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Comparative Data Processing Methods for Non-Stationary Thermal Wave Imaging

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Abstract

Use of infrared waves for non-destructive sub surface analysis has been gaining interest due to its non-contact, whole field and surface radiation based detection supported by the application of various processing procedures and modulated excitation techniques. This paper introduces a novel principal component based analysis for subsurface anomaly detection using windowed digitized frequency modulated thermal wave imaging. The capability of this approach has been compared with existing correlation and phase based analysis methods by taking signal to noise ratio for qualitative assessment. Applicability of the proposed processing methodology has been verified through the experimentation carried over a mild steel specimen containing embedded flat bottom holes.

1. Introduction

In the recent decade, there has been a colossal growth in the use of various non destructive testing (NDT) techniques for assessing the integrity of the test object without impairing its future usefulness. Infrared thermography (IRT) is one of these methods in which subsurface anomalies are identified using captured temperature map over its surface. This IRT approach is further divided into passive and active. In passive, the natural thermal response of object is used to identify subsurface anomalies [1], where as in active thermography modulated stimulus is given to the test object and its thermal response is captured using the infrared camera. Depending upon the applied stimulus active thermography is further classified into pulsed thermography (PT), lock in thermography (LT), Pulsed Phase Thermography (PPT) and Frequency Modulated Thermal Wave Imaging (FMTWI).

Pulsed thermography employs a short duration and high peak power stimulation to energize the surface of a test object. The deposited energy initiates the thermal waves on very thin layer near to the surface which will propagate through the object due to thermal conduction. During its cooling phase, the object tries to come back to equilibrium by dissipating its heat to surrounding and the IR camera records the temporal thermal response. The Localized temperature contrast at defect locations and their time of appearance in a thermogram is used in the analysis of the PT. Use of high peak power sources are non uniform radiation limits the scope of this method.

Lock in thermography (LT) is a continuous wave imaging technique in which low power periodic wave stimulation is given to the test object. Given stimulation induces a mono frequency modulated thermal waves in the test object and subsequent thermal response is recorded using IR camera. The recorded thermal response is processed using either amplitude or phase analysis. The merits of phase based analysis are being less sensitive to non uniform radiation, non uniform emissivity and providing more depth analysis. Pulsed phase thermography (PPT) uses the frequency resolution capability of Fourier transform by employing phase based analysis over recorded thermal data acquired in experimentation similar to PT.

In order to overcome the problems of conventional methods like high peak powers of PT and repetitive experimentation with LT, Frequency Modulated Thermal Wave Imaging (FMTWI) is introduced [1]. In this method, a heat stimulus of a suitable band of frequencies will be imposed on to the test object, which simultaneously probes the entire thickness in a single experimentation cycle. Digitized frequency modulated thermal wave imaging (DFMTWI) is a digital counter part of the chirped version used in FMTWI[2].

2. Methodology

In the IRNDT, the test object is excited thermally using a modulated optical stimulus and the corresponding captured temperature map over the surface known as thermogram is extracted. The processing of this data is carried by considering the data from each pixel of the extracted thermograms and treating it as the thermal profile of corresponding pixel [2,3]. Consequently, the processing of the extracted data is carried corresponding to the steady state term in stimulus is removed by using proper fitting methods. Furthermore, the processing techniques can be applied to these thermal profiles in order to eliminate the unwanted components like non-uniform radiation and thermal noise which are assumed to be embedded in the data. As a result of this procedure, the assessment enhances the defect’s contrast. So, the different processing methods like Phase Analysis, Correlation and Principal component analysis(PCA) [4] have been performed by the processing unit. Initially the thermal response corresponding to the steady state term in stimulus is removed by using proper fitting method.

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2.1. Theory of digitized frequency modulated thermal wave

The theoretical analysis of temperature evaluation at the surface due to the propagating thermal waves generated by the chirped simulated excitation and its depth resolving capability is presented in the following section[4]. Theoretical analysis of surface temperature evolution because of the incident thermal waves was done by applying the one dimensional heat equation to the homogeneous, isotropic and semi-infinite media, in the absence of any heat sink or source. The one dimensional heat equation is given by

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

Solving eqn.1 for response under stipulated boundary conditions in Laplace domain

$$\tilde{T}(x,s)_{\text{semi infinite}} = \frac{e^{-\sigma x}\sum_{n=-\infty}^{\infty} P_n Q_n\left(\frac{s}{2n+1}\right)}{k\sigma} - \frac{T_0}{s} \tag{2}$$

Where 'P_n' is coefficient of n thharmonic $= \frac{2\,Q_0\left(-1\right)^n}{\pi(2n+1)}$, '$Q_n$' is n thharmonic $= e^{j\varphi_n}$, 'Q_0' is the amplitude of the heat flux, 'k' thermal conductivity, 'α' is thermal diffusion coefficient and $\sigma = \sqrt{\frac{s}{\alpha}}$.

2.1.2. Windowed thermal wave and processing

In order to obtain frequency resolution through analysis and to avoid spectral leakage from side lobes in complex spectra various windowing methods were applied over the temperature profiles and further processing has been carried. This contribution introduces hamming windowed DFMTWI.

In this approach, captured hamming window is applied on mean removed thermal profile of each pixel and further processing like phase analysis, correlation, PCA have been applied. Phase based analysis uses the frequency resolution provided by fast Fourier transform (FFT) to generate phasegram corresponding to a frequency for identification of defect location. Though phase analysis performs well, the noise embedded in the corresponding frequency component and blind frequencies hide a few defects in phasegrams.

Unlike noise distribution over the spectrum in phase analysis, feature separation methods like principal component analysis (PCA) separates the noise and provide better detection. In order to employ PCA, each thermogram is arranged as a column vector in a matrix generated by all the captured thermograms and single value decomposition has been employed. PCA details are extracted by forming images from the data of various principal components in order to obtain enhanced subsurface details [4].

In correlation approach, a cross correlation is carried between the mean removed thermal profiles of all the pixels in view and the reference profile. This cross correlation of each pixel's profile results in a corresponding normalized correlation data sequence. A similar correlation profiles are computed for all the pixels profiles in view. These profiles were rearranged so that the normalized correlation coefficients of all the pixels at a delayed instant are kept in their respective spatial locations to form correlation image at that delayed instant.

3. Results and discussion

A mild steel specimen was prepared for the examination as shown in Fig.1.a with the dimensions 40cm long, 10cm wide and 1cm thick and 10 artificial flat bottom holes were introduced. The flat bottomed holes were introduced into the sample at the depths of 0.1cm, 0.15 cm, 0.2cm, 0.25cm, 0.30cm respectively. The top surface of the specimen is exposed to digitized frequency modulated optical stimulus sweeping a band of frequencies from 0.01 to 0.1 Hz in 100 s, using a set of halogen lamps of 1kW each, driven by a control unit. The temporal thermal response of the surface is captured by an infrared imager at a frame rate of 25 Hz.

Fig.1.b, correlation image at a delayed instant of 5.24 s exhibited all the large sized defects (a to e). But reduced strength of the signal due to windowing hides the deeper defects and produced a feeble contrast. Whereas the reduced spectral leakage with windowing established a better detectability in phase image obtained at 0.02Hz as shown in Fig.1.c. Ninth principal component image is exhibiting even smaller and deeper defects as shown in Fig.1.d

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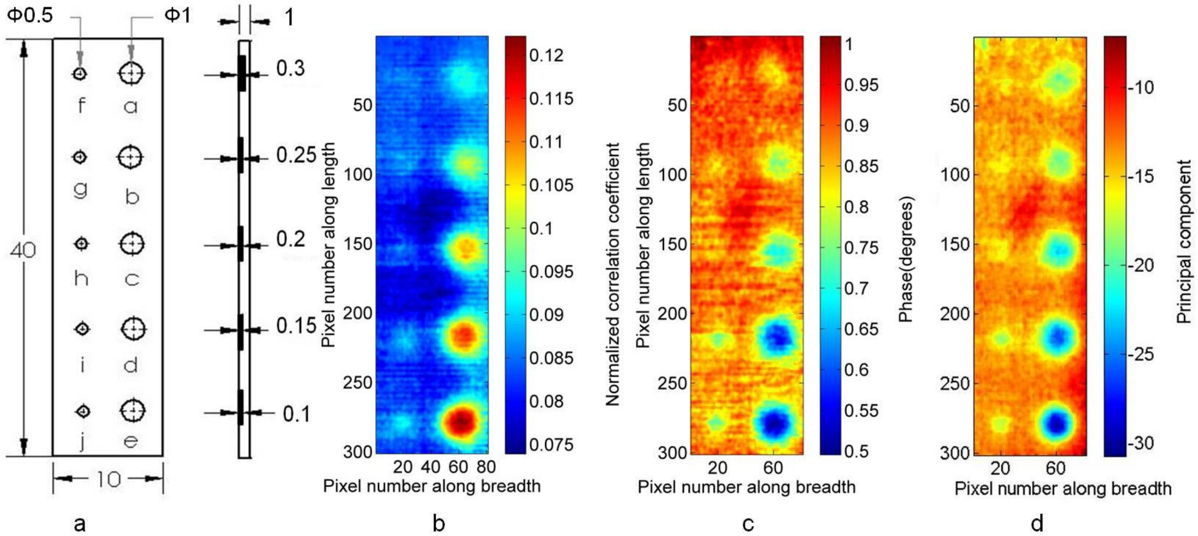

Fig. 1.a. *Sample layout of mild steel specimen used for experimentation.* ***b.*** *Correlation image at 5.24 s* ***c.*** *Phase image at 0.02 Hz and* ***d.*** *Ninth principal component image*

Detectability among these approaches has been compared using signal to noise ratio (SNR) of the defects as shown in table 1 and given by

$$SNR=20\log\left(\frac{\text{Mean of the defective region - Mean of the non defective region}}{\text{Deviation of the non defective region}}\right)\text{ dB}$$

Defect	a	b	c	d	e	f	g	h	i	j
Correlation	39.8	36	31	27	21	18	13	-3	4	-1
Pca	40.3	38.5	35	30	30	20	21	18	18	15
Phase	31.2	30	18	12	-10	15	14	-13	-11	-60

4. **Conclusion** A principal component based processing approach for digitized frequency modulated thermal wave is experimentally tested and its edge over existing analysis methods has been verified.

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