Quantitative Non-destructive Evaluation of CFRP Components by Sampling Phased Array

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Abstract.
Continuous improvements in microelectronics performance and signal processing techniques have positively impacted development in NDE techniques specifically also with regard to aeronautical applications.
Composite materials such as carbon fibre based (CFRP) have gained increasing application in aerospace over the past years and decades. Their primary advantage is their strength-to-weight ratio. It is of parallel importance to ensure the quality of structures made from CFRP in production as well as in service. Ultrasonic non-destructive testing of CFRP is not always easy due to the anisotropic properties it exhibits. This can result in faulty defect sizing and image artefacts while ultrasonic testing. This paper intends to describe and discuss some of the applications and results using the Sampling Phased Array (SPA) technique with Reverse Phase Matching for the purpose of inspecting CFRP components without compromising the testing speed in real time quantitative imaging. The Principle of SPA is briefly described followed by a comparison of results with the state-of-the-art techniques, e.g. Phased array method. CFRP samples with built-in defects have been used for measurements and the results prove the potential advantages of the SPA technique with Reverse Phase Matching.

Keywords: Carbon fiber Reinforced Plastic (CFRP), Ultrasonic Phased Array, Sampling Phased Array (SPA), Synthetic Aperture focussing Technique (SAFT), Reverse Phase Matching, Anisotropy.

Introduction

Mechanical characteristics of the carbon fibre reinforced plastics (CFRP) are one of the reasons why they are extensively used in many applications. The non-destructive testing (NDT) plays major role in quality assurance of the manufactured carbon-composites. Naturally, the produced composites are susceptible for defects like delaminations, debonds, porosity, fiber breakage, etc. The importance of NDT techniques is not only to find out the defects, which are in the structures but also to characterize them arguably. Among the NDT techniques, ultrasonic testing is most widely used technique for carbon-composites.

The result of beam skewing effects due to anisotropy causes several problems like inaccurate sizing and faulty location of the defects with respect to quantitative non-destructive evaluation [1]. The complexity of ultrasonic inspection not only arises from the nature of anisotropy but there are other problems due to complex geometries. Typically components in the aerospace industry contain corners such as spars, stringers, and top-hat structures. Traditional ultrasonic inspections are performed manually with conventional ultrasonic probe which is of more operator dependant and tedious.

The ominous growth in the microelectronics and computer components leads to the discovery of phased array ultrasonic system. A phased array system is a multi-channel ultrasonic system, which uses the principle of time-delayed triggering of the transmitting transducer elements, combined with a time corrected receiving of the detected signals. The promising aspect of phased array is its ability to generate the ultrasonic beam where parameters such as angle of incidence and focal distance are controlled electronically. So, one can generate the ultrasonic beam that can be focussed or steered across the material to be inspected. The other important aspects are its ability to visualize the beam steering through the use of angular beam scan (so called Sector-scan) images. However, the inspection speed remains no change when compared to traditional ultrasonic testing. Moreover, there is no possibility to take into consideration of material's anisotropy during the examination.

Some major inspection requirements for the purpose of ultrasonic NDT of aerospace components include real-time imaging, reasonable defect sizing, ability to inspect complex shapes, inspection of multi-layered composite structures and last but not least, faster and reliable inspection and interpretation.

The Sampling Phased Array (SPA) developed in Fraunhofer IZFP is an advanced signal processing and image reconstruction technique [2] which has unique features for the purpose of high-speed, real-time quantitative imaging of anisotropic materials.

This paper demonstrates the principle of sampling phased array (SPA) and its application to the carbon fiber composites. The artificial defects with various sizes are embedded into the CFRP plates at different depths. Then, SPA with Reverse Phase Matching principle is explained. This paper also gives short description of SPA examination of multi-layered laminates using simulation tools which are part of our future work that is under progress.

1. Sampling Phased Array

1.1 Principle of Sampling Phased Array (SPA)

The difference between the conventional phased array and the Sampling Phased Array (SPA) is their data acquisition and data processing procedures. The data acquisition of SPA is explained in the figure 1.1a, where the receiving ultrasonic signal from one single shot of the transducer element is received by all the other elements. The information from this single shot is shown in fig 1.1b as a matrix. Here each cell represents data (A scan) of a particular sender- receiver combination. Thus, when all the elements are fired and received, a full matrix is obtained. In traditional phased array this information is lost due to the phase summation which is a remarkable difference between SPA and traditional phased array.

In one transmission cycle (fig 1.1c), all the information about the inspection volume is obtained. When this process is repeated for all the elements and the data is summed then high signal to noise ratio is obtained due to the constructive interference of the signals. From the obtained information-matrix, it is possible to reconstruct the image for any arbitrary angles.

Secondly, the image reconstruction is performed through Synthetic Aperture Focussing Technique (SAFT) in real time [3]. The diverged sound beam due to the smaller aperture gives an option to overlap many such received signals from the inspection volume which is divided into pixels (fig 1.1d). For every pixel point, travel time is calculated to and back from the position of the transducer elements and stored as external file (Look-Up Table). This process is done well before the start of the inspection. So, during the inspection, the amplitude values from the obtained A-scans are summed up for the corresponding time values for all the pixel points in the inspection volume, which results in significant increase in sensitivity and resolution in the near field of the transducer. Thus, it is possible to focus virtually at all the points in the inspection through the application of SAFT.

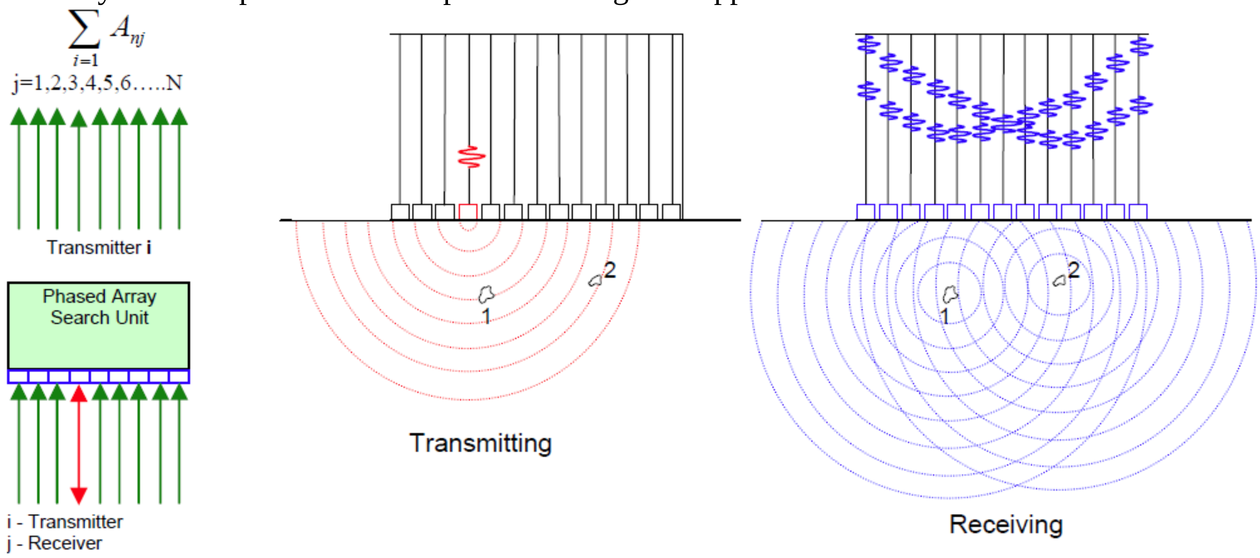


Figure 1.1a Data acquisition of SPA

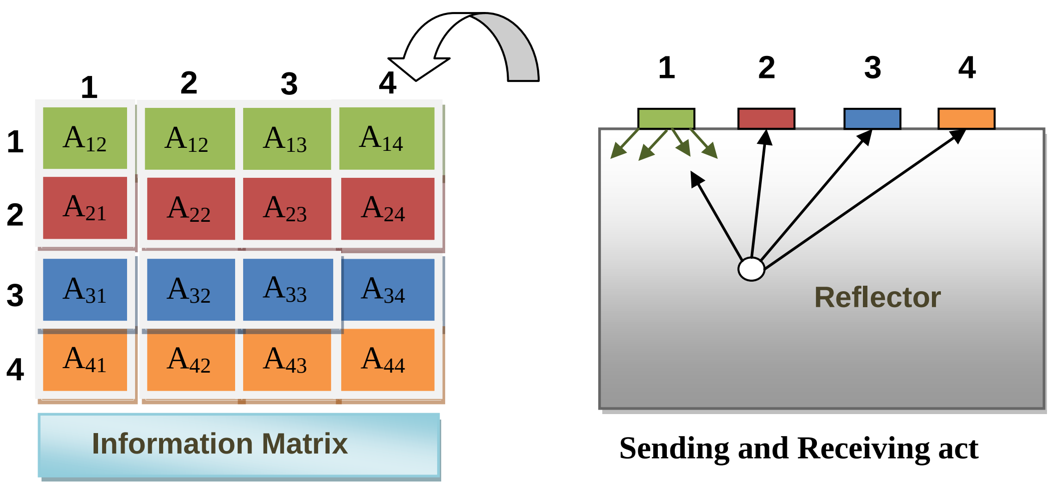


Figure 1.1b Information Matrix, 1.1c one shot of SPA

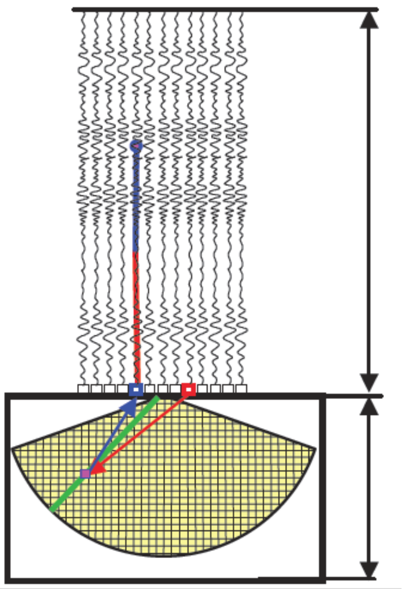


Fig 1.1d SPA Sector scan -Image reconstruction

The foremost highlight of the SPA when compared to traditional phased array is its inspection cycle speed. Suppose, when conventional phased array requires ‘N’ beam angles to cover the inspection volume which means, it has to complete N shots. Whereas, the same can be achieved in one single shot for SPA thereby accounting to the time saving by a factor of N. Other advantages like ability to adapt for the given material conditions i.e., inspection of anisotropic materials through *Reverse Phase Matching* will be discussed in the subsequent texts.

1.2 Reverse Phase Matching

In general, the phased array system offers advantages when compared to traditional ultrasonic NDT but when it comes to the inspection of carbon fiber composites, this system fails to take into account of the exact property of the material that is being inspected. Each composite material can be characterized by its elastic constants. For example, uni-directional carbon fiber can be characterized by means of five independent elastic constants, which falls under the transverse-isotropic class.

It is clear from the mechanics of anisotropic wave propagation that properties of the medium depends on direction of wave propagation and the wave fronts are no more spherical as velocity changes with the direction. It means velocity at one particular angle is different from any arbitrary angles. By principle, SPA gives option to correct the material property through its phase controlled overlapping of signal amplitude values. This forms the basis of Reverse Phase Matching method.

The principle is outlined in the fig 1.2a where the velocity distribution can be obtained through stiffness matrix and this distribution is unique for one particular composite. So, if we know the elastic constants of a medium, then it is possible from the imaging perspective that the pixel to the element transit time can be obtained by ray tracing algorithm. Initially, Sector scan (2D) reconstruction is obtained then, 3D image is obtained when all the sector scans are over lapped when the transducer is scanned all over the surface which gives way for 3D- real time imaging [4].

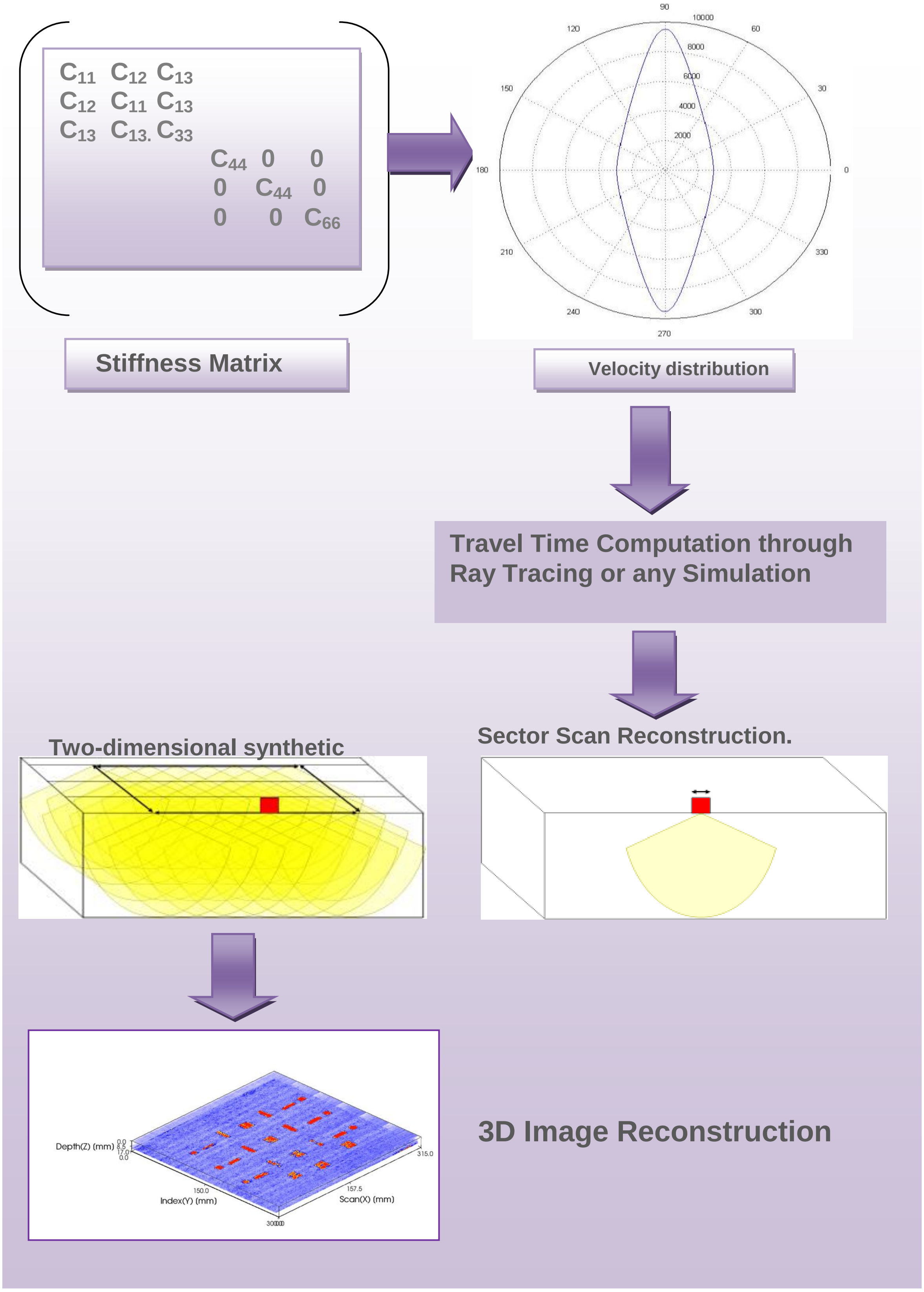


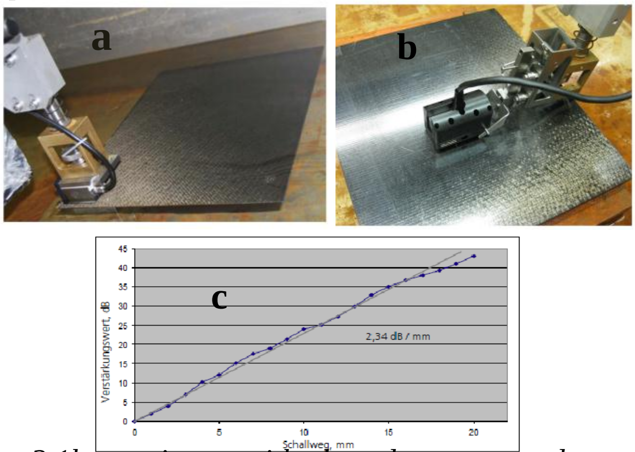
Fig 1.2 SPA with Reverse Phase Matching

When the properties of the particular composite material are known in advance, the velocity distribution is computed and the corresponding transit-time is stored as external file, which is used during real-time image reconstruction. This principle is called as *Reverse Phase Matching*. This particular feature is also helpful for inspecting composite materials and austenitic stainless steel welds [5].

2. Experiment setup

2.1 General Procedure

- 5 MHz - 64 element phased array transducer is used.
- Time gain compensation is obtained as shown in fig 2.1d.
- By means of pulse echo contact testing, measurement is conducted on an ultrasonic measuring station that consists of immersion tank, three-axis manipulator and 64-channel phased array system capable of multi-channel inspection in both conventional phased array and sampling phased array modes with either immersion or contact techniques [6].



2.1(a) - **Size**: 359 x 307 mm
Thickness: 14 mm

2.1(b) Step wedge specimen (4 steps)
Size: 294 x 363 mm.
Thicknesses: 8.6, 6.5, 4.3 and 2.3 mm

2.1(c) Time Gain Compensation Curve

Fig 2.1a, 2.1b, specimens with phased array transducer, 2.1c.TGC

3. Results and Investigation

Fig 3.1 and 3.2 represent the results of SPA with reverse phase matching.
C-scan images with gating and fast 3D scan images are obtained as shown in the figures. The fig 3.1 is the result of 14 mm thick CFRP specimen shown in fig 2.1 (a). It shows 24 rectangular shaped artificial defects with different sizes located at various depths as mentioned in the figure 3.2d (3D image). The defects are located at three different depths (0.6mm, 7.2mm, 13.7mm). Since the SPA always operates in transmitter-receiver mode, It is possible to detect defects which are very close to the surface i.e., it can overcome problems due to the dead zone effect. In near field, SPA can focus all the point whereas CPA can focus only at one depth.
Fig 3.2 is the result shows 31 rectangular shaped artificial defects with two different sizes located at seven different depths (1, 2, 3, 4, 5, 6, 7 mm from the surface). The elastic constants are required for the specimen in order to do Reverse Phase Matching. In our case we assumed the elastic constants. One can also measure the elastic constants of the CFRP

materials if it is not available from the manufacturer [7]. The group velocity is computed for a given elastic constants and corresponding travel time is calculated using well known ray tracing algorithm.

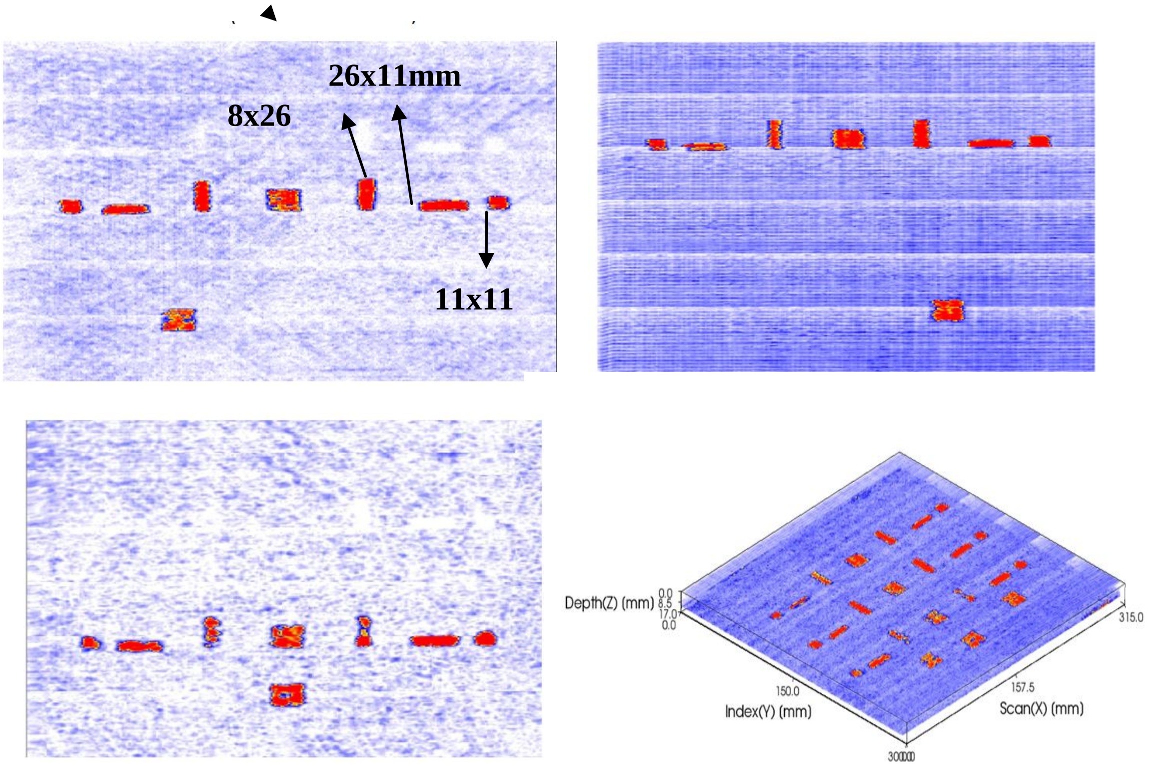


Fig 3.1a, 3.1b, 3.1c C-scan images gated at different depths Fig 3.1d fast 3D image

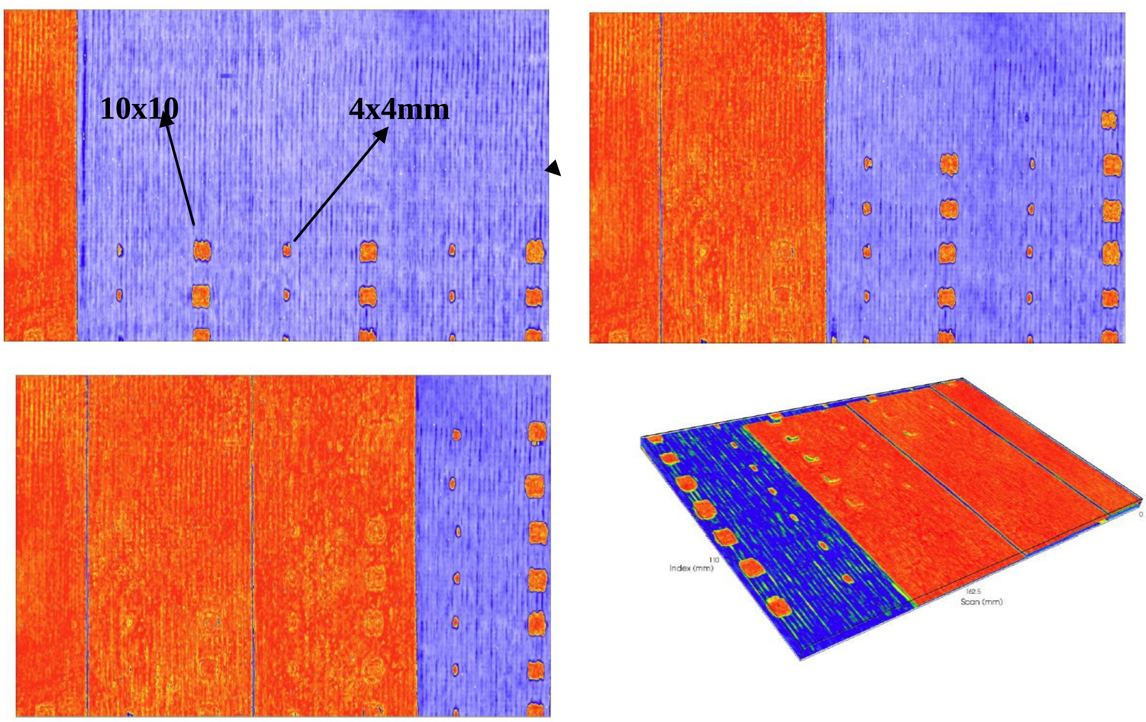


Fig 3.2a, 3.2b, 3.2c C-scan images gated at different depths Fig 3.2d fast 3D image

4. SPA of multi-layered composites

The challenge of any ultrasonic NDE of carbon fibre composites lies in the inspection of multi-layered medium as the reflection and transmission phenomena at the interface is complicated and cannot be defined by simple Snell's law that is meant for isotropic-layered medium. The anisotropy in solid materials has tendency to change the direction of the wave energy vector along the preferred orientation. Several studies have been made to understand the wave propagation in multi-layered composites. Transfer matrix method [8] proposed by A.H. Nayfeeh (1995) is useful for obtaining reflected and transmission coefficients of multi-layered medium. This technique has limitations while using for thick multi layered structures with intricate orientations. Delta operator technique has been suggested as a remedy. There is a Numerical truncation algorithm, which is a replacement for delta operator technique to avoid numerical instabilities due to the thick multi-layered structures with complicated orientations. The comparative study of these techniques can be obtained from Krishnan Balasubramaniam et.al [9].

Various simulation tools like Civa [10], RAYTRAIM ray-tracing tools [11] etc., have been developed in the recent past to study and simulate the wave propagation in multi-layered media. Pencil model which is proposed by Civa is very useful for studying such mediums. The detailed study of multi-layered medium using pencil model was done by Deydier et al [12]. This model makes use of Ray Based Homogenization (RBH) approach where it calculates the average energy path of the layered medium, which results in effective stiffness tensor [10]. The RBH method has greater sensitivity when compared to similar approach by Postma [13].

A Modular Multi-Gaussian beam model is suggested by W.Schmerr et al is used to simulate ultrasonic beam field for multiple interfaces through superimposing 10 single Gaussian beams. The amplitude and phase of a propagating Gaussian beam in the medium can be completely described by solving the paraxial wave equation [14, 15]

Tang Wei proposed traveltime computation using ray tracing for multi-layered transversely isotropic medium with vertical symmetry axis [16] where the exact expression for phase velocity, group velocity and Snell's law for multi-layered medium is derived.

The exact formula for calculating transmitted group angle using slowness surface is given by Slawinski [17] where he uses ray tracing algorithm to compute travel time for a weak transversely-isotropic media for the purpose of determining the simulated arrival time.After the detailed study of the literatures, a new hybrid model is developed for the purpose of SPA examination of multi-layered composites which comprises of both travel time computations and amplitude estimations. The travel time can be computed by ray tracing approach as proposed by Slawinski [17, 18, 19] while amplitude of the phased array beam field is computed through Multi Gaussian Beam model as proposed by Schmerr et al [8]. The simulated beam field will be mapped on the obtained experimental data and subsequently corrected during the image reconstruction. This technique can be implemented in real-time testing after validation. In order to validate this technique, the test samples with multiple layers with different fibre orientations are proposed. A mock-up model using this approach has been successfully implemented and validation with actual sample is the work under progress.

The correct reconstruction of image with SPA is only possible when elastic constants are known for a particular composite material. Fraunhofer IZFP has developed the Gradient Elastic Constants Descent Method (GECDM) for the purpose of inspecting inhomogeneous anisotropic materials with unknown elastic constants. This method is developed for inspecting austenitic weld materials whose elastic constants are usually not known prior to the inspection. This technique is based on iterative adjustment of material properties based upon the result of the known reflector position. More details can be obtained from Pudovikov et al [20]. This technique can also be used to characterize CFRP materials whose elastic constants are unknown.

5. Conclusion

Sampling Phased Array (SPA) principle with Reverse Phase Matching is described with the application to two composite specimens having various embedded defects with different shapes and sizes. The results of real time C scan and 3D images show why SPA always play an important role in quality assurance of carbon composites in aerospace industries. SPA with reverse phase matching enables unique features like faster inspection, higher spatial resolution, greater sensitivity and inspection of anisotropic materials in real-time. SPA of multi-layered composites also briefly explained which our work under progress.

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