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Empirical mode decomposition approach for defect detection in non-stationary thermal wave imaging

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ABSTRACT

This paper introduces a novel empirical mode decomposition based anomaly detection in Quadratic frequency modulated thermal wave imaging. Being suited for non-stationary signal analysis, its edge over other contemporary processing modalities in its anomaly detection capability has been verified using experimentation carried over a mild steel specimen with embedded flat bottom holes. It also addresses the effect of size and depth on anomaly detection using the proposed methodology in addition to considering the signal to noise ratio of defects for detection.

1. Introduction

Use of thermal waves for subsurface analysis has witnessed a colossal growth for testing the integrity of object without impairing its future usefulness due to its whole field, noncontact and non destructive testing modality. This infrared thermography (IRT) makes use of temperature contrast provided by subsurface anomalies from captured temperature map over the surface of the test object.

This IRT is further classified as passive and active approaches. In passive, the natural thermal response over the object surface is used to identify subsurface anomalies. Whereas in active thermography, the test object is exposed to a modulated stimulus and its thermal response is captured using the infrared imager. Further anomaly detection can be done by employing various processing methods on captured temporal thermal history.

Depending upon the applied stimulus active thermography is further classified into Pulsed thermography (PT), Lock in thermography (LT), Pulsed Phase Thermography (PPT) and other modulated non stationary thermal wave imaging methods like Frequency Modulated Thermal Wave Imaging (FMTWI) and its digitized version (DFMTWI).

In Pulsed thermography [1–4], the test object is energized by a high peak power short duration pulsed stimulation from a flash lamp and cooling phase thermal response from the surface is analyzed using the time of appearance of an anomaly in its thermal history depending upon its contrast. But, use of high peak powers and non uniform radiation effects in detection limits its application. Subsurface analysis in this method can be extracted either by raw thermogram analysis and contrast enhancement approaches or by the application of various post processing approaches like absolute contrast [5], Thermal Signal Reconstruction and derivative approaches [6,7], Singular value decomposition, Principal component analysis [8–10], Phase analysis, Wavelet and Hough transform [11] etc.

Lock in thermography (LT) is a modulated continuous wave imaging technique [12–16] in which a low power, low frequency sinusoidal stimulation is provided to the test object to induce similar thermal waves, the subsequent thermal response is captured by IR imager and further processed using either amplitude or phase analysis. Being less sensitive to non uniform radiation, non uniform emissivity and providing more depth detection, phase based analysis has been widely accepted for LT. In order to qualify the testing method for reliable detection a probability of detection (POD) based methodology has been used in verification of composite specimens containing defects of various sizes and depths [12].

Pulsed phase thermography (PPT) uses the frequency unscrambling capability of Fourier transform [17–19] by employing phase based analysis over recorded thermal data acquired in experimentation similar to PT.

In order to overcome the problems with conventional methods, a Frequency Modulated Thermal Wave Imaging (FMTWI) is introduced by Mulaveesala et al. [20]. In this method, a heat stimulus of suitable band of frequencies will be imposed onto the test object in a single experimentation cycle [21–25]. Recently

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introduced Quadratic Frequency Modulated Thermal Wave Imaging (QFMTWI), cater to the needs by providing a band of frequencies similar to its linear frequency counterpart in addition to containing more energy with low frequency components in a single experimentation cycle and further subsurface analysis can be obtained by various high resolution approaches [26,27]. All state of art approaches uses Fourier transform(FT) based methodologies. But non stationary signals can be effectively analyzed with methodologies like empirical mode decomposition(EMD) than FT based methods [28–31]. Due to the non stationary nature of QFMTWI and analysis of EMD based on signal dependant basis formation make it attractive for its application here.

This paper introduces an empirical mode decomposition(EMD) based processing approach for subsurface analysis and compares it with contemporary methods like Correlation, Hilbert phase and Principal component based approaches using an experimentation carried over a mild steel specimen.

2. Theory of non stationary thermal wave

Theoretical analysis of surface temperature evolution due to incident thermal waves can be obtained by solving one dimensional heat equation to the homogeneous, isotropic and semi-infinite media, in the absence of any heat sink or source, corresponding to a QFM stimulation.

In QFMTWI, a quadratic chirped optical stimulus is provided to the test object surface as given by

$$H(t) = H_0 \,\mathrm{Sin}(at + bt^3) \tag{1}$$

where 'a' is initial frequency and 'b' is bandwidth of the muti-frequency sweep of chirped excitation, 'H_0' is the peak stimulating power from lamps.

The stimulation given to surface creates a similar thermal perturbation over a thin layer nearer to it, which further propagates deeper into the test object as diffusive thermal waves. These waves uniformly progress inside the object and contributes for temperature over the object surface depending on thermal properties of the underneath substance. In case of any subsurface anomaly, due to their thermal inhomogeneity, the propagation path of these waves perturbs and create a localized temperature difference on the surface over the defective locations. This temperature pertaining to chirped activation can be estimated by solving one dimensional heat equation for a homogeneous solid given by

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

where 'α' is diffusion coefficient of the medium.

The above equation is solved under adiabatic boundary conditions i.e. heat flux exchanged at the back end is negligible and is given by

$$-k\frac{\partial T}{\partial x}\bigg|_{x=L} = 0 \tag{3a}$$

But in QFMTWI, the surface of the test object which is at an initial temperature 'T_0' is stimulated by a quadratic chirped optical energy. This incident energy is attenuated in a thin layer over the sample surface and produces a similar heat flux at the top end of the sample as given in its exponential form by

$$-k\frac{\partial T}{\partial x}\bigg|_{x=0} = \mathrm{Q}_0\, \mathrm{e}^{\mathrm{j}\,2\pi\,(a+bt^2)\mathrm{t}} \tag{3b}$$

Where 'k' is the thermal conductivity of the material which is assumed to be independent of the temperature. 'L' is the finite thickness of the sample and 'Q_0' is the amplitude of heat flux. By using this above boundary conditions, Eq. (2) is solved in Laplace domain results in

$$\tilde{T}(x,s) = \frac{Q(s)}{k\sigma(1-e^{-2\sigma L})}\left[e^{-\sigma x} + e^{\sigma(x-2L)}\right] - \frac{T_0}{s} \tag{4}$$

Where $\sigma = \sqrt{s/\alpha}$ and results in a diffusion length [26]

$$\delta \propto \sqrt{\frac{\alpha}{1.77245\,(a+\,\mathrm{b}t^2)}} \tag{5}$$

From the above Eq. (5), it is clear that QFM stimulation provides a depth resolution with time varying instantaneous frequency.

3. Thermal data processing

In IRT, the test object surface is energized by a modulated stimulus as shown in Fig. 1, which induces similar thermal perturbations over it. These perturbations further contribute to propagation of diffusive thermal waves into the interiors of the object and create a temperature contrast over the object surface as impeded by non uniform thermal properties of subsurface anomalies. This temporal temperature map of the object surface is recorded by a thermal imager and anomalies are extracted by processing the captured temperature history.

3.1. *Pre processing*

In order to process the data for defect detection, prior to the application of various processing methods, response corresponding to the dynamic part of the stimulation is extracted from thermal profiles of each pixel by employing either discrete cosine transform or by the application of linear fitting procedure to remove stationary response corresponding to static component in the stimulation.

A linear fitting procedure is employed here to remove the stationary part of the thermal response due to its linear rise over time except for an initial exponential thermal transient. The responses obtained by the fitted mean free thermal profiles contribute only for the dynamic part of stimulation i.e. chirped stimulation, as shown in Fig. 2.

Further various processing methods will be applied over these mean removed profiles and corresponding subsurface details are extracted.

3.2. *Post processing methodologies*

Post processing of data is carried by considering the data from each pixel of the captured thermograms and extracting the dynamic part of response [21–26] by treating it as the thermal profile of corresponding pixel. Further processing techniques like phase analysis, pulse compression can be applied over these thermal profiles to detect defects with enhanced contrast.

This contribution introduces empirical mode decomposition (EMD) based processing methodology for defect detection for recently introduced quadratic frequency modulated thermal wave imaging.

3.2.1. *Correlation analysis*

Diffusive thermal wave from defects at different depths will undergo different attenuations and exhibit a variation in delay among their thermal profiles corresponding to the defect depths. Correlation based analysis makes use of this time delay to discriminate defect locations from their non-defective counter parts. In this process, the mean removed data corresponding to a pixel