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NDT of a Composite Domain Using Ultrasonic Tomography

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Abstract

Non-destructive testing (NDT) of engineering materials, components and structures has steadily increased in recent years at an unprecedented rate because of all-round thrust for improving material quality, component integrity and performance reliability. Ultrasonic testing is a versatile NDT method, which is applicable to most materials, metallic or non-metallic. The relevance of computed tomography (CT) in state-of-the-art non-destructive evaluation (NDE) is enormous. CT uses computer reconstruction to combine the information obtained from multiple projections. For quicker and reliable results there is a need to have clear ideas regarding performances of reconstruction algorithms. In the present investigation, the NDT of a composite domain using ultrasonic CT is presented. The sample is of rectangular shape and consists of a continuous phase made of steel and a square shaped insert made of resin. Reconstruction is done by ART like algorithms on a set of time-of-flight (TOF) data collected between transducers for multiple ray paths in each of the different views. For each reconstruction, the reconstructed image is compared with the actual one and a corresponding L1 error is calculated. Performance of each algorithm, with different relaxation parameters is studied and compared in terms of accuracy and iteration numbers.

Keywords: *Tomography, Time-of-Flight, Reconstruction, ART, MART*

1. Introduction

Non-Destructive Testing (NDT), Non-Destructive Evaluation (NDE), Non-Destructive Inspection (NDI) are terms used to represent the techniques that are based on the application of the physical principles employed for the purpose of determining the characteristics of materials or components or systems and for detecting and assessing the in-homogeneities and harmful defects without impairing the usefulness of such materials or components or systems.

NDT plays an important role not only in the quality control of the finished product but also during various stages of manufacturing. NDT is also used for condition monitoring of various items during operation to predict and assess the remaining life of the component while retaining its structural integrity. NDT enables optimum utilization of components without sacrificing safety. The use of microprocessors for data acquisition and processing and automated devices for reliable testing has vastly improved the condition monitoring of the complex components and plants. The operator dependency for routine inspection is reduced and thus the person can concentrate more on the technological aspects. The end result is the saving in time, cost and improvement in precision and reliability of the results obtained.

The relevance of Computed Tomography (CT) in state-of-the-art Non-Destructive Evaluation (NDE) is enormous. CT is a powerful NDE tool that has seen a rapid development in the past two decades. CT uses computer reconstruction to combine the information obtained from multiple projections. The quantitative CT information is displayed as a reconstructed slice plane of the part.

Besides X-rays, CT techniques can also be used with other energy sources such as neutrons, ultrasound, magnetic resonance and microwave etc. Among these, the ultrasonic computed tomography (UCT) technique has received considerable attention for medical diagnostics and non-destructive testing of materials. In material characterization by UCT, the property in question could be the slowness, i.e., the reciprocal of the acoustic wave speed in the domain. Since the acoustic wave speed is a direct function of the elastic properties of the domain, so slowness also represents the domain characteristics in some way. The projection data in case of the UCT is the time-of-flight between a pair of ultrasonic transmitter and receiver, the line joining them being the ray path. Several ray paths having the same orientation constitute a view and projection data from multiple views are used for reconstruction of the domain. Reconstruction is the process of obtaining the concerned domain property over a grid of pixels by superposition of all the projections at each pixel.

Reconstruction methods can be either direct or iterative. The direct methods can be further classified into direct algebraic methods and Fourier Transform based methods. The iterative methods include the algebraic reconstruction technique (ART), simultaneous iterative reconstruction technique (SIRT) and multiplicative algebraic reconstruction technique (MART) etc. Censor [1] documented an article in the field of series expansion reconstruction methods. A discretized model for an image reconstruction problem was presented. ART, discovered by Gordon et al. [2] is presented along with the technique to convert the problem of solving equations into a problem of solving inequalities.

Kline and Wang [3] explored the use of tomographic imaging to map out material property variations in the polymeric media with a set of target samples containing known variations in the cure state. Ultrasonic transit times for multiple ray paths were measured and tomographic images were created using a modified ART algorithm. Jansen et al. [4] used the SIRT algorithm with necessary modifications to reconstruct arbitrary sampling geometries and a fast approximate ray bending correction was developed. Dusaussoy and Abdou [5] proposed a new scheme of iterative MARTs, QMART1 and QMART2 to solve large system of linear equations. The proposed techniques showed better imaging capabilities but at the cost of more iterations. Kishore et al. [6] implemented a ray-tracing algorithm based on Fermat's principle to determine the actual curved paths of the rays for various modes of the rays. The ray-tracing solution was incorporated into the ART for determination of elastic constants.

In the present investigation, ultrasonic transit time measurements for different ray paths are conducted on a composite domain, followed by reconstruction of the slowness of a grid of pixels covering the domain by ART based algorithms. Transit time measurement has been performed on the sample, shown in Fig. 1(a), which is made of two acoustically different isotropic materials It is of rectangular shape and consists of continuous phase

(Steel) that contains a square shape insert (Resin).

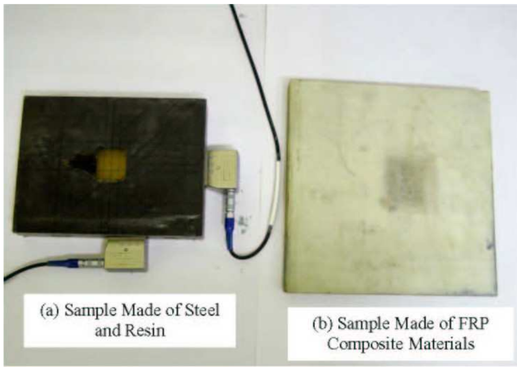

Fig. 1: Photograph of the Samples

The essential working units, as shown in Fig. 2, for experimental setup to acquire ultrasonic tomographic data are the PCUS11 ultrasonic board, the associated QUT software and the interfacing computer. Two normal beam ultrasonic transducers (4 MHz) and two 45_0 angular beam transducers (4 MHz) have been used for projection data acquisition.

Fig. 2: Photograph of the Experimental Setup to Acquire Ultrasonic Tomographic Data

Two-view and four-view projection data have been used in the present reconstruction by ART and MART algorithms. Necessary software to (1) generate the projection matrix, (2) undertake the reconstruction iterations (3) distribute the slowness values of the adjacent pixels to the each node points and (4) to plot the reconstructed images has been developed for the purpose. For each reconstruction, the reconstructed image is compared with the actual one and a corresponding L1 error is calculated. Performance of each algorithm, with different relaxation parameters is studied and compared in terms of accuracy and iteration numbers.

2. Reconstruction Algorithms

Tomographic reconstruction can be defined as a procedure to generate the distribution of any concerned domain characteristic over a grid of pixels from the projection data. In the following paragraphs, the theory of the conventional ART, and that of the MART are discussed briefly.

In ART, the concerned domain is discretized into a Cartesian grid of square pixels. The reconstruction problem is then to determine the average value of the variable of interest for the image in the pixel. In ultrasonic tomography, the most convenient parameter to measure is the transmit time from source to receiver. Hence in application to ultrasonic tomography the reconstructed image is a distribution of the slowness (reciprocal of the longitudinal wave speed) throughout the image.

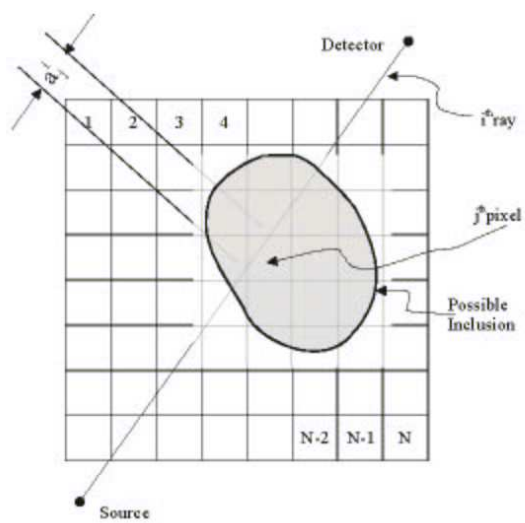

Fig.3: Schematic Representation of the Discretized Object Plane

With reference to Fig. 3, let s_j be the average slowness value within the j_{th} pixel, t_i is the measurement of the i_{th} travel time and a^i_j is the length of the segment of the ray-path i within the pixel j, one can write

$$t_i = \sum_{j=1}^{N} s_j a^i_j \qquad (1)$$

where N is the total number of pixels in the grid. Values of a^i_j for different rays constitute the projection matrix. The projection matrix and the transit time vector being known, the slowness vector may be obtained by solving equation (1). Direct solution, however is not possible as number of unknowns are much more than the number of equations. Iterative procedures like ART, MART are, therefore, necessary for solution. An iterative procedure starts with an initial approximation $\mathbf{S^o} \varepsilon R^n$ to the slowness vector. The reconstruction techniques, mentioned above, differs from each other in terms of the initial approximation

In an iterative step involved in ART, the current iterate s^k is corrected to a new iterate $\mathbf{s^{k+1}}$ by considering only a single ray and changing only the image values of those pixels which are influenced (i.e., intersected) by this ray. Mathematically the updating of the iterate s^k with relaxation parameters can be expressed as

$$s^{k+1} = s^k + \lambda_k \frac{t_i - \langle a^i * s^k \rangle}{\left\| a^i \right\|^2} a^i_j \qquad (2)$$

in which λ_k is the relaxation parameter with $\varepsilon_1 < \lambda_k < 2 - \varepsilon_2$ *and* $\varepsilon_1, \varepsilon_2 > 0$

In MART, the typical iteration step may be expressed as

$$\langle a^i * s^k \rangle = \sum_{j=1}^{N} a^i_j s^k_j \quad \text{and} \quad \left\| a^i \right\|^2 = \sum_{j=1}^{N} (a^i_j)^2 \qquad (3)$$

Initialization that has been used can be expressed as

$$s^{k+1} = s^k + \lambda_k \frac{t_i - \langle a^i * s^k \rangle}{\left\| a^i \right\|^2} a^i_j \qquad (4)$$

where e is the base of the natural logarithms, 1 is the vector with all ones, and λ_k are the relaxation parameters such that $\varepsilon_1 < \varepsilon \le \lambda_k \le 1$

$$S^0 = e^{-1} 1 \qquad (5)$$

each of the reconstruction methods (i.e. ART and MART), the slowness vectors obtained in a particular iteration step are compared to that obtained from the immediate previous iteration step. If the difference for every pixel is smaller than a prescribed small quantity, convergence is considered to have taken place.

3. Results and Discussion

As outlined in the previous section, computer code has been developed for generation of the projection matrix for a given rectangular domain and all possible ray paths in different views. It takes number of divisions required along x and y directions in the domain and number of views of the rays as input to generate the projection matrix. All possible rays are automatically considered for any particular view. Computer codes have also been developed for implementing ART and MART with relaxation parameters. The projection matrix, projection data (transit time in UCT) and necessary convergence parameter are taken as inputs. The transit times, that have been considered here, are obtained experimentally and these transit times closely conform to the shear wave speeds of Steel and Resin for inclined ray paths. The schematic diagram of the domain with insert and typical ray paths in 4-views are shown in Fig. 4.

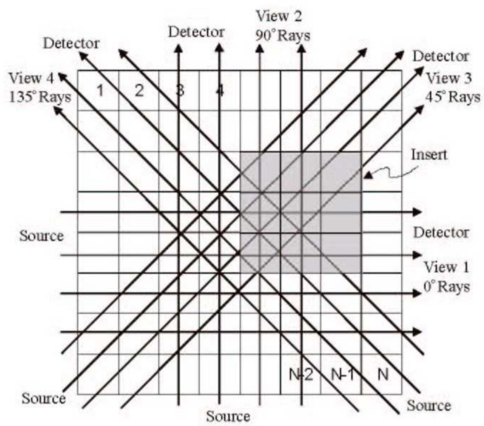

Fig. 4: Discretized domain with ray-paths for different views

Typical signals that have been used for the measurement of the time-of-flight (TOF) are shown in the following figures. A sample signals pertaining to the normal beam measurement (for 00 view) have been shown in Fig. 5 and that of angle beam measurement (for 450 view) have been shown in Fig. 6. In each view two signals, one that travels through the Steel only and another that travels through the Steel as well as Resin insert, have been shown.

Before going for the actual reconstructions, the codes are validated for a small domain containing 5 by 5 pixel grid in which the reconstructed results are checked with manual calculations.

3.1. Reconstruction Results

In Figs. 7a and 7b the image for a 2-view reconstruction by ART with relaxation parameter 1 and 0.5 are shown. A cross like appearance, extended from the insert, is seen in the image. This is due to the less number of ray-paths (hence less number of equations) available in the reconstruction. The 2-view reconstruction images by MART are shown in Figs. 8a and 8b respectively. The images, obtained through MART, are slightly better but a cross type pattern is still visible.

Reconstructions using ART and MART are conducted from 4-view projection data with different relaxation parameters. Two representative images each for ART and MART are shown in Figs. 9a, 9b and in Figs. 10a, 10b respectively.

For a quantitative comparison among the images an error estimate, based on L1 error, is done. The L1 error represents the measure of deviation of the reconstructed image from the ideal image and is computed as

$$E_{L1} = \frac{1}{N}\sum_{i=1}^{N}\left|(s_r)_i - (s_a)_i\right| \tag{6}$$

where $(s_r)_i$ and $(s_a)_i$ are the reconstructed and actual slowness values respectively of the ith pixel in the N pixel domain.

From the above images it is clear the image quality is distinctly better in the 4-view case than the 2-view case for both the algorithms. This is expected as in the 4-view case more number of equations is available during reconstruction. A closer look of the images shown in Figs. 7a through 10b reveal that image produced by MART are superior to that obtained by ART. The cross type patterns are faintly visible in the ART images. Moreover, less number of iterations is required in case of MART to achieve convergence. A detailed comparison of the two methods in terms of accuracy and iteration numbers for different relaxation parameters is listed in Table 1.

4. Conclusions

A comparative study regarding the performance behaviors of ART and MART was conducted for a compound domain. It is observed that MART results are more encouraging than ART, as they

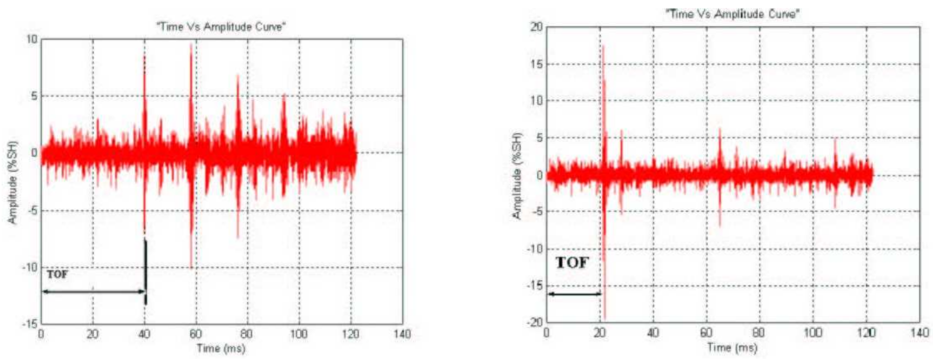

Fig. 5: (a) Signal used for the TOFmeasurement for zero degree view (10thray passing through the steel as well asresin insert) (b) Signal used for the TOFmeasurement for zero degree view (7thray passing through the steel only)

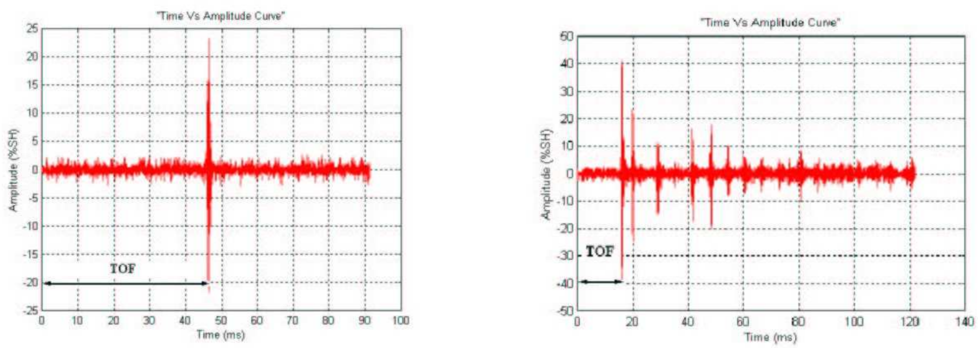

Fig. 6: (a) Signal used for the TOFmeasurement for forty five degree view(19th ray passing through the steel aswell as resin insert) (b) Signal used for the TOFmeasurement for forty five degree view(31st ray passing through the steel only)

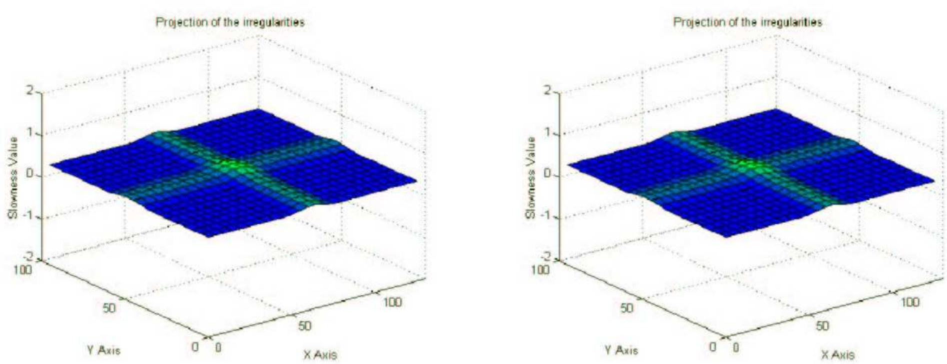

Fig. 7: (a) 2-View Image by ART, ë=1.0 (b) 2-View Image by ART, λ=0.5

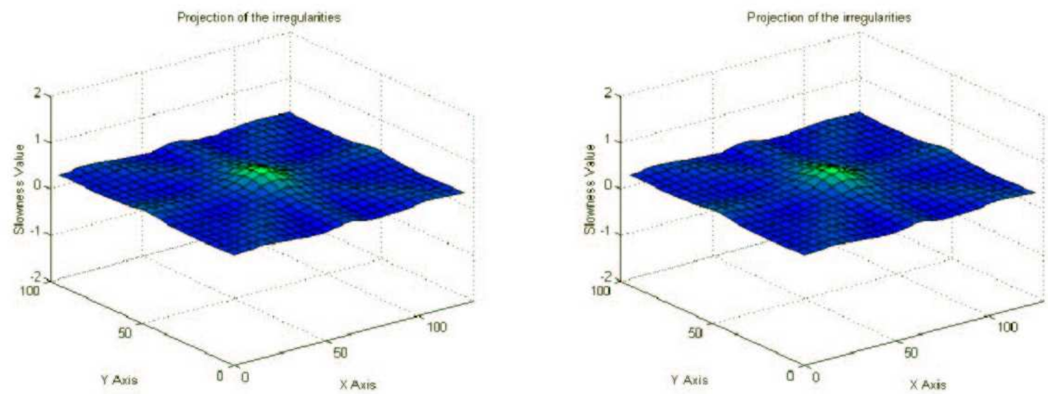

Fig. 8: (a) 2-View Image by MART, λ =0.1 (b) 2-View Image by MART, λ =0.05

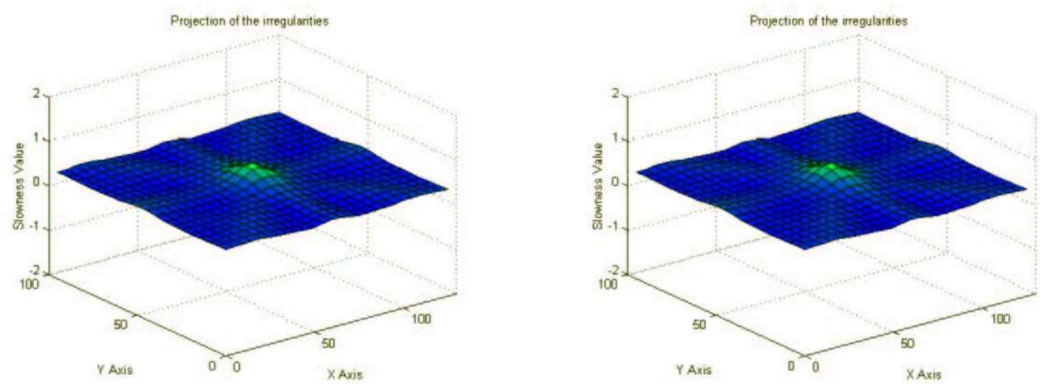

Fig. 9: (a) 4-View Image by ART, λ =1.0 (b) 4-View Image by ART, λ =0.5

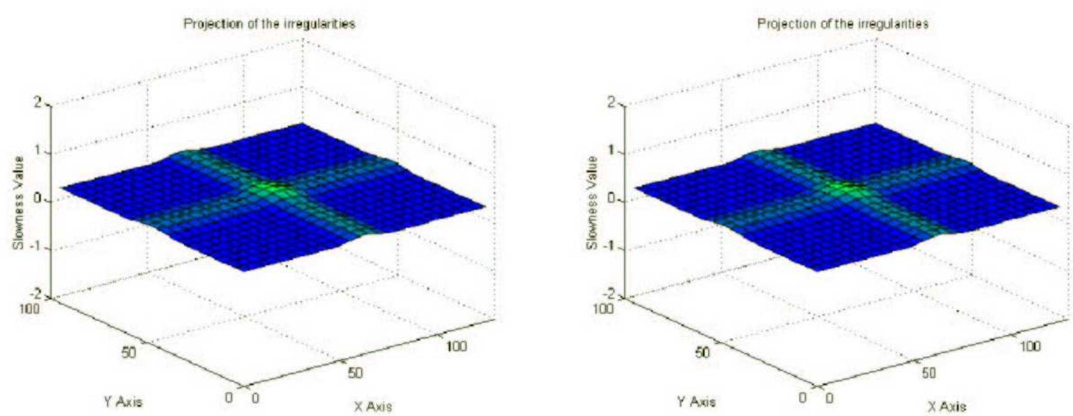

Fig. 10: (a) 4-View Image by MART, λ =0.1 (b) 4-View Image by MART, λ =0.05

Table 1

Algorithm	View	Relaxation Parameter	Iteration Count	L1-Error
ART	2-View	0.5	21	0.043033
		1.0	27	0.043033
		1.5	33	0.043033
	4-View	0.5	287	0.040796
		0.75	382	0.040796
		1.0	716	0.040796
		1.25	403	0.040796
		1.5	315	0.040796
MART	2-View	0.05	22	0.040282
		0.075	14	0.040282
		0.1	6	0.040282
		0.125	8	0.040282
		0.15	10	0.040282
	4-View	0.05	41	0.037933
		0.075	32	0.037933
		0.1	20	0.037933
		0.125	23	0.037933
		0.15	27	0.037933

rapidly converge in case of projection data with more number of views. A relaxation parameter of 0.5 is found to be suitable for ART in the present case. Similarly relaxation parameter of 0.1 is found to be suitable for MART as it helped to achieve convergence at a faster rate.

5. References

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