Chirp Z transform based Enhanced Defect Depth Resolution for Thermographic analysis of Composites

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Abstract

Active thermography is emerging as a reliable quality assurance method due to its whole field, non contact, non invasive and fast inspection modality. It makes use of temperature map over the surface of test object energized by an external stimulus like pulse, sine or chirp. Recent past witnessed the introduction of a few non stationary thermal wave imaging modalities to overcome the shortfalls of conventional thermographic methods. Quadratic frequency modulated thermal wave imaging is one of these techniques which imposes a continuous frequency sweep containing more energy with low frequency thermal waves in a single experimentation cycle to facilitate entire depth probing of the test object, unlike its linear frequency counterpart.

In order to extract fine subsurface features in this modality, the temporal thermal history of the stimulated object is captured using an infrared imager and post processing methods like phase analysis or pulse compression etc., have been carried out. But all these existing post processing methods are based on Fourier transform which provides limited frequency resolution based on the number of captured thermograms and their capturing rate. This inadequate frequency resolution subsequently limits the depth resolution capability of this modality and required to be enhanced.

This contribution highlights a novel post processing methodology based on chirp z transform for enhanced defect detection and depth resolution with the numerical study carried on carbon fiber reinforced plastic specimens containing flat bottom holes and compares it with other contemporary post processing methods.

I. Introduction:

The usage of carbon fiber reinforced polymer increased from last few decades because of their low weight and high strength. Quality and safety of these materials requires a rigorous testing before their use in various applications. Among all the available non invasive testing methods IRNDT facilitates a reliable, non contact and non destructive testing of composites. It uses the temperature contrast over the object surface to distinguish defective subsurface locations. It is categorized as passive and active approaches. In passive approach a natural thermal contrast over the object surface is used for analysis, but the poor thermal contrast from deeper defects limits its applicability. To overcome this limitation, in active thermography an external heat stimulation is imposed on to the object to create similar thermal waves inside it. These waves will create a temperature contrast due to thermal in homogeneity associated with the subsurface anomaly which is further recorded and used to distinguish defective locations from their non defective counterparts. Among various
contemporary conventional IRNDT approaches, in pulse thermography [1] a short duration and high peak power stimulation is imposed over the surface of the object and subsequent thermal response in cooling phase will be captured by IR camera. Whereas in lock in thermography [2] a low frequency, low power excitation is imposed onto the object surface and data analysis has been done using phase based method due to it less sensitivity to non uniform radiation and non uniform emissivity. But the repetitive experimentation to analyze a realistic object for sufficient depth resolution limits the it’s applicability. To overcome the problems with these conventional methods, non stationary thermal wave imaging methods have been proposed in recent past.

In these non-stationary imaging methods a low power, low frequency sweep stimulations are employed to energize the test object in a single experimentation cycle to facilitate the entire depth scanning of the object. FMTWI [3] uses a chirp like stimulation where as DFMTWI uses a digitized version of FMTWI by probing more harmonics as compared to its analog version. Recently introduced QFMTWI [4,5] provides a group of frequencies similar to its linear frequency counterpart in addition to more energy with low frequency components. In order to extract subsurface details from the captured temporal thermal history, various post processing methods have been used which are based on Fourier transform. But analysis corresponding to some important frequencies may be lost due to inadequate frequency resolution of FFT, which subsequently limits the depth resolution capability. Hence to enhance frequency resolution, a novel chirp z transform based processing method is adopted and subsequent numerical study has been carried on CFRP specimen and the results are further compared with the conventional processing approaches.

II. Theory of QFMTWI:

In Quadratic frequency modulated thermal wave imaging modality a quadratic chirp stimulation has been provided to the test object surface. The incident optical energy contributes for a temperature gradient between the two ends of object and induces similar diffusive thermal waves inside the object and further generates temperature over the object surface which can be determined by 1D heat equation in rectangular coordinate system given by

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t}$$

(1)

Where ‘α’ is thermal diffusivity, T(x,t) is the thermal response at time ‘t’ consequent to depth ‘x.’ Assuming the object has thickness ‘L,’ stimulated with a quadratic chirp heat flux of magnitude‘Q0’ at the front surface of object, with initial frequency ‘a’ and sweep rate ‘b,’ using the boundary conditions resulting in a temperature in Laplacian domain as

$$T(x,s) = \frac{Q(s) e^{\alpha x}}{k\sigma}$$

(2)

Where $\sigma = \sqrt{\frac{s}{\alpha}}$

III. Processing Methodologies:

In order to extract subsurface details, various post processing modalities like FFT based phase analysis, Hilbert and Chirp Z transform base phase analysis etc., have been employed over the dynamic response of the capture temporal thermal history.
a) FFT based phase Analysis:

It is a frequency domain method, employing fast Fourier transform (FFT) for frequency unscrambling. Fast Fourier transform applied over the mean removed thermal profile of each pixel and phase values to corresponding each frequency component is obtained, phase images are formed by inserting the phase values in to its respective pixel position. The constructed phase images exhibits phase contrast due to a differential phase delay contributed from thermal waves of anomalies at different depths, which is obtained from phase difference [5,6]. The frequency corresponding to the phase image exhibiting the defects is estimated by

\[ f = \frac{F_s n}{N} \]

\( F_s \) = Sampling frequency or Capturing rate.

\( N \) = Total number of the samples in thermal profile.

\( n \) = Number of the phase image.

b) Hilbert phase:

It is a multi transform method, in which a reference profile is selected from pixel’s profile, further Hilbert transform applied over it next fast Fourier transform has been employed over the Hilbert transformed reference profile and complex conjugate of it is calculated. Further fast Fourier transform has been applied over remaining pixel profiles. Then inverse FFT is calculated to multiplication of complex conjugate profile and FFT profiles.

\[ Q_1 = \text{IFFT} \left[ (\text{FFT(Hilb(T_n)))} \ast \{\text{FFT(T)}\} \right] \]  \hspace{1cm} (3)

In the next stage ordinary cross correlation has been carried as given as

\[ Q_2 = \text{IFFT} \left[ \{\text{FFT(T)}\} \ast \{\text{FFT(T)}\} \right] \]  \hspace{1cm} (4)

Finally the time domain phase will be obtained using

\[ \theta = \tan^{-1} \left( \frac{Q_1}{Q_2} \right) \]

From the calculated phase, time domain phase images are formed by arranging above phase values in to their respective locations [7, 8].

c) CZT Phase:

Chirp Z transform provides a fine frequency information from the spectrum. It computes chirp z coefficients everywhere on the spiral contour inside or outside the unit circle as it is done by z transform over a unit circle, which is not available in case of Fourier coefficients. The desired band of frequencies can be analyzed by selecting the starting point and angular spacing in the contour which subsequently provides better frequency information than FFT. It can be computed using eqn.1.

\[ \text{czt}(x[n]) = \sum_{n=0}^{N-1} x[n]z^{n} \bigg|_{z = Ae^{j\omega}} \]  \hspace{1cm} (5)
It is easily computed from circular convolution as given in the above eqn.5.

\[
czt(x[n]) = \sum_{n=0}^{N-1} x[n] A^{-n} w^{mn} = w^{-\frac{m^2}{2}} \left[ \text{IFFT} \left\{ \text{FFT} \left( x[n] A^{-n} w^{\frac{n^2}{2}} \right) \right\} \right]^{(6)}
\]

Where ‘w’ is the twiddle factor and ‘m, n’ are arbitrary numbers chosen according to the required bandwidth for spectral zooming [9].

In order to apply chirp z transform, a desired frequency resolution over a suitable range of frequencies is applied over thermal profile of each pixel. Further phase values to corresponding frequency component has been obtained, finally phasegrams were constructed by arranging phase values of particular frequency in to their corresponding pixel position and the phase contrast in phasegrams has been used to visualize the defects.

IV. Results and discussion:

In order to test the proposed methodology a numerical study has been carried over a CFRP specimen of dimensions 100×100×3mm containing nine flat bottom holes, each of diameter 20mm with defect depth varying from 0.2mm to 1.8mm from the front surface of the specimen. The front surface of the object is energized by Quadratic chirp stimulation of a heat flux of 2 KW for duration of 100 seconds. Further the object thermal response is captured at a frame rate of 20 Hz.

During analysis phase, FFT provides a frequency resolution of 0.01 Hz, where as CZT based phase analysis is capable to provide a frequency resolution is $4.8828 \times 10^{-4}$, by zooming the frequency band of 0.02 to 0.04 with 4096 samples.
Fig. 2. a) Sample layout (all dimensions are in cm), b) FFT Phase Depth resolution, c) Hilbert phase depth resolution, and d) CZT phase depth resolution.

Fig. 2.b to d represents depth resolution capability of post processing approaches. Fig. 2.a represents modeled CFRP sample layout containing flat bottom holes. Fig. 2.b is a FFT based phase image which resolves the defects with a depth resolution of 0.6mm similar to Fig. 2.c obtained from Hilbert phase. Whereas CZT phase image in Fig. 2.d resolves all the defects at different frequencies with an enhanced resolution of 0.2mm also.

V. Conclusion:

A novel chirp z based spectral zooming methodology has been proposed and its enhanced frequency resolution and subsequent depth resolution capability has been numerically studied. And it outperformed over conventional and Hilbert phase methods.

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VII. References:


