# Recent Advances in Non-stationary Thermal Non-destructive Characterization

**Venkata Subbarao Ghali and Ravibabu Mulaveesala**

InfraRed Imaging Laboratory (IRIL), Electronics and Communication Engineering Research Group, PDPM-Indian Institute of Information Technology Design and Manufacturing, Jabalpur, India-482005.

## *ABSTRACT*

*Thermal wave imaging is one of the widely used nondestructive testing and evaluation (NDT&E) methods for detecting subsurface defects in most of the solids. Presently, three different active thermographic techniques are predominantly in use: Pulsed Thermography (PT), Lock-in Thermography (LT) and Pulsed Phase Thermography (PPT). To overcome some of the limitations of these widely used conventional thermographic techniques (requirement of high peak power and long experimentation time), present work focuses on recently proposed non-stationary thermal excitation technique for non destructive testing. This present paper highlights advantages and limitations of the proposed method by comparing with the conventional thermographic methods.*

## Introduction

Being a whole field, non contact evaluation and due to its dependence on thermal properties of the test object, active thermography became a precursive non destructive evaluation procedure for structural integrity assessment applications [1]. In this method, a known thermal excitation is imposed over the test object and thermal response of the surface is captured by an infrared camera. Imposed heat flux generates a similar thermal wave on the surface which can further propagate through the object. This thermal wave propagation perturbed by the defect bounded thermal inhomogeneity causes a temperature contrast over the surface of the object which can be used for identification of subsurface defects. In order to obtain qualitative and quantitative analysis of subsurface anomalies underneath the surface, various thermal excitation schemes and processing methods have been developed and still developing. Among the active thermographic methods, Pulse thermography [2] and Lock in thermography [3] are popular and mostly used techniques. In pulsed thermography [PT] a short duration, high peak power heat burst is imposed on the test object surface and analysis can be carried during its cooling process. Differential thermal properties offered by defective and non defective regions contribute for variation in cooling rates and temperature contrast which can be used for defect detection and quantitative analysis. High peak powers demanded for deeper subsurface analysis, non uniform emissivity of the surface and non uniform heating over the sample challenging its applicability even though it is the quickest means of detection. Lock-in thermography [LT] uses a periodic sinusoidal thermal excitation at considerably low peak powers as compared to pulsed thermography. Selection of a suitable frequency by avoiding blind frequencies and repetitive experimentation required to resolve different depths are limiting its applicability. Defect detection can be carried either by phase or magnitude analysis. Capability of phase method for deeper subsurface analysis has been used in Pulsed phase thermography [PPT] with an excitation similar to PT [4]. Recently introduced frequency modulated thermal wave imaging[FMTWI] overcome the limitations of the above techniques by sweeping a suitable band of frequencies into the sample in a single experimentation cycle [5-13] with relatively low peak power sources exciting for a longer duration.

In order to compare the detectability of the above techniques due to their diversity and peak power limitations in excitation, as all these excitations are analyzed with phase based analysis [12], a frequency domain phase analysis based energy matching has been adopted. Sub surface analysis has been carried with the frequencies better suited for defect depths, which is possible when and only when that frequency component posses sufficient energy to probe the entire thickness (similar to lock in). As energy matching in time domain [5] may not be guaranteed that the corresponding component used for analysis may contain the same energy in the excitations used among different techniques, we preferred frequency domain comparison based on finite element based simulation and modeling. This contribution presents a comparative analysis of the advantages and limitations of different thermographic approaches using phase based analysis by probing equal energy to the frequency component used for analysis in phase based processing.

## Methodology

For matched energy phase based analysis, FFT has been applied over temperature response profile of a chosen non defective pixel over the surface for different excitations individually. Energy of the component frequency which better provides the subsurface details is computed for all the excitation schemes. Excitation peak power of the corresponding scheme was adjusted so that the mean removed profiles in all the schemes can provide same energy value at that frequency.

Pulse and FMTWI excitations contain a number of frequencies unlike lock in. These are treated as the superposition of the components frequencies which can be decomposed from their separation in frequency domain. In order to extract equivalent response from the same frequency component in all the excitations, equal energy is to be provided to the component used for analysis. In time domain matched excitation energy, the shape of the excitation decides the energy of the components which may not be equal in all the excitations for the component used for analysis. Energy of the chosen component among different excitations can be equated by equating the frequency domain energy of that component with the help of FVTool of MATLAB by adjusting the excitation power.

## Results and discussion

In order to test the proposed approach, finite element simulations have been carried on a plain carbon steel sample of thickness 1cm with flat bottom hole defects of diameter 1cm kept at various depths as shown in Fig.1. Sample has been modeled with a fine mesh using 3D tetrahedral elements. FEA has been carried by imposing a suitable heat flux according to the excitation to meet the proposed requirement as shown in Table.1.

**Table 1: Comparison of different excitation schemes.**

| Excitation scheme | Amplitude of imposed heat flux | Duration | Frequency |
|---|---|---|---|
| PPT | 50 k W/m$^2$ | 5s on, 95s off | - |
| LT | 0.8 k W/m$^2$ | 200s | 0.02 Hz |
| FMTWI | 2 k W/m$^2$ | 100s | 0.01 to 0.1Hz |

The proposed heat flux is imposed over the test object and the surface thermal response has been captured at a frame rate of 10Hz. Simulations have been carried, by loading the sample properties like thermal conductivity 43w/m-K, specific heat 440J/Kg-K density 7800 kg/m$^3$ etc. and the sample is kept at an ambient temperature of 300K.

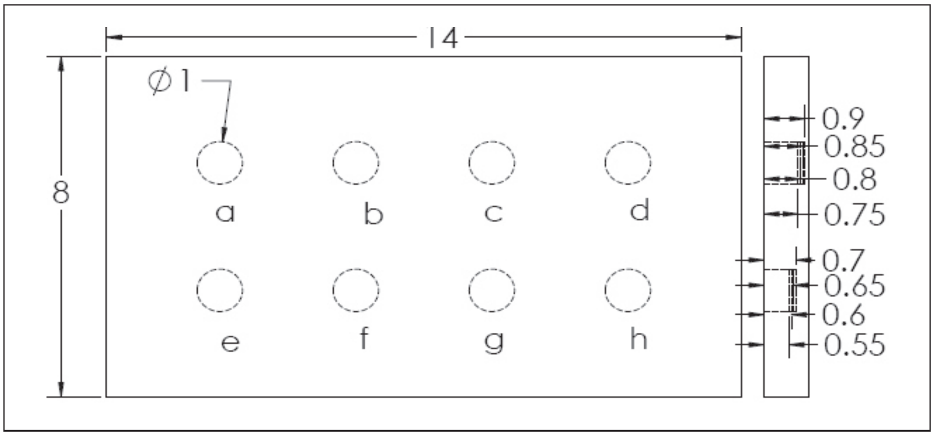


**Fig. 1: Top and cross sectional view of simulated mild steel sample**
(all the dimensions are in cm) with flat bottom-hole defects of diameter 1 cm at different depths.

### Energy matching from temperature profiles

Mean is removed from each profile as subsurface details have been extracted from the time varying component of the response. Fourier transform of the profiles of the same non defective pixel location over the sample has been extracted and magnitude component at the frequency of interest has been identified. In the present context all the phase images are extracted at 0.02Hz hence the magnitude at that frequency is obtained. In order to match the component energy, by taking the same sampling rate (10 Hz) and sample number in all the excitations, the component magnitude value has been matched at 0.02Hz as 33 dB as shown in Fig. 2 and the corresponding excitation peak powers have been identified.

In PT, pulsed excitation of 5s with a peak power of 50kW s is imposed on the front end of the sample and the sample response during cooling region of the profile has been used for phase analysis. A sine wave of 0.02Hz with peak power of 0.8kW has been probed for 200s for LT. The response has been collected during excitation. Last two cycles of the response is averaged after properly removing the drift and used for analysis. In FMTWI, A linear frequency modulated up sine chirp of frequencies swept from 0.01Hz to 0.1Hz in duration of 100s is used with a peak power of 2kW.

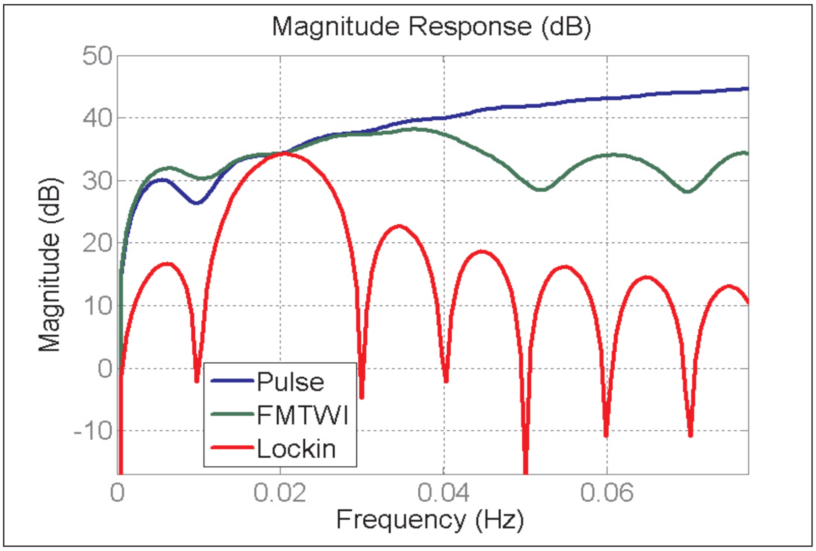


**Fig. 2: Frequency domain analysis of mean removed temperature responses of different excitations.**

### Phase based analysis

Thermograms are recorded simultaneously during the experimentation/simulation in all the schemes. Recorded temporal temperature history of each pixel from all thermograms has been formed as temperature profile of the pixel and temperature drift due to transient component has been removed from each profile with the help of a linear fitting routine. Further phase analysis has been carried over these mean removed profiles, since the phase delay encountered at the location of defects as compared to the non defective region provides reliable information about the location of the defects beneath the surface.

In order to obtain the phase delay information, Fast Fourier Transform (FFT) is applied over the temporal thermal profile of each pixel in view. FFT applied over temporal thermal history of the pixel disintegrate the phase detail in frequency domain and provides phase information corresponding to the constituent frequency components. 1D fft on thermal profile of the pixel provide phase delay corresponding to different frequencies which can be obtained by computing

$$\varphi(n) = \tan^{-1}\left(\mathrm{Im}(X_n) \,/\, \mathrm{Re}(X_n)\right)$$

Phase contrast at a particular frequency of all the pixels in appropriate positions constitutes the phase image at that frequency. Spatial phase contrast in phasegram at a particular frequency provides the details of defects at a corresponding depth.

Phase image of the simulated sample obtained at frequency 0.02Hz in different excitation schemes has been shown in Fig.3. Due to equal and sufficient energy with the frequency component of analysis all the defects are clearly detectable among all the schemes. Phase contrast among all the phase images is nearly same and a similar phase response has been observed. Relative phase degradation from nearer to deeper defects among all the excitation schemes exhibits the influence of depth on the detection.

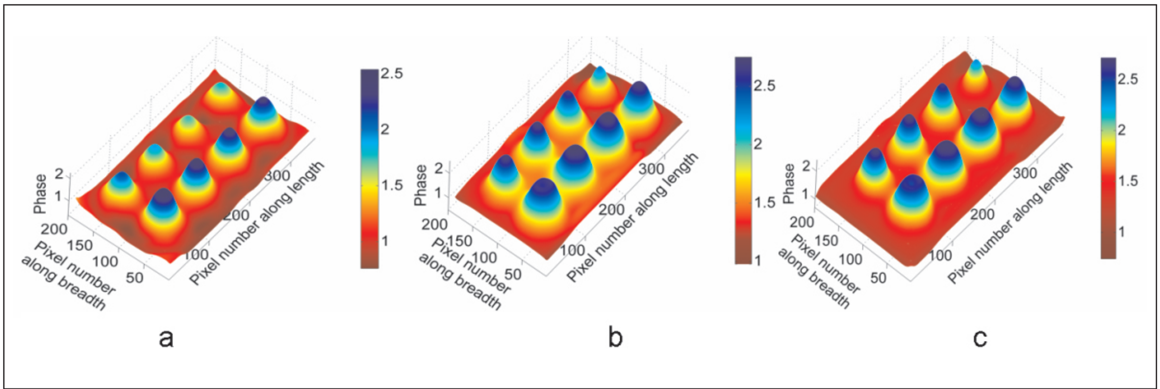


**Figure 3. Phase image at a frequency of 0.02Hz in a) PPT b) LT and c) FMTWI**

## Conclusions

Matching the energy of the frequency component used for analysis in different schemes almost provide the relatively similar detection for the defects. Even peak powers required for the lock in is far less, repetitive experimentation to avoid blind frequencies is a drawback of lockin thermography. High peak power requirement for deeper depth analysis limits the applicability of pulse thermography even though it is a quickest and efficient method of evaluation. FMTWI is a better alternative by grabbing the advantages of both the techniques and stands as a remedy for their drawbacks.

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