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Enhanced Data Fusion through Non-Subsampled Contourlet Transform

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Abstract.

The goal of image fusion is to integrate data from different images of the same scene. The outcome of image fusion is a new image that is more suitable for both human and machine observation, as well as for further image processing tasks. Thermal images often suffer from noise issues such as non-uniform radiation and non-uniform emissivity, which can overshadow the subtle thermal contrast of deeper defects. Consequently, various signal processing methodologies have been employed to minimize noise and delve into deeper depth details. However, no single method has proven superior in providing comprehensive details, necessitating the merging of information obtained from different processed images using various fusion algorithms. To achieve more precise subsurface details, we are interested in applying suitable fusion techniques to processed thermal images and then combining them into a new single image. This paper proposes a non-subsampled Contourlet transform-based data fusion approach to incorporate all subsurface details into a single image, enabling precise subsurface analysis. The effectiveness of this approach has been verified through experiments conducted on a carbon fiber-reinforced plastic specimen containing embedded flat-bottom holes, employing various processing methods.

Keywords:

Data fusion, Pulse Compression, Phase analysis, and Quadratic frequency modulated thermal wave imaging.

1. Introduction

Nonstationary thermal wave imaging is one of the nondestructive testing and assessment (NDT & E) method that is broadly utilized for quality of materials without hurting physical utility and post administration applications. The essential standard of active thermography is applying external stimulus on to the surface of the object and subsequent thermal history inside of the material is captured by infrared camera. The vicinity of imperfections changing the rate of heat flow so that the deficient regions have an alternate heat slope regarding non-faulty zones. An infrared camera is utilized to screen the worldly assessment of temperature on the material surface.Among the distinctive strategies for thermal evolution, pulse Thermography (PT) and constant thermal wave techniques they are for the most part used. In high peak power PT a brief time heat pulse is constrained on the surface of the test article and examination can be finished in the cooling process. High peak powers required for the more significant subsurface examination, additionally, effect of non-uniform emissivity and non uniform radiation controls its suitability regardless of the way that its speediness. Of course, continues thermal wave's frameworks make use of low peak power sources for excitation and more compasses to overview more imperativeness into the test object.Lock-in thermography employs sinusoidal stimulations with lower peak powers compared to PT. However, its applicability is limited by the challenge of selecting an appropriate frequency to avoid blind frequencies and resolve deeper defects. Frequency Modulated Thermal Wave Imaging (FMTWI), introduced by Mulaveesala et al., addresses this limitation. This method imposes a heat stimulus with a suitable band of frequencies on the test object, allowing it to simultaneously probe the entire thickness in a single experimental cycle. Quadratic frequency modulated thermal wave imaging (QFMTWI), introduced by V.S Ghali, further caters to these needs. It provides a band of frequencies similar to its linear frequency counterpart while containing more energy, especially in the low-frequency components, within a single experimental cycle. However, the lower contrast exhibited by the defects in QFMTWI necessitates the use of various processing approaches to locate them and estimate their parameters, including size, shape, and depth. Additionally, the backscattering of thermal waves from the defects affects the size assessment based on defect signatures, leading to the requirement for data fusion obtained from various processing approaches such as phase analysis, pulse compression, Hilbert phase.

2.Methodology

In Infrared Non-Destructive Testing (IRNDT), the surface of the test sample is exposed to a quadratic frequency-modulated optical stimulus. This stimulus initiates similar thermal waves in a very thin layer close to the surface, which then propagate into the object's interior through diffusion wave propagation. As a result, it creates a temperature contrast on the object's surface, highlighting subsurface anomalies. To extract fine details from beneath the surface, the captured thermal data undergoes various processing methods. These include phase analysis, pulse compression, Hilbert phase analysis, Principal Component Analysis, and Random Projection processing methods. These methods are applied with the aim of defect detection using the recently introduced Quadratic Frequency Modulated Thermal Wave Imaging technique.

2.1 Phase analysis

Phase analysis is a frequency domain method in which the analysis is carried out in terms of phases. The original raw data contains the mean elevated temperature value in each temporal thermal profile. To perform phase analysis, the mean elevated temperature value is removed from all thermal profiles using a linear fitting procedure. Subsequently, fast Fourier transform is applied to each pixel in the thermal profile, calculating phase values for each frequency component. Phase images are then created by arranging the phase values of corresponding frequency components into their respective pixel positions. These constructed phase images exhibit phase contrast because different defects located at varying depths exhibit distinct phase delays relative to their corresponding time delays. This feature makes it easier to visualize defects. Additionally, the frequency of the phase image matches the corresponding frequency of the samples in their respective phase profiles, as determined by:

$$f = \frac{F_s n}{N}$$

Fs=Sampling frequency or Capturing rate.

N=Total number of the samples in thermal profile.

n=Number of the phase image.

2.2 Pulse compression

Pulse compression is a time-domain analysis method wherein data from each pixel is organized into a sequence referred to as a thermal profile. During this process, a reference profile is chosen from an area known to be non-defective within the region of interest. Subsequently, a correlation is conducted between the reference profile and all other pixels. This cross-correlation of the profiles of each pixel yields a normalized correlation data sequence. These profiles are then rearranged so that the normalized correlation coefficients of all pixels at a specific delay are preserved in their respective spatial positions, thereby forming a correlation image at that particular delay. The contrast within the correlation image is harnessed to visualize defects.

2.3 Hilbert Phase

Hilbert transforms are used to shift the phase of a signal by introducing a 90-degree lag across all its frequency components. The operation of the Hilbert transform is interpreted as a convolution operation. This process involves multiple steps. Initially, a reference profile is selected from the view, and the Hilbert transform is applied to it. Subsequently, a Fourier transform is applied to the remaining pixel profiles, and their conjugates are calculated. The Hilbert transform profile obtained from the reference is then multiplied by the computed conjugate profiles, followed by the execution of an inverse Fourier transform.

$$H_1 = IFFT\left[\{FFT(Hilb(p_r))\}^* \{FFT(P)\}\right] \text{....} \qquad (7)$$

Where ‘*’ represents complex conjugate.

In the subsequent stage, the cross-correlation between the reference thermal profile and the temporal thermal profiles of all the pixels in the view has been calculated, as indicated by:

$$H_2 = IFFT\left[\{FFT(Hilb(p_r))\}^* \{FFT(P)\}\right] \text{......} \qquad (8)$$

Additionally, time-domain phase information will be acquired from

$$\theta = \tan^{-1}\left(\frac{H1}{H2}\right) \qquad (9)$$

A time-domain phase image has been derived from the aforementioned equation and positioned in their respective locations.

2.4 Non-Subsampled Contourlet Transform (NSCT)

It effectively reduces noise interference in the fused image and enhances the amount of information derived from the fused images. NSCT-based fusion relies on two factors: a non-subsampled pyramid filter bank is employed for multi-scale decomposition, and a non-subsampled directional filter bank is used to address the direction of each subband image at different scales. This approach is primarily employed in image enhancement and denoising applications. The images are decomposed into low-frequency coefficient images and high-frequency coefficient images, and the fusion rule is applied to the low-frequency coefficients.

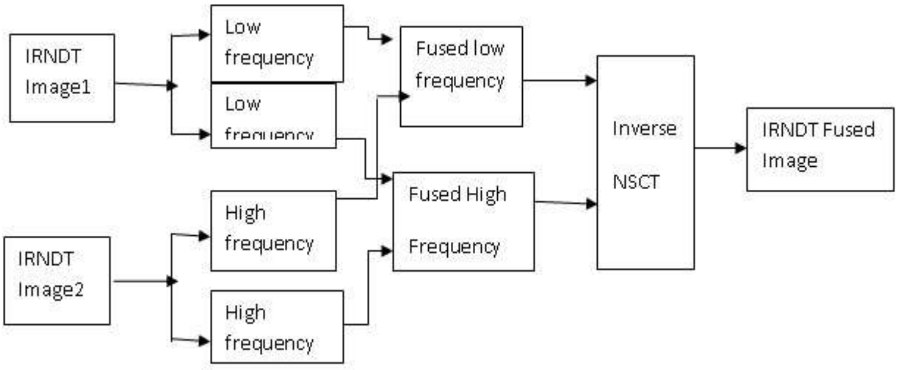

Fig.1 Block diagram of NSCT

3.Results and Discussion

To validate the proposed methodology, experiments were conducted using a sample of carbon fiber-reinforced plastic (CFRP) with a thickness of 0.65 cm. The sample featured flat-bottomed holes of varying sizes and depths. The top surface of the test object was exposed to a quadratic frequency-modulated optical stimulus, sweeping through a frequency range from 0.01 to 0.1 Hz over a period of 100 seconds. This stimulus was generated using a set of 1KW halogen lamps controlled by a control unit. An infrared imager recorded the temporal thermal response of the surface at a frame rate of 25 Hz. Subsurface features were then extracted using various processing methods, including phase analysis, pulse compression (PC), Hilbert phase. The dynamic component of the response was isolated by removing the static part using an appropriate polynomial fitting procedure. Notably, the Phasegram obtained at 0.02 Hz revealed all larger and shallower defects with varying defect sizes. These images were obtained by applying image fusion to all the methods, and the performance of each figure is detailed below.

The defect Detectability obtained from various processing methods is compared in terms of

$$\text{SNR (db)} = \frac{\text{Mean of the defective region- Mean of the non defective region}}{\text{Standard deviation of non defective region}}$$

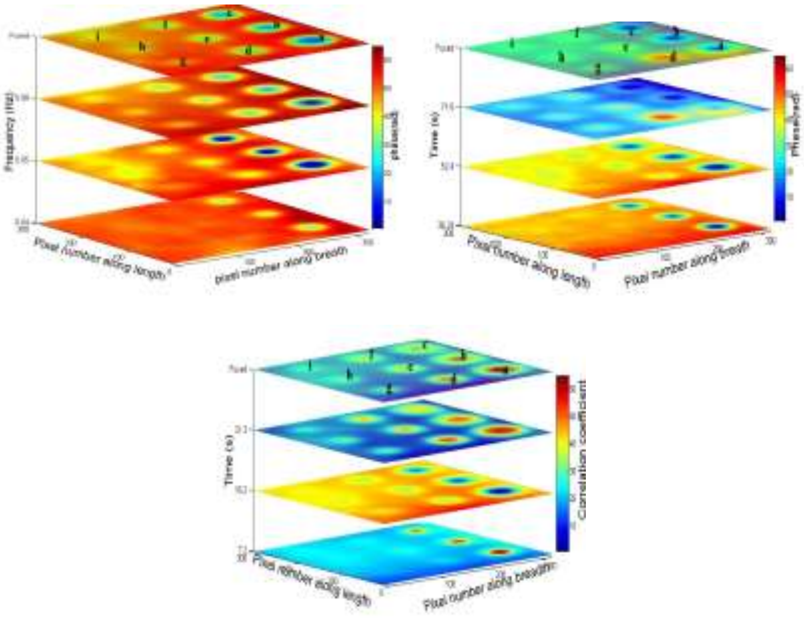

Fig. 2. FFT, Hilbert phase and Pulse Analysis

4. Conclusions

Through experimentation with Three processing methods, we have determined that Hilbert and PC effectively visualize even deep and smaller defects. The fused images in these cases are notably clearer when compared to the remaining processing methods. This clarity is achieved by combining the details obtained from various subsurface analysis approaches during experiments conducted on a CFRP sample for quadratic frequency modulated thermal wave imaging.

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