ABSTRACT
Active infrared thermography makes use of temperature contrast over the object surface generated by distorted heat flow due to subsurface anomalies present in the material. This paper presents a wavelet transform based analysis for subsurface anomaly detection in recently introduced Quadratic frequency modulated thermal wave imaging for the subsurface analysis specimen and compares it with the contemporary Fourier transform based phase analysis using an experimentation carried over a carbon fiber reinforced plastic specimen with embedded flat bottom holes.

Keywords: active thermography, QFMT, wavelet analysis, fourier analysis.

INTRODUCTION
As there is more demand for quality and defect less products leads to research of various non-destructive evaluations. Among them Infrared Non-Destructive Testing (IRNDT) emerged as reliable and non-destructive evaluation. It mainly depends on thermal conductivity of specimens made it necessary for applications in various fields. It can be carried out in both active and passive approach. In active approach an external stimulation is necessary where as in passive approach no external stimulation is needed and it cannot give better contrast than active approach. Various processing methods are introduced to extract the minute contrast details to identify subsurface defects.

Among the existing techniques pulse Thermography, pulse phase thermography, lock in thermography [1] are known for their reliability and application ease. But more computation time in LT and high power stimulation in PT are substituted by recently introduced non stationary thermal wave imaging. It makes use of temperature contrast captured during stimulation phase and further analyzed with various processing modalities in either time domain or frequency domain.

For frequency domain purpose Fourier transform (FT) can be used to decompose the signal into various constituent frequency components and phase analysis will be carried. But it cannot simultaneously preserve the temporal information. However, there is a possible alternative approach with the use of wavelet transform in this analysis; it will decompose the signal into scaled and translated replicas of mother wavelet. In wavelet transform technique there are so many proposed wavelets in existence which we can use any of those wavelets.

This paper exhibits wavelet analysis based subsurface analysis using experimentation carried on a composite specimen.

Theory
When the energy is incident on the surface of the solid metal specimen then the metal will absorb some of the energy from the incident wave. Due this a localized heat flow will be generated. This is a time-dependent heat flow [2] which is finely described with following one-dimensional heat diffusion.

\[ \frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \]  \hspace{1cm} (1)

Where \( T \) is temperature with time varying function and \( \alpha \) the thermal diffusivity \( \alpha (\rho, c) = k \), \( \rho \) is mass density, \( c \) is specific heat and \( k \) are thermal conductivity of the medium. To obtain the periodic heat flow from the material, incident energy should be modulated due to this periodic heat flow periodic temperature disturbances will be produced.

For QFMTWI [3], we assume that a material is excited by a quadratic frequency modulated [4] heat flux at the top of the surface and due to excitation the temperature of the defect increases is given by

\[ T_d(x,t) = \frac{Q_0}{k_o} \left[ \frac{\cosh(L-x)}{\sinh L} \right] \exp(i(f_o + bt^2)t) \]  \hspace{1cm} (2)

Where:
\[ \sigma = \frac{\sqrt{\left( \frac{f_o}{\frac{1}{2}} \right) (f_o + 3bt^2)}}{\sqrt{f_o + 3bt^2}} \]

Where \( Q_0 \) peak value of incident flux and \( f_o \) is initial frequency and \( k \) is thermal conductivity \( b \) is sweep rate.

The thermal diffusion length for QFMTWI is given by

\[ \mu = \frac{2a}{\sqrt{f_o + 3bt^2}} \]  \hspace{1cm} (3)

Where \( t \) determines the capability of analysing the defects. Subsurface analysis is done by applying the processing methods on the thermal history corresponding to each pixel. For QFMTWI this has been explored by using Fourier phase analysis and wavelet phase analysis.
Processing methods

Fourier analysis

Fourier transform is applied to each pixel to convert the time domain into frequency domain. The algorithm of Fourier transform [5] allows the function to decompose into summation of several periodic sinusoidal signals.

$$X(\omega) = \int x(t) e^{i\omega t} dt$$ (4)

The magnitude of the resultant FT wave can be obtained from the amplitude of the frequency components and phase also can be determined from the arctan(Imaginary parts/real parts).

QFMT wave was non-stationary wave which contains more than one frequency component. For a non-stationary wave there was another approach in Fourier analysis by following window technique called Short Term Fourier Transform (STFT) [6]. But the drawback in FT was it loses temporal information and it cannot provide the time resolution for this reason we go with another approach.

Wavelet analysis

Continuous wavelet transform

Wavelet transforms approach was introduced here as an alternate approach to overcome the missing information with Fourier Transform. The wavelet transform [7-9] uses a waveform function to provide time resolution and frequency resolution as well. This can be achieved by scaling and shifting of the basis function of wavelet which is also called mother wavelet. The wavelet function or mother wavelet can be expressed as follows:

$$\psi(t) = \frac{1}{\sqrt{a}} \psi\left(\frac{t-b}{a}\right)$$ (5)

Where $\psi(t)$, can be referred as mother wavelet which is a time or space function and ‘a’ and ‘b’ represents scaling and shifting parameters respectively from this a Continuous Wavelet Transform (CWT) [9] was defined as below:

$$W(a,b) = \frac{1}{\sqrt{a}} \int f(t) \psi\left(\frac{t-b}{a}\right) dt$$ (6)

From the above equation it is very clear that CWT signal can decompose the signal into several frequency components by scaling and shifting the basis wavelet function.

Wavelet analysis is presently used in various applications including speech recognition [10], fingerprint recognition and medical applications.

This contribution introduces the proposed processing modality to non-stationary thermal wave imaging.

Complex Morlet wavelet

The Morlet complex wavelet contains a complex sinusoid described in a complex envelope which can defined with the equation described below:

$$\psi(x) = \frac{\pi^{1/4}}{\left(\frac{\pi}{2}\right)^{1/2}} f_x f_{fb} e^{i2\pi f_x x} e^{-\pi f_x^2}$$ (7)

Where ‘fc’ denotes the centre frequency i.e. number of oscillations of sinusoidal wave within the Gaussian window and ‘fb’ indicates band width parameter.

![Complex Morlet wavelet](image_url)

There is a possibility of scaling and shifting of mother wavelet function such that there is a chance of providing fine tuning by choosing appropriate values of ‘fc’ and ‘fb’.

EXPERIMENTATION AND RESULTS

In order to detect the defect experimentation is carried on a CFRP material having 0.7cm thickness with flat bottomed holes of various diameters and depths as shown in the Figure-1. The test specimen was energized using a quadratic chirp modulated heat wave. Here unlike pulsed thermography a low power quadratic chirp of frequency sweep 0.01 Hz to 0.1 Hz is imposed in 100 seconds. The temperature map of the specimen is captured at a frame rate of 25 Hz by an infrared camera.
Defect detection using Fourier analysis

First the thermal wave regarding to a particular pixel is taken as a reference and the Fourier transform is applied to it and the phase of the result is obtained by arctan (image/real) and the result is again placed in to corresponding location. A similar procedure is taken over all the pixel profiles in view and corresponding results are preserved.

Defect detection with wavelet analysis

As Fourier phase approach is suitable only for stationary waves, being non stationary frequency modulated thermal waves at different frequencies and time instants are analyzed here with Wavelet phase approach. In this Morlet wavelet transform is applied over mean removed thermal profiles and the phase of the wavelet coefficients is obtained and preserved in that corresponding location. In this paper we morlet wavelet transform for N=512 and we have used complex morlet wavelet with having center frequency 0.45Hz and having bandwidth parameter f_b=0.9.

The Signal to Noise Ratio (SNR) of the defects are calculated by

\[
SNR = 20 \log_{10}\left(\frac{\text{Mean of Defective region} - \text{Mean of non-defective region}}{\text{Deviation of non-defective region}}\right)\text{db}
\]
As shown in the Table-1, SNR values of the both Fourier phase and Wavelet phase was plotted for defects in the specimen.

3. CONCLUSIONS

As far as QFMTW technique is concerned it maintains a non stationary wave hence it has multiple frequencies for different time instants so there was a chance for better estimation of defects with different depths. The application of wavelet analysis over Fourier analysis has given same or qualitatively better results. In particular cases Fourier analysis cannot give the true shape of the objects compared with wavelet analysis. Hence wavelet analysis can be considered as one of the powerful tools for active thermography.

REFERENCES


