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BARKER CODED MODULATED THERMAL WAVE IMAGING FOR DEFECT DETECTION OF GLASS FIBER REINFORCED PLASTIC

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ABSTRACT

Infrared active thermography provides subsurface details of the test object depending on the thermal inhomogeneity of the constituent material. Effective analysis of various defects existing at different depths in realistic objects demands novel processing approaches to enhance detectability and excitations facilitating depth analysis with constituent band of frequencies. This contribution is intended to exhibit the depth analysis provided by recently introduced phase modulated coded stimulation for infrared imaging validated with glass fiber reinforced plastic plate with embedded Teflon inserts. Experimental results exhibited the enhanced defect detectability using the accumulated energy in pulse compression over that of the distributed energy in the existing phase analysis.

Keywords: infrared non destructive testing, glass fiber reinforced plastic, barker code, pulse compression, fourier transform.

1. INTRODUCTION

Recent years witnessed growing interest in the use of fiber reinforced plastics in various applications demanding high strength, light weight and more corrosion resistance. Unavoidable presence of delaminations and subsurface defects developed during manufacturing of these materials severely damages their in-service applicability and leads to chaos, which demands a thorough evaluation before hand to the applications. Whole field, non contact and non destructive evaluation using IRNDT emerged as a reliable testing procedure among NDT applications. In active thermography, the test object is stimulated by a known controlled excitation method and the temporal temperature map of the surface is captured using an infrared camera. Weak thermal responses due to diffusive thermal waves are further processed using a suitable processing technique and subsurface details can be extracted. But larger thermal attenuation offered by substances to the propagating thermal waves demands either more energy deposition or improvement of SNR with the temporal thermal profiles to provide sufficient thermal contrast for deeper defect detection. A significant research has been carried in last few years for invention of novel excitation and processing approaches to accomplish this task. Pulse Thermography (PT), Lock-in Thermography (LT) and Pulsed phase thermography (PPT) are widely used in IRNDT applications. Requirement of high peak powers and non uniform emissivity limits the applicability of PT [1] even though it is the quick and easiest method of detection. PPT [2] is similar to PT in providing stimulus but analysis can be carried using phase grams by employing Fourier transform to reduce non uniform emissivity problems. In order to avoid the use of high peak powers, continuous thermal wave techniques like LT [3], frequency modulated thermal wave imaging (FMTWI) and recently introduced Barker coded stimulation techniques have been used. But repetitive experimentation needed with mono frequency LT for depth resolution of defects at different depths is time consuming. FMTWI and its digital counterpart (DFMTWI) [4, 5, 6] and Barker coded [7] stimulations overcome the limitations of the above techniques by probing a suitable band of frequencies swept into the sample in a single experimentation cycle with relatively low peak power sources. In these processes defect detection can be carried either by recently introduced pulse compression processing or conventional phase analysis. In pulse compression approach [4, 5, 7, 8], energy was distributed over the main lobe and side lobes after compression. Reduction in the size of side lobes concentrate more energy into main lobe and improve detection performance and depth resolution. This paper exhibits the frequency dependent depth resolution capability of recently introduced 7 bit barker coded thermal wave imaging using phase analysis and compares with the analization capability of pulse compression processing which can improve SNR.

2. THEORY

2.1 Barker coded excitation for IRNDT

Barker code is the simplest binary code providing minimized compression side lobes and generated easily than other modulated schemes. Further, this code can give compression ratio proportional to the length of the code in its auto correlation. However, selection of the code length is a compromise between experimentation time and side lobe reduction demanded. In thermographic context, too much experimentation time dilutes the advantage of the technique, where as smaller experimentation time may demands high peak power heat sources. Thus, a suitable code length and experimentation time is to be exercised for optimum response.

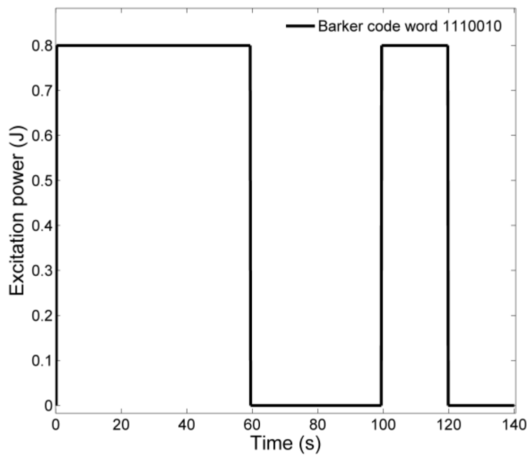

Figure-1. 7 bit barker coded excitation employed.

A 7 bit barker code employed here is shown in Figure-1, which can exhibit minimum response among the available coded schemes.

2.1.1 Physics of coded thermal waves

Thermal waves generated by the incident excitation can be obtained by solving the one dimensional heat equation given by

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

Where α is thermal diffusivity, $T(x,t)$ is the temperature response and $P_0$is the peak power of coded flux. Proposed excitation is considered as a combination of delayed step responses defined as

$$f(t) = \sum_{i=1}^{4} \ (-1)^{n_i}\ u(t - a_i \tau)$$
$$\text{where}\, n_i = 0,1,2,3; \quad a_i = 0,3,5,6 \tag{2}$$

Hence the temperature response obtained from an error function based solution [9] is given by

$$T(x,t) = \frac{4(\sqrt{\alpha})^3 P_0}{K(\sqrt{\pi})\ x^2} \sum_{i=1}^{4} (-1)^n (t - a_i\tau)^{3/2} e^{-x^2 / 4\alpha(t - a_i\tau)} \tag{3}$$

Temperature so obtained is a function of depth of the subsurface anomaly and applied flux. Integration of energy into the main lobe with pulse compression provides better resolution even with low peak power sources. In addition, reduced side lobe level in this excitation improves detection sensitivity.

2.2 Pulse compression for IRNDT

Pulse compression through matched filtering is the commonly employed detection methodology in RADAR engineering to improve range resolution and SNR in noisy environments. 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 of 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. In IRNDT context, thermal responses obtained over the test object considered at the defect locations (centre of the defect) are not only attenuated but also delayed depending on the depth and thermal properties of the sample underneath the surface. Similarity between the nature of thermal wave responses and RADAR signal processing allowed the adoption of matched filtering in IRNDT.

2.2.1. Correlation based pulse compression

Correlation based pulse compression is carried by cross correlation of the received signal 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 (impulse response) and the delayed response from the object can be represented as

$$g(\tau) = \int_{-\infty}^{\infty} s(t)\ h(\tau + t)\ dt \tag{4}$$

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. The ratio of the time durations of transmitted and compressed signals is called the compression ratio and equals to T B. The depth dependent delay and attenuations provided by the defect locations used for defect detection in pulse compression based processing. Cross correlation of the delayed thermal response profiles with a chosen reference results in sinc shaped compressed pulses which can contribute for contrast in correlation image at any chosen instant of time. This contrast at the defect locations discriminate them from non defective regions. Additional reduction of side lobe energy in compressed profiles provided by the proposed excitation can be assessed with peak to side lobe level given by

$$\text{Peak sidelobe level (PSL)} = 20\log\left(\frac{\text{Sidelobe magnitude}}{\text{Peak value}}\right) = -20\log(N) \tag{5}$$

Where N is the length of the code word used. However, for a 7 bit Barker code PSL equals to -16.99 dB.

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3. RESULTS AND DISCUSSIONS

In order to validate the detectability of the proposed method for GFRP, experimentation has been carried in two stages for two different purposes.

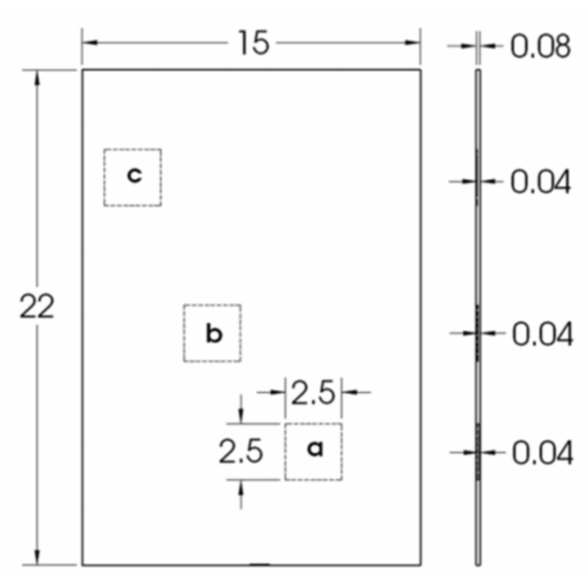

Figure-2. GFRP sample with Teflon inserts of different thickness of 0.036, 0.024, 0.012 for a, b and c respectively (all the dimensions are in cm).

In the first stage to study the detection capability of the proposed method, the experimental sample contains Teflon patches of different thickness as shown in Figure-2 with a GFRP sample of thickness 0.8 mm with 8 plies. Defects ‘a’, ‘b’ and ‘c’ are Teflon patches of size 2.5 cm kept with different thicknesses 0.036, 0.024, 0.012 cm respectively kept at the same depth from the surface as shown in Figure-2.

In the second experiment the shape preserving capability of the proposed processing method has been studied with another GFRP sample containing Teflon inserts of different shapes and dimensions as shown in Figure-3.

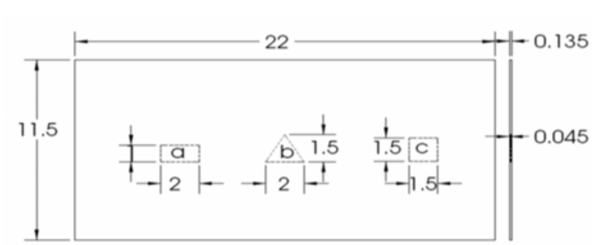

Figure-3. GFRP sample with Teflon patches of different shapes (all the dimensions are in cm).

In both the cases front end of the sample is stimulated by two halogen lamps generating power of 0.8 kW each, driven by an in built control unit with the signal as shown in Figure.1. Temporal temperature map of the surface has been recorded by an Infrared camera at a frame rate of 25 Hz during 140 s of the experimentation.

3.1 Pulse compression approach

Pulse compression is performed by cross correlation of the mean removed resultant temporal thermal profile of each pixel with that of a chosen reference temporal thermal profile. Correlation images are extracted from the delayed cross correlation profiles of each pixel.

3.1.1 Reduction in non uniform radiation/emissivity

Non uniform radiation and emissivity are the problems generally encountered with time domain infrared data analysis. Normalized correlation performed between the reference and profiles of all the pixels over the test object produces better correlation with the similarity among them. Hence the non uniform radiation/emissivity will be reduced as shown in Figure-4.a. Thermogram obtained at 39.2s better explained the non uniform irradiation obtained in thermograms. From correlation based processing a sequence of correlation images provides the details of the defects with better contrast. The pulse compression image at 4.48s better narrates the reduction in non uniform emissivity/radiation through correlation processing. Larger attenuation offered by the material results in a PSL of -11.6 db only.

3.1.2 Defect detection using pulse compression

Correlation image extracted at a delayed instant of 4.48s, shown in Figure-4.b for the sample shown in Figure-2, all the defects at different depths and nature have been detected with a variable contrast according to their depth and size has been observed. Thicker defect ‘a’ is providing better contrast than thin Teflon insert ‘c’ assures the ease of detectability of the thicker defects. Debonding at the edges of the Teflon inserts has been identified in correlation image with bright edges.

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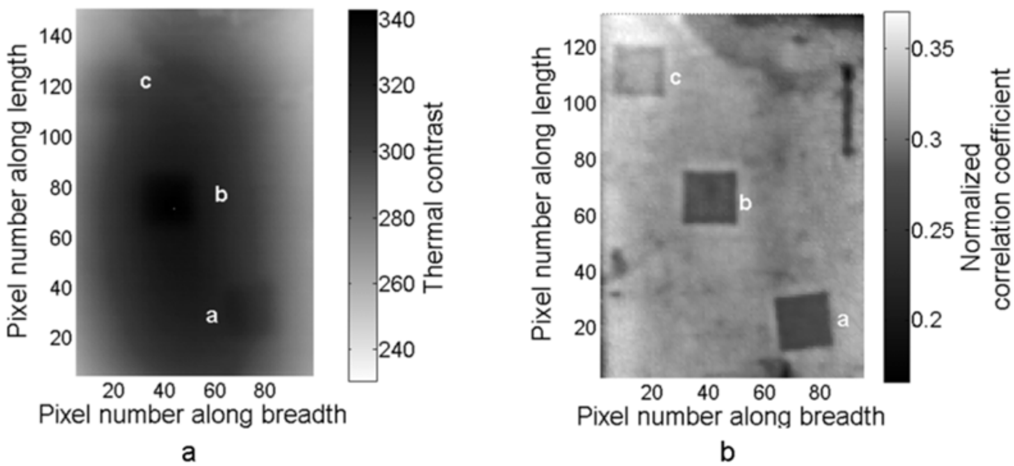

Figure-4. a. Thermogram at 39.2 s b. Correlation image at 4.48 s.

Impressions of a linear patch and a delamination have been found at the right edge and top right corners of the sample respectively.

3.2 Phase approach

In phase approach, phase information is extracted using the one-dimensional Fast Fourier transform (FFT) applied over temporal thermal profile of each pixel of the thermogram. This is repeated for all the pixels in the field of view, in order to obtain the phase images at various frequencies. Among the phasegrams obtained at different frequencies, thicker defects (a, b) are clearly visible among all the phase images. Impression of defect c is gradually decreased from Figure-5.b to c has been found. Phase inversion is observed from Figures 5.a to 5.b and from 5.b to 5.c.The linear patch at the right edge has been provided maximum contrast in Figure-5.c.

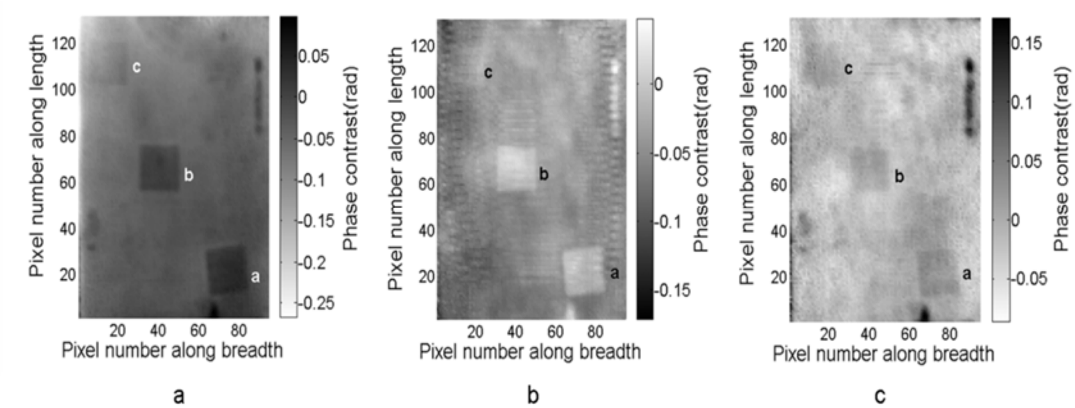

Figure-5. Phase image obtained at the frequency of a. 0.04 Hz b. 0.12 Hz c. 0.25 Hz.

Thus phasegrams are providing better information at the frequency corresponding to their depth and nature of the defect material as well. Where as in pulse compression due to presence of all the frequencies with maximum integrated energy in the main lobe, all the defects are visible in a sequence of images with better contrast and removes the ambiguity over the existence of the defect and its location as shown in Figure-4.b, unlike phasegrams.

In the second experiment with the sample shown in Figure-3 Teflon patches of different shapes are detectable in both the images of Figure-6. Correlation image obtained at 1.18s is exhibiting better detectability than Phasegram at 0.06Hz has been observed. In both the images, shape of the defect has been better preserved.

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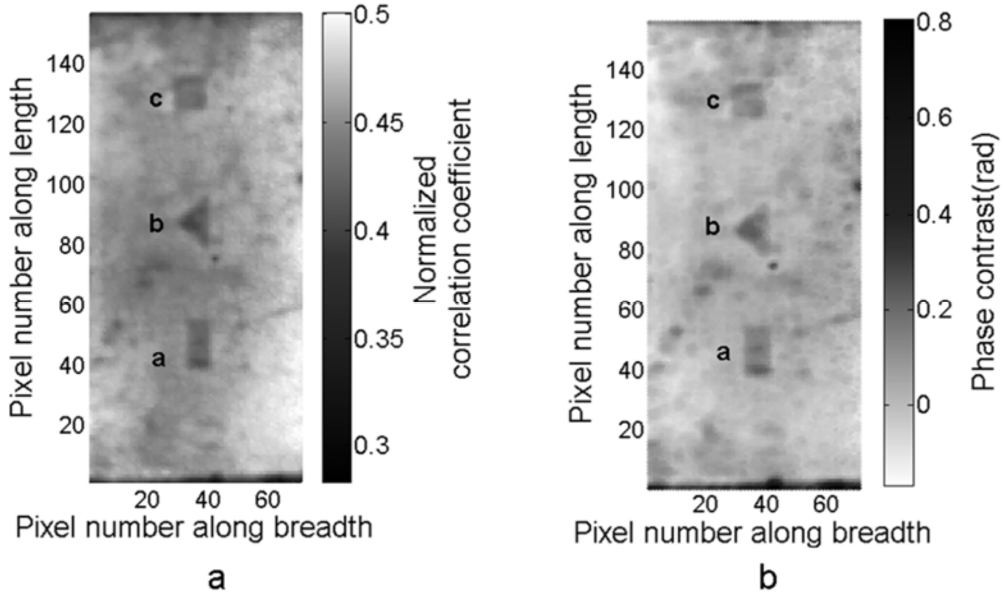

Figure-6. a. Correlation image obtained at 1.18s. b. Phasegram at the frequency of 0.06 Hz.

4. CONCLUSIONS

Validity of the barker coded thermal wave imaging has been done using the experimentation carried on GFRP samples with embedded Teflon inserts to simulate different defects encountered during their manufacturing phase. Presence of all the constituent frequency components with integrated energy in main lobe of correlation profile produces better visibility in correlation image than phase image has been proved. It has been also observed that the non uniform radiation/emissivity was reduced in correlation based processing in addition to defect shape preserving capability.

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