Frequency and Time Domain Data Analysis Approaches for Detection and 
Evaluation of Subsurface Defects using Active Thermography

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Abstract
Non-destructive Testing and Evaluation (NDT&E) techniques are widely used for inspection of a variety of materials, 
structures and components. Among all NDT&E techniques, infrared thermography is widely accepted by testing and 
evaluation community due to its non-contact, whole-field and fast monitoring capabilities. The experimental and theoretical aspects of frequency modulated thermal wave imaging (FMTWI) is discussed. FMTWI is used for 
inspection of a mild steel specimen with artificially simulated circular defects of equal diameters but located at various 
depths. The acquired data has been analyzed in the frequency domain using Fourier transform and in time domain 
using pulse compression approach to visualize the defects and a comparative qualitative analysis has been carried out 
among these processing techniques. It was observed that, pulse compression approach significantly improves the 
defect’s visualization with improved signal to noise ratio (SNR). Further, quantitative information regarding the depth 
has also been determined using the Fourier approach.

Key words: Active infrared thermography, Frequency modulated thermal wave imaging, Pulse compression, Fast 
Fourier transform, Non-destructive thermography.

1 Introduction
In recent years, subsurface defect detection in structures is a highly researched area in many 
fields like aerospace, manufacturing industries etc. and the structures have to be tested for quality 
assurance. There are already existence of many non-destructive testing and evaluation (NDT&E) 
techniques which are fast and reliable. It is used in many industrial application such as in 
manufacturing industries to reduce the fabrication costs, to ensure the product integrity and 
reliability, to keep the quality level uniformity etc.

Now days, infrared thermography has also played a major role in the area of non-destructive 
testing and evaluation of subsurface defects in materials and composite structures due to its special 
advantages like non-contact, noninvasive technique. Infrared thermography technique has broadly 
classified into two, active and passive thermography. The most popular active thermography, which 
is used to detect subsurface defects: pulse thermography (PT) [1,2], pulse phase thermography 
(PPT) [3] and lock-in thermography (LT) [2]. Each technique has its advantages and limitations. 
Pulse thermography requires short duration, high peak power energy to excite the specimen. The major disadvantages of the PT, it is affected by emissivity variations, surface geometry variation, 
reflections from the environment and non-uniform heating. Pulse thermography is a popular 
technique and widely used for industrial application due to its simplicity, faster response and ease 
to analyze. Another technique pulse phase thermography (PPT) is similar to the PT but acquired 
data is processed differently. Lock-in thermography (LT) uses periodic thermal wave of low peak 
power for long duration to stimulate the specimen and provide uniform heating all over the surface. 
Single frequency sinusoidal thermal excitation wave is used in lock-in thermography (LT), which 
may not be capable to detect the defects located at various depths and also need to perform several
number of experiments with different frequency to cover an entire range of depths, which is a time consuming process. To overcome with the limitation of conventional thermography (PT and LT), high peak power, depth resolution capability, non-uniform heating, long time experiments, a new technique frequency modulated thermal wave imaging (FMTWI) [4] has been proposed.

2 Frequency Modulated Thermal Wave Imaging

The experimental setup of frequency modulated thermal wave imaging [5] is shown in Figure 1. The data acquisition is performed on a mild steel sample containing six drilled circular bottom holes, each of diameter 1 cm located at various depths from non-defective end. A frequency modulated thermal wave, frequency range from 0.01 Hz to 0.1 Hz is used to excite the sample for duration of 100 seconds with the help of two excitation sources (halogen lamps) of power of 1 kW each. Thermal waves propagate through the specimen and on encountering defects, it changes the amplitude and phase of the thermal response. Thermal response is recorded by the mid-band thermal camera at frame rate of 20 Hz. A control unit is used to synchronize the time between the launch of the thermal pulse and the thermal camera recording. Propagation of thermal wave through the specimen is depends upon the thermal properties of the materials and thermal excitation frequency. The thermal diffusivity of mild steel sample is $1.152 \times 10^{-5} \text{ m}^2/\text{s}$.

![Figure 1: (a) Experimental setup and data acquisition process by FMTWI (b) Dimension of mild steel sample](image)

2.1 Theory

1D solution of Fourier’s law for a periodically varying thermal wave is [4]:

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

whereas, $T(x, t)$ and $\alpha = \frac{k}{\rho c}$ are the surface temperature and thermal diffusivity of the sample respectively, the direction of heat flow $x$, the thermal conductivity $k$, the material density $\rho$, and the specific heat $c$.

Solution of the instantaneous temperature $T(x, t)$, by considering the boundary condition on the sample surface, can be written as [4]:
T(x, t) = \sum_{\alpha} \left[ \frac{x}{\alpha} \pi(f_0 + bt) + jx \sqrt{\frac{\pi(f_0 + bt)}{\alpha}} \right] \exp \left[ 2\pi j \left( f_0 t + \left( \frac{b}{\tau} \right) t^2 \right) \right]

Thermal diffusion length for frequency modulated thermal wave imaging is [4]:

$$\mu_{FM} = \frac{\alpha}{\sqrt{\pi(f_0 + \frac{B}{\tau})}}$$

whereas, $\frac{B}{\tau}$ is the rate of change of frequency modulated signal, which controls change in the frequency w.r.t. time. The thermal diffusion length depends on the bandwidth of the modulated thermal excitation and the selected bandwidth helps to probe the entire depth of the specimen.

3 Frequency Domain Analysis using Fourier Transform

Fast Fourier Transform has been applied on mean centered temporal thermal profile of each pixel and from obtained complex data, phase and amplitude image has been extracted. Fourier transform of function $f(t)$ is given by [3]:

$$F(u) = \sum_{k=0}^{N-1} f(k \Delta t) \exp \left( \frac{j2\pi uk}{N} \right) = R(u) + jI(u)$$

where, $u$ is the number of sample in FFT and resultant real and imaginary components are $Re$ and $Im$. Amplitude and phase can be calculated by $A = \sqrt{R(u)^2 + I(u)^2}$ and $\phi(u) = \tan^{-1} \left( \frac{I(u)}{R(u)} \right)$ expression, respectively. The phase is almost not affected by non-uniform heating, surface geometry variation, etc. Therefore, these advantages are very efficient for quantitative analysis. Depth information can be calculated by using the blind frequency concept [3].

At the lower frequency, deeper and at higher frequency, shallower defects are visible in the phase images. The blind frequency $f_b$ is chosen with the help of phase profile plots, $f_b$ is located at a frequency at which phase profile becomes zero or no significant phase can be observed. From thermal diffusion length equation: $\mu = \frac{\alpha}{\sqrt{\pi f_b}}$, depth: $z = \phi, \mu$ is related to $f_b$ and phase delay.
4 Time domain analysis using Pulse Compression

Pulse compression [6] is a signal processing technique commonly used in radar design to enhance the target range resolution. The same concept has been used in active thermography for subsurface defect detection. Temporal thermal profile \( s(t) \) of non-defective pixel is cross-correlated with temporal profile of other pixels \( s'(t) \). The cross-correlation \( g(\tau) \), between two signals is defined as:

\[
g(\tau) = \int_{-\infty}^{+\infty} s(t)h'(\tau + t)dt
\]

Pulse compression concentrates the total applied energy into mainlobe of compressed pulse with delayed response based on depth of defects. Peak of mainlobe in compressed pulse get attenuated and delayed depending upon defect’s depth. The pulse compression method also increases signal to noise ratio (SNR).

5 Results and Discussion

5.1 Fourier Transform approach

In Fourier transform approach, phase images are extracted from the obtained phase data after application of 1-D FFT to mean centered temporal thermal profiles of each pixel. There are a number of phase images at various frequencies, but the best phase image which visualize the shallower as well as deeper defects, obtained at a frequency of 0.27 Hz as shown in Figure 3.

5.2 Pulse compression approach

Pulse compression is performed by cross correlation of the mean centered temporal thermal profile of each pixel with choosing a reference temporal thermal profile. Correlation images at the instant of 1.1 Sec in Figure 3, have been extracted from the delayed cross-correlation profiles of each pixel of compressed pulse. The defects at lower depth (near the surface) are clearly visible and shows more contrast than deeper defects.

![Phase image at frequency 0.27 Hz and Correlated image obtained at 1.1 Sec](image)

In Figure 4, the peak of the cross-correlated compressed pulse of each defect not only attenuated but also delayed corresponding to their depth. The peaks of the correlation profile for the deeper defects are far from the reference profile, whereas the peaks for shallower defect are near to the reference profile. This is because of response from deeper defects delayed more than shallower one with respect to non-defected reference profile. The amplitude of the compressed pulse deeper defects attenuated more than shallower one. Figure 4 illustrates, reliance of peak delay on depth.
SNRs of defects in Figure 5, shows that pulse compression technique has significantly improves SNR than the phase approach. SNR value decreases with increasing depth of defects, higher for shallower defects and lower for deeper defects.

Phase profile of defects is shown in Figure 6, and blind frequency is marked by a circle. It can be observed that blind frequency \(f_b = 0.03\) Hz is practically same for all the defects. Phase change of each defect w.r.t. non-defect at \(f_b\) is marked with elliptical box as shown in Figure 7. Phase is practically unaffected by non-uniform heating, so the phase profiles are correctly distributed from the shallowest to the deepest defects. Shallower defects has smaller change and deeper defects have greater change. The estimated depth vs phase contrast plot is shown below in Figure 7. A comparison between actual depth, estimated depth and percentage error is shown in Table 1.
Table 1: Estimated depth using FMTWI

<table>
<thead>
<tr>
<th>Defect</th>
<th>Actual Depth (cm)</th>
<th>Estimated Depth (cm)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.120</td>
<td>0.1224</td>
<td>2</td>
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<td>0.137</td>
<td>0.1328</td>
<td>3.07</td>
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<td>0.197</td>
<td>0.1844</td>
<td>6.40</td>
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<tr>
<td>4</td>
<td>0.213</td>
<td>0.1733</td>
<td>18.64</td>
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<tr>
<td>5</td>
<td>0.232</td>
<td>0.2293</td>
<td>1.16</td>
</tr>
<tr>
<td>6</td>
<td>0.342</td>
<td>0.3539</td>
<td>3.48</td>
</tr>
</tbody>
</table>

6 Conclusion

Phase and pulse compression methods have been implemented on the same mild steel sample data. The cross-correlated images show a better visualization of defects than a phase image with improved SNR. Furthermore, peaks of compressed pulse of deeper defects delayed more similar as phase change in phase analysis. Additionally, depth of defects can be estimated using depth retrieval concept of blind frequency by FMTWI, with the only prior knowledge of material thermal diffusivity $\alpha$. FMTWI approach has better control on deposition of energy, it need to perform a less number of experiments to probe entire depth range, less power (compared to PT) and requires less time (compared to LT) to detect and analyze the defects located at various depths.

References


