EVALUATION OF DIFFERENT IMAGING ALGORITHMS AND CONVENTIONAL ULTRASOUND METHODS ON COMPOSITE STRUCTURES WITH DIFFERENT DEGREES OF HETEROGENEITY

Ameni.ASCHY[1], N.TERRIEN[1], S.ROBERT[2], M.BENTAHAR[3]
[1]CETIM,Nantes,France
[2]CEA LIST Centre de Saclay,Saclay,France
[3]Laboratoire d'Acoustique de l'Université du Maine,UMR CNRS 6613,LE MANS Cedex9,France

Abstract. Ultrasonic Phased Arrays (PA) have shown a growing interest in the industrial non-destructive testing and evaluation of materials. The application of PA in different areas (such as aerospace, nuclear industry, line control industry, etc.) proved its efficiency and flexibility especially during specific controls where the geometry of component parts has to be taken into account to perform reliable imaging in a short time with a consequent gain in productivity. The aim of this communication is to compare different PA imaging methods applied to components made of different materials. In particular, it puts forward the influence of materials and geometries on the performance of the different methods in terms of sensitivity of detection, SNR...

Under the above mentioned conditions, the application of different imaging methods on the same samples provided different results. It was then necessary to establish criteria, according to the defect sought and operating conditions, in order to favour the use of a specific imaging method over another by identifying the performances and limitations of each one of them.

Keywords: ultrasonic imaging, phased-array probes, composite structures, defect characterization.

Corresponding author
Phone: (0033) 2 40 37 36 64
Mail address: ameni.aschy@cetim.fr
Address: 74 Route de la Jonelière, 44000 Nantes

Introduction

The phased-array technology evolves in industry for over twenty years [1], offering the possibility to adapt the focusing beams, and to allow easy control of heterogeneous materials of complex geometries with a multitude of solutions applied on metal parts. The principle of electronic focusing consists in exciting the piezoelectric elements of a probe with different delays to focus the incident wave at the desired point in the region of interest. These delays have an effect similar to that of a focusing lens and enable focusing at various depths and directions. The electronic focusing allows only one phased-array probe to be used where several single-element probes with different focal distances would be necessary. The technology also provides good performances in terms of sensitivity of detection, precision and sizing [2, 3]. In NDT in aerospace, the phased-array technology is mainly studied to increase frame rates and to limit inspection times for large structures. An ultra-fast imaging method for composite structures consists in the transmission of a large plane wave by firing all the array elements without delay law, and receiving elementary signals in parallel [4]. This represents the fastest way of scanning all the area with only one measurement per probe position using all the elements and move on. The Single Plane Wave Transmission (SPWT) was originally developed in medical imaging [5]. In NDT, it offers a maximum scanning speed for large composite structures (frame rates up to about 1000 fps) with reduced memory issues. The SPWT imaging however offers a poor spatial resolution if no processing is applied to the data. Despite the above-mentioned qualities, the presented methods are rapidly disrupted when the inspected part has a complex geometry. In particular, the imaging techniques are not adaptive because they rely on a ray-based model to calculate the delay laws adapted to the medium with a specific geometry and/or material.

To overcome this insufficiency, different techniques and methods have been developed. The real-time adaptive imaging method was developed to master a normal incidence transmission through various complex surfaces using a conventional no-shaped phased array (typically a linear or matrix array with a flat active aperture) [6]. The self-adaptive SAUL technique (Surface Adaptive ULtrasounds) has been implemented in the MultiX systems, designed by the M2M Company. As in the conventional SPWT, the processing begins with the transmission of a large plane wave by simultaneously exciting all elements and recording elementary signals in parallel with the whole array. Next, the times of flight between the elements and the surface are measured to calculate a delay law that transmits in water a wave front partially adapted to the surface. This processing is iterated as many times as necessary until the incident wave ideally fits the surface. Another technique that gives the same results as SAUL is based on a linear electronic scanning. The elements are fired one by one to transmit divergent cylindrical waves, and the delay law deduced from the time-of-flight measurement transmits a wave front rigorously parallel to the specimen surface. In this work, all these techniques have been tested and evaluated on two composite parts: an aerospace standard including artificial defects and a complex geometry footplate with a higher degree of heterogeneity. Results and discussion will be developed in the next section.

1. Comparison of different PA imaging methods

The above-mentioned techniques have been first tested and evaluated on an aerospace standard made of carbon epoxy composite in which artificial defects are created. Artificial defects have different diameters and are distributed over three different thicknesses (Fig. 1).

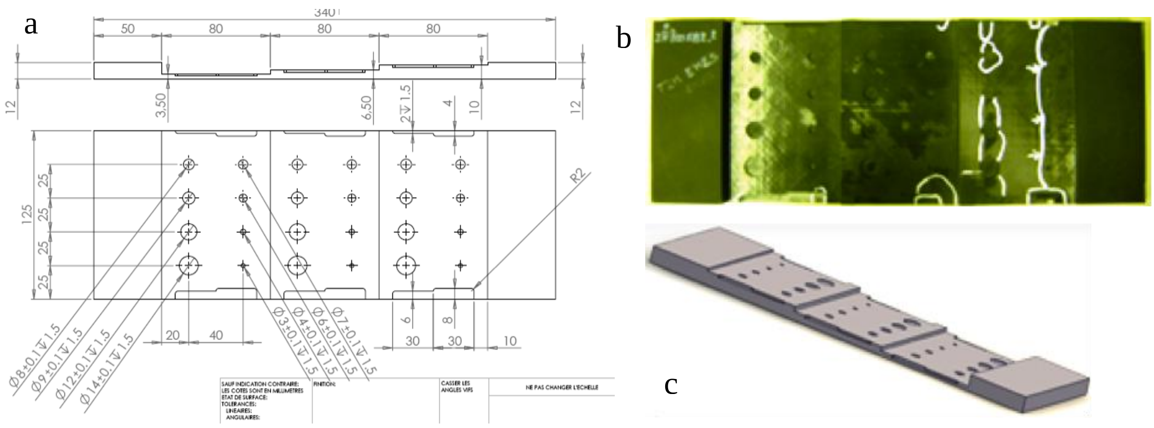

Figure 1. The aerospace standard made of carbon epoxy composite and including artificial defects: (a) Drawing definition; (b) Top view; (c) 3D view.

Imaging techniques, mentioned above, were tested on this specimen to determine their advantages and limitations. Acquisitions were made in immersion, under the same conditions and with the same settings to inspect the entire specimen with a linear transducer (with 64 elements, 5 MHz central frequency and 0.6 mm pitch). In parallel, an acquisition with a circular single-element probe (5 MHz central frequency) with a spherical focusing was carried out and taken as a reference for comparison.

The application of different imaging methods on this sample provides different results. It was then possible to establish criteria in order to favour the use of a specific method over another by identifying the performances and limitations of each one of them.

The SPWT imaging was optimized by determining the ideal number of receive elements contained in the sub-aperture (the ideal number is 8 in the present case). This sub-aperture is electronically moved along the whole aperture to obtain an image with an improved SNR compared to a conventional SPWT (the sub-aperture contains a single receive element). Subsequently, additional tests were conducted to further optimize the SPWT trying to focus at reception with 8 elements at mid-thickness of the plate. The Cscan images provided by the different method are represented in (Fig.2)

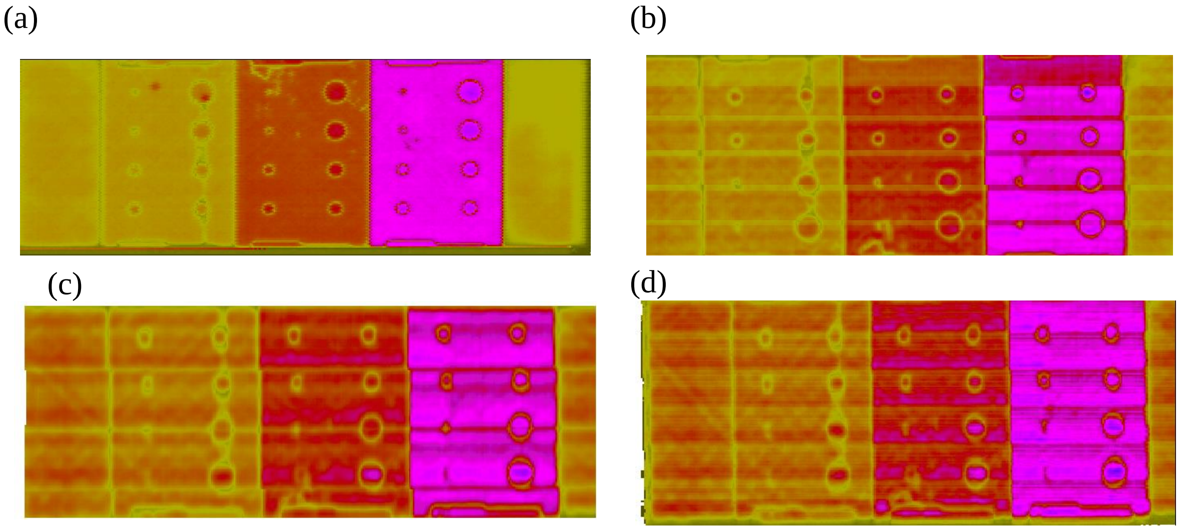

Figure 2. CScan images of the artificial defects with different diameters and distributed over three different thicknesses (from right to left 3.5mm; 6.5mm and 10mm): (a) Single-element control; (b) Focused electronic scanning; (c) Optimized S.P.W.T; (d) Classical S.P.W.T

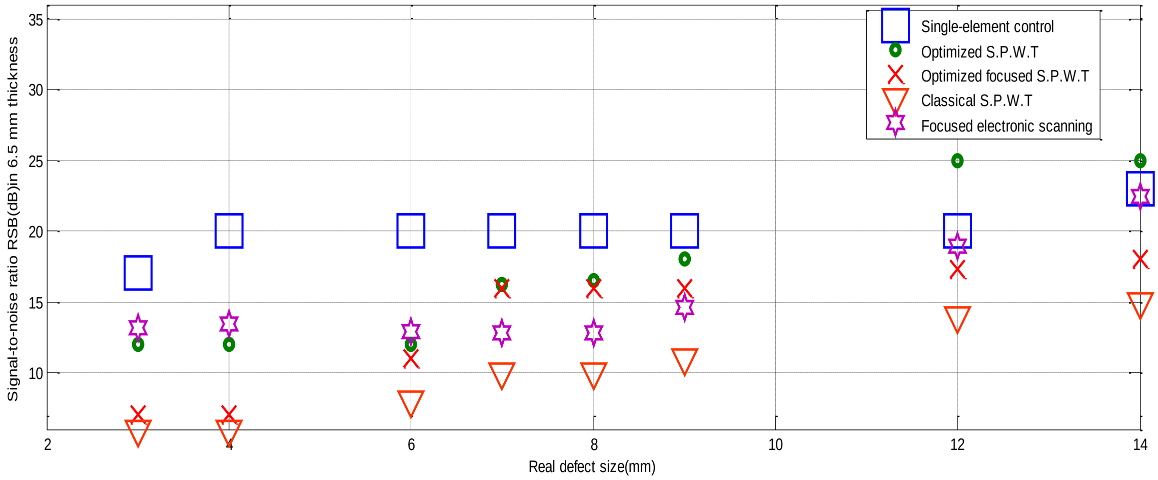

Figure 3. Evolution of the SNR for the 6.5-mm thickness part according the defect size.

The signal-to-noise ratio (SNR) variation according to the defect size is displayed in (Fig. 3). Results revealed that the single-element, the focused electronic scanning, and the optimized plane-wave transmission methods offer the best SNRs (for the 6.5-mm thickness part). In addition, it can be observed that a focusing in receive mode can increase the SNR of 7 dB (e.g. the defect of 12-mm diameter) for the SPWT images.

Defect characterisation (taken at - 6dB) differs from one method to another. The sizing error (%) in the 6.5mm thickness part for each method is given in (Fig.4).

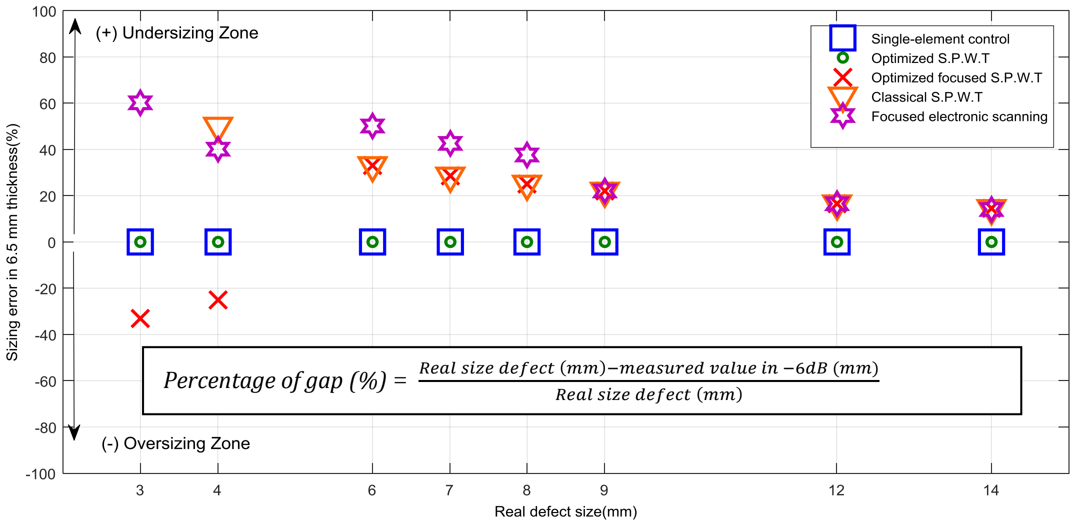

Figure 4. Evolution of the sizing error (%) for the 6.5-mm thickness part according the defect size.

2. Evaluation of adaptive imaging algorithms on composite structures

2.1. The SAUL algorithm

The goal of the SAUL method is to transmit in water an incident wave-front parallel to a complex surface (normal incidence technique). In the context of the inspection of metal parts, the SAUL algorithm may also be applied to estimate the surface geometry with a small number of ultrasonic shots. Figure 5 hereafter illustrates the principle of the SAUL method for the first iteration. The iterative processing begins with the transmission of a plane wave by simultaneously firing with all the elements (Fig. 5a). The reflected wave is received by the phased-array and the times of flight between all the elements and the surface are measured (Fig. 5b). Then, a delay law is calculated from these measured times of flight and applied to a second ultrasonic shot (Fig. 5c).

Depending on the geometry complexity, the process is iterated as many times as necessary to converge and to obtain an incident wave-front parallel to the surface.

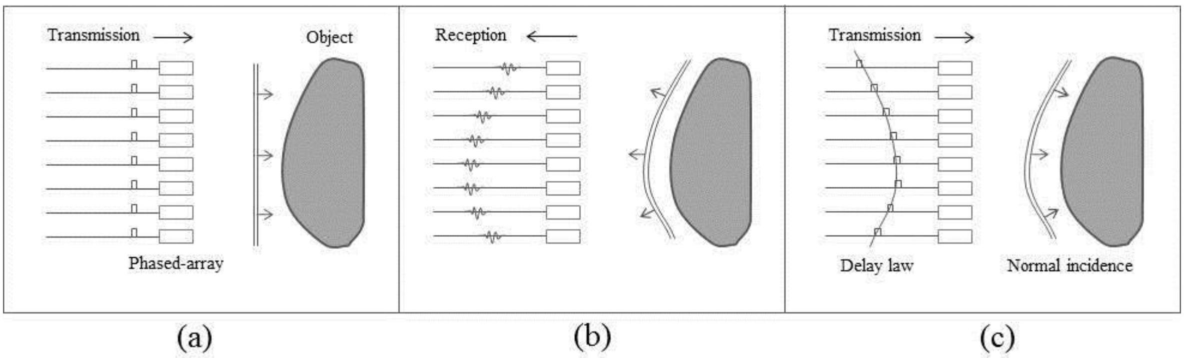

Figure 5. Three steps of first SAUL iteration: a plane wave is transmitted by firing with the full array (a); the reflected wave is received by the array and times of flight are measured (b); a delay law is deduced from these measurements and applied to obtain an incident wave-front parallel to the object surface (c).

If M is the number of measured times of flight ($M < N$ where N is the total number of elements), the transmission and reception delays applied to an element m ($1 \leq m \leq M$) are defined as:

$$E_m^{(j+1)} = E_m^{(j)} - \frac{t_m^{(j)}}{2} - \underset{k:1\to M}{\mathrm{Min}}\left(E_k^{(j)} - \frac{t_k^{(j)}}{2}\right) \qquad (1)$$

$$R_m^{(j+1)} = \underset{k:1\to M}{\mathrm{Max}}\left(E_k^{(j)} - \frac{t_k^{(j)}}{2}\right) - E_m^{(j)} + \frac{t_m^{(j)}}{2} \qquad (2)$$

where j (j = 1, 2,…) denotes the shot number in the iterative processing (j = 1 corresponds to the first transmission without delay law, i.e. $E_m^{(1)} = 0 \;\; \forall m$), and $t_m^{(j)}$ is the measured time of flight for an element m and a shot j. Equations (1) and (2) express a summation of delay laws, iteration after iteration, until the convergence is satisfactory. In general, this is achieved after no more than four or five ultrasonic shots.

2.2. Illustration of the SAUL method with a carbon epoxy plate

During inspection of composite plates, a slight disorientation of the phase-array probe may significantly alter the control quality due to the anisotropy effects. Then, the SAUL method is useful to compensate in real-time this disorientation by forcing a normal incidence transmission in the component. This is what is demonstrated in Fig. 6 for the previous aerospace mock-up. A probe (central frequency= 5 MHz; pitch=0.6 mm) is placed over the specimen, in a position where there is no defect (the thickness is 6.5 mm). In Fig. 6(a), the Bscan image was recorded when the probe is rigorously parallel to the surface. The backwall echo is detected without specific processing because the plane wave is transmitted with a normal incidence. In Fig. 6(b), the probe inclination is 5° and the backwall echo is not detected anymore because of the non-zero incidence angle. The SAUL algorithm is applied in Fig. 6(c) with 2 iterations, which provides an image of the backwall with a correct SNR.

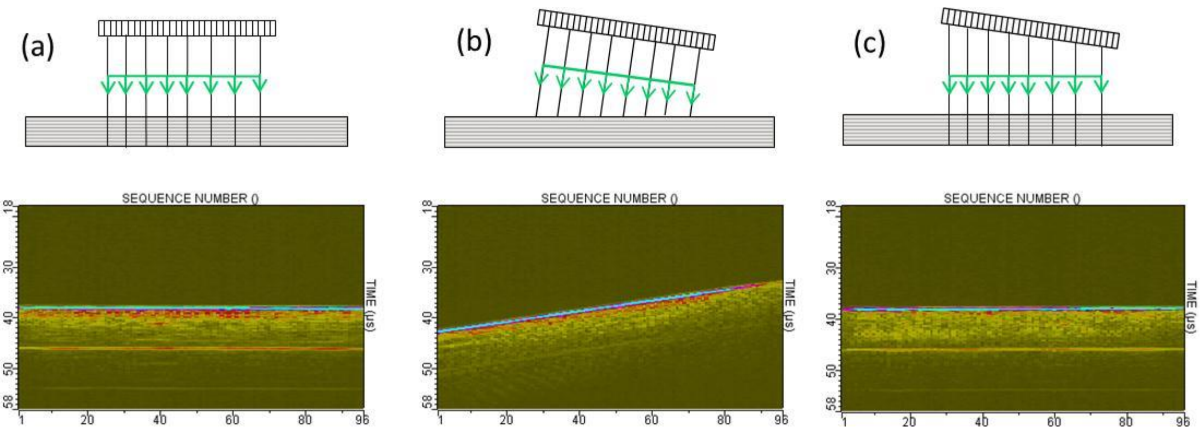

Figure 6. (a) Bscan images in a composite plate with 6.5 mm thickness: image when the probe is parallel to the surface (a); images when the probe is inclined of 5° without adaptive processing (b) and by applying SAUL with 2 iterations.

2.3. Evaluation of imaging algorithms on the foot prosthesis

The second specimen is an epoxy carbon foot prosthesis with a complex geometry. This will highlight the limitations of conventional ultrasound techniques and the necessity of the transition to adaptive techniques to control this type of geometry.

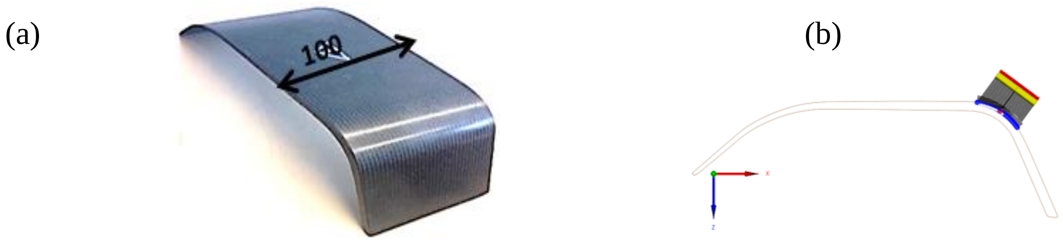

Figure 7. Foot prosthesis with a complex geometry ; (a) Perspective view of the foot plate; (b) profile view of the transducer and the foot plate

Adaptive techniques such as SAUL and adaptive linear scanning were performed on the convex portion of the foot prosthesis with a phased array transducer (64 elements, 5 MHz central frequency and with a pitch of 0.6 mm). The results obtained with the adaptive linear scanning and the SAUL techniques are respectively shown on figures 8 and 9.

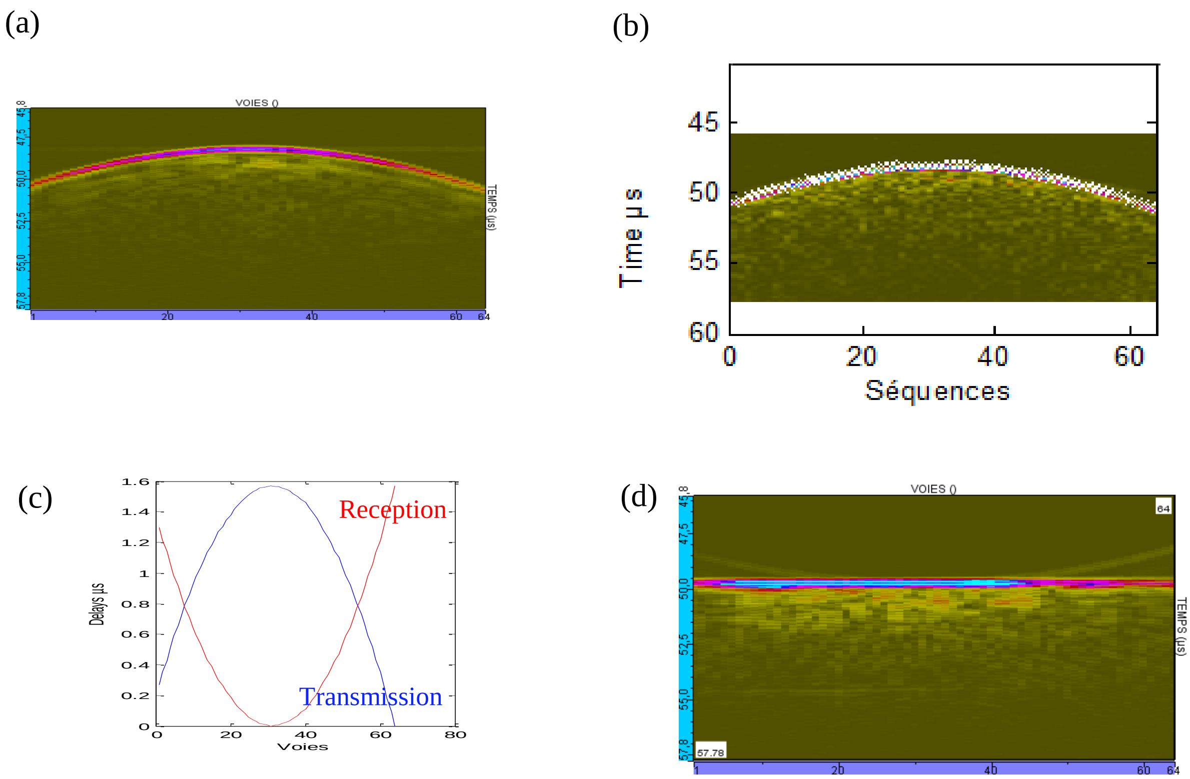

Figure 8. Illustration of adaptive linear scanning with a fixed position of the transducer in the center of the convex portion: (a) Bscan image obtained from an electronic scanning in transmission; (b) The time of flight curve superposed to the Bscan image obtained from an electronic scanning in transmission; (c) Delays laws deduced from an electronic scanning in transmission; (d) Bscan image obtained when adaptive delay laws are deduced from an electronic scanning in transmission.

The backwall echo is invisible because of the heterogeneity of the material. Nevertheless, in practice, adaptive linear scanning technique is not applicable to industrial controls for two reasons. First, as a single element is used at each transmission, the

amplitude level of the surface echo is much lower than the one obtained by transmitting with the full array and times of flight may be difficult to be measured.
Second, the large number of shots may dramatically decreases inspection rates compared to the plane wave transmission used in the SAUL method. The time-of-flight measurement required a cycle of 64 shots since the transducer array is composed of 64 active elements.

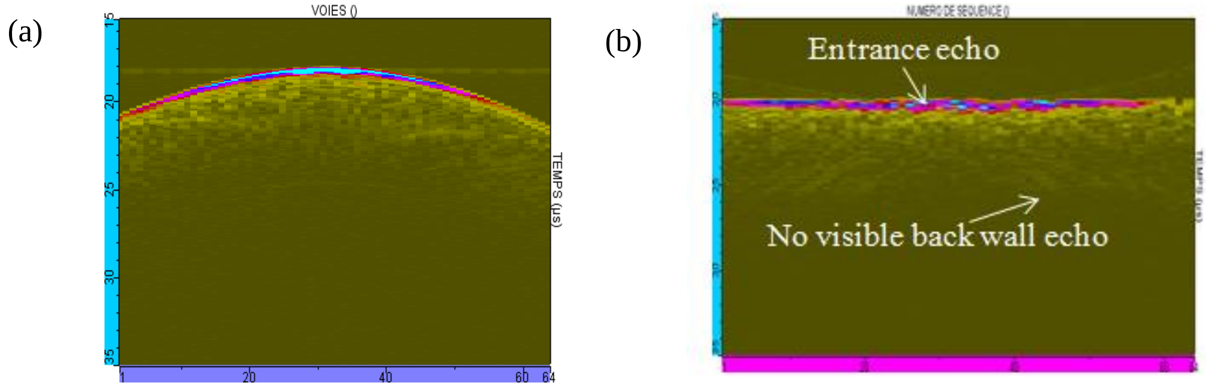

Figure 9. Application of the adaptive technique SAUL: (a) BScan (channels/time) before the application of SAUL technique; (b) BScan (channels/time) after application of the SAUL technique.

The obtained results show the bottom echo (around 27 µs) remains difficult to detect because of the high degree of heterogeneity of this material. New acquisitions were made with another phased array transducer (64 elements, 1.5 MHz central frequency and with a pitch of 1 mm).

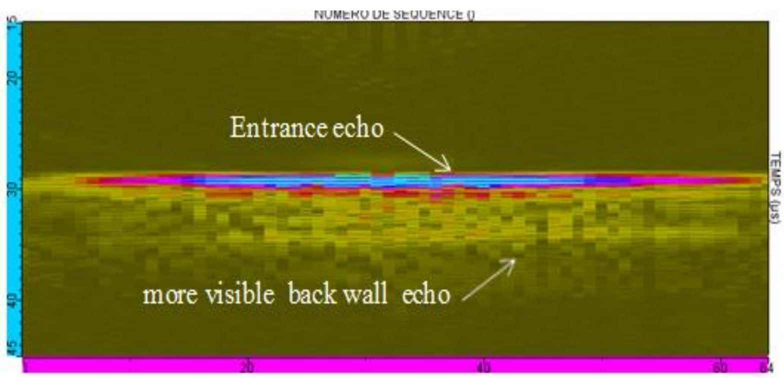

Figure 10. Application of the adaptive technique with a 1.5MHz probe.

Compared to the previous result, the back wall echo can now be identified in figure 10, which confirms that the delay law calculated with SAUL algorithm transmits an incident wave front approximately parallel to the surface. The anisotropy effects due to the fibrous nature of the material are minimized by forcing a normal incidence transmission. However, the backwall echo is not clearly visible because of the high level of heterogeneity in this material.

Conclusion

In this paper, different PA imaging methods were applied on composite materials. In particular, this study puts forward the influence of materials and geometries on the performance of the different methods in terms of sensitivity of detection and SNR.

The SAUL adaptive technique has been presented and tested. This technique is based on an iterative processing of a single-plane wave transmission acquisition and requires only a small number of ultrasonic shots to master a normal incidence transmission through a complex surface of a composite structure. All different parts of a given component can be inspected using a same transducer array, such as a conventional probe with a flat active aperture.

Future work will focus on the geometry reconstruction from different algorithm in order to improve the defect characterization.

References

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