} f(n)e^{j\omega n}$$
$$= \sum_{n=0}^{N-1} \mathrm{Re}\left(F(n\omega)\right) + \mathrm{Im}\left(F(n\omega)\right) \qquad (6)$$

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

$$\phi(n) = \tan^{-1}\left(\frac{\mathrm{Im}(F(n\omega))}{\mathrm{Re}(F(n\omega))}\right) \qquad (7)$$

2.2.2 Pulse Compression:

Pulse compression is time domain processing approach in which, each pixel thermal response g(t) is cross correlated by a preselected reference pixel profile h(t) from non-defective region. Further, from the obtained correlation response, peak delays correspond to defective and non-defective thermal profiles is analyzed for quantitative evaluation of defect depth. This time domain analysis perfectly matches for NSTWI to provide defect depth resolution which was out performed by FFT phase analysis and also produces better thermal contrast in thermogram sequence which resulted in improved signal to noise ratios. The correlation analysis mathematically represented by [7, 8]

$$R(t) = \int_{-\infty}^{\infty} h(t)g(t+\tau)dt \qquad (8)$$

2.2.3 Principal component analysis

The basic idea behind the implementation of principal component analysis (PCA) is that to represent the thermographic data as a linear combination of limited number of orthogonal basis vectors with maximized variance. One can obtain these basis vectors either from measured data or numerical simulations. From the maximized variance which can be observed in corresponding Eigen values, either manual or automatic projection of corresponding few Eigen vectors (L<<N, N is length of thermal response) will result in reduced dimensionality of thermal response with better defect detection as principal components. The projection of these Eigen vectors V into the original data S is given by [9]

$$PCs = \sum_{n=1}^{L} V^T S \text{ where } L << N \qquad (9)$$

2.2.4 Random projection Transform

The general Eigen decomposition of computed covariance matrix produces orthogonal basis vectors in principal component analysis. Random projection relays on the projection of orthonormal basis vectors into the original dataset. A matrix with orthonormal vectors is generated by Gram-Schmidt algorithm [10]. These two statistical measure based techniques requires the 3D thermographic data to be reshaped into 2D and then at the end of the process, again reshaped to represent as sequence of few thermograms. Further dimensionality reduction is obtained in thermographic data with improved signal to noise ratios through these techniques.

3. EXPERIMENTATION

To test the proposed modality, experimentation has been carried out using Carbon Fiber reinforced polymer specimen of dimensions 160mm x 160mm x 5mm with flat bottom holes of different sizes at different depths is shown in fig 1. b . A heat flux using halogen lamps has been projected onto the material with frequencies in the range of 0.01Hz to 0.1Hz for duration of 100sec. The thermal response from the surface of the material is recorded using an Infrared Imager at a rate of 25frames per sec. This captured thermal response has been mean removed and linear fitted to acquire only dynamic part of the thermal response and further various post processing techniques employed to extract the subsurface details.

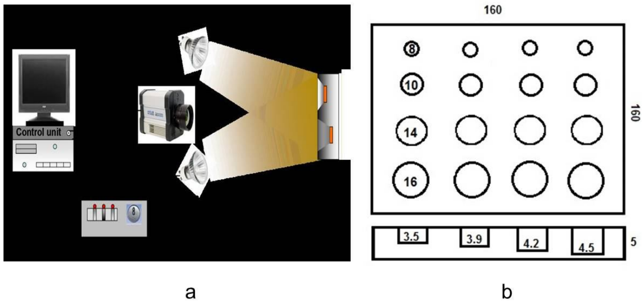

Figure 1 a. Experimental schematic of QFMTWI and b. Layout of CFRP sample (all dimensions in mm).

4. RESULTS AND DISCUSSION

The linear fitted and mean removed thermal response and Bartlett windowed thermal response is post processed through FFT phase ; Pulse compression, principal component analysis and Random projection transform techniques. FFT phase employed by applying fast Fourier transform to each pixel thermal response and corresponding phase response is visualized as phasegrams at a certain frequency. In contrary to FFT phase, pulse compression employed in time domain by cross correlating each thermal response with thermal response from a non-defective region. This cross correlation gives the correlation peak time delays of thermal waves which correspond to defects at different depths. Further, based on these time delays, defect depth quantification is carried out.

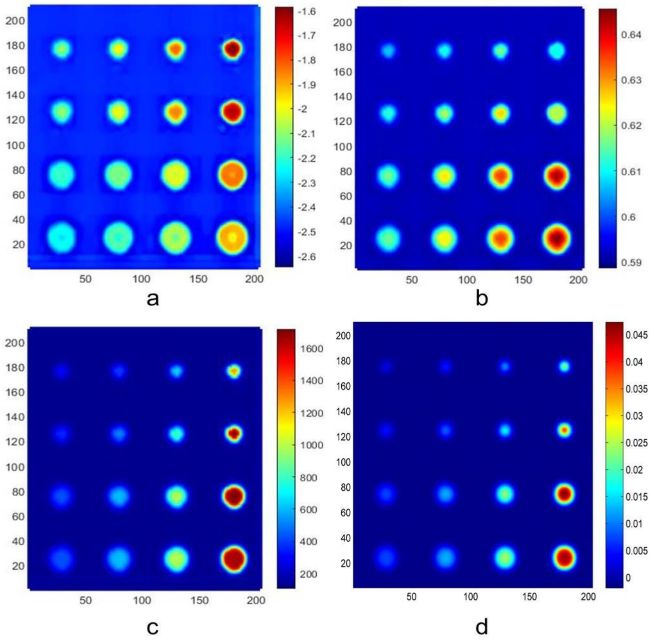

Figure 2 a. FFT phase at 0.027Hz, b. Pulse compression at 16.08sec, c. 2nd principal component and 1st random projection component for raw thermal response.

Whereas, principal component analysis and random projection transform are processing techniques based on signal statistics such as mean, variance etc., to perform these techniques, the data is first reshaped from 3D to 2D such that the pixels will be rearranged in columns and their corresponding time variations arranged in rows.

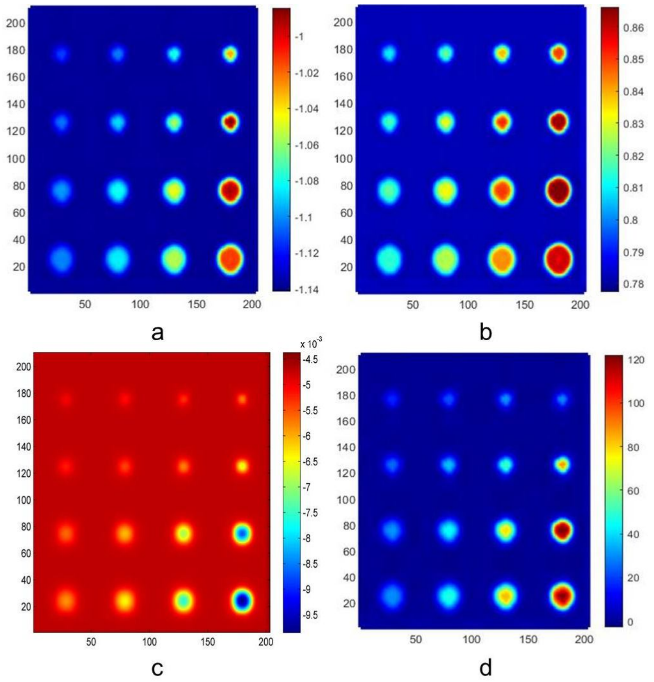

Figure 3 a. FFT phase at 0.012Hz, b. Pulse compression at 8sec, c. 1st principal component and d. 12th random projection component for Bartlett windowed thermal response.

Then, on the 2D data set, Eigen vector decomposition is employed on the covariance matrix in PCA, QR decomposition is carried out in RPT which results in orthogonal and orthonormal basis vectors respectively.

Projecting these basis vectors into a data driven model produces a few number of principal components in PCA and random projections in RPT. The selection of number of basis vectors is dependent on user's choice or one can select based on the energy distribution observed in diagonal Eigen values. This limited number of projection reduces the dimensionality and improve SNR's of the system. The observations of these post processing methods obtained for raw thermal response is given in fig 2. With observed FFT phase at 0.027Hz, Pulse compression at 16.08sec, 2nd PCA and 1st random projection component in a, b, c and d respectively. Similarly, FFT phase observed at 0.012Hz, pulse compression at 8sec, 1st PCA and 12th random projection component observed for the Bartlett windowed thermal response, given in fig 3. a, b, c and d respectively. Further the observed thermal response is characterized by performance metrics like signal to noise ratio. Signal to noise ratio is taken by dividing the difference between mean of defective region to mean of non-defective region by standard deviation of non-defective region as given below

$$SNR(dB) = 20\log\left(\frac{\mu_{Defective} - \mu_{Non-Defective}}{\sigma_{Non-defective}}\right) \quad (10)$$

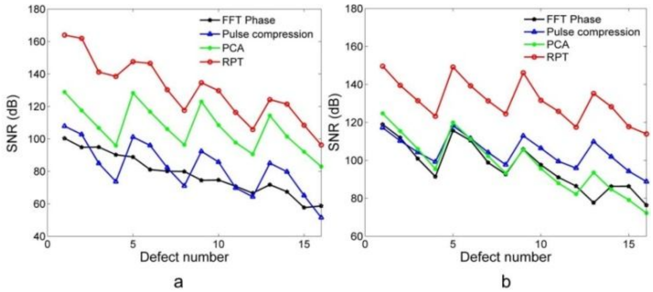

Figure 4: Signal to noise ratios of different post processing techniques employed on a. QFMTWI thermal response and b. Bartlett windowed QFMTWI thermal response.

The observed signal to noise ratios of both raw and Bartlett windowed thermal response for all the defects using these post processing schemes is given in fig 4.a and b respectively. From the observations of thermograms and their respective defect signal to noise ratios, it is concluded that random projection transform provide better results for non-destructive evaluation of CFRP sample through Bartlett window based QFMTWI.

5. CONCLUSION

In present article, the performance of Bartlett window on the thermal response obtained from exciting a CFRP specimen with flat bottom holes of different sizes at different depths using Quadratic frequency modulated heat flux is analyzed. By employing various processing schemes on observed thermal response and Bartlett windowed thermal response and qualitatively analyzing the obtained thermogram results along with signal to noise ratios, it is concluded that Bartlett window efficiently works on improving the detection capabilities of QFMTWI.

REFERENCES

1. Maldague X P V, ***Theory and Practice of Infrared Technology for Non-Destructive Testing***, (New York: Wiley), 2001.
2. Vladimir P.Vavilov and DouglasD.Burleigh, **Review of pulsed thermal NDT: Physical principles, theory and data processing**, NDT&E International73(2015)28–52. https://doi.org/10.1016/j.ndteint.2015.03.003
3. S. Pickering, D. Almond, **Matched excitation energy comparison of the pulse and lock-in thermography NDE techniques**, NDT E Internat. 41 (7) (2008) 501–509. https://doi.org/10.1016/j.ndteint.2008.05.007
4. PPT Ibarra-Castanedo C. and Maldague X. **Pulsed Phase Thermography Reviewed**, Proceedings of QIRT 7 – Quantitative Infrared Thermography, 2004. Poster. https://doi.org/10.3166/qirt.1.47-70
5. Ravibabu Mulaveesala and Suneet Tuli, **Theory of frequency modulated thermal wave imaging for non-destructive subsurface defect detection**, Applied Physics Letters 89, 191913-2006. https://doi.org/10.1063/1.2382738
6. G. V. Subbarao and R. Mulaveesala, **Quadratic frequency modulated thermal wave imaging for Non-destructive testing**, Progress in Electromagnetics Research M, Vol. 26, 11-22, 2012. https://doi.org/10.2528/PIERM12062101
7. Ravibabu Mulaveesala, Jyani Somayajulu Vaddi, and Pushpraj Singh, **Pulse compression approach to infrared nondestructive characterization**, Review Of Scientific Instruments 79, 094901-2008. https://doi.org/10.1063/1.2976673
8. Subhani S.K., Suresh B., Ghali V.S., **Empirical mode decomposition approach for defect detection in non-stationary thermal wave imaging**,2016, NDT and E International, Vol: 81, Issue: pp: 39 - 45, ISSN 9638695.
9. Suresh B., Subhani S., Vijayalakshmi A., Vardhan V.H., Ghali V.S., **Chirp Z transform based enhanced frequency resolution for depth resolvable non stationary thermal wave imaging**,2017 Review of Scientific Instruments, Vol:88, issue:1.
10. Venkata Subbarao Ghali, Nataraj Jonnalagadda, and Ravibabu Mulaveesala, **Three-Dimensional Pulse Compression for Infrared Nondestructive Testing**, IEEE Sensors Journal, Vol. 9, NO. 7, JULY 2009. https://doi.org/10.1109/JSEN.2009.2024042
11. V.S.Ghali, S.Sukumar, D.L.Srinivas, K.L.Mallika and Sk.Subani, **Principal component non stationary thermal wave imaging**, International journal of systems and Technologies, Vol 6, Issue 2, 2013, PP 6-10.
12. S.Subhani, B.Suresh and V.S.Ghali, **Orthonormal Projection approach for depth – resolvable subsurface analysis in non – stationary thermal wave imaging**, Insight, 58(1), pp.42-45 (2016). https://doi.org/10.1784/insi.2016.58.1.42

13. Vanita Arora and Ravibabu Mulaveesala, **Pulse Compression with Gaussian Weighted Chirp Modulated Excitation for Infrared Thermal Wave Imaging**, Progress In Electromagnetics Research Letters, Vol. 44, 133-137, 2014. https://doi.org/10.2528/PIERL13111301
14. Geetika Dua, Ravibabu Mulaveesala and Juned A Siddique, **Effect of spectral shaping on defect detection in frequency modulated thermal wave imaging**, J. Opt. 17 (2015) 025604.
15. Vanita Arora, Ravibabu Mulaveesala and Paolo Bison, **Effect of Spectral Reshaping on Frequency Modulated Thermal Wave Imaging for Non-destructive Testing and Evaluation of Steel Material**, J Nondestruct Eval (2016) 35:15. https://doi.org/10.1007/s10921-015-0333-5
16. Geetika Dua, Ravibabu Mulaveesala, Vansha Kher and Anju Rani, **Gaussian windowed frequency modulated thermal wave imaging for non-destructive testing and evaluation of carbon fibre reinforced polymers**, Infrared Physics & Technology, Volume 98, May 2019, Pages 125-131.
17. Julius O. Smith III, ***Spectral Audio Signal Processing***, W3K Publishing, 2011, ISBN 978-0-9745607-3-1.
18. Peter D. Welch, **The Use of Fast Fourier Transform for the Estimation of Power Spectra: A Method Based on Time Aver. aging Over Short, Modified Periodograms**, IEEE Transactions On Audio And Electroacoustics, Vol. Au-15, NO. 2, JUNE 1967.
19. Teku S.K., Koteswara Rao S., Prabha I.S., Contrast enhanced low-light visible and infrared image fusion ,2016, Defence Science Journal, Vol: 66, Issue: 3, pp: 266 - 271, ISSN 0011748X. https://doi.org/10.14429/dsj.66.9340
20. Prasad C.R., Kishore P.V.V., **Bogie segmentation algorithms and their performance for train rolling stock examination**,2017 Far East Journal of Electronics and Communications, Vol:17, issue:2, pp: 361-388, https://doi.org/10.17654/EC017020361
21. Rao M.N., Rao M.V.G., **A fusion technique to classify glaucoma from fundus images**,2016, IIOAB Journal, Vol: 7, Issue: 9Special Issue, pp: 812 - 824,
22. Suresh B., Subhani Sk., Ghali V.S., Mulaveesala R., **Subsurface detail fusion for anomaly detection in non-stationary thermal wave imaging**,2017 Insight: Non-Destructive Testing and Condition Monitoring, Vol:59, issue:10, pp: 553-558,
23. Kumar K.V.V., Kishore P.V.V., Sastry A.S.C.S., Kumar D.A., Kumar E.K., **Computer vision-based dance posture extraction using slic**,2017 Journal of Theoretical and Applied Information Technology, Vol:95, issue:9, pp: 2031-2037.
24. Rao G.A., Kishore P.V.V., Kumar D.A., Sastry A.S.C.S., **Neural network classifier for continuous sign language recognition with selfie video**,2017 Far East Journal of Electronics and Communications, Vol:17, issue:1, pp: 49-71. https://doi.org/10.17654/EC017010049
25. Vijaya Lakshmi A., Gopitilak V., Muzammil Parvez M., Subhani S.K., Ghali V.S., **Artificial neural networks based quantitative evaluation of subsurface anomalies in quadratic frequency modulated thermal wave imaging**, Infrared Physics and Technology, ISSN: 13504495, Vol No:97, 2019, pp:108-115. https://doi.org/10.1016/j.infrared.2018.12.013
26. Hazel Mae A. Adriano, Dustin A. Reyes, Kristelee Jem B. Tan, Daniel D. Zagada, Reggie C. Gustilo, **Defensive Turret Defensive Turret with Fully Automated Motion Detection Using Infrared Technology**, International Journal of Emerging Trends in Engineering Research, Volume 7, No. 9 September 2019. https://doi.org/10.30534/ijeter/2019/05792019
27. Eko Julianto, Waluyo Adi Siswant, Marwan Effendy, **Characteristics of Temperature changes and Stress of Float Glass under Heat Radiation**, International Journal of Emerging Trends in Engineering Research, Volume 7, No. 9 September 2019. https://doi.org/10.30534/ijeter/2019/03792019