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Pulse Compression with Gaussian Weighted Chirp Modulated Excitation for Infrared Thermal Wave Imaging

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Abstract—This paper proposes a novel signal processing approach to thermal non-destructive testing by incorporating Gaussian window function onto the linear frequency modulated incident heat flux to achieve better pulse compression properties. The present work highlights a finite element analysis based modeling and simulation technique in order to test the capabilities of the proposed windowing scheme over the conventional frequency modulated thermal wave imaging method. It is shown that by using Gaussian weighted chirp thermal stimulus, high depth resolution can be achieved.

1. INTRODUCTION

Infrared Thermography (IRT) describes the propagation of thermal waves inside the test sample, with the aim of obtaining its surface and subsurface details [1–9]. Nowadays, IRT has gained significant importance because of its whole-field, fast and remote inspection capabilities. This technique can be broadly classified into two categories: passive, in which the sample is assessed at ambient temperature without any heat stimulus and active, in which external thermal energy is applied to the test sample. The heat pattern over the sample is captured and is analyzed to detect the presence of defects in the test sample. Pulse Thermography (PT) [2, 3], Lock-in Thermography (LT) [5] and Pulse Phase Thermography (PPT) [2, 4] are more common types of active IRT techniques. Each of these conventional technique have certain limitations [8] as requirement of high peak power heat sources and sensitivity to surface artifacts in case of PT, fixed depth resolution and need of test repetition in LT, whereas PPT demands high peak power as to detect deeper defects located inside the sample.

In order to address these limitations, several contributions have been made especially in non-stationary infrared thermal wave imaging methods, primarily on pulse compression and side lobe reduction mechanisms by various research groups [6, 10–17]. This paper proposes a Gaussian weighted Linear Frequency Modulated (LFM) Thermal Wave Imaging (LFMTWI) [6, 7, 9] method named as GLFMTWI for sub-surface defect detection. A finite element analysis has been carried out on a mild steel sample containing flat bottom holes as defects located at various depths within it. The present work highlights the capabilities of the proposed Gaussian Weighted Chirp (GWC) approach using pulse compression and compares its depth scanning performance with that obtained using conventional previously proposed LFM thermal wave imaging proposed by the same group of authors [10–13].

2. THEORY

In FMTWI, LFM heat stimulus of desired band of frequencies (decided by the thermal properties of sample and its thickness) with considerably low peak power (Figure 1(a)) is launched into the sample to detect the presence of defects located at various depths inside the sample in a single test cycle. The

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one-dimensional solution of heat equation for a LFM incident stimulus onto semi-infinite solid, using appropriate boundary conditions is given by [9]:

$$T(x,t) = T_0 e^{-x\sqrt{\frac{\pi}{\alpha}\left(f+\frac{Bt}{\tau}\right)}} e^{-jx\sqrt{\frac{\pi}{\alpha}\left(f+\frac{Bt}{\tau}\right)}} e^{2\pi j\left(ft+\frac{Bt^2}{2\tau}\right)} \quad (1)$$

where $T(x, t)$ is the temperature at a given spatial location x units deeper from the surface of the sample at a time instant t, α the thermal diffusivity of the sample, T_0 the peak temperature, f the initial frequency, B the bandwidth, and τ the total duration of excitation.

In GWC thermal wave imaging technique, a linear frequency modulated sinusoid with Gaussian envelope modulated (Figure 1(b)) heat flux is incident on the sample. The mathematical representation of chirp modulated Gaussian pulse is given as:

$$T = g(t) \cdot e^{2\pi j\left(ft+\frac{Bt^2}{2\tau}\right)} \quad (2)$$

where $g(t)$ is the Gaussian window function which is expressed as follows:

$$g(t) = e^{-\frac{(t-\mu)^2}{2\sigma^2}} \quad (3)$$

where μ and σ are the mean and variance respectively.

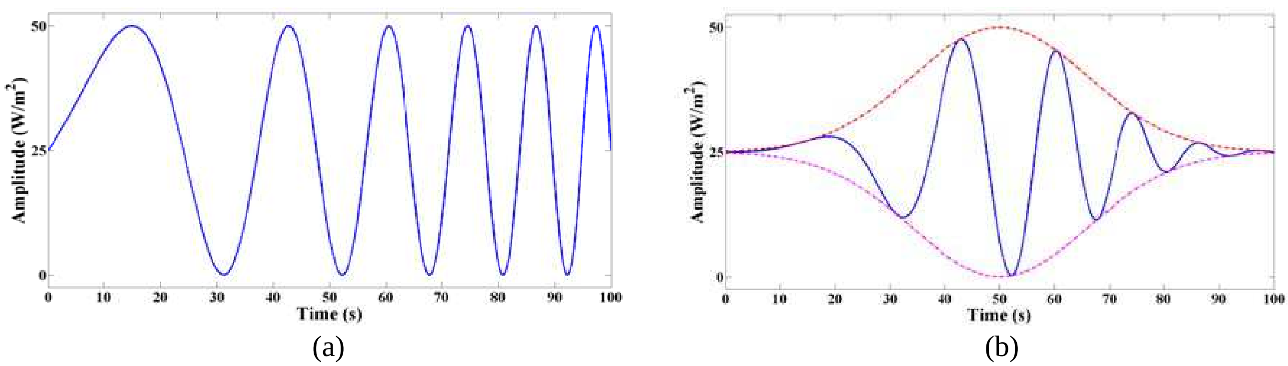


Figure 1. (a) Linear frequency modulated signal and (b) its Gaussian weighted form.

3. CORRELATION BASED PULSE COMPRESSION

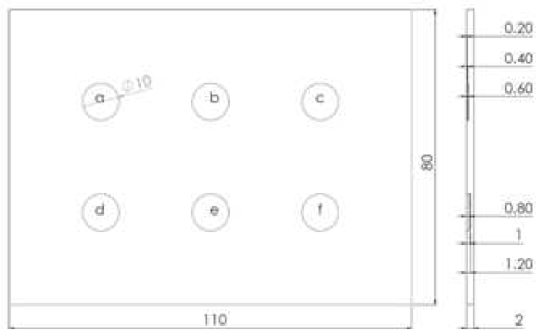
In pulse compression analysis, the cross-correlation between the mean removed captured temporal thermal distribution of each pixel $h(t)$ with chosen non-defective reference pixel $s(t)$ for a given frequency modulated thermal excitation is computed as [10]:

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

This technique leads to the generation of pseudo-pulse (sinc-shaped) with most of the energy concentrated in the main lobe of the compressed pulse, and provides detection range and resolution comparable to that achieved with short duration, high peak power pulse based methods [10, 11, 18].

4. NUMERICAL MODELING

A 3D finite element analysis has been carried out on a mild steel sample using COMSOL Multiphysics. The sample consists of flat bottom holes as defects of 10 mm diameter located at depths ranging from 0.2 mm to 1.2 mm in increments of 0.2 mm from the front surface of the sample as shown in Figure 2. The thickness of sample is 2 mm, and the parameters used are summarized in Table 1.



Defect	Depth from front surface
a	0.2
b	0.4
c	0.6
d	0.8
e	1.0
f	1.2

Figure 2. Top and cross-sectional view of simulated mild steel sample (all dimensions are in mm).

Table 1. Sample parameters.

Parameters	Mild Steel
Thermal Conductivity, k [W/m·K]	60.5
Heat Capacity, C_p [J/(Kg·K)]	434
Density, ρ [Kg/m^3]	7854

5. RESULTS AND DISCUSSIONS

To study and compare the depth scanning performance of LFMTWI and its modified form (GLMTWI), a LFM and GWC forms of incident heat fluxes of 50 W/m^2 with a linear frequency variation of 0.01 to 0.1 Hz for 100 s durations, are imposed onto the test sample. The resulting temperature distribution over the sample surface is captured at a frame rate of 20 Hz. Correlation between the mean removed temporal thermal profiles of each pixel with chosen reference non-defective pixel is then computed.

Figures 3(a) and (b) show the depth scanning performance obtained from GWC and LFMTWI schemes respectively. It has been visualized that the shape of defects 'a'-'e' is preserved in both the techniques but all the defects show better detectablity with GLMTWI approach (Figure 3(a)) as it concentrates more energy into the main lobe of the compressed pulse obtained from correlation analysis, allowing to detect defects located at deeper depths.

For the defects located at different depths, the resultant thermal wave distribution over the material exhibits different delays. This can be measured from the peak shifts of their cross correlation profiles, giving an estimate about the depth of the defect. The peak delays of cross correlation profiles of the

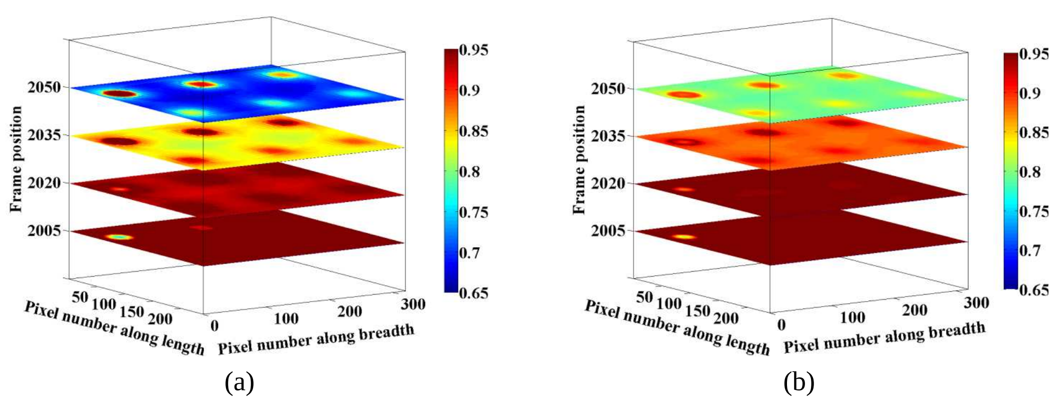
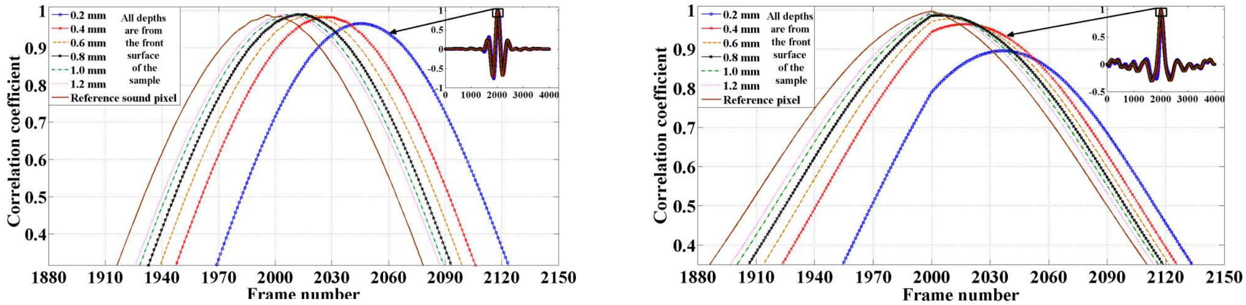


Figure 3. Depth scanning performance. (a) Depth scanning obtained from Gaussian weighted chirp LFMTWI. (b) Depth scanning obtained from LFMTWI.



(a) (b)

Figure 4. Obtained correlation profiles at various defect locations in the mild steel sample (inset shows compressed pulse). (a) Obtained correlation profiles for GLFMTWI. (b) Obtained correlation profiles for LFMTWI.

thermal responses of GLFMTWI and LFMTWI, at the center of the defects with respect to the auto correlation of the non-defective pixel is illustrated in Figures 4(a) and (b), respectively. The shallowest defect exhibits more delay than that of the deeper defect which clearly shows the detection capabilities of shallow defects is higher than that of the deeper defects. Results show that better compression properties with improved sensitivity and resolution are achieved with GWC scheme compared to that obtained using LFM approach.

6. CONCLUSIONS

In this paper, Gaussian weighted Linear Frequency Modulated Thermal Wave Imaging technique is numerically presented on a mild steel sample containing flat bottom holes as defects located at various depths from the sample surface. The capabilities of the proposed scheme have been verified using correlation based pulse compression approach and compared with LFMTWI. The simulated results show that GLFMTWI scheme leads to improved detection sensitivity and resolution in detecting the subsurface defects compared to conventional LFMTWI. Also deeper depth of penetration is obtained from GLMTWI technique using pulse compression analysis.

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