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Complementary Coded Thermal Wave Imaging Scheme for Thermal Non-Destructive Testing and Evaluation

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Abstract

Active InfraRed Thermography (IRT) is an emerging technique in the field of Non-Destructive Testing and Evaluation (NDT&E). In recent years, pulse compression supportive techniques and associated data processing schemes have been proposed by various research groups to enhance the inspection capabilities of these techniques as well as to make the experimentation simple and more reliable. This paper exploits a suitable complementary coded excitation for thermal NDT&E along with the associated pulse compression favorable data processing scheme. The proposed scheme has been implemented on a metallic sample in order to test its capabilities for subsurface defect detection and characterization.

1. Introduction

Active IRT technique has been developed as a non-destructive and non-contact thermal evaluation technique to detect surface and sub-surface attributes based on monitoring the surface's emitted infrared waves in response to applied heat stimulus [1]. It is a leading technique that has the potential to provide quantitative information about the hidden defects in a quick manner [2-10]. It has numerous applications in aerospace, electrical, mechanical, construction and medical fields [1]. Various approaches of IRT have been proposed by several research groups based on the employed thermal stimulus and the post-processing analysis schemes [11-20]. Widely used IRT approaches either use pulse or mono-frequency sinusoidal thermal stimulus [1-5].

The trade-off between resolution and depth of penetration is a key issue [21-31]. Higher resolution with deeper depth of probing can be achieved by increasing the peak power in case of pulse based excitation schemes. Whereas in case of mono-frequency thermal stimulus, repetition of the test at different modulating frequencies is required to detect defects located at different depths inside the test specimen. Coded excitation schemes using pulse compression have been introduced to extend the bound of this trade-off without increasing the peak power and sacrificing depth resolution [22-28]. The present study highlights the depth scanning capabilities of a special pseudo-random code pair (complementary Golay code pair) excitation for IRT to assess a structural steel specimen having six different slag inclusions incorporated as defects. Theoretically this coded pair is characterized by a valuable property that the sum of their auto-correlation functions produces zero value sidelobe and much of the energy is concentrated in the main lobe. The numerical investigations about the proposed approach have been accomplished by Finite Element Analysis (FEA) method.

2. Theory

In this work, a coded thermal wave imaging technique is introduced to achieve better pulse compression properties with improved defect detection capabilities. Pulse compression approach facilitates the use of long duration low peak power heat stimulus to attain high defect detection sensitivity as well as resolution. The proposed technique makes use of a complementary coded pair thermal stimulus that suppresses the side lobes considerably.

The pair of sequences ($g_a(n)$ and $g_b(n)$ (figure 1(a) and (b))) composing the code can be represented as follows:

$$g_a(n), g_b(n) \in \{+1, -1\}, \qquad n = 1,2 \dots N \tag{1}$$

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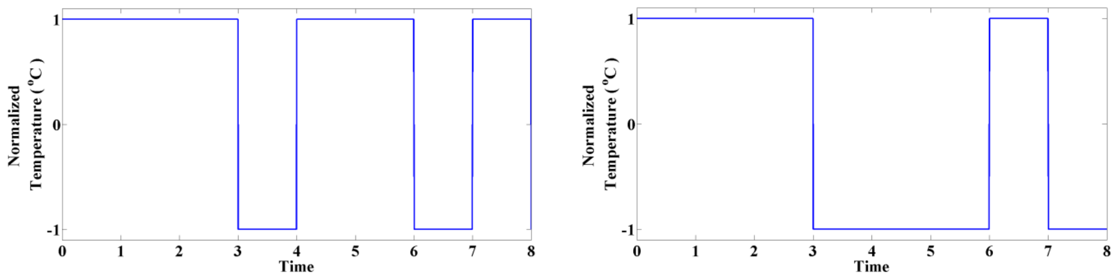

(a) (b)

Fig. 1. *8-bit complementary code pair (a) sequence g_a (b) sequence g_b*

The auto-correlation function of the two sequences is expressed as:

$$R_{g_a}(k) = \left\{ \begin{matrix} \sum_{i=1}^{N-k} g_a(i)g_a(i+k), & 0 \le k \le N \\ R_{g_a}(-k), & -N \le k \le 0 \end{matrix} \right\} \tag{2}$$

and

$$R_{g_b}(k) = \left\{ \begin{matrix} \sum_{i=1}^{N-k} g_b(i)g_b(i+k), & 0 \le k \le N \\ R_{g_b}(-k), & -N \le k \le 0 \end{matrix} \right\} \tag{3}$$

The sum of these two auto-correlation functions results in a single peak of twice the original sequence length at time lag k = 0 and zero sidelobes:

$$R_{g_a}(k) + R_{g_b}(k) = \left\{ \begin{matrix} 0 & k \neq 0 \\ 2N & k = 0 \end{matrix} \right\} \tag{4}$$

This property allows the complete removal of side lobes from the compressed pulse as illustrated in figure 2.

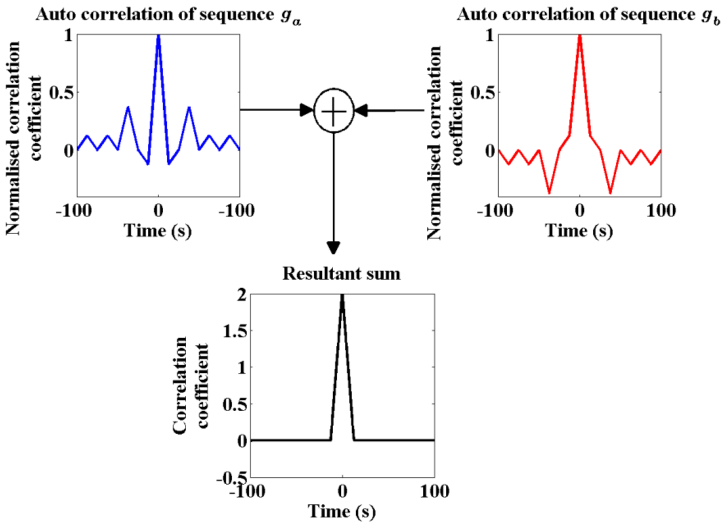

Fig. 2. *Auto-correlation functions of complementary code pair and their resultant sum*

3. Numerical FEA approach

For the present study, a structural steel specimen of dimensions 100×70×2.3 mm containing six circular shaped inclusions (slags) each of diameter 10 mm having 1 mm defect thickness located at a depth of 0.3 mm from the front surface of the specimen is modeled and simulated. Figure 3 shows the schematic diagram of the modeled specimen. The model geometry is meshed with finer tetrahedral elements. The defects a-f are filled with magnesium oxide, aluminium oxide, titanium dioxide, calcium fluoride, zirconium oxide, and silicon dioxide respectively, to simulate artificial inclusions. Table 1 summarizes the specimen parameters.

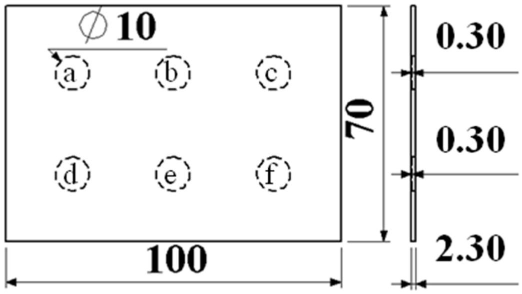

Fig. 3. *Modeling of mild steel specimen (all dimensions are in mm)*

Table 1. *Specimen parameters*

Specimen and Defects	Material	Thermal Conductivity k [$W/(m\cdot K)$]	Heat Capacity C_p [$J/(Kg\cdot K)$]	Density ρ [Kg/m^3]
Specimen	Structural steel	14.9	477	7900
a	Magnesium oxide	60	1030	3580
b	Aluminium oxide	38.5	955	3980
c	Titanium dioxide	11.8	697	4050
d	Calcium Fluoride	9.71	854	3180
e	Zirconium oxide	1.7	502	6100
f	Silicon dioxide	1.5	730	2650

4. FEA results

In order to verify the enhanced defect revealing capabilities of the proposed coded excitation scheme, a pair of complementary coded thermal stimulus of 1 kW/m^2 heat flux is imposed over the specimen for a duration of 100 s. The temporal thermal history over the specimen is acquired at a frame rate of 20 Hz. For each one of the complementary coded sequence, correlation coefficient between the mean removed temporal thermal map of each pixel in the field of view with a chosen reference non-defective pixel is computed. The obtained correlation profiles are added in order to achieve maximum peak with suppressed sidelobes.

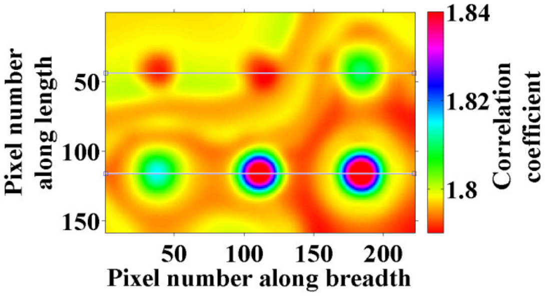

Fig. 4. *Obtained correlation sum image at a time instant of 2.5 s using Golay complementary coded pair*

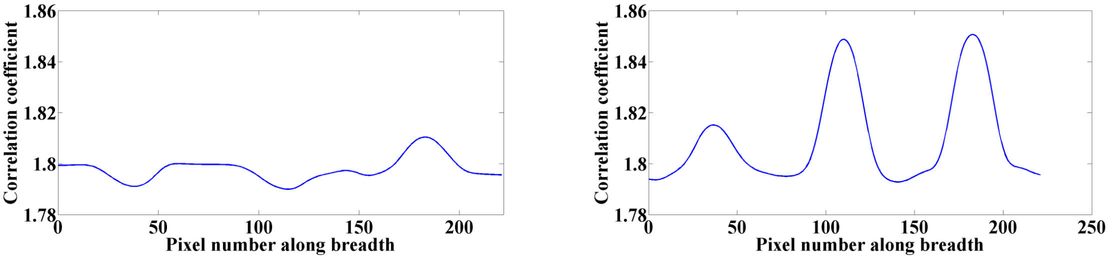

Fig. 5. *Correlation profile obtained over (a) slags located in the top row (b) slags located in the bottom row (left to right)*

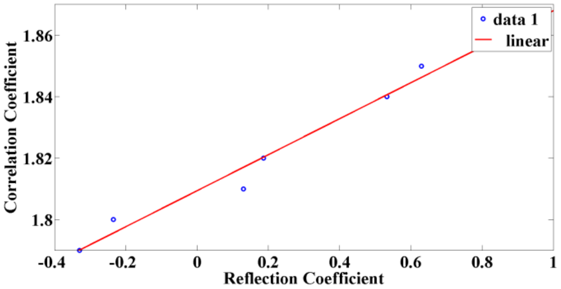

Fig. 6. *Correlation Coefficient versus Reflection Coefficient*

Figure 4 illustrates the resultant correlation sum image of complementary coded sequence. The correlation coefficient profile obtained on the surface of the specimen over the slags is shown in figure 5. Figure 6 depicts the reflection coefficient versus correlation coefficient profile.

5. Conclusions

A finite element analysis based modeling is proposed to simulate Golay Coded Thermal Wave Imaging Technique (GCTWI) for the inspection of a structural steel specimen having different slag type inclusions. The results show that addition of correlation profiles of complementary coded pair sequences leads to reduced sidelobes with most of the energy concentrated in the main lobe. This technique has great potential to make defect determination with higher resolution and sensitivity.

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