# Development of an ultrasonic dry-coupling inspection wheel for Online NDI composite application

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**Abstract**

The application of ultrasonic waves to the inspection of aeronautic components is based on the use of couplants (water, gel, etc...) to facilitate the propagation of the sensing wave through the material. Although several solutions have been designed to integrate the use of these couplants and the NDT operations in different stages of component life (from production to in-service operation) its use increases the complexity of the process and the cost of the inspection because in some cases special infrastructures may become necessary.

Some of the research effort developed in the last decades has been addressed to reduce the necessity of couplant gel or fluids. In this sense, the development of ultrasonic inspection wheels based on special rubbers with a high degree of humidity has been proposed and is being commercialized nowadays. However, its use is not allowed in applications where the condition of completely dry coupling is imperative. Other tools based on air-coupling have been also developed but they mainly operate in through transmission arrangements and its use is limited to low frequencies.

This work examines a new wheel-based tool which can operate in dry condition . It has been developed in the context of the ICARO Project (Innovación en Composites Avanzados y Rear-End Optimizado) to provide a nondestructive inspection solution to be integrated into an Out of Autoclave (OoA) composite manufacturing process based on electron beam curing technology layer by layer. The solution requires be able to inspect very thin composite specimens (from 0.5mm) in clean and dry conditions compatible with the manufacturing process. To overcome these conditions, a special inspection wheel prototype has been developed that integrates a 5MHz ultrasonic array transducer composed by 128 elements mounted in a particular wedge. This aperture operates in pulse-echo and generates an ultrasonic image based on linear scanning beamforming process and a synthetic aperture acquisition procedure known as 2R-SAFT.

Inspection results obtained from reference standard of different thickness are presented. These results are compared with conventional immersion UT inspections and show the high potential of this inspection wheel for this special applications

**Keywords:** ultrasound, dry-coupling, aerospace, carbon fiber composite, Online NDI

## 1. Introduction

Most composite material parts today are traditionally manufactured according to autoclave curing processes. Although this stage is consolidated in the manufacturing process and considered technologically mature, it still shows some weaknesses that should be improved in relation to the efficiency and the flexibility of the process.

Nowadays large autoclaves are needed to house big parts for being cured. Such infrastructure joined with all the elements associated with the autoclave process, imposes a heavy investment, reduces the energetic efficiency of the manufacturing process and increases unnecessary the final cost. It also limits the design capabilities to the autoclave dimensions.

Among the options considered to overcome these drawbacks, would be the use of alternative technologies for curing/reticulating the resin without the need of autoclave is gaining interest. Some of these technologies are based on electron beam curing, microwave curing, radiofrequency curing and induction curing. Each of these technologies has its advantages and drawbacks as well as its particular design and degree of maturity for different applications.

Based on the need of a non-destructive inspection of the composite parts according to the new processes, the integration of the NDT inspection into the manufacturing process can provide also additional values such as the support into the manufacturing process by introducing the monitoring capability during the process to ensure the proper quality of the final product [1,2,3].

However, one of the issues that can limit the applicability of the UT on the inspection of some specific carbon fiber parts is the need of a coupling medium between the transducer and the inspected materials. This is because coupling agents can become contaminants for the material in some particular applications.

This work presents an ultrasonic NDT solution developed to be integrated into an Out of Autoclave (OoA) composite manufacturing process based on electron beam curing technology layer by layer. It address the most important handicap of this application, the assurance of a good ultrasonic coupling between the transducers and the composite material to be inspected in clean and dry conditions (no water at all) compatible with the process. This inspection system is to allow the early detection of defects during this manufacturing platform, enabling the performance of corrective measures in real time.

## 2. The Ultrasonic Inspection System

Linear array scanning is a common tool in ultrasonic NDE. These systems use electronic scanning and beamforming to activate a subaperture to capture/compose a single Ascan along the subaperture axis. This subaperture is swept along the length of the probe to create a cross-sectional profile without moving the transducer. Successive subapertures produce successive A-scans that are stacked to create a B-scan image.

Due to the fact that steering is not used, to increase the energy radiated in linear array probes the transducer elements are usually made higher than conventional phased-array elements (a wavelength or more). Therefore, beamforming is limited to improve the A-scan quality in axis, with fixed focus on emission and dynamic focussing on reception. Furthermore, the distance between image lines the lateral resolution and the maximum subaperture size are limited by the distance between elements in the aperture. Thus, although this technique is very simple and effective, it is unable to provide high quality images.

The superior performance of beamformed image for better evaluation of location and morphology of defects, in front of traditional B-scan imaging, has been discussed previously [1]. Then, in order to adapt beamforming techniques to linear array imaging to increase the image quality, synthetic aperture imaging techniques (SAFT) [6,7,8] has been used. This technique divides the image generation process in two stages: the first one is the acquisition stage, where all signals needed to compose the image are captured; and the second one is the beamforming stage, that can be dynamically tuned to the image requirements. Then the system is composed by three basic elements: sensor, acquisition and processing.

The sensor system is an ultrasonic inspection wheel adapted to operate in dry coupling conditions. A 5MHz 128 transducer array is placed inside the wheel.

The acquisition system is a SITAU 32:128 (DASEL S.L.) configured to operate in 2R-SAFT acquisition mode. The acquisition procedure is based on minimum redundancy coarray, that means it needs 255 signals to compose an image. At the basic operating mode the system generates 2 signals per shot (128 shots are needed per image) but it is able to produce up to 32 signals per shot, reducing to 8 the number of shots needed and consequently increasing the operating speed.

The signal processing stage is implemented by a GPGPU beamformer that implements a linear scanning operation being able to obtain up B-scan 100 images per second. Furthermore, at each B-scan some adaptive operations are performed to compensate small curvature shape in the parts. After this analysis thresholds are adjusted to compose C and D scan images.

### *2.1. The Ultrasonic Inspection Wheel*

The proposed solution is composed by an ultrasound inspection roller provided with a wheel, and an ultrasonic array system for linear scanning and image composition. The inspection wheel is presented in figure and it is composed by several elements:

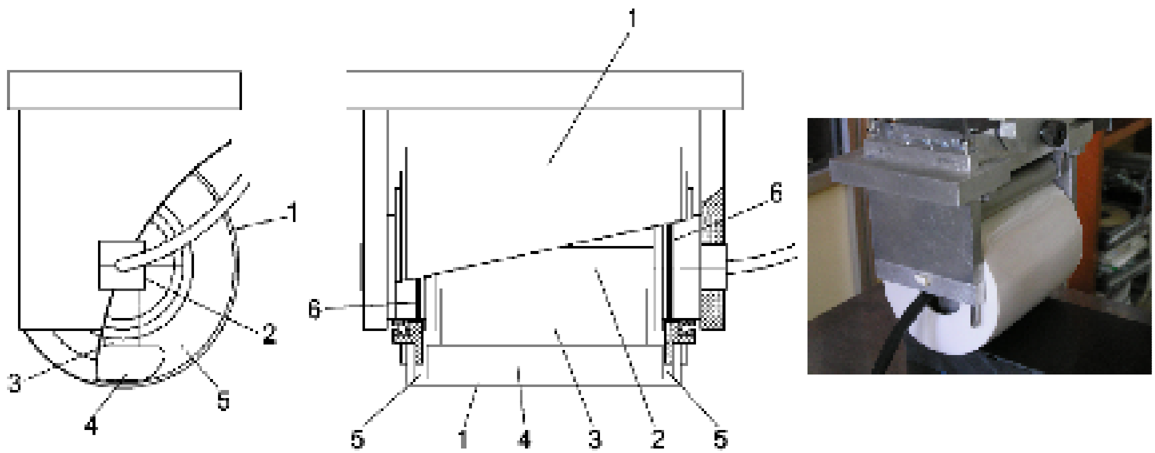


Figure 1. Ultrasonic inspection wheel. (1) elastomer, (4) wedge, (3) ultrasonic array, (6 and 2) elements to fix the array, (5) cavity with high density liquid. At left, picture of the wheel.

The wheel cover is made of a compatible elastic material. Inside the wheel an ultrasound phase array probe (128 elements operating at 5Mhz), wherein a special wedge adapted to the curvilinear shape of the wheel has been integrated with a selected fluid that enables the acoustic coupled among the sensory system, the wheel cover and the wedge.

The material of the elastomer has a hardness between 4 and 55, so that is sufficiently deformed when applying a moderate pressure on the part to be inspected.

*2.2 The synthetic aperture acquisition procedure*

Due to the reduced time-of-flight and the changeable nature of the part to be inspected, the acquisition parameters should be under the reconsideration at every moment. If conventional linear scanning is used it means that complex control procedures should be implemented to adapt the acquisition procedure. To avoid this issue, synthetic aperture approach has been used, where acquisition procedure is addressed to obtain a set of signals able to produce a complete coarray. Several strategies are possible to achieve this objective [8,9,10]; here we have implemented 2R-SAFT [11] described in the figure 2.

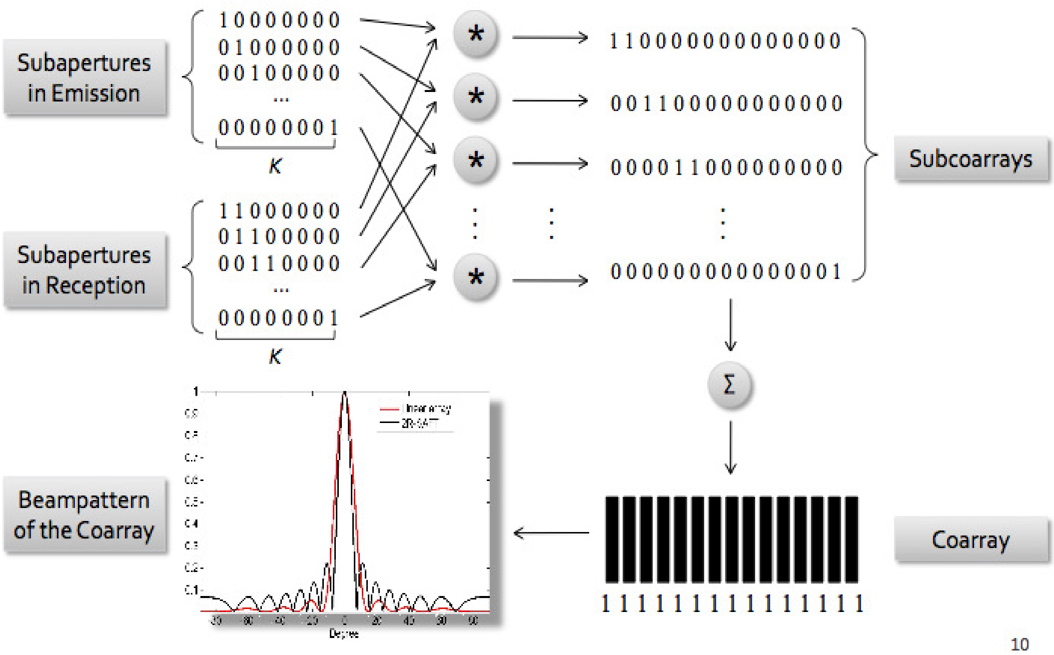


Figure 2. Acquisition procedure for 2R-SAFT strategy. This process produce a minimum redundancy coarray able to produce image.

The completeness of the coarray guarantees the quality in the image and allows to adapt the composition of the image without interfering with the acquisition process. The advantages that can be achieved are: (1) dynamically focussing in emission and reception can be applied, increasing considerably the quality of the resulting images; and (2) the subaperture size can be dynamically adapted to the depth of focus, providing convenient resolution at all image points.

***2.3. Signal processing stage***

The inconvenience of the synthetic aperture approach is that it needs a high computational power in order to maintain the synchronization with the acquisition process. Because of that, processing stage has been implemented in parallel based on GPGPU techniques [9].

The linear scanning beamformer is described in detail in [12]. According to the acquisition procedure the coarray is composed by two kinds of signal, (i,i) and (i, i+1) pairs, represented in the image by squares an dots respectively. The coarray extension is 255 elements, and covers the same region of the original array with 128 elements. Then the movement of the scanning window is smaller than in conventional linear scanning (see figure 3) providing a more detailed image. In the figure the difference between conventional linear scanning and the SFAT approach can also be seen. Intentionally, porosity has been induced in the part to evaluate the performance of the technique.

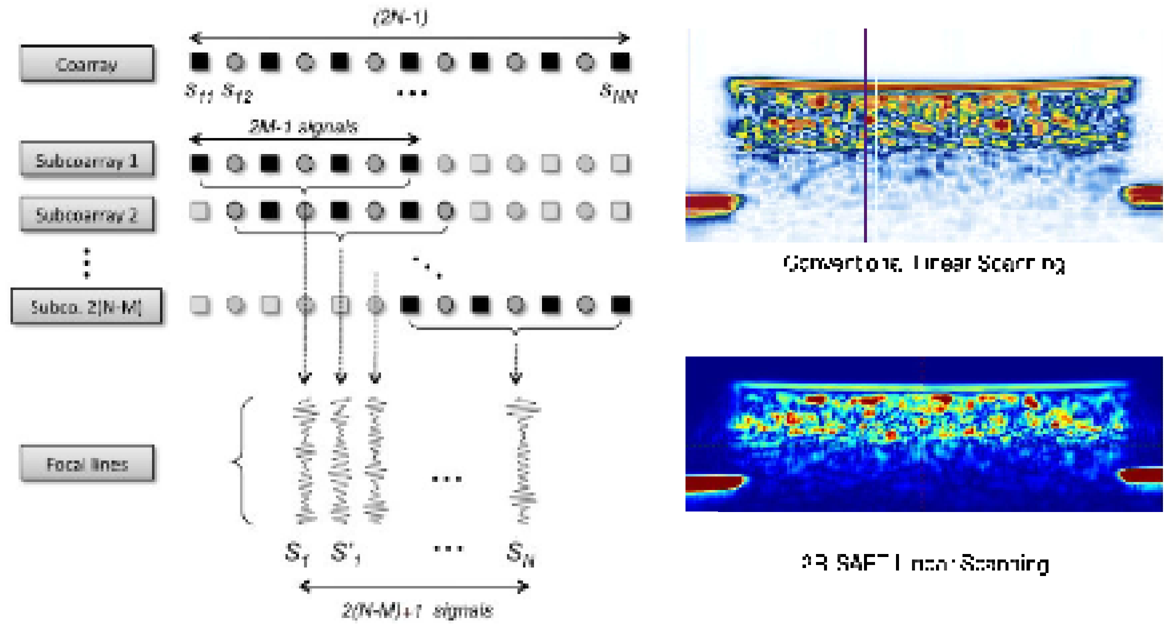


Figure3. Procedure to choose the focussing aperture and its displacement. On right-top a B-scan image obtained with conventional linear scanning. On right-bottom image of the same position composed by saft linear scanning.

Figure 3 shows that energy in the first interface of the conventional scanning is higher, due to emission focus, meanwhile it is lower in the SAFT linear scanning. However, SAFT approach allows compensating the emission and the reception delay producing a high quality image where main pores are well identified and located.

Also some processing work is needed to compensate small differences in the alignment of the part with the sensor system. This can be due also to small curvatures in the shape of the part. Based on the determination of the fist interface at each line of the B-scan image, an analysis gate is defined and moved according to the detection of this interface. Then C-scan and D-scan images are composed and presented with the B-scan and one selected A-scan in real time.

The system implemented in a GeForce GTX295 (NVIDIA) is able to produce up to 100 B-scan images per second. Figure 4 shows a detail of the result window where A-scan, B-scan, C-scan and D-scan are presented on-fly as data is being captured. The image shows the evolution of the inspection in dry-couplig conditions of the test component described in figure 5.

## 3. Experimental results

In order to test the capability of the inspection system several reference standards were produced and inspected. They all were evaluated firstly by conventional immersion inspection system and then with the developed dry coupling wheel. The thickness specimens were 0.5mm, 1.0mm and 1.5mm, and are representative of the manufacturing process. The figure 5 shows a drawing of one of the reference standard (thickness 1mm) and the corresponding D-scan image using conventional immersion PE and and the dry coupling system developed in the Project. Details of the A-scan, B-scan, C-scan and D-scan in dry coupling are presented in figure 4.

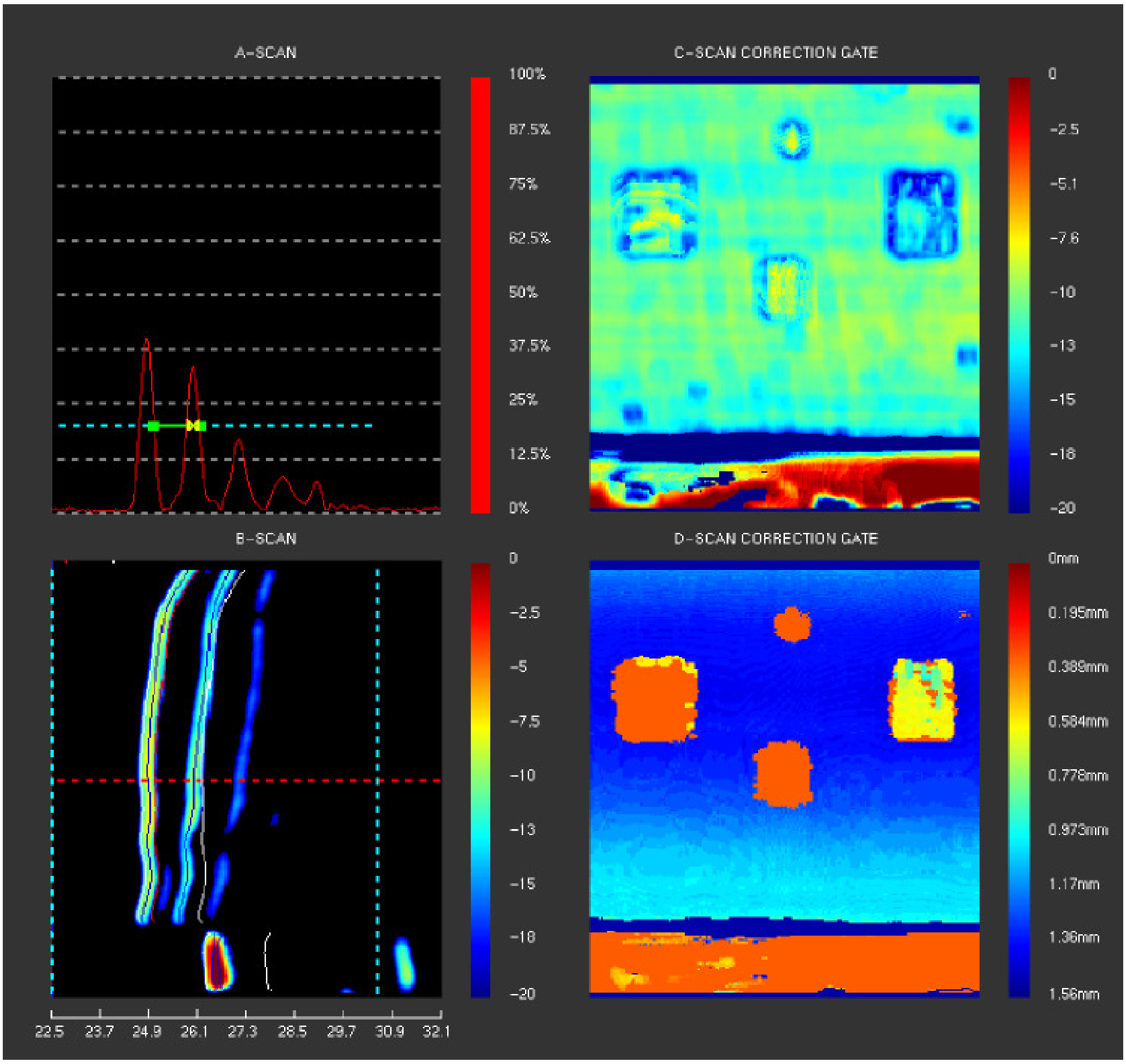


Figure 4 Detail of the screen-result. A-scan, B-Scan, C-scan and d-scan are presented in real time. The analysis gate is adapted to the variation in the interface shape of the B-scan.

A 128 elements 5Mhz array was used in the experimentation. The data was acquired and the images were composed in Matlab. Both ultrasonic images produce the same results (differences in the colormap of both images is due to the software employed in the inspection, but the values obtained confirms the data shown in the scheme).

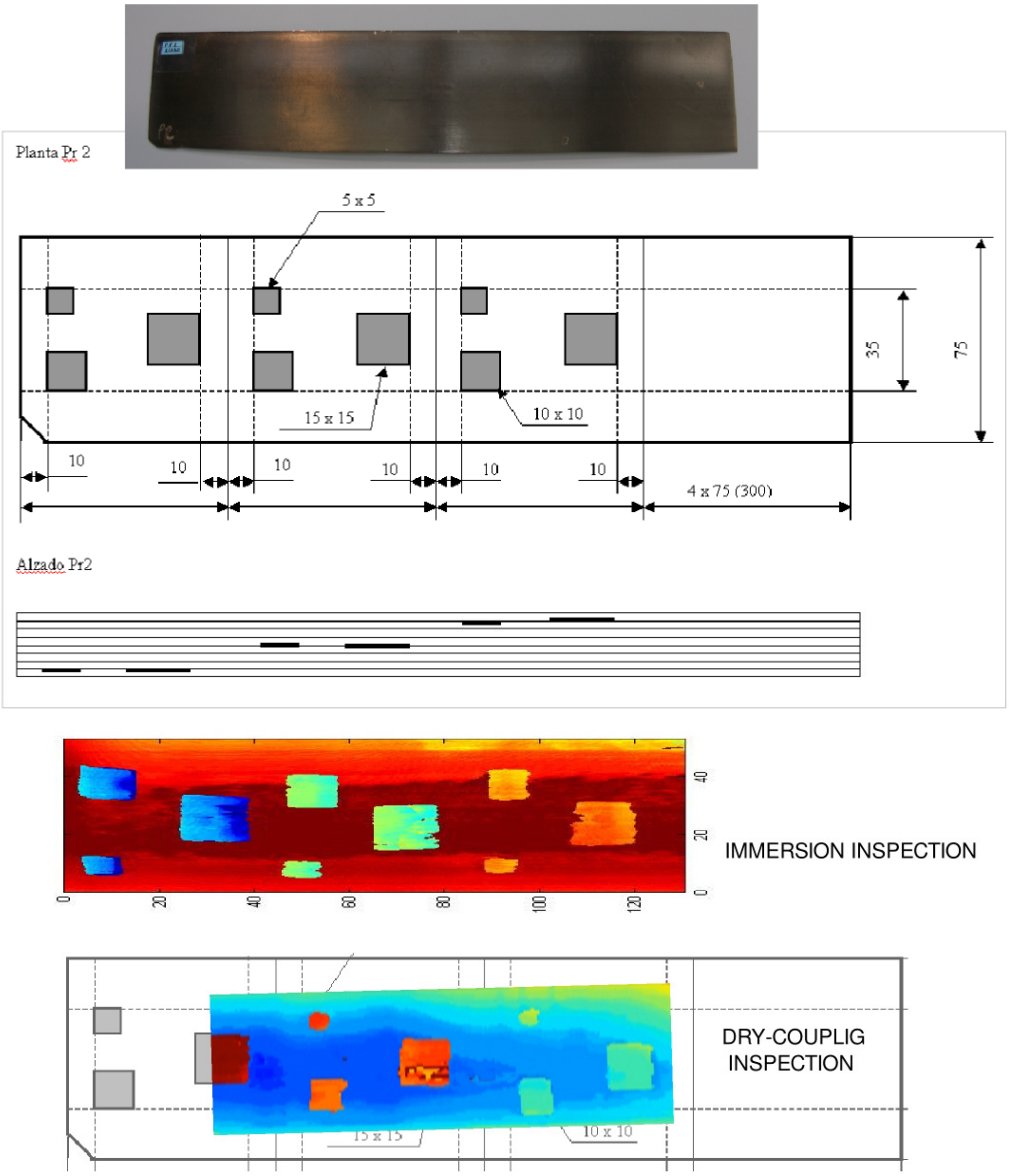


Figure 5. Test piece with a scheme of the inclusion locations. D-scan image obtained by immersion linear scaning and image composed by saft data (linear scanning composition) with dry-coupling acquisition.

## 4. Conclusions

The work presented describes an ultrasonic inspection wheel system able to work in applications requiring dry and clean coupling conditions. The experimental results have demonstrated the potential of the system to inspect by UT PE very thin composite specimens using dry coupling and providing similar results to those obtained by conventional immersion ultrasonic inspection.

The integration of this inspection system into this manufacturing composite platform is a clear example of the Online NDI concept, where the sensing compatibles technologies inside the process would perform not only inspection tasks inside production time but also contribute to the optimization of the manufacturing process as a whole. This in fact means very important advantages for this new production & inspection concept such as the reduction of the manufacturing time and the costs of rejected material, early detection of the defects and hence the sooner correction actions, and deeper knowledge of the process itself enabling to know the accurate influence of the manufacturing parameters with the process defectology.

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