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QUADRATIC FREQUENCY MODULATED THERMAL WAVE IMAGING FOR NON-DESTRUCTIVE TESTING

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Abstract—Thermal non-destructive testing and evaluation of glass fibre reinforced plastic materials has gained more importance in aerospace industry due to low weight and high strength capabilities in severe environmental conditions. More recently, pulse compression favorable non-stationary excitation schemes have been exhibiting reliable defect detection capabilities in infrared non-destructive testing. This paper introduces a novel infrared non-destructive testing method based on quadratic frequency modulated thermal wave imaging with pulse compression for characterization of glass fibre reinforced plastic materials. Defect detection capability of the proposed method has been experimentally validated using a glass fiber reinforced plastic (GFRP) sample with embedded Teflon inserts. Experimental results proved the enhanced depth resolution capability of the proposed excitation method as compared to the linear frequency modulation with pulse compression.

1. INTRODUCTION

Increasing demand for high quality and defect free products motivated the research of various non-destructive evaluation procedures. Among them, in the last few decades infrared non-destructive testing (IRNDT) has emerged as a reliable, non-contact and non-destructive evaluation procedure for testing the structural integrity of the objects. Its dependence on thermal conductivity of materials made it potentially worthy for applications in various fields. It can be performed by

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mapping the temperature contrast over the test object caused by the defect bound thermal inhomogeneity of the test object. It has been carried in either passive or active approaches. In passive approach inherent thermal response of the test object is captured and analyzed to reveal subsurface features. Uncontrolled stimulation procedure and its inability to produce better contrast for deeper defect information limited its applicability. Whereas active approach, with its controlled heat stimulation and well supported processing techniques emerged as a reliable qualitative and quantitative testing procedure for surface and subsurface non-destructive evaluation. In active approach, temperature contrast is induced by excitation through a controlled external stimulation and temporal thermal map of the surface has been recorded. Various processing approaches have been employed on the captured data with the intent of extracting the minute contrast details embedded in the captured temporal temperature evolution to reveal subsurface details. In addition to these processing approaches, detection is also influenced by the energies contained in the frequency components and bandwidth of the stimulation.

Among the various excitation methods, Pulsed Thermography (PT), Lock-in Thermography (LT) and Pulse Phased Thermography (PPT) are widely used in numerous thermographic applications. Simplicity of evaluation, advanced processing methods and rapidity of inspection popularized PT [1]. In PT, a short duration high peak power stimulus is given to the sample and temporal temperature map has been captured. Slope variation of the temperature profiles is used for defect detection in PT. Influence of non uniform emissivity and non uniform heating over the surface may result in erroneous predictions in this direct contrast method and limits its applicability inspite of its quickest evaluation. Continuous wave thermography i.e., LT and Frequency modulated thermal wave imaging (FMTWI) make use of low peak power sources for longer durations and improve penetration of thermal waves. Less attenuation provided by low frequency thermal waves has been used by LT [2] to provide deeper depth details. But mono frequency excitation may not better resolve the defects at different depths and demands repetitive experimentation using a number of frequencies in realistic applications. In PPT [3], test object is stimulated as it was done in PT, but analysis is carried by the application of Fast Fourier Transform (FFT) over thermal profiles of each pixel and detection can be carried from phasegrams at different frequencies. A chirped stimulation of a suitable band of frequencies at moderate power imposed in FMTWI [4] which provides an excellent depth resolution in a single experimentation cycle using a suitable band of frequencies unlike mono frequency excitation in

LT and with moderate powers unlike PT. Recently introduced pulse compression based processing [5–8] has been proved as a promising approach for defect detection with this stimulation method than conventional phase based analysis. But low time bandwidth product of this non stationary excitation used in IRNDT applications resulting in ripples in the spectrum contributing for large side lobes influences the defect detection capability in pulse compression approach. In order to reduce these side lobes, to enhance the resolution and dynamic depth detectability, predistortion methods either in time domain or in frequency domain are to be employed [9]. These pre-distortion methods reduce the side lobes at the cost of SNR ultimately reduces the detectability. Hence the excitation which may introduce predistortion inherently with their modulation function in matched filtering and improve dynamic range resolution without influencing SNR, like non linear chirp, is a viable alternative for pre-distortion methods. This paper proposes a non stationary nonlinear (Quadratic) frequency modulated thermal wave imaging (QFMTWI) which can provide more energy deposition, better depth resolution, improved dynamic range and side lobe reduction as compared to the coded excitations available in thermographic literature.

2. THEORY

In active thermal wave imaging with non stationary excitations, a set of optical sources were driven by the control unit using a signal of chosen parameters which facilitates a continuous wave excitation for affective thermal analysis of the sample. This optical excitation induces a similar thermal disturbance over a thin surface layer. The surface bounded thermal disturbance further diffuses into the sample due to thermal conductivity and leads to progressive thermal waves. In a thermally homogenous sample these thermal waves causes a uniform temperature distribution over the surface. But temperature contrast over the surface due to defect bounded inhomogeneity leads to individuate the location of the defects from its homogenous non defective counter part. The detectability and resolution of the under laid defects depends on the parameters of the excitation, thermo physical properties of the object material and processing technique used as well.

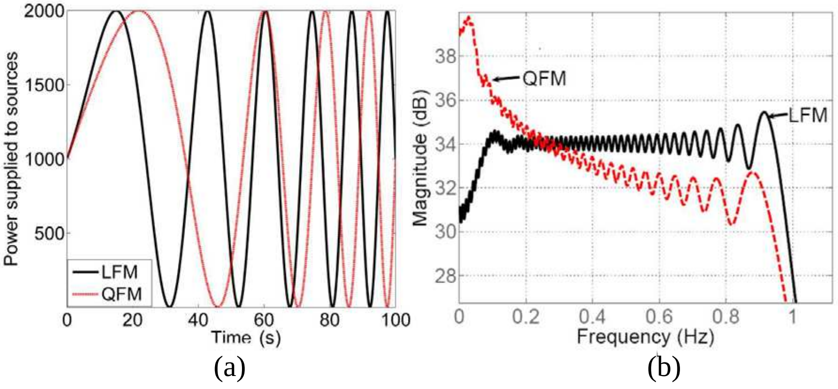


Figure 1. (a) Time domain plot of QFM and LFM, (b) spectrums of QFM and LFM.

2.1. Features of the Proposed Quadratic Frequency Modulated Excitation Method

In frequency modulated thermal wave imaging, a preselected band of frequencies better suited for depth analysis [2, 4, 6] of the test object have been swept in a single experimentation cycle. This frequency sweep facilitates the detection of the defects at different depths even with moderate peak power sources. Attenuation properties of thermal waves support deeper depth analysis using low frequency thermal waves whereas shallower details are analyzed using high frequency components. In addition deeper depth probing demands sufficient energy with these low frequency waves. Excitations distributing more energy to lower band of frequencies enhance penetration of thermal waves and improve depth detection capability. Proposed QFM possess the following features favoring the thermal wave probing.

As observed from excitation point of view, smooth variation in time domain with QFM is compatible with lamp response and facilitates generation of excitation from optical sources as shown in Figure 1(a). In addition, the proposed quadratic frequency modulated excitation redistributes the energy of high frequencies to low frequencies and facilitates more depth analysis than its linear modulated (LFM) counter part. It is observed from illustration in Figure 1(b) that LFM posses relatively less energy than QFM in low frequency region of their spectra using which more deeper details are extracted.

From processing point of view, deeper depth analysis with pulse compression demands more energy imposition, whereas resolution can

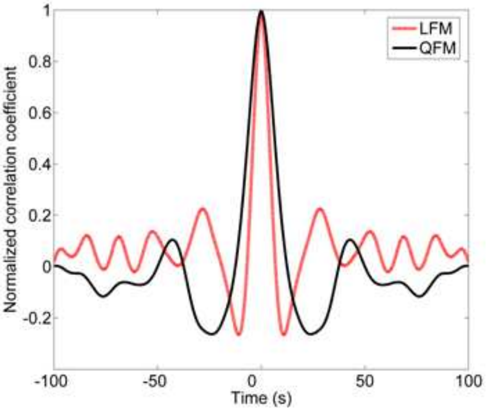


Figure 2. Side lobe suppression with correlation profile of a non-defective pixel with LFM and QFM.

be decided by the band width of excitation [10]. Even with same bandwidth, duration and peak power with sources, QFM imposes more energy than LFM which enhances depth probing and SNR.

Side lobe reduction in pulse compression improves dynamic range detection, which enhances the detectability. This reduction in side lobes is estimated using

$$\text{Peak side lobe level (PSL)} = 20 \log \left(\frac{\text{Peak of the side lobe}}{\text{Peak of the main lobe}} \right) \text{dB} \quad (1)$$

For QFM it is about $-23\,\text{dB}$ (as shown in Figure 2) with correlation of thermal profile against $-13\,\text{dB}$ of the same for LFM and far side lobes are almost flat which is not possible with LFM. Thus modulation function of QFM itself reduces range side lobes even without any external pre-distortion methods to obtain the same with LFM.

2.2. Theory of Quadratic Frequency Modulated Thermal Waves

The temperature evolution over the homogenous material can be obtained by solving the 1D heat equation under the boundary conditions i.e., (a) The sample is excited by the proposed heat flux and a similar temperature raise is expected at $x = 0$. (b) At $x = \infty$ temperature gradient is zero.

The 1D heat equation with heat propagation in the x direction is given by

$$\frac{\partial^2 T(x,t)}{\partial x^2} - \frac{1}{\alpha}\frac{\partial T(x,t)}{\partial t} = 0 \quad (2)$$

where $T(x,t)$ is the temperature at the point located 'x' units deeper from the surface at the instant 't', and 'α' is the thermal diffusivity of the material.

To facilitate the excitation by optical sources, an offset is added to the proposed continuous wave [11]. Thus the excitation from the sources can be considered as the combination of step and the proposed continuous excitation. Hence the temperature evolution over the sample surface (by considering the sample as a linear time invariant system) is the response due to both the excitations considered independently. Temperature evolution due to static part (offset treated as step excitation) is given by [12]

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

where k is the thermal conductivity of the material.

Dynamic part of the excitation, i.e., quadratic frequency modulated thermal wave, leads to the temperature raise equals to

$$T_d(x,t) = \frac{Q_0}{k\,\sigma}\left(\frac{\cosh\,\sigma(L-x)}{\sinh\,\sigma L}\right)\exp\left(i(\omega_0 + b\,t^2)t\right) \tag{4}$$

where 'Q_0' is peak value of the incident heat flux and 'L' the thickness of the test object.

Where $\sigma = \sqrt{\frac{1}{\alpha}(\frac{(i+1)}{2}(\omega_0 + 3b\,t^2))}$, 'ω_0' is the initial frequency of the quadratic chirp and 'b' is the sweep rate. Hence the temperature evolution

$$T(x,t) = T_s + T_d \tag{5}$$

Thermal diffusion length with the quadratic frequency modulated thermal wave imaging is given by

$$\mu_{qfm} = \sqrt{\frac{2\alpha}{(\omega_0 + 3b\,t^2)}} \tag{6}$$

From Equation (6), it is evident that the second term in the denominator is a variable quantity depending on the chosen bandwidth of the chirp which is capable to probe the defects at different depths.

2.3. Thermal Wave Detection and Ranging

Pulse compression through matched filtering is the commonly used detection methodology in RADAR engineering to improve range resolution and SNR in noisy environments [13]. It is employed between two waves of similar shape with a delay existing between them. As a result of pulse compression, the resultant applied energy is concentrated into a pseudo pulse whose peak concentrates at a delayed instant depending on the time delay between the signals used. It facilitates the probing through low peaks power sources and concentrating energy into the main lobe similar to a high peak power pulsed excitation. Similarity between the nature of thermal wave responses and RADAR signal processing allowed the adoption of matched filtering in IRNDT.

From Equation (4), it is clear that thermal responses obtained over the test object considered at the defect locations are not only attenuated but also delayed depending on the depth (x) and thermal properties of the sample underneath the surface. This depth dependent delay and attenuations helps for defect detection in pulse compression based processing. Cross correlation of the delayed thermal response profiles with a chosen reference can contribute for contrast in correlation image at any chosen instant of time in their correlation profiles. This contrast in correlation coefficients at the defect locations discriminate them from non defective counterparts and individuate the defect locations.

Correlation based pulse compression is carried by cross correlation of obtained temperature profile at any location over the surface $s(t)$ with the impulse response $h(t)$ of the matched filter (which is similar to received signal except a finite attenuation and delay). The cross correlation of the chosen reference and the delayed response from the object can be represented as

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

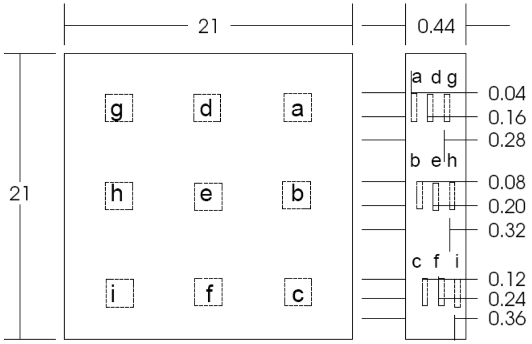
As the result, the long duration (T sec) signal $s(t)$ is compressed to duration $1/B$, governed by the bandwidth B (Hz) of the waveform.

3. RESULTS AND DISCUSSION

3.1. Materials and Experimentation

In order to verify the defect detection capability of the proposed excitation, experimentation has been carried over a GFRP plate with embedded Teflon inserts which resemble the de-lamination between the layers. Nine square shaped Teflon inserts of $2\,\text{cm}^2$ each has been inserted after every two layers of a 20 layered GFRP sheet as shown in Figure 3.

Chosen specimen has been stimulated by the optical excitation from two halogen lamps of power 0.8 kW each driven by a quadratic



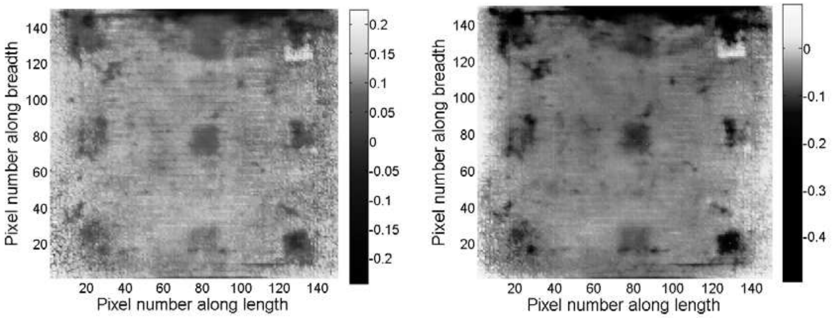
(a) (b)

Figure 3. Experimental GFRP specimen of $21 \times 21\,\mathrm{cm}^2$ containing Teflon inserts of $2\,\mathrm{cm}^2$ kept below every two GFRP layers (all the dimension are in cm). (a) Front view, (b) cross sectional view of the sample.

and linear frequency modulated up chirp excitations of frequency swept from 0.01 Hz to 0.1 Hz in 100 seconds duration in consecutive experiments under same experimental conditions. Optical sources are driven by the built-in control unit and temperature map of the stimulated surface of the sample has been captured at a frame rate of 25 Hz with infrared camera.

3.2. Defect Detection Using Pulse Compression

In order to reveal subsurface defects and compare the depth probing in frequency modulated schemes, pulse compression is employed over the captured temporal temperature map of the specimen surface. To study the dynamic response corresponding to the chosen excitations, the response due to the steady component has been removed with the help of a linear fit for temporal temperature profile of each pixel. Further cross correlation has been performed between each mean removed temperature profile with the chosen reference profile. Depth dependent delay of temperature profiles of the defect locations from non defective region provides correlation coefficient contrast in the correlation image. This correlation coefficient contrast is used to discriminate defects from the non defective counterpart of the specimen. Figure 4 shows the correlation images obtained at 16 seconds in LFM and QFM temperature responses of the sample. Defects 'a' to 'e' are clearly visible in both the schemes. But defects 'f' and 'g' are giving better detectability in Figure 4(b) than 4(a), as QFM is probing relatively



(a) (b)

Figure 4. Correlation images obtained at a time instant of 16 s with (a) linear FM and (b) with quadratic FM incident heat fluxes over the sample respectively.

more energy than LFM which favors deeper depth probing in pulse compression. Only feeble impressions of 'h' and 'i' are have been found in both the schemes. Defect visibility has been quantified in terms correlation coefficient contrast with SNR of defects computed using

$$\text{SNR} = 20\ \log\left(\frac{\text{Mean of the defect area-mean of the non defective area}}{\text{standard deviation of non defective region}}\right) \tag{8}$$

Figure 5 illustrates the comparison of detection capabilities of LFM and QFM. It is observed that the proposed excitation scheme is performing similar to LFM, due to its constituent energy redistribution and existing special features with processing.

3.3. Depth Analysis of Subsurface Features

From Equation (4), it is clear that temporal thermal response from defect locations is attenuated and delayed depending on the depth of the sub surface anomaly. Delay between these thermal profiles can be assessed through the delay between the peaks of correlation profiles. Thus correlation peak delay is a measure of defect depth. Preliminary comparative studies on the correlation peak delay of QFM and LFM has been illustrated in Figure 6. Insert shows the peak delays of the cross correlation profiles of the defect centers with respect to the auto correlation profile of the non defective location for QFM. Delay profiles shown in the main Figure 6, represent the delays obtained in both QFM

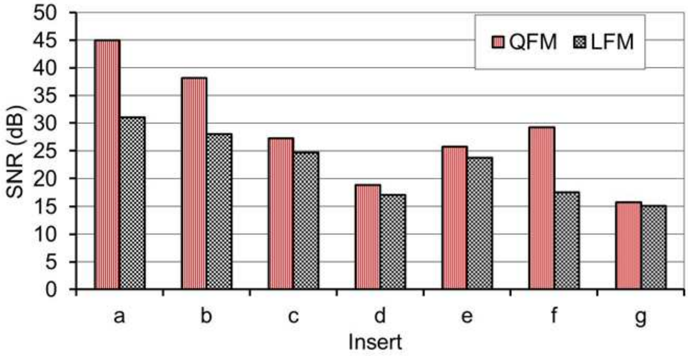


Figure 5. SNR of the inserts.

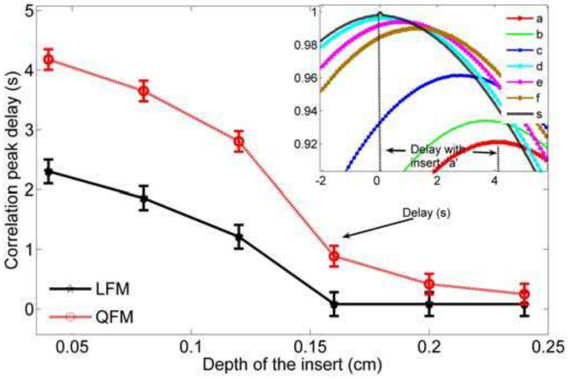


Figure 6. Illustration of correlation peak delays of LFM and QFM schemes. (Insert) Cross correlation peak shifts due to Teflon inserts with QFM.

and LFM for resolution comparison. It has been observed that LFM is able to resolve depths about 0.16 cm only whereas QFM has been resolved about 0.24 cm.

It also found that the slope of the peak delay curve of QFM is more than LFM resemble the enhanced resolvability of the proposed technique due to its more energy even though they are of same bandwidth. In spite of the suitability of the bandwidth for defect resolvability, insufficient energy with the low frequency components may not allow them to penetrate more into the deeper depths in LFM which is superseded by the redistribution of energy in the proposed excitation.

Unlike RADAR, a non-defective pixel profile has been chosen here as reference for cross correlation. This results in more delay with the shallowest defect than that for the deepest as the depth difference of shallower defect with respect to non defective region is more than that of the deeper defect.

4. CONCLUSION

A theoretical basis for the proposed quadratic frequency modulated thermal wave imaging has been provided. Capability of the proposed excitation scheme has been experimentally verified on glass fibre reinforced plastic materials for subsurface defect detection using pulse compression technique based on correlation approach and compared with existing linear FMTWI. Enhanced depth of penetration and resolvability through pulse compression analysis has been investigated in this study on the proposed method.

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