Frequency Modulated Infrared Imaging for Non-Destructive Testing of Steel Materials

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ABSTRACT

Infrared non-destructive evaluation (IRNDE) is an emerging approach for non-contact inspection of various solid materials such as metals, composites and semiconductors for industrial and research interest. This paper focuses on the inspection of plain carbon steel materials, which are widely used, particularly in the power and steel industries. This paper describes some applications of recently proposed pulse compression based approach to the inspection of steel specimens. Present work highlights both phase and correlation based approaches for defect detection using frequency modulated thermal excitation scheme and comparison has been made on these proposed schemes.

Introduction

Safety and demand for quality of in-service products require rigorous evaluation and reliable monitoring methodology to avoid hazardous failures. Non destructive testing accomplishes this task through various methods fit for different conditions and requirements according to the testing needs. Thermography [1] has been emerged as a reliable non contact, non destructive tool to quickly interpret surface or subsurface details of the test object. It depends on the temperature contrast created by heat flow alterations due to the presence of defects in the test objects. It can be carried either in passive or in active modes. In passive thermography temperature map of the object is captured and used for assessment without providing any external stimulus. Where as in active approach, temporal thermal response of the object driven by a controlled stimulation is extracted and used for evaluation. Various methods have been developed for affective extraction of subsurface details against weak responses provided by highly attenuating thermal waves. Among the various active infrared thermographic methods, Pulse thermography [2], Lock in thermography [3] and Pulsed phase thermography [4] are widely used in applications. Recently introduced Frequency modulated thermal wave imaging (FMTWI) avoids the problems associated with these conventional methods and provide better depth resolution by probing the object with a suitable band of frequencies using low peak power excitations[5,6]. Being prevalent in RADAR, pulse compression methodology allows more energy imposition with low power, long duration stimulation and resolving the detail using compressed profiles [7-11]. Which can subsequently enhances signal to noise ratio, provides better resolution and facilitates deeper depth probing as well. This contribution highlights the defect detection capability of pulse compression method and its edge over conventional phase based detection for FMTWI, with the experimentation carried over a mild steel specimen containing flat bottom holes.

Theory

In Frequency Modulated Thermal Wave Imaging (FMTWI), a linear frequency modulated heat flux is imposed on the surface of the test object. The absorbed heat energy propagates through the object by conduction and produces a time varying thermal response over the surface of the object depending on the homogeneity of the substance. The theoretical model to study this thermal response is based on 1D heat equation

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

where a is the thermal diffusion coefficient, T(x.t) is the instantaneous temperature on the surface and x is the direction of heat flow (perpendicular to the surface). On solving the above equation for FMTWI under boundary conditions [21], instantaneous temperature is obtained as

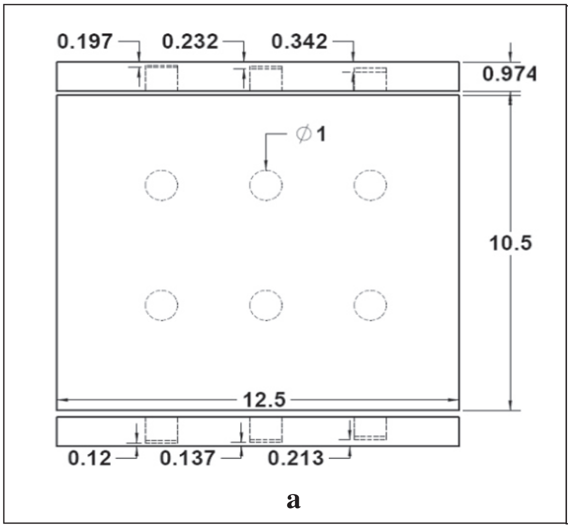
$$T(x,t) = T_0 \exp\left[-x\sqrt{\frac{\pi(f_0 + b\,t)}{\alpha}} - j\,x\sqrt{\frac{\pi(f_0 + b\,t)}{\alpha}} \right] \exp\left[2\pi j \left(f_0 t + (b/2)t^2\right)\right] \qquad (2)$$

where B/p is the frequency sweep rate of the chirp and p is duration of excitation.

The thermal diffusion length of this frequency modulated thermal wave is given by

$$\mu = \sqrt{\frac{\alpha}{\pi\left(f_0 + \frac{b\,t}{\tau}\right)}} \qquad (3)$$

The dependence of thermal diffusion length (Equation 3) on the bandwidth of the modulated excitation assures the depth scanning of the sample, with the suitable band of frequencies in a single frequency modulation cycle.



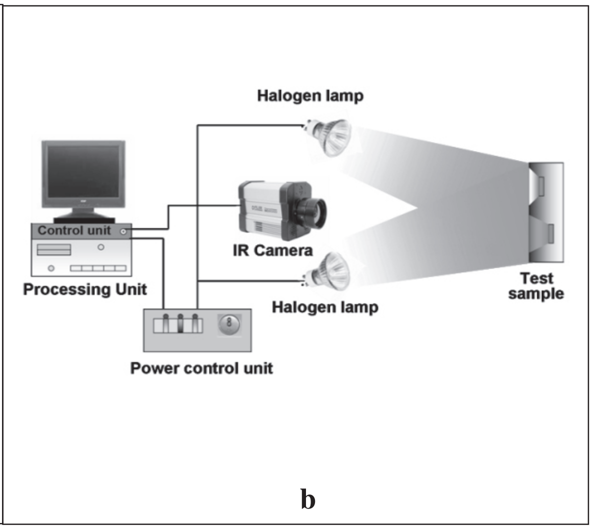


Fig. 1: a. Layout of the experimental mild steel sample b. Experimental set up

Materials and experimentation

Experimentation has been carried over a mild steel sample of dimensions as shown in Fig. 1.a. The experimental mild steel sample contains six drilled bottom holes of diameter 1cm each kept at different depths from the non defective end. A frequency modulated chirped stimulation of frequencies swept from 0.01Hz to 0.1 Hz in 100s, has been provided to the sample with the help of two halogen lamps of power 1kW each. Lamps are driven by a built in control unit as shown in the experimental set up of Fig. 1.b with the chosen stimulation. Temporal thermal response has been captured at a frame rate of 20Hz using a mid band infrared camera. A suitable processing method is to be applied over the captured thermogram sequence and subsurface information is extracted.

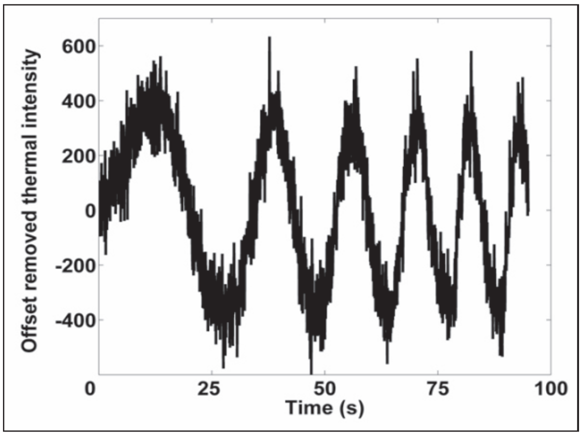


Fig. 2: Temporal thermal profile of a non defective pixel

Results and discussion

In order to reveal subsurface features, the offset in temporal thermal profiles of each pixel is removed by a linear fit and further processing has been carried over these mean removed profiles of each pixel in view.

Fig.2 shows the mean removed temporal thermal profile of a non defective pixel contaminated with experimental noise. In general, thermal responses from deeper subsurface anomalies are more contaminated by noise which produces low signal to noise ratio (SNR). It results in the deeper anomalies to be buried in noise which provide false alarms in detection. Processing methods applied over these profiles to reduce noise influence or improving signal to noise ratio of these profiles will enhance detection performance and reveal deeper subsurface features.

Pulse compression applied over these noise contaminated profiles enhances the SNR and provides better defect detection for coded excitations, which has been adopted in this contribution in addition to conventional phase based methodology for defect detection. In correlation based pulse compression, mean removed thermal profiles of each pixel has been cross correlated with a reference profile and correlation coefficient contrast due to depth dependent delay is used for detection. Let the actual response and be the noise contaminated with the profile and is the reference. Cross correlation of the profiles is given by

$$\begin{aligned} y(t) &= \int (s(\tau)+n(\tau))\ r(t+\tau)d\tau \\ &= (s(t)+n(t)) \oplus r(t) \\ &= (s(t)\oplus r(t)+n(t)\oplus r(t)) \\ &= s(t)\oplus r(t) \end{aligned} \tag{4}$$

As random noise n(t) may not correlate with r(t) results in the second terms of equation 4 to zero. Pulse compression results in an improved SNR of , where ' τ' is the experimentation time and 'B' is the band width.

Conventional phase analysis results in a phase profile of variance [14]

$$\sigma_s = \left(1/E^2\right) \sigma_n \tag{5}$$

Where σ_n the variance of the noise and E is is the energy of the profile. Thus the phase response depends on the noise parameters, whereas pulse compression minimizes it.

On the application of the above processing methods over mean removed temporal profiles, correlation image can be developed by arranging the normalized correlation coefficients at delayed instants in appropriate pixel position. Correlation coefficient contrast depending on the delay is used to identify defect signatures in this approach. In phase analysis, FFT is applied over the temporal profiles of each pixel and phase information is obtained by using

$$\Phi(n) = \tan^{-1}\left(\frac{Im(S_n)}{Real(S_n)}\right) \tag{6}$$

Where S_n is the n^{th} term in the FFT of the profile. Phase contrast has been computed by subtracting the phase profile of the non defective pixel from all the remaining pixels in view. Phase images are constructed by arranging the phase values of each pixel at a particular frequency in their respective locations. Phase contrast in a phasegram is used to individuate defects. Frequency of the phasegram is obtained from

$$F_n = n\frac{F_s}{N}$$ where 'n' is number of the phasegram.

Correlation image at 15.2 s visualizes all the defects clearly than the phase image obtained at 0.02 Hz as shown in Fig. 3. Enhanced detection capability in pulse compression under noisy environment has been clearly represented in this context.

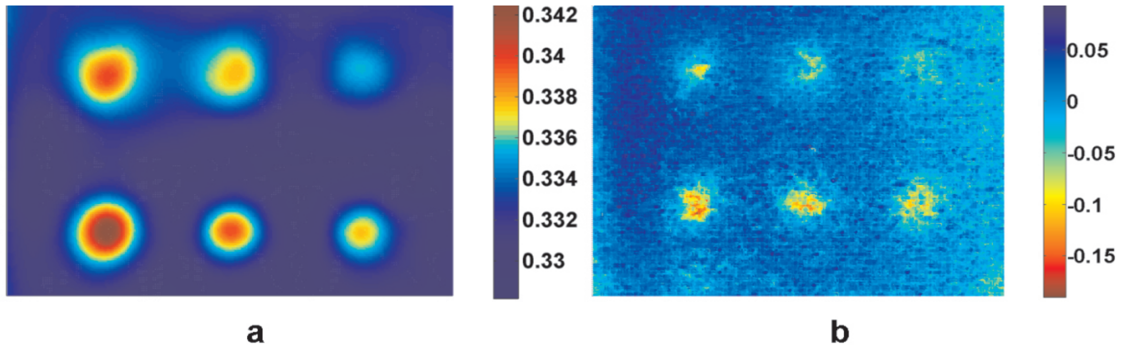


Fig. 3: a. Pulse compression at delayed instant of 15.2s b. Phase image at 0.02 Hz

In thermal wave propagation through the material over the defects at different depths, waves can not only attenuated but also delayed. This delay is a measure of depth of the defect which can be assessed using peak delays in pulse compression. Delay in correlation peaks represents the group delay between the temporal profiles of the defect location with the reference profile. Fig.4.a illustrates the peak delay of the correlation profiles corresponding to the centers of the defects. The shallowest defect with its most delayed profile (as compared to reference) is far from that of the deepest one as the non defective profile has been considered as reference (enlarged view of peaks is shown in insert of Fig.4.a). Peak delay vs depth of the defect has been empirically fitted as shown in Fig4.b.

Conclusions

Defect detection capability of frequency modulated thermal wave imaging with recently introduced pulse compression method has been utilized and compared with the conventional phase based analysis. Pulse compression with its SNR improvement enhanced the defect detection capability and provides the subsurface details with more effectively than phase based methodology. It has been clearly visualized with the deepest defect located at the top right end of the specimen.

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