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Application of golay complementary coded excitation schemes for non-destructive testing of sandwich structures

Vanita Arora, Ravibabu Mulaveesala*

InfraRed Imaging Laboratory (IRIL), Department of Electrical Engineering, Indian Institute of Technology Ropar, Nangal Road, Rupnagar, 140001 Punjab, India

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ABSTRACT

In recent years, InfraRed Thermography (IRT) has become a widely accepted non-destructive testing technique to evaluate the structural integrity of composite sandwich structures due to its full-field, remote, fast and in-service inspection capabilities. This paper presents a novel infrared thermographic approach named as Golay complementary coded thermal wave imaging is presented to detect disbonds in a sandwich structure having face sheets from Glass/Carbon Fibre Reinforced (GFR/CFR) laminates and core of the wooden block.

1. Introduction

Sandwich structures are increasingly deployed in many industrial applications due to their high strength to weight ratio, good corrosion resistance, superior thermal insulating and energy absorption properties. Non-destructive evaluation of the structural integrity is essential for the quality assurance during the manufacturing and in-service phases. Among the modern-day Non-Destructive Testing and Evaluation (NDT & E) methodologies, InfraRed Thermography (IRT) is a technique with growing importance due to its abilities to inspect surface and sub-surface details in a fast, reliable, remote and quantitative manner. Active IRT is based on exciting the test object using a heat source, followed by monitoring the surface temperature distribution, further to enhance the defect visualization, post-processing techniques are applied onto the recorded thermal data [1–10].

Many IRT approaches have been developed in the literature based on the type of thermal stimulus and processing method adopted. Pulse Thermography (PT), Lock-in Thermography (LT), and Pulse Phase Thermography (PPT) are the widely used techniques [1–3]. However, these classical thermographic techniques have some limitations reported by several researchers [9–15] as the demand of high peak power heat sources in pulse based techniques and long experimentation time (demand of repetitive experimentation for resolving defects located at different depths inside the test specimen) in LT. In order to find a way to overcome these limitations, pulse compression favorable aperiodic thermal wave imaging techniques such as Frequency Modulated Thermal Wave Imaging (FMTWI) [4,9–12], Gaussian Weighted Frequency Modulated Thermal Wave Imaging (GWFMTWI) [14], Quadrature Frequency Modulated Thermal Wave Imaging (QFMTWI) [5], Digitized version of FMTWI (DFMTWI) [6] and Barker Coded Thermal Wave Imaging (BCTWI) [8,15] techniques have been proposed in recent years. The issue of maximizing penetration depth with concurrent retaining or enhancement of test resolution constitutes one of the time invariant challenges in infrared thermal wave imaging community. Concerns about potential and undesirable side effects set limits on the possibility of overcoming the frequency dependent attenuation effects by increasing peak imposed heat flux amplitudes probing into the test specimen. To overcome this limitation a pulse compression technique employing 8 bits Complementary Golay Code (CGC) [16] was implemented in comparison with other, earlier proposed, coded excitation schemes, such as FMTWI, GWFMTWI, QFMTWI, DFMTWI, BCTWI to evaluate the integrity of a sandwich structure etc..

2. Golay coded thermal wave imaging

This technique is based on the application of Golay complementary coded heat stimulus onto the test object. The complementary code consists of a pair of code sequences having a valuable property that the sum of their auto-correlation functions results in a compressed pulse with a peak of twice the sequence length and zero side lobes. This property allows complete removal of side lobes from the compressed pulse. The obtained compressed pulse improves the defect detection capabilities and permits the use of low peak power heat sources. Individual Golay sequences have relatively flat spectra. The signal to noise ratio of a Golay sequence can be shown to be bounded by its length. However, longer code lengths increase the experimentation time. So based on the test time constraints, a suitable code length is to

* Corresponding author.
E-mail address: ravibabucareiitd@yahoo.co.in (R. Mulaveesala).

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be selected for optimum response by taking sensitivity and resolution into consideration. The present work considers binary Golay complementary code thermal excitation of length 8 [16].

The applied thermal energy propagates into the test specimen by diffusion and can be described by one-dimensional heat equation in the absence of any heat source and sink inside the specimen as [17]:

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

where $T(x,t)$ is the temperature at a given spatial location $x$and at a given time t and α is the thermal diffusivity of the specimen. The applied 8-bit complementary coded pair stimulus can be expressed as the combination of step functions given by:

For sequence a:

$$f_a(t) = P_0 \sum_{i=1}^{6} (-1)^{n_i} u(t - a_i\tau) \text{ where } n_i = 0, 1, 2, 3, 4, 5; \quad a_i = 0, 3, 4, 6, 7, 8. \tag{2}$$

and P_O is the peak excitation power.

For sequence b:

$$f_b(t) = P_0 \sum_{i=1}^{4} (-1)^{n_i} u(t - a_i\tau) \text{ where } n_i = 0, 1, 2, 3; \quad a_i = 0, 3, 6, 7. \tag{3}$$

The solution to Eq. (1) for a semi-infinite solid on the application of boundary conditions ($x=0$, $T(x=0,t)=T_O$(constant temperature) and $x\rightarrow\infty$, T - ambient temperature) and initial condition ($T(x,t=0)=0$) given by Carslaw and Jaeger (p. 60 of [17]) is as follows:

$$T(x,t) = T_0 erfc\left(\frac{x}{2\sqrt{\alpha t}}\right) \tag{4}$$

As the imposed complementary coded pair excitation consists of a combination of time shifted step functions. The solution is first extracted for a step function and then the same approach is applied for all the time shifted step functions of both the complementary coded sequences.

The flux of heat at the surface of the object is given by:

$$f_1(t) = -K\frac{\partial T(x,t)}{\partial x} \tag{5}$$

where K is the thermal conductivity of the material. Step excitation (P_O $u(t)$) causes a constant flux over the surface at $x=0$, given as:

$$f_2(t) = \beta P_0 u(t) erfc\left(\frac{x}{2\sqrt{\alpha t}}\right) \tag{6}$$

where β is a constant relating surface temperature and incident heat flux. From Eq. (5):

$$T(x,t) = -\frac{1}{K}\int_x^{\infty} f_2(t) \quad dx \tag{7}$$

Substituting value of $f_2(t)$:

$$T(x,t) = -\frac{1}{K}\int_x^{\infty} \beta P_0 erfc\left(\frac{x}{2\sqrt{\alpha t}}\right)dx$$

As $i^n erfc(x) = \int_x^{\infty} i^{n-1} erfc(x)dx$, so the above equation reduces to:

$$T(x,t) = -\frac{2\beta P_0\sqrt{\alpha t}}{K} ierfc\left(\frac{x}{2\sqrt{\alpha t}}\right) \tag{8}$$

Simplifying further using

$$ierfc(x) = \frac{1}{\sqrt{\pi}}e^{-x^2} - x erfc(x) \text{and} erfc(x) = \frac{e^{-x^2}}{\sqrt{\pi}}\left(\frac{1}{x} - \frac{1}{2x^3} + \frac{3}{4x^5}\dots\right)$$

and neglecting higher order terms of x (x^5), the obtained solution for unit step excitation can be expressed as:

$$T(x,t) = \frac{4\beta P_0(\sqrt{\alpha})^3}{K\sqrt{\pi}x^2}(\sqrt{t})^3 e^{\left(-\frac{x^2}{4\alpha t}\right)} \tag{9}$$

Applying the same approach for all the shifted step excitation functions of both coded sequences as follows:

For sequence a:

$$f_{a_2}(t) = \beta P_0 erfc\left(\frac{x}{2\sqrt{\alpha t}}\right)\{u(t) - u(t-3\tau) + u(t-4\tau) - u(t-6\tau) + u(t-7\tau) - u(t-8\tau)\} \tag{10}$$

For sequence b:

$$f_{b_2}(t) = \beta P_0 erfc\left(\frac{x}{2\sqrt{\alpha t}}\right)\{u(t) - u(t-3\tau) + u(t-6\tau) - u(t-7\tau)\} \tag{11}$$

The temperature response over the object for the stimulation given in Eqs. (10) and (11) is obtained as:

For sequence a:

$$T_a(x,t) = \frac{4\beta P_0(\sqrt{\alpha})^3}{K\sqrt{\pi}x^2}\begin{bmatrix} (\sqrt{t})^3 e^{\left(-\frac{x^2}{4\alpha t}\right)} \\ -(\sqrt{t-3\tau})^3 e^{\left(-\frac{x^2}{4\alpha(t-3\tau)}\right)} \\ +(\sqrt{t-4\tau})^3 e^{\left(-\frac{x^2}{4\alpha(t-4\tau)}\right)} \\ -(\sqrt{t-6\tau})^3 e^{\left(-\frac{x^2}{4\alpha(t-6\tau)}\right)} \\ +(\sqrt{t-7\tau})^3 e^{\left(-\frac{x^2}{4\alpha(t-7\tau)}\right)} \\ -(\sqrt{t-8\tau})^3 e^{\left(-\frac{x^2}{4\alpha(t-8\tau)}\right)} \end{bmatrix}$$

$$T_a(x,t) = \frac{4\beta P_0(\sqrt{\alpha})^3}{K\sqrt{\pi}x^2}\sum_{i=1}^{6}(-1)^{n_i}(t - a_i\tau)^{3/2} e^{-\frac{x^2}{4\alpha(t-a_i\tau)}} \tag{12}$$

For sequence b:

$$T_b(x,t) = \frac{4\beta P_0(\sqrt{\alpha})^3}{K\sqrt{\pi}x^2}\begin{bmatrix} (\sqrt{t})^3 e^{\left(-\frac{x^2}{4\alpha t}\right)} \\ -(\sqrt{t-3\tau})^3 e^{\left(-\frac{x^2}{4\alpha(t-3\tau)}\right)} \\ +(\sqrt{t-6\tau})^3 e^{\left(-\frac{x^2}{4\alpha(t-6\tau)}\right)} \\ -(\sqrt{t-7\tau})^3 e^{\left(-\frac{x^2}{4\alpha(t-7\tau)}\right)} \end{bmatrix}$$

$$T_b(x,t) = \frac{4\beta P_0(\sqrt{\alpha})^3}{K\sqrt{\pi}x^2}\sum_{i=1}^{4}(-1)^{n_i}(t - a_i\tau)^{3/2} e^{-\frac{x^2}{4\alpha(t-a_i\tau)}} \tag{13}$$

3. Experimentation

The sample used in this study is realized by bonding a Glass Fibre Reinforced Fibre Ploymer (GFRP) sheet of 5.1 mm thickness on one side of 30.8 mm thick wooden block.

The other side of the core is comprised of 5.1 mm thick Carbon Fibre Reinforced Fibre Ploymer (CFRP) sheet as shown in Fig. 1. Disbonds of different sizes are introduced at different locations within the sample Fig. 2 shows the experimental setup used for the present study. Two halogen lamps are of each delivering a power of 0.5 kW kept at a distance about 1 m from the sample to illuminate the sample uniformly. The intensity of these lamps is modulated by source control unit in accordance with a pair of complementary coded excitation for a duration of 100 s. The infrared camera (FLIR SC 5000 cooled camera with a spatial resultion of 320 × 256 having a InSb detector with a spectral sensitivity in the mid infrared wavelength from 2.1 to 5.1 µm) is arranged at a location to capture the temporal thermal history over the sample at a frame rate of 25 Hz. The mean rise in thermal profile during the active heating is removed by proper polynomial fit. For both code sequences, the correlation coefficient between mean removed