Application of Sampling Phased Array Technique for Ultrasonic Inspection of CFRP Components

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Abstract. The article presents latest results on ultrasonic inspection of carbon-fiber structures by the Sampling Phased Array method. A comparative study of inspection results obtained by common single element transducer and classical Phased Array methods is done. The advantages and potential of Sampling Phased Array technique for practical use are also discussed.

Introduction

Quality of complex CFRP (CFK) structures is subjected to very high requirements. Only the material defects in strictly defined tolerable ranges are allowed in the completed CFK-units. Thus NDT methods have to be applied to assure the quality of components within given preferred tolerances. The most applied NDT technique is ultrasonic testing which is an economic and effective testing modality for characterizing material defects.

A cost effective inspection of complex CFK-structures is a challenging task. In contrast to material testing in other branches (e.g. steel production) aerospace has innovative techniques and solutions due to rapid development of manufacturing technologies. Thus, the advanced techniques like Phased Arrays are finding increasing applications in the inspection of aircraft components.

The Sampling Phased Array Technology is the latest advancement in the phased array technology, which allows improved defect finding and characterisation of material for fast and the cost-effective quantitative automatic inspection for all applications. The current article presents the latest results of Sampling Phased Array testing of CFK-components.

1. Task definition and solution approaches

1.1 Ultrasonic testing of CFK-components. Characteristic material defects

The ultrasonic testing of CFK-components has a number of distinct challenges when compared with other applications. Practical use of ultrasonic testing is strongly correlated with the defects prevalent for this type of material. The most important of them are as follows:

- **Delaminations**
  Delaminations refer to two types - interlaminar (matrix failure) and intralaminar (matrix/fiber failures.
- **Porosity**
  The ultrasonic testing of porosity is normally based on measurement of back wall echo amplitude. For the inspection of porosity, a stable back wall echo signal with sufficient signal to noise ratio has to be ensured.
- **Plastic or paper films**
  Detection of films can be carried out by measurement of back wall echo attenuation and by measurement of intermediate echoes in the pulse-echo mode.

Normal probes are often used for ultrasonic testing of CFK-components since the components usually have very small wall thicknesses and due to in-plane orientation of material defects. For complex shapes, e.g. testing of curved profiles or radii testing, phased array transducers can be applied.

1.2 Sampling Phased Array Technique

The Phased Array technology provides test data via an array of individual transducers, which transmit and receive in a phase-controlled fashion. The phase control is via the electronics and / or software [1]. The implementation of Phased Array systems for material testing and evaluation utilizes only a small portion of the overall data acquisition capability, since the acoustic transmissions for specific angle of incidence are time-phased and the received signals are then summarized. This means that the entire array acts as a single transducer in accordance with the Sampling Theorem. However, if the time-domain signals from the individual transducer elements are acquired, the resulting data can then be summarized with arbitrary phase information to permit data processing of all physically possible angles of incidence and focus points from a single data set. This concept is referred to by Fraunhofer-IZFP as the “Sampling Phased Array” system [2, 3].

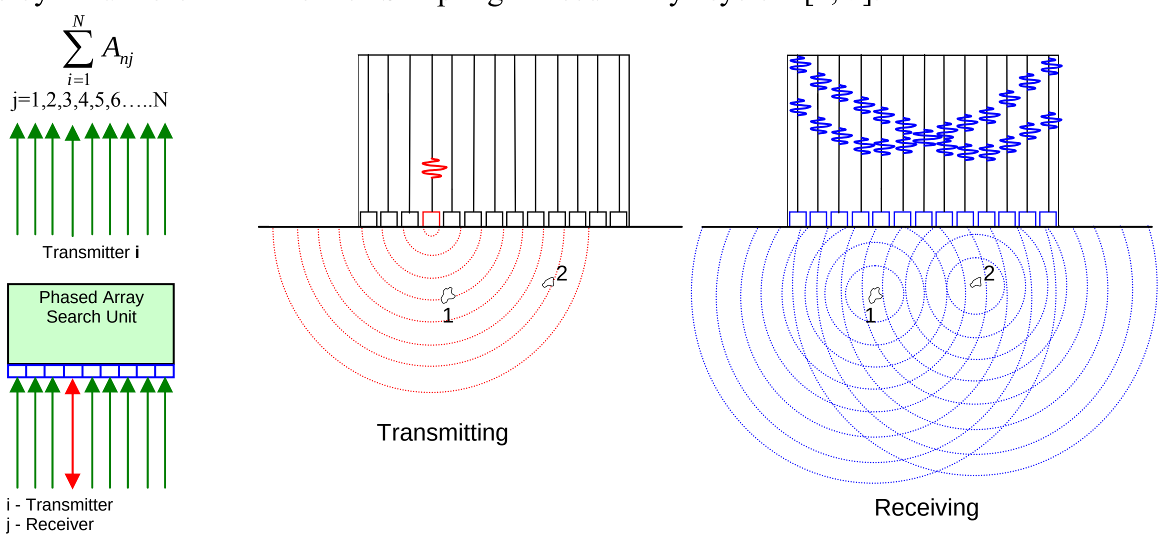


Figure 1: Data acquisition and Processing for Sampling Phased Array

The measurement of signals in a time domain $A_{ij}(t)$ with $i = j$ (i: transmitter element number, j: receiver element number) is the essence of the Synthetic Aperture Focus Technique (SAFT) where one Phased Array element is virtually steered over the aperture of the array. The additional acquisition of the time domain signals A_{ij} with $i \neq j$ can be used as a data set for the solution of migration algorithms (e.g. Kirchoff Algorithm), for image reconstruction, as shown in Figures 1 and described in References [4] and [5]. This reconstruction principle is illustrated in Figure 2 below.

A significant benefit of this reconstruction technique, referred to by Fraunhofer-IZFP, as the “SynFoc” technique is that the small test sampling errors in the algorithm solution will not adversely affect the image reconstruction.

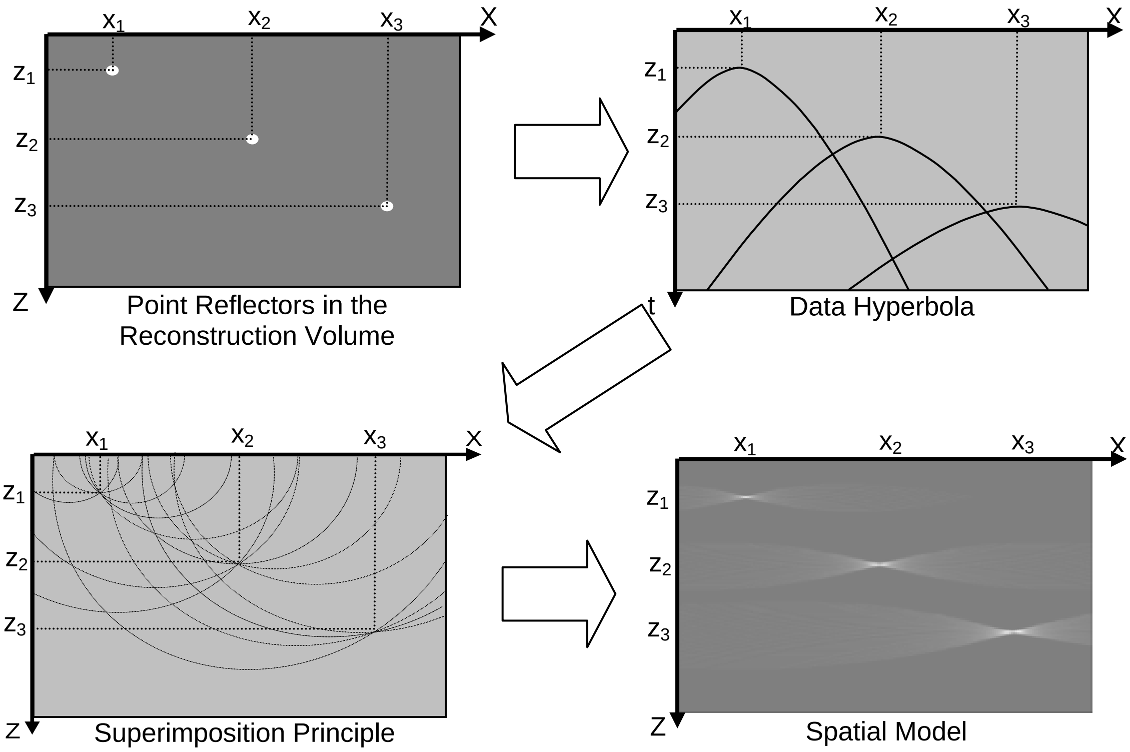


Figure 2: Image Reconstruction via Kirchoff Algorithm

1.3 Task definition

A set of test specimens with artificial and natural defects was investigated in this development project. The objective was to quickly evaluate the suitability of applicable ultrasonic techniques for detecting characteristic defects in CFK components in an automatic inspection environment. The immersion technique is preferred for automatic inspection.

The following are selected:

1. Traditional Pulse Echo testing with single element transducer.
2. Conventional phased array testing.
3. Sampling phased array.

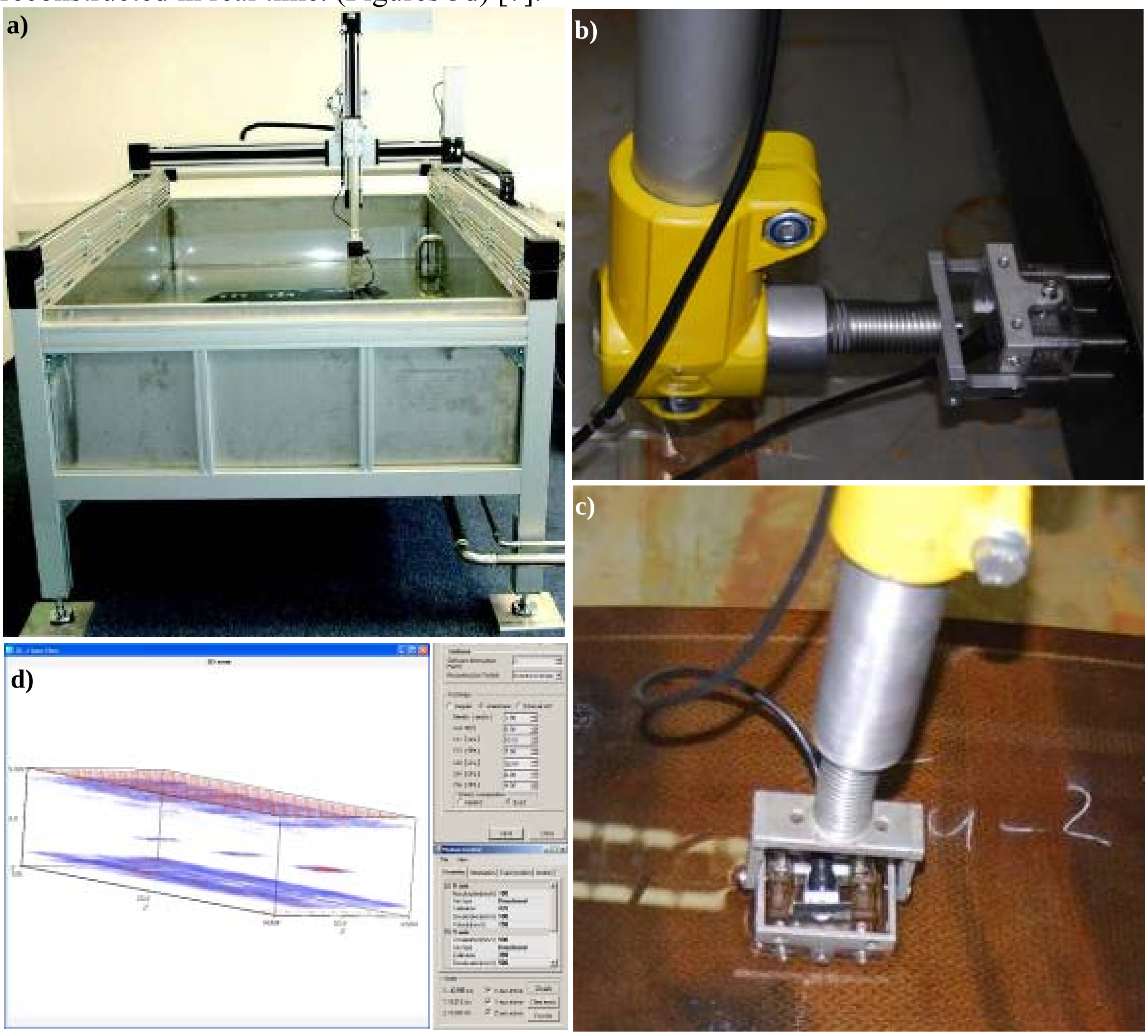
Results of these three techniques are compared and discussed in the present article.

2. Experimental set-up

Ultrasonic measurements were conducted on ultrasonic measuring station that consists of immersion tank, 3-axes manipulator (Figure 3a), and 64-channel phased array system capable of multichannel inspection as well as Conventional Phased Array and Sampling Phased Array inspection in contact or immersion technique [6].

Double-gimballed probe holders were designed for testing objects with slightly curved surfaces (Figures 3b and 3c).

In Sampling Phased Array mode 3D-images of inspected volume can be reconstructed in real time. (Figures 3d) [7].



a) Immersion tank with 3-axes manipulator
b) Double-gimballed probe holder for scanning on slightly curved vertical surfaces
c) Double-gimballed probe holder for scanning on slightly curved horizontal surfaces
d) Representation of inspection results in 3D-view

Figure 3: Ultrasonic measuring station

3. Investigation results

3.1 Test specimens

A variety of test specimens were investigated under the scope of the project. Due to confidentiality requirements, only a few results are presented in this paper.

A special step-wedge specimen is used for sensitivity calibration. This type of test specimen is commonly used for porosity testing. Besides this, the properties of the step wedge should be equivalent to the material properties of the CFK-structure.
Furthermore, the specimen has artificial defects (flat bottom holes) placed close to face and the back wall for every step. Figure 4 represents the photo of the step wedge.

Figure 4: Step wedge

In the current project, another test specimen with embedded film type defects (Figure 5) is used for measurement. Unlike delaminations, these defects are embedded into the structure and are difficult to detect due to poor reflectivity. The wall thickness measured is 4 mm.

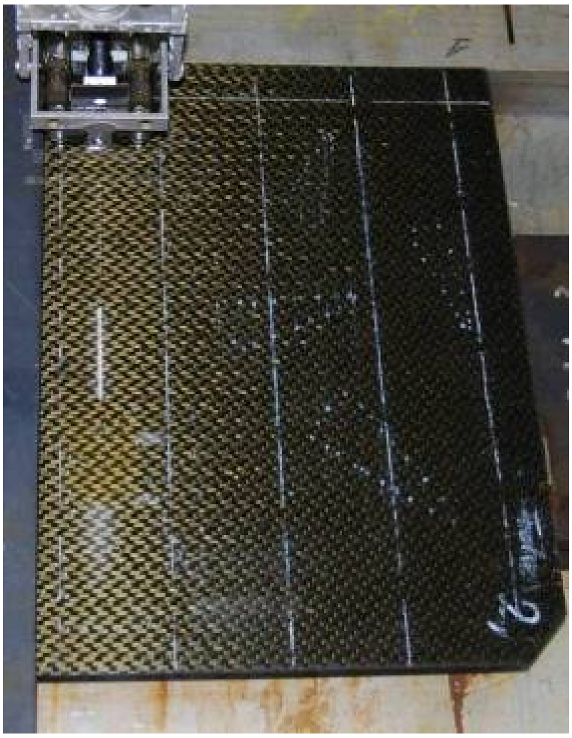


Figure 5: Test specimen with film-like defects

The third specimen that was tested (Fig.6) represents a CFK-component with a slightly curved surface.

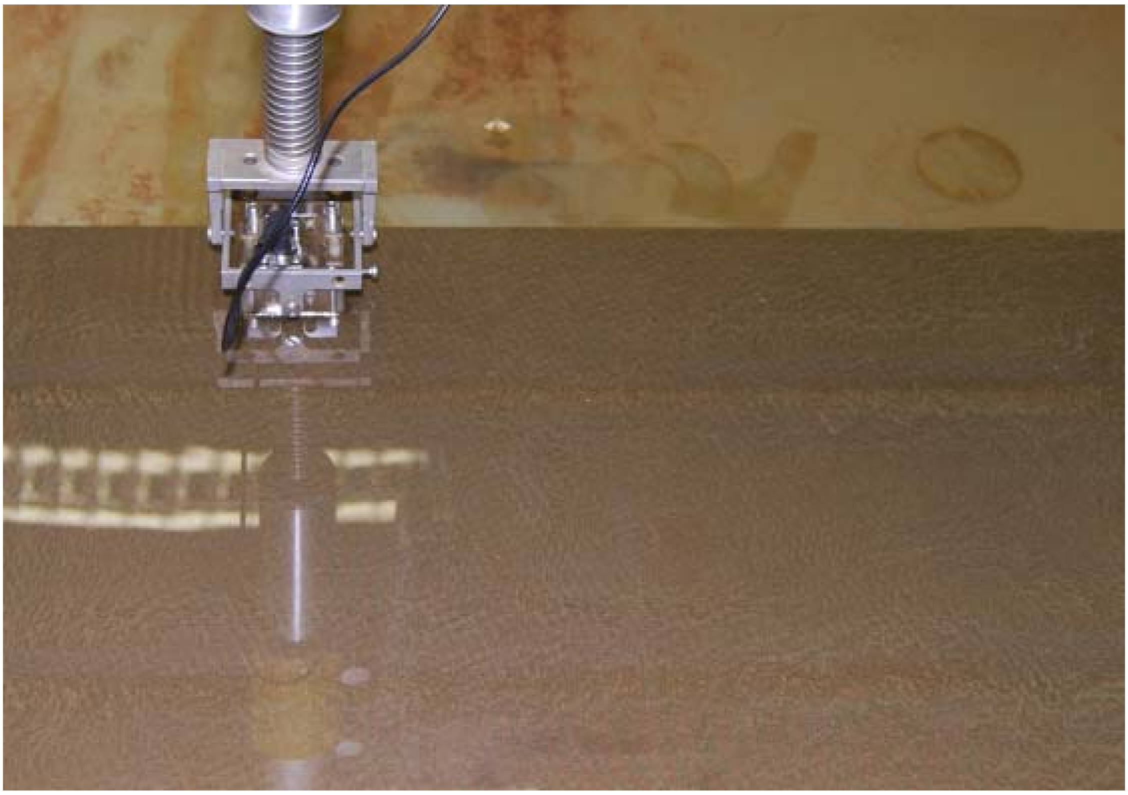


Figure 6: Real CFK component

3.1 Ultrasonic transducers

A single element transducer designed specially for testing of thin CFK-components is used as a "reference" for phased array inspection due to its excellent properties for detection and characterization of relevant material defects. This probe with the angle of incidence of 0˚ and a wedge of 17 mm is well suited to detect near surface delaminations. This is enabled by the design of wedge parameters and selection of appropriate crystal size.

However, a probe of this type cannot be used for automatic testing since mechanical contact is not feasible for components with complex geometries or limited accessibility.

Phased Array inspection in immersion technique was favoured as being more suitable for automatic inspection purposes. The Phased Array probes from Olympus 5L16 (pitch 0.6 mm, element length 12 mm) was applied with the water gap of 12 mm.

3.2 Results of ultrasonic testing

Step wedge described in chapter 3.1 is used for sensitivity calibration. TGC curves are measured for three modes, single element probe, conventional Phased Array mode and Sampling Phased Array mode. The results are shown in Figure 7. In the undisturbed area, all the steps deliver equal back wall echo height and thus represent the same colour in B-Scan images.

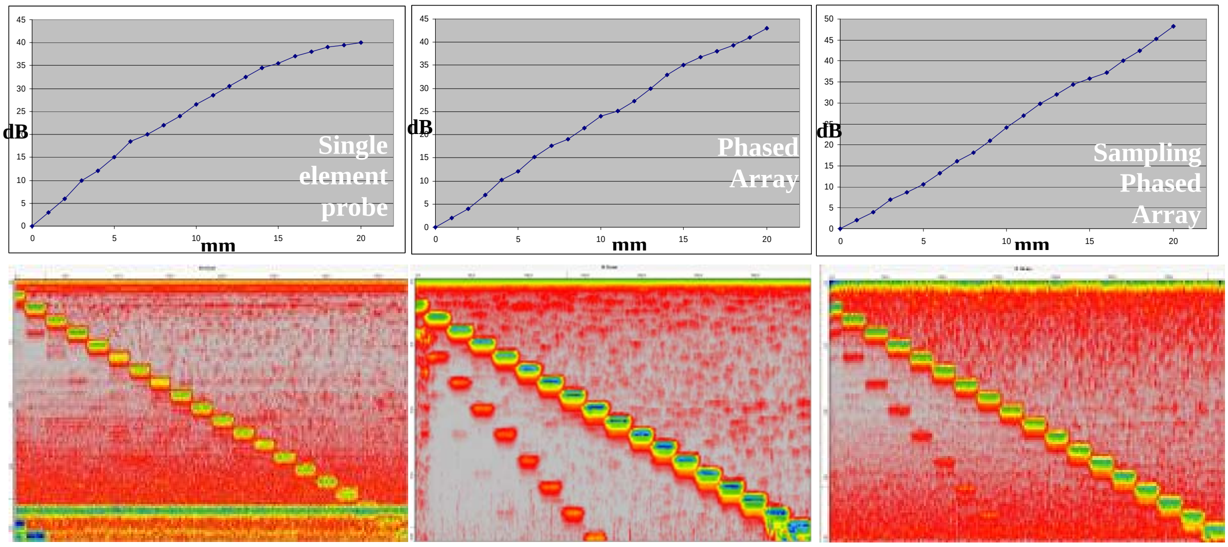


Figure 7: Sensitivity calibration on step wedge

3.2.1 Detection of delaminations

Step wedge represented in chapter 3.1 has artificial defects FBH ∅ 3 and 5 mm placed close (0.5 mm) to the front and back wall of the specimen.

Measurements with a single element probe from IntelligeNDT, made in contact technique provide excellent detection of reflectors up to the depth of 15 mm (Figure 8). With increasing depth the resolution decreases and detectability also becomes reduced.

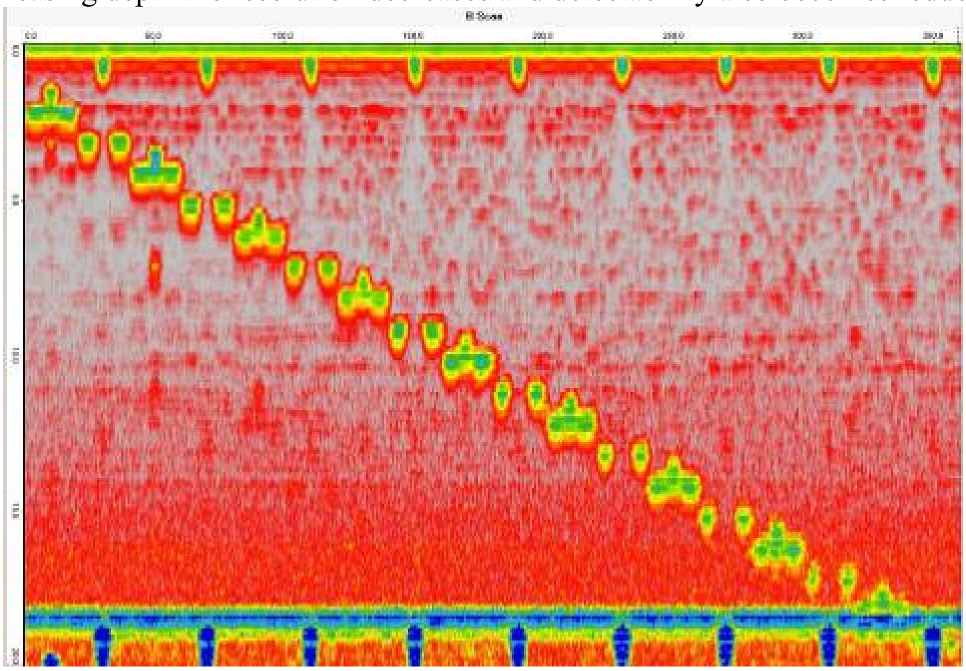


Figure 8: B-Scan of step wedge with artificial defects measured by single element probe

The results of Conventional Phased Array technique measured at the same area are represented in Figure 9. Due to rather low resolution and presence of surface echo the detectability of near surface delamination can be stated as being very poor.

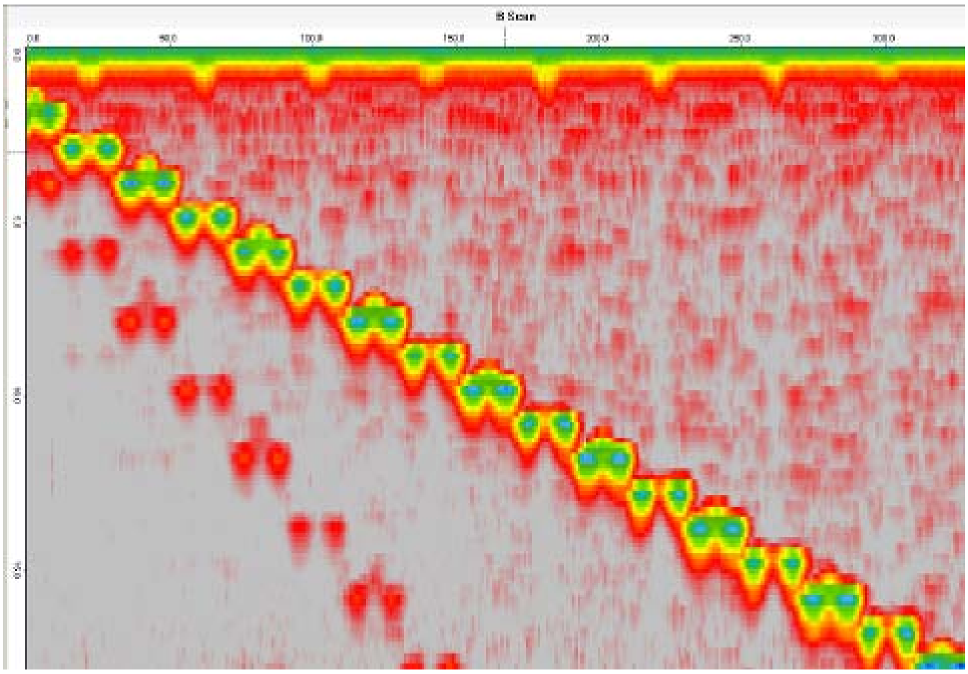


Figure 9: B-Scan of step wedge with artificial defects measured in conventional Phased Array mode

In the Sampling Phased Array mode B-Scan view obtained with measurements from the same transducer view allows detection of near to surface defects (Figure 10).

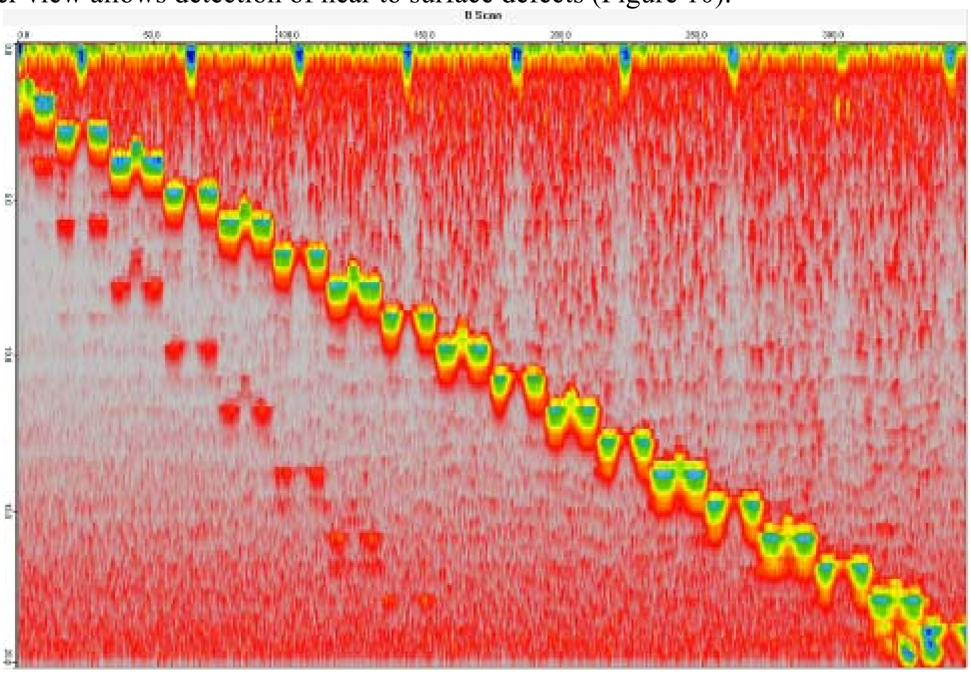


Figure 10: B-Scan of step wedge with artificial defects measured in Sampling Phased Array mode

4.2.2 Detection of film-like defects

Discontinuities of this type are usually caused by the so-called “human factor” which include incorrect operations or operator error.

These defects can be difficult to find since the acoustic impedance mismatch caused by melted film may not be significant. The film type and manufacturing process are critical factors that determine detectability. Nevertheless such inclusions can be critical and have to be detected.

The test specimens with different type of embedded films are manufactured to investigate their detectability by ultrasonic testing (Figure 11). The results achieved by ultrasonic testing are rather promising.

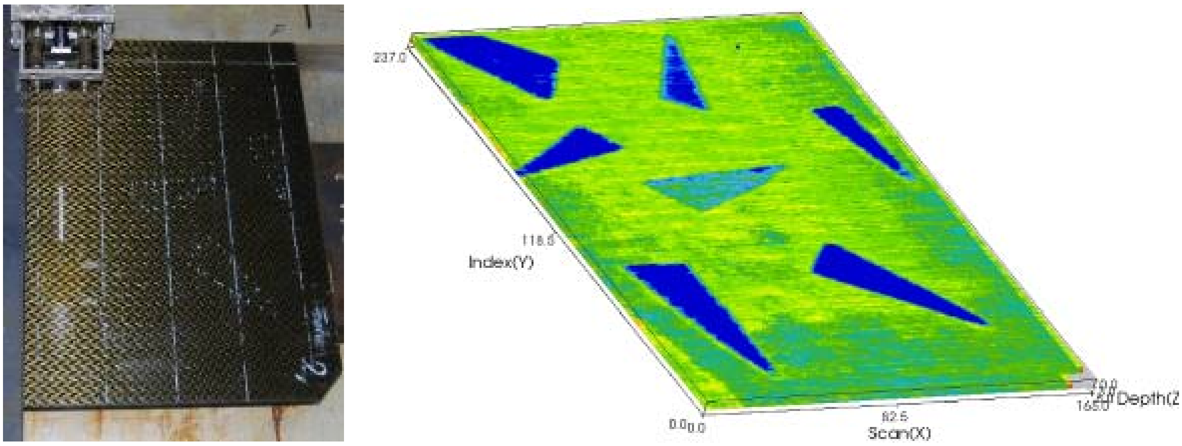
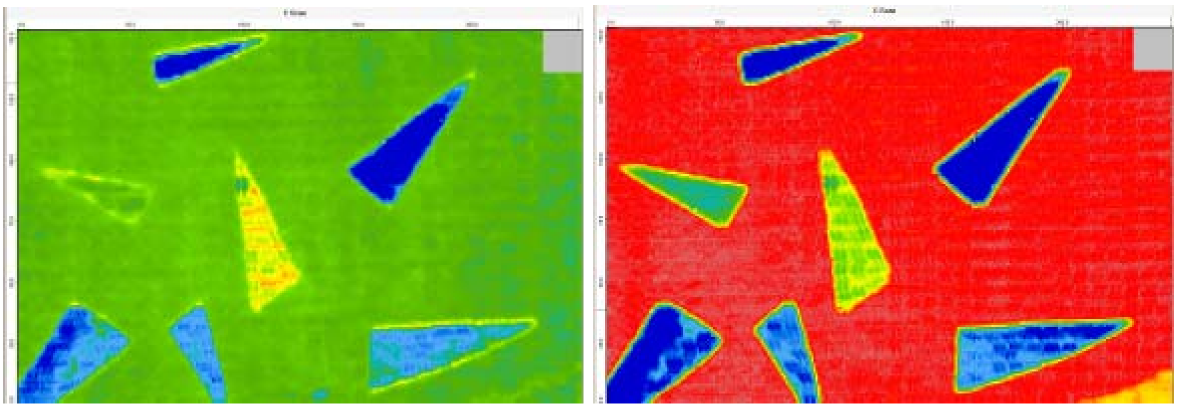


Figure 11: Test specimen with film-like defects and its 3D-image obtained by Sampling Phased Array technique

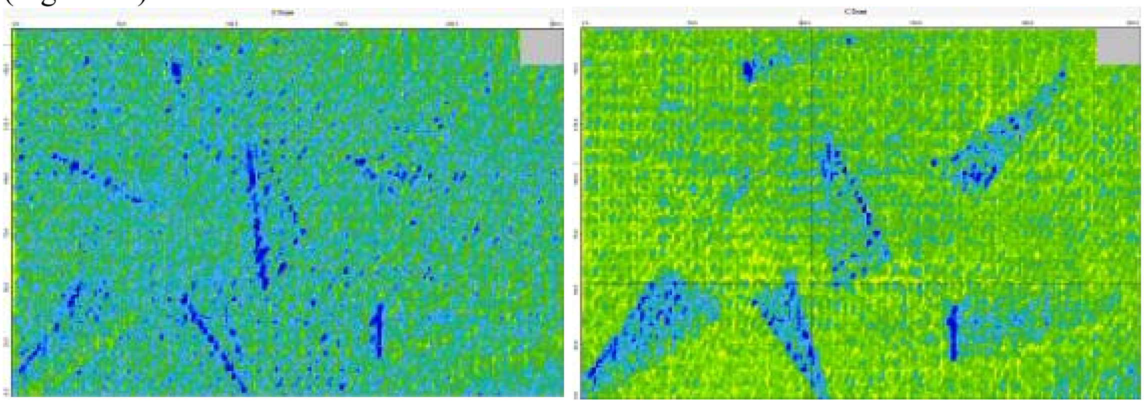
Figures 12 – 14 represent inspection results on the specimen by three techniques. Single element probe in contact technique could distinctly find all the artificial defects. As it can be seen in Figure 12 only monitoring of back wall echo is not sufficient for detection of film-like defects due to low contrast of indications. The gating out of the back wall echo signal in the C-Scan view increases image contrast and improves detection of film-like defects.



a) C-Scan with gated in backwall echo b) C-Scan with gated out backwall echo

Figure 12: Detection of film-like defects with single element transducer in contact technique

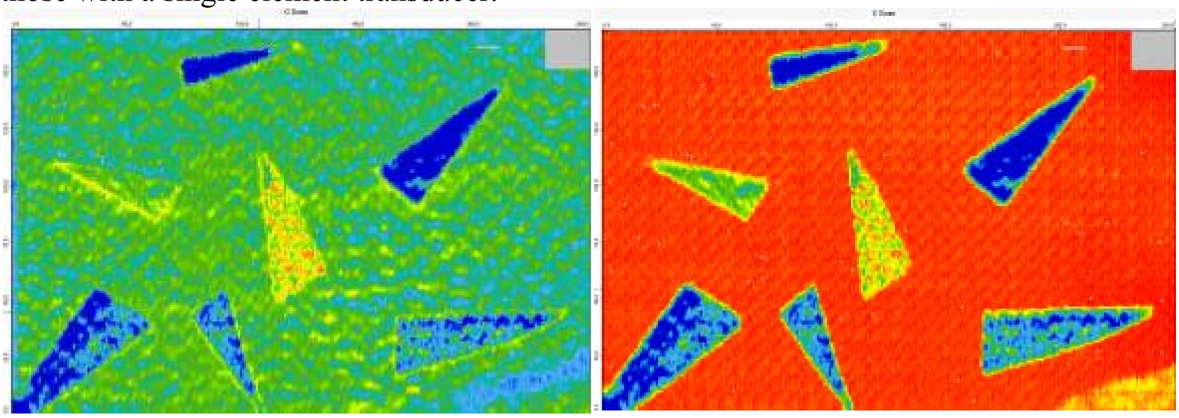
Inspection results using conventional Phased Array method in immersion technique provides reasonable detection of film-like defects. However, low sensitivity and resolution and poor signal to noise ratio cannot be overlooked in the C-Scan views (Figure 13).



a) C-Scan with gated in backwall echo b) C-Scan with gated out backwall echo

Figure 13: Detection of film-like defects with PA-transducer in conventional phased array mode in immersion technique

Unlike conventional Phased Array technique the Sampling Phased Array method in immersion offers high contrast of ultrasonic images (Figure 14). The results are as good as those with a single element transducer.



a) C-Scan with gated in backwall echo b) C-Scan with gated out backwall echo

Figure 14: Detection of film-like defects with PA-transducer in Sampling Phased Array mode in immersion technique

4.2.3 Porosity testing on an actual CFK- component

After sensitivity calibration for every method (see Figure 6), an actual CFK-component is inspected. The results are represented in Figures 15 – 17. For each method a C-Scan image over entire scanning area and a B-Scan image for one index position are represented.

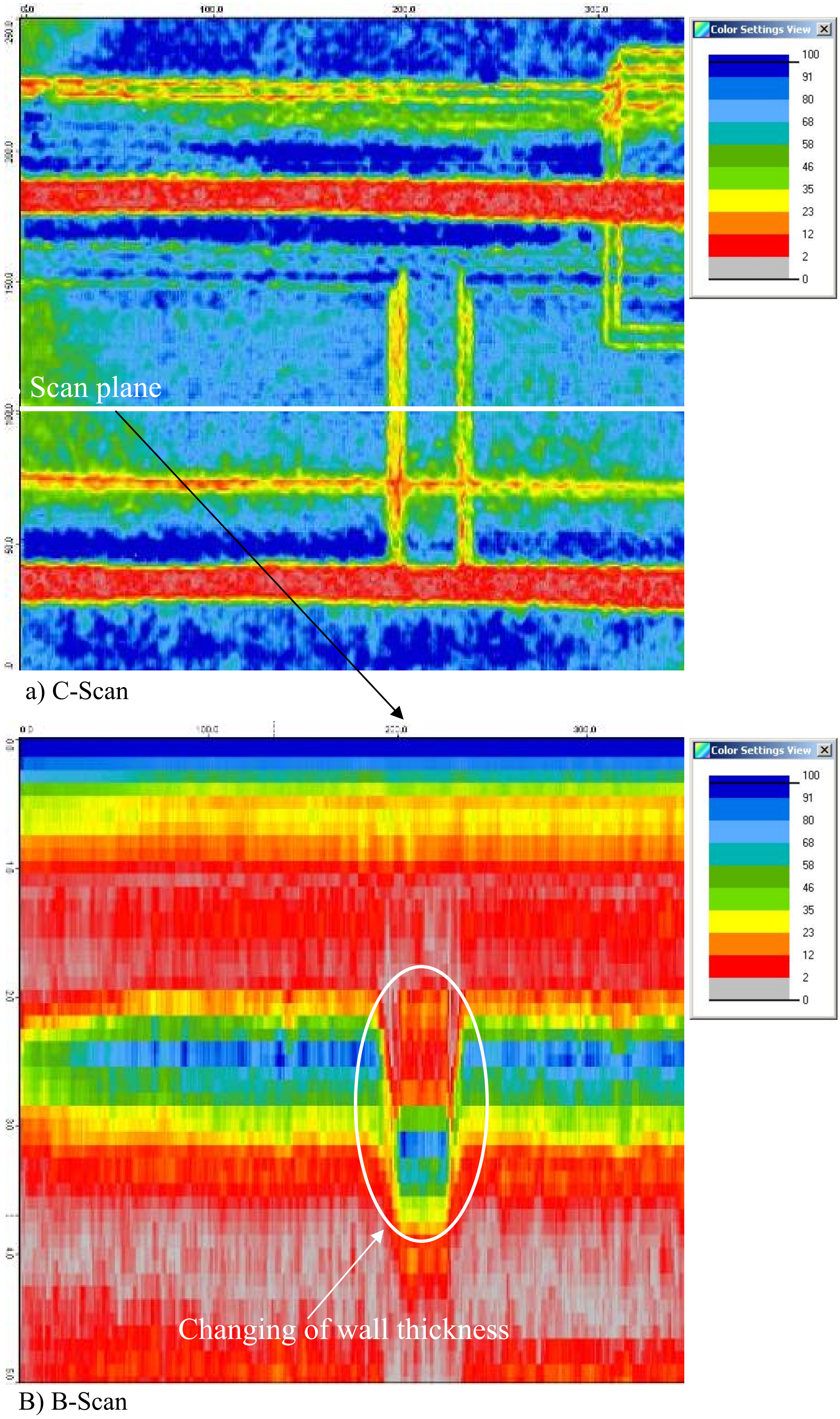


Figure 15: Ultrasonic testing of an actual CFK component with single element transducer

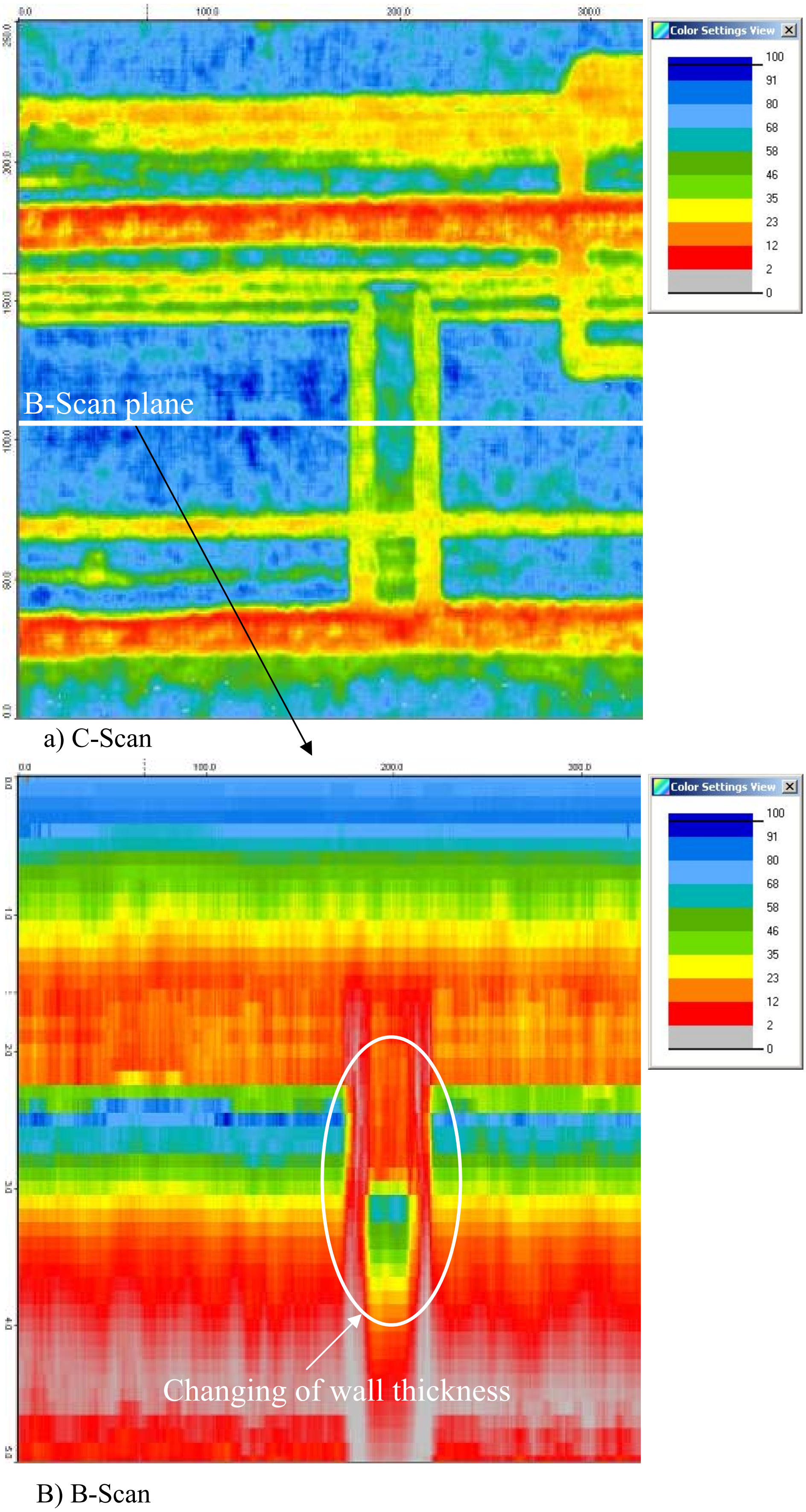


Figure 16: Ultrasonic testing of an actual CFK component with conventional phased array technique

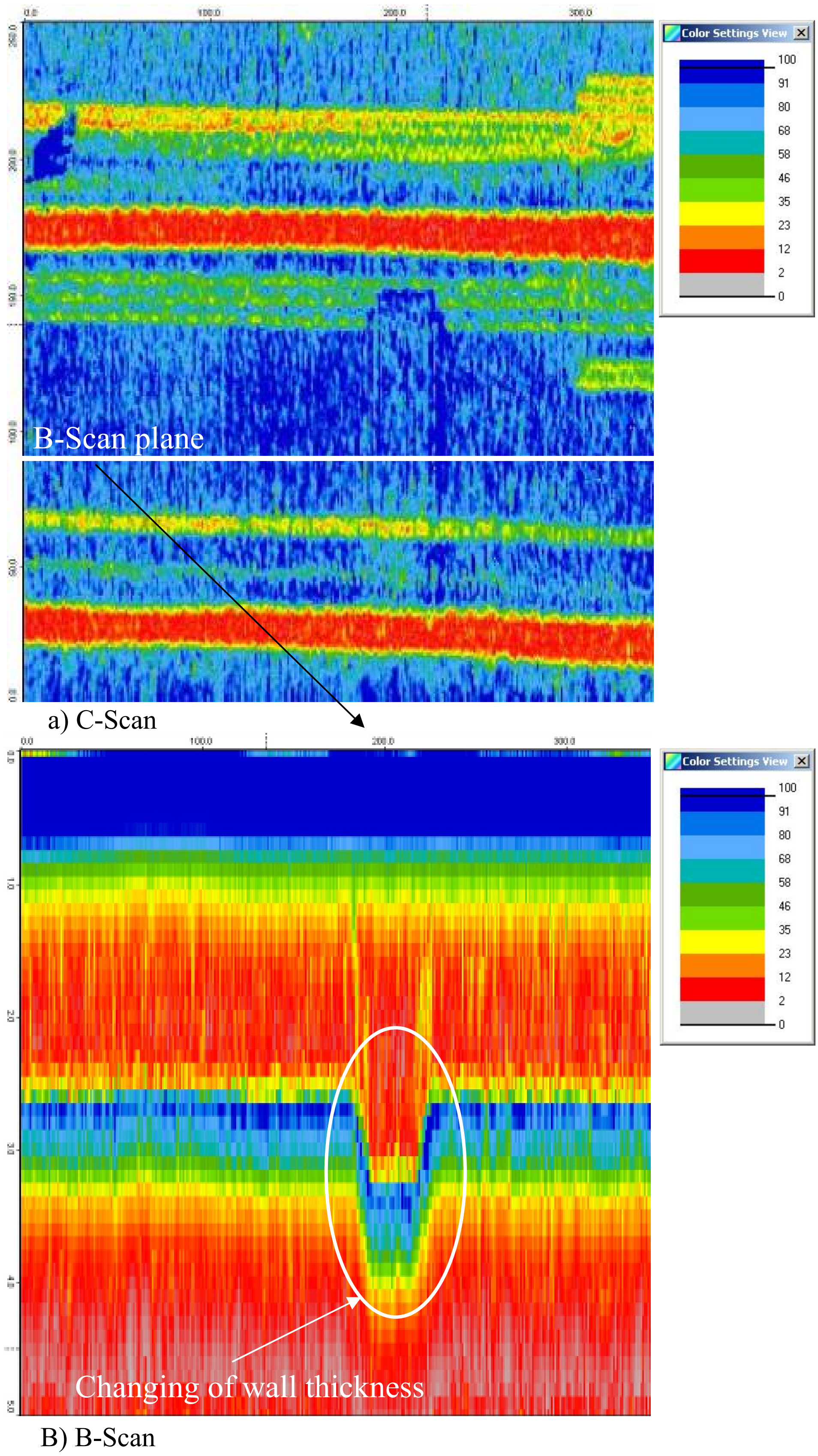


Figure 17: Ultrasonic testing of an actual CFK component with Sampling Phased Array technique

Comparing these three images we can say that Sampling Phased Array method provides higher resolution in the steering plane. Even inclined backwall area (see marked area in the B-Scan) can be mapped well, unlike the image by single element probe and conventional phased array mode.

4. Industrial Implementation

A potential implementation of testing procedure for coplanar and slightly curved CFK-components is shown in Figure 18. A linear Phased Array transducer consisting of reasonably large number of elements (e.g. up to 128) is moved across its sweeping plane. Several virtual transducers (group of elements functionally associated together for one transmitter-receiver act) are working in parallel according to Sampling Phased Array principle. To cover the entire volume in every probe position, several parallel shots may be required. Thus transmitting and receiving elements have to be multiplexed to build virtual Sampling Phased Array transducers. The use of parallel transducers ensures that a very high inspection speed can be achieved.

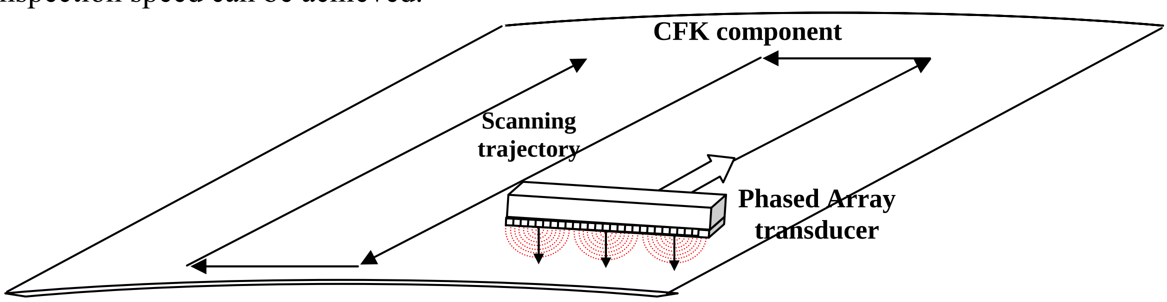


Figure 18: Principle of fast testing procedure by Sampling Phased Array technique on slightly curved CFK component

Since an arbitrary angle of incidence can be reconstructed after one shot of virtual Sampling Phased Array transducer, a correct backwall echo monitoring for slightly curved surface can be implemented for taking into account the local inclination in every probe position.

Nevertheless for exact positioning of ultrasonic transducer with respect to the component a robotized motion control system is to be integrated for highly reproducible and reliable inspection. Several synchronized robot arms can simultaneously scan an inspection object for achieving the shortest required inspection time.

5. Future Directions

5.1 Radii inspection

Detection of material discontinuities in areas with strong curvature (radius up to 3 mm) is a challenging task. The best solution for CFK-components with varied or complex geometries would be testing in immersion technique.

Currently the first simulation (Figure 19) and experiments for practical application of Sampling Phased Array method in immersion technique are in progress. The results are expected in the near future.

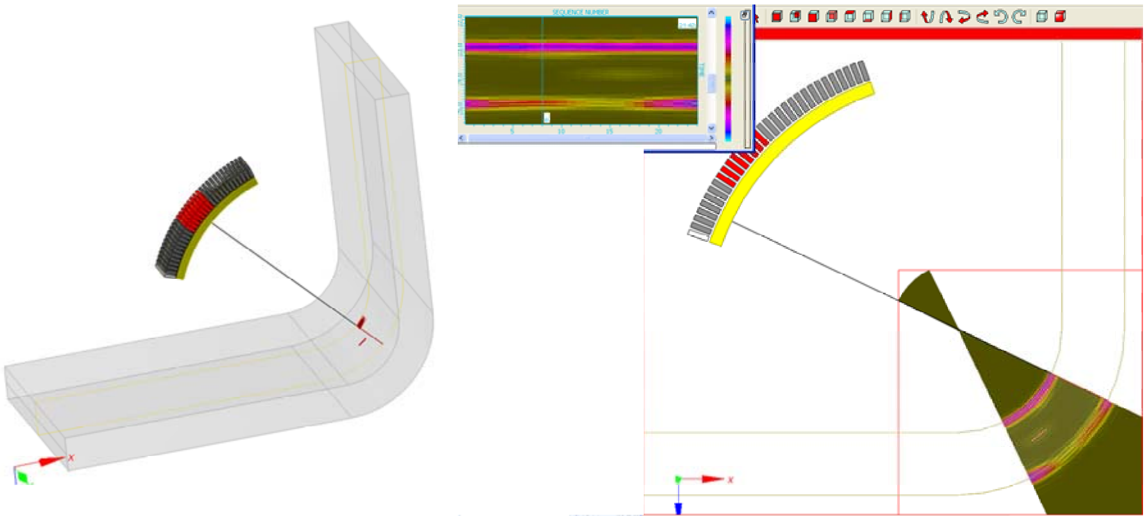


Figure 19: Simulation of radii testing by curved phased array transducer

5.2 Automatic 3D evaluation of inspection results

Sampling Phased Array technique provides a fast reconstruction of ultrasonic images in 3-dimensional space (Figure 20). An important task for practical use of this advantage is a fully or semi-automated interpretation of ultrasonic images, which provides a maximum support to operator by evaluation of inspection results.

This task has to be solved by means of modern tools for 3D image processing, adapted for needs and requirements of automatic ultrasonic testing and code based evaluation procedures.

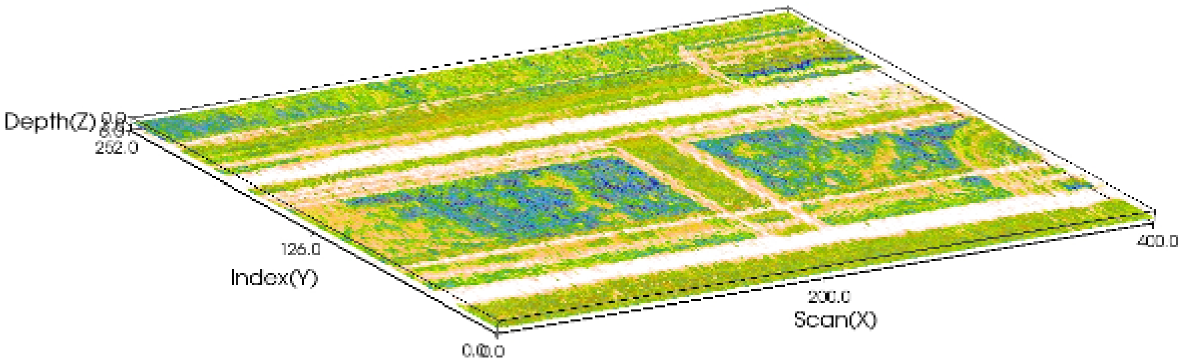


Figure 20: 3D representation of inspection results

6. Conclusion

Three inspection techniques were evaluated with respect to the immersion testing of CFK components and the detection of characteristic defects like delaminations, porosity and films.

The results obtained by Sampling Phased Array method and the single element transducer in contact mode are comparable and provide good results, while conventional phased array provided poor detectability of defects due to its low sensitivity and resolution.

It is noteworthy that, the single element probe is specially designed for testing of thin CFK-components and can be only used for limited tasks. The use of this type of transducers for industrial applications would be difficult due to reasons of limited inspection range, small effective aperture and consequential limited coverage of the inspection volume. Further this probe can't be used for radii inspection or testing objects of complex shapes.

The Phased Array transducers with Sampling Phased array technique can replace conventional phased array techniques. It provides reasonably good inspection results and offers all advantages of phased array technique, e.g. for radii inspection in immersion and contact. Furthermore Sampling Phased Array technology offers improved detectability of characteristic defects and offers high potential for industrial implementation of quantitative automatic inspection systems.

The ongoing project is focussed on developing a practical solution for radii inspection with Sampling Phased Array technique and automatic evaluation of inspection results.

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