ULTRASONIC NONDESTRUCTIVE TESTING OF COMPLEX COMPONENTS WITH FLEXIBLE PHASED-ARRAY TRANSDUCERS

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Abstract. The ultrasonic inspection of parts showing variable or irregular geometries is a real challenging issue. The conventional methods using contact probes are limited by the problem of coupling between the probe and the part. Moreover the efficiency of both immersed and contact techniques suffer from the perturbations induced on the transmitted beam by the interaction between the wave and the surface. A solution based on the use of flexible array is developed at CEA-LIST in the aim of overcoming these effects and enabling efficient inspection of irregular and complex parts. To master the characteristics of the focus beam during the scanning, the smart flexible array techniques couple flexible apertures for fitting the surface, embedded profilometer for measuring the local surface distortion and real time processes for computing the optimized delay laws. Those delay laws are computed by the M2M acquisition system and applied in real time to the piezoelectric elements. The 2D and 3D-flexible probes are manufactured by IMASONIC Company. In this communication, we present recent developments and examples of results obtained with this technique on industrial applications to locate and to size the flaw in the part. Moreover, real time reconstruction of parts exploiting the measurement from the external and the internal geometries thanks to the embedded profilometer and the acoustical back-wall echo are presented. Finally, advanced reconstruction algorithms coupled to smart flexible phased-arrays are evaluated on representative mock-ups.

Introduction

In most of industries as aeronautics, aerospace and nuclear, the ultrasonic inspections of components are usually performed in contact with conventional monolithic wedge transducers. The active aperture is adapted to a particular surface but in case of an irregular surface, the fixed shape of wedge cannot be fit the evolving geometry. Acoustical Mismatching between the surface profile under test and the base of the wedge produces an irregular coupling layer which leads to beam distortions and can reduce the inspection performances. The development of flexible ultrasonic arrays answers to the lack of adaptability to complex geometry of common ultrasonic probes. 2D flexible arrays, suitable for 2D or 2.5D pieces, have been developed and previously presented [1,2]. Experiments have shown their ability to focus longitudinal and shear waves, to measure the emitting surface deformation with a good accuracy, and to calculate delay laws in real-time. 3D flexible phased-array probes have also been developed in order to improve inspections of 3D geometries [3].

The first part of this paper is devoted to the 2D flexible phased-array transducer. The probe and the acquisition system are described, and a first application presents a multi-shot configuration to inspect a 2D realistic profile mock-up containing artificial reflectors. Furthermore, a new real time functionality allowing the geometric reconstruction of complex component is shown. This reconstruction consists in an external geometry measurement with the embedded profilometer and an acoustical back-wall echo detection for the internal geometry measurement.

The second part presents two applications of 3D flexible phased-arrays. In the first one, a flexible probe is moved by a robot in order to perform complex trajectories. Reconstructed

data in the 3D geometry are presented using reconstruction tools of the CIVA software. In the second part, another 3D flexible phased-array is used to control a complex 3D component containing flaws around a weld.
In the last part, an advanced reconstruction algorithm coupled to the smart flexible phased-array technology is evaluated on representative mock-ups. This post-processing algorithm, implemented in the CIVA software under the name of FTP algorithm (French acronym of "Focalisation en Tout Point"), exploits the complete set of elementary signals corresponding to all the pairs of transmitting and receiving elements of the array [4,5]. The acquisition technique of these elementary signals is frequently called "Full Matrix Capture" (FMC). The applied FTP processing then consists in a coherent summation of elementary signals (synthetic focusing) based on a time of flight inverse matching. In this paper, we present an application of a new multi-modal version of the FTP algorithm [6] to the imaging of crack-type defects in a complex mock-up.

1. 2D flexible phased-array transducers

1.1 Principle

The flexible array transducer is composed of 32 linear piezoelectric elements, mechanically assembled to obtain a structure able to deform its shape to a bending radius of 15 mm (see Figure 1). This ultrasonic sensor is housed with two other systems: a mechanical device pushing the elements on the surface and an instrumentation measuring the irregular profile fitted by the transducer. The profile measurements are then processed in real time by an algorithm calculating the delay laws matched to the profile. This technology insures to master the beam’s characteristics (i.e. orientation, focusing depth, steering). The probe is manufactured by IMASONIC Company.

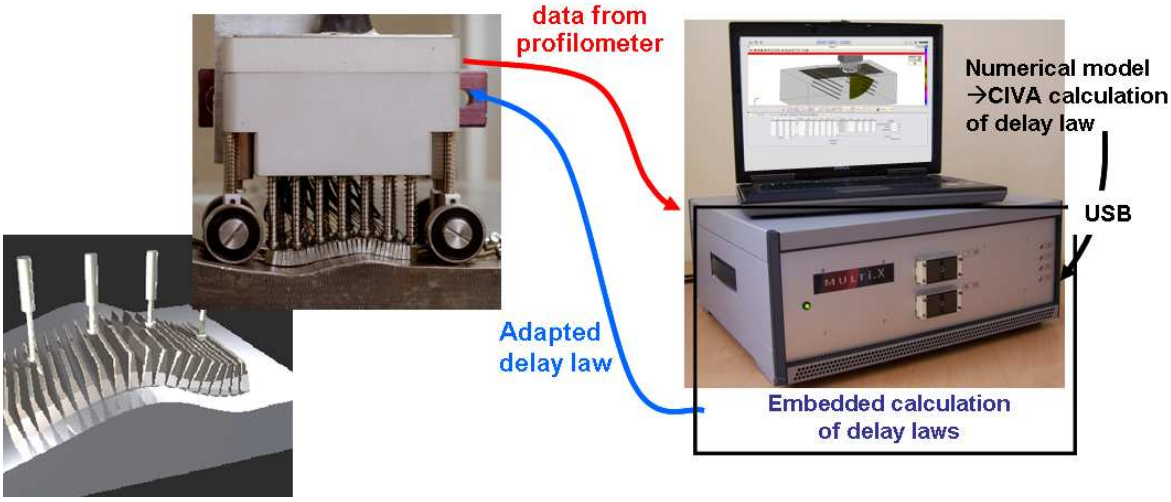

Figure 1: 2D flexible transducer and the acquisition system Multi-X 128 parallel channels.

The transducer is fixed to an arm, driven by stepping motors. A real time UT acquisition system (provided by M2M Company) controls the scanning, the electrical excitation of each element, the adaptive process and the data storage. The real time calculation of the delay laws is performed by the FPGA component of the system. These delay laws take into account the focus characteristics and the actual deformation of the emitting surface given by the instrumentation. The repetition rate can be up to 1000 times per second to calculate and to apply one delay law. This particular operating mode using the embedded calculation functionality of the acquisition system requires the hardware Multi-X acquisition system.

1.2 Experimental detection under a 2D irregular geometry

To demonstrate the ability of the flexible probe in real time adaptive mode, experiments have been carried out with a complex profile mock-up containing artificial reflectors (see Figure 2). The mock-up is representative of a welded component with an irregular surface, measured on a realistic profile measurement. The component contains two identical sets of four Side Drilled Holes (SDH) of 2 mm diameter, at 20, 30, 40 and 50 mm depth. The first set of SDH is located below a flat interface, as reference reflectors, while the second set is placed below an irregular profile. The mock-up inspected is a planar extrusion so the validation had been done using the 2D flexible transducer.
To cover the zone of interest for one mechanical position of the probe, acquisitions were carried out in longitudinal waves by focusing 30 focal points between 0° to 55° at 40 mm depth. In this configuration, the repetition rate of the embedded process is about 300 Hz for the application of the 30 delay laws. This rate is compatible with the resolution of acquisition and displacements of the probe on irregular surfaces.
Figure 2 shows ultrasonic signatures for two detection positions of the probe. In both cases, the set of SDH are detected with a good sensitivity and accurately positioned. These results show that the self-adaptive process allows to master the characteristics of the different focused beams below the plane surface as well as below the irregular profile (orientation, focusing depth, steering).

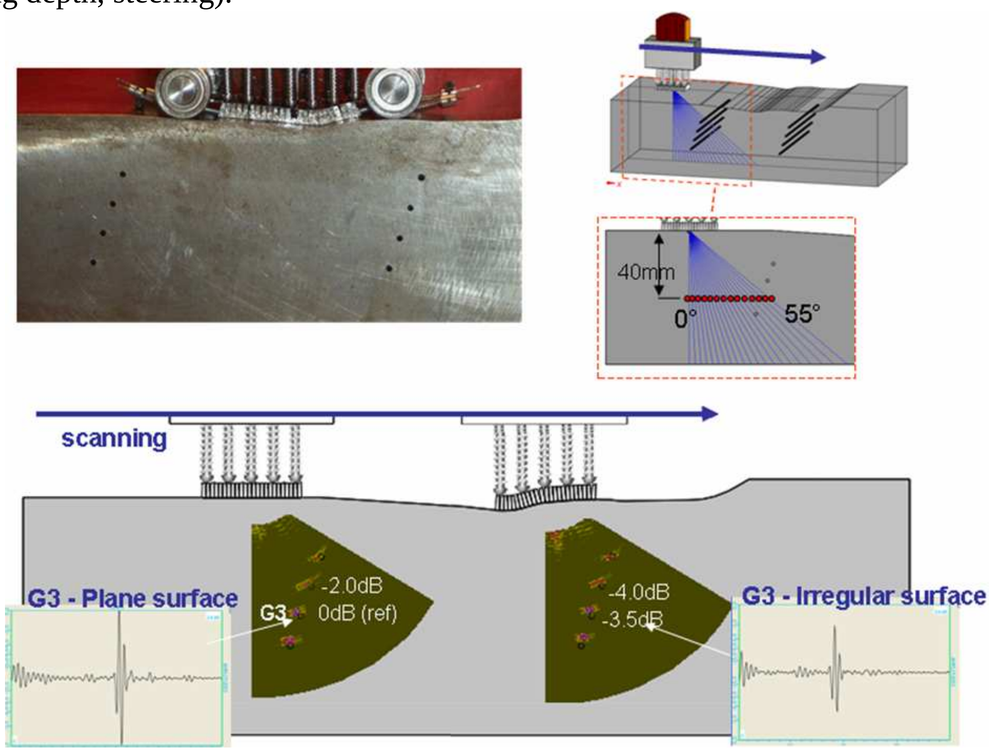

Figure 2: Sides Drilled Holes detection under a 2D realistic profile using a multi-shots configuration.

1.3 Real time reconstruction of the external and internal geometry

A new real time functionality allowing the reconstruction of the complete 2D geometry of a complex component has been developed. This functionality uses the profilometer to reconstruct the external geometry. Then, the control of a focusing beam LW0° along the

scanning allows to measure the local thicknesses (from the time of flight of the back-wall echo), and then to deduce the internal geometry of the component.
Figure 3 illustrates the real time geometry reconstruction of a mock-up representing a realistic butt weld. Both external and internal profiles are reconstructed with a good accuracy, i.e. ±0.1 mm for the external profile, and ±0.4 mm for the internal one.
The reconstructed geometry can be saved as a CAD file and used in CIVA software for other applications.

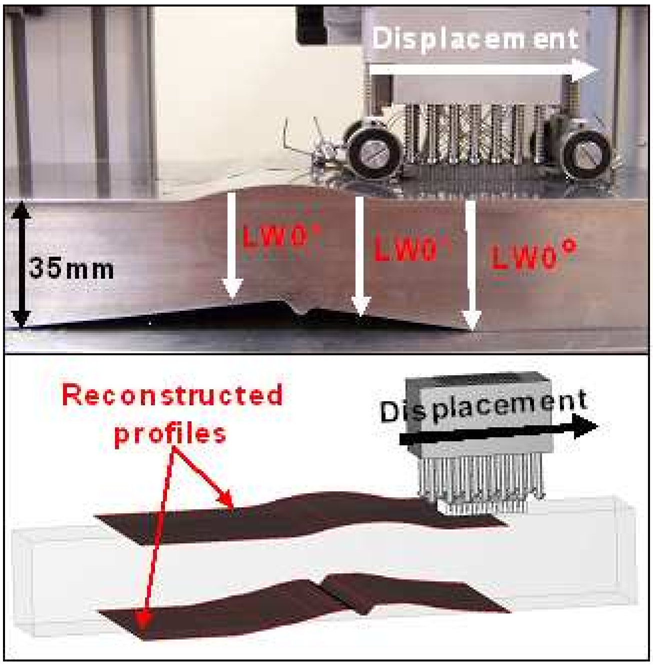

Figure 3: Real time reconstruction of the external and internal profiles of a complex component with a 2D flexible phased-array.

2. 3D flexible phased-array transducers

In order to extend the application field of the flexible phased-array to 3D geometries, 3D sensors have been developed. The aperture is now a matrix distribution of piezoelectric elements molded in a soft resin.
The 3D array presented in Figure 4 is composed of 12x7 elements (1.8x2.5 mm²) molded in a 50mm-diameter resin. The effective aperture of the probe is 32x 26 mm². The mechanical part is composed of 3 by 3 matrix pistons which push the array to the surface of the component and measure the deformation of the surface, by means of displacement sensors. As the 2D concept, the 3D flexible phased-array probe is also manufactured by IMASONIC Company.
The MultiX-UT acquisition system presented previously is used to monitor, both the signals and the voltages coming from instrumentation (deformation measurement).

2.1 Experimental detection of a 3D geometry using a robot

The nozzle mock-up displayed in Figure 5 represents the upper part of pipes junctions (only for geometry) contained in circuits of nuclear power plants. It corresponds to a stainless steel mock-up, without welding junctions. The mock-up contains a flat-bottom hole (FBH), distant of 40 mm from the surface and located where the internal profile is conical.
To insure complex 3D trajectories, acquisitions were carried out with a robot. These acquisitions were carried out with LW0° (from the local normal direction) for the detection of the FBH located under the cylinder/cone junction.

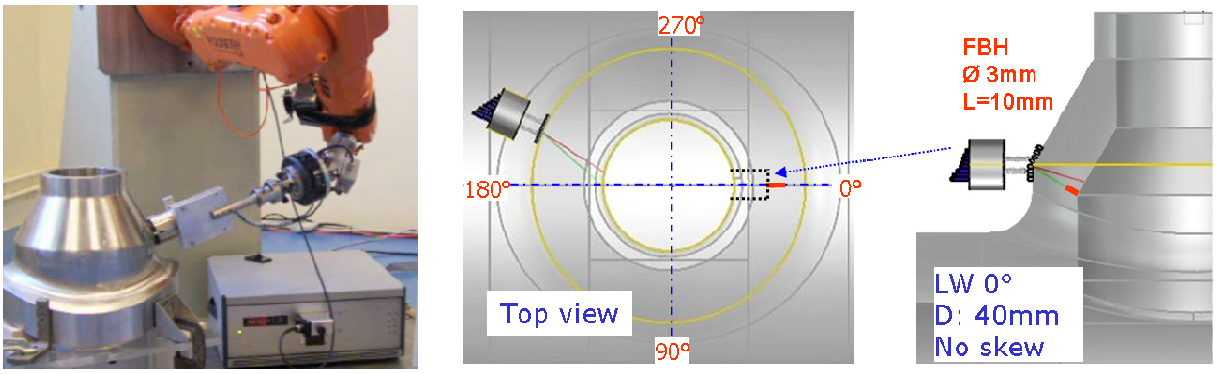

Figure 5: Nozzle mock-up and inspection configuration.

Figure 6 below presents the experimental detection results of the defect performed along the circumference using an angular scanning of 50° around the nozzle.

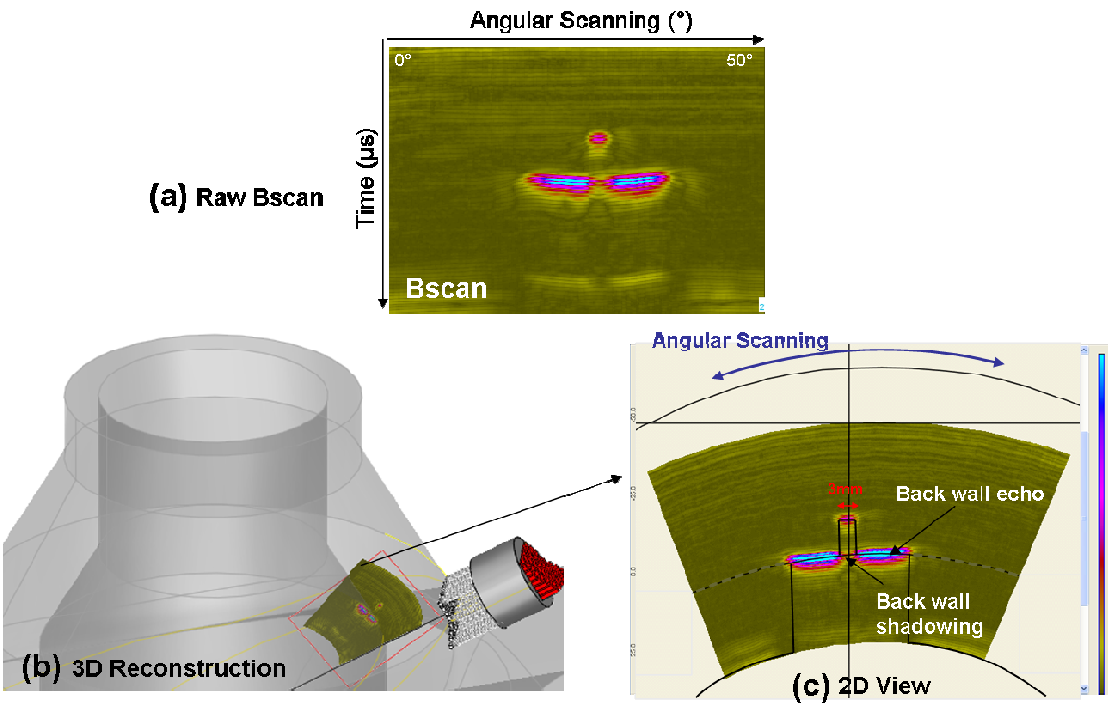

Figure 6: Detection, positioning and sizing of a FBH: raw Bscan (a), reconstructed Bscan in the 3D CAD mock-up (b), 2D view (c)

As shown in Figure 6(a), experimental results can be represented as raw Bscan, but can also be reconstructed in the incidence plane defined by the orientation of mean beams for each position. Figure 6(b) shows the experimental result reconstructed in the 3D geometry with LW mode on the FBH (diameter 3 mm, height 10 mm). This representation facilitates the interpretation of echoes (coming from the flaw and the back-wall), and the accurate positioning of the defect (angular position and depth). Strong back wall echoes are present along a limited angular sector of the scan (where the back wall is parallel to the conical external surface).

The result validates the mechanical part of the flexible array, the efficiency of the acoustical matrix aperture and the embedded process, which reconstructs the 3D surface and computes in real time the adapted delay laws.

2.2 Detection and characterization of defects in a complex varying geometry mock-up

The mock-up displayed in Figure 7 reproduces a part of the mixing zones present in circuits of nuclear power plants. The 3D sensor is used for the inspection of a welded junction between two nozzles. In collaboration with EDF, we have studied the control of this area with a flexible matrix probe. The testing area corresponds to the inner part of the geometry just before the welded joint (15 mm on both sides from the welded joint). Figure 7 also illustrates the mismatches between a probe with solid wedge and the complex surface of the testing area.

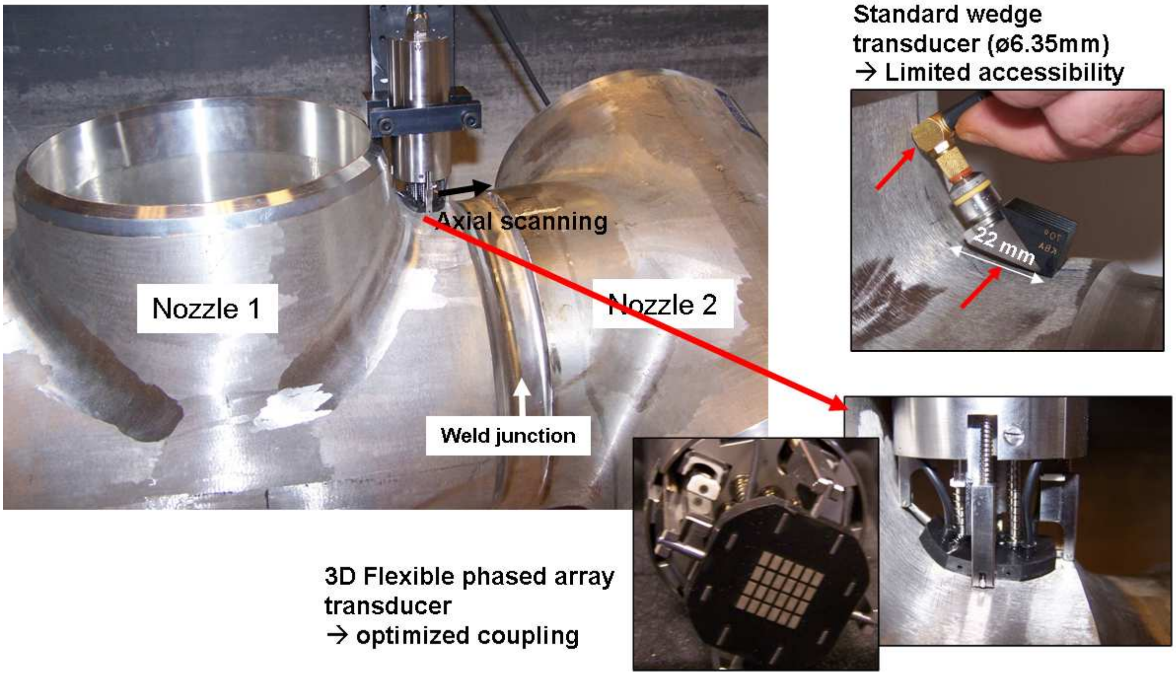

Figure 7: Problematic and inspection configuration with the 3D flexible phased-array.

Figure 8 describes the mock-up geometry. 4 notches had been machined below the most restrictive surface of inspection (presence of the fillet radius of the secondary pipe corresponding to the nozzle 1), for which conventional wedge transducers are not adapted. The reference for the notch positioning is the edge of the welded joint. The defects have 2-mm height and are positioned between 0 mm and 9 mm from the welded joint.

In order to cover the zone of interest for one mechanical position of the probe, acquisitions were performed using 20 focal points located between 30° to 65° in shear waves at 15 mm depth. An axial scanning had been defined to optimize the signal amplitude.

To conform to the irregular profile (requiring a radius of curvature up to 20 mm), and to inspect the zone of interest with shear waves beyond SW60°, a specific 3D flexible phased array transducer has been developed. For reason of accessibility, the mechanical part of the probe had been reduced.

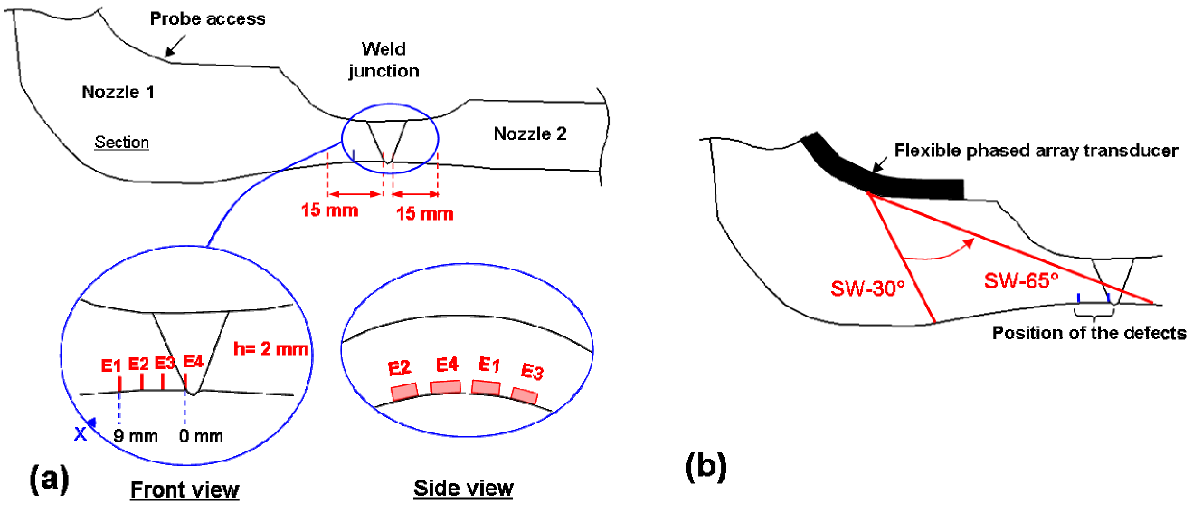

Figure 8: Experimental configuration with the 3D flexible phased-array.

Figure 9 below presents the detection results of the two notches located at 9 mm and 6 mm away from the welded joint. The reconstructed Bscan view and the A-scan corresponding to the maximum of detection are presented.

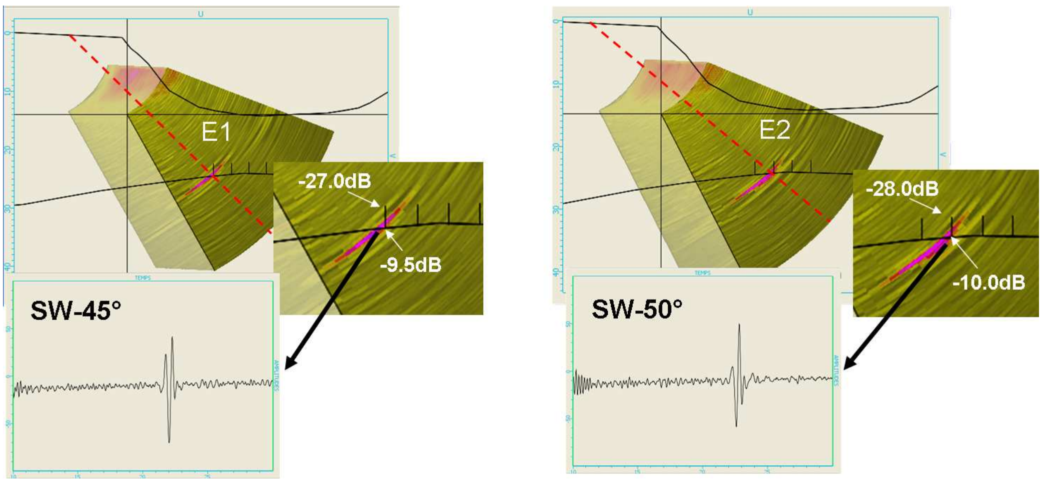

Figure 9: Experimental results of detection at 9 mm and 6 mm away from the welded joint.

Detection results show that the two notches are well detected with a good signal to noise ratio. Regarding the E1 notch, the detection is optimized with SW-45° and reaches a level of -9 dB compared to the reference (detection of a notch under a plan surface at the same inspection depth). Regarding E2, the detection is optimized with SW-50° and the detection level reach -10 dB compared to the reference. Moreover, acquisition results emphasize the tip diffraction echoes so that can be used to characterize their height (2 mm).

These results confirm that the matrix developed has a sufficient directivity to detect the notches closest to the welded joint. In conclusion, the flexible phased array probe is able to cover the entire area of interest in this representative mock-up.

3. Imaging notches in a complex component with the post-processing algorithm FTP

3.1 The imaging algorithm FTP

From a general standpoint, the synthetic imaging algorithm FTP is the mapping in the region of interest of an estimator measuring the likelihood of the presence of a scatter at a point of this region. The FTP algorithm basically consists in coherently summing the received signals which leads to obtain maxima of such an estimator at the location of the scatterers [4,5]. This idea of synthetic focusing signals has been firstly introduced in ultrasonic NDE field with the well-known SAFT algorithm [7]. The experimental results presented in the following have been obtained by applying the FTP algorithm to FMC data, i.e. the complete set of elementary signals corresponding to all the pairs of transmitting and receiving elements of the flexible probe.
In order to improve the imaging of crack-type defects near the back-wall of a component, the FTP algorithm has been generalized to multimodal echographies [6] that take into account so-called corner effects, involving one reflection on the defect and one on the back-wall. The mode conversions between longitudinal (L) and transverse (T) polarizations at each interaction have also been taken into account. In the following, a given wave path characterized by a succession of interactions defect/back-wall and mode conversions is called “mode”.

3.2 Imaging notches in a complex component

Experiments have been performed on a steel block exhibiting a complex geometry representative of a welded component and containing a 10 mm breaking notch. The geometry can be seen in Figure 10. A 2D flexible phased-array, 24 elements, 2 MHz, has been used on this part to generate FMC data.
Figure 10 presents the images obtained for a position of the probe that corresponds to a focusing LW45° on the bottom tip of the notch. In the FTP algorithm, the time of flight computations take into account the complex geometry of the entrance surface and of the back-wall. Image (a) is obtained using the direct mode TT that does not involve reflection on the back-wall. The images (b), (c) and (d) respectively correspond to corner modes LLT, TLL and LTT involving one reflection on the back-wall. In these notations, the reflection on the back-wall takes place between the first and second terms.

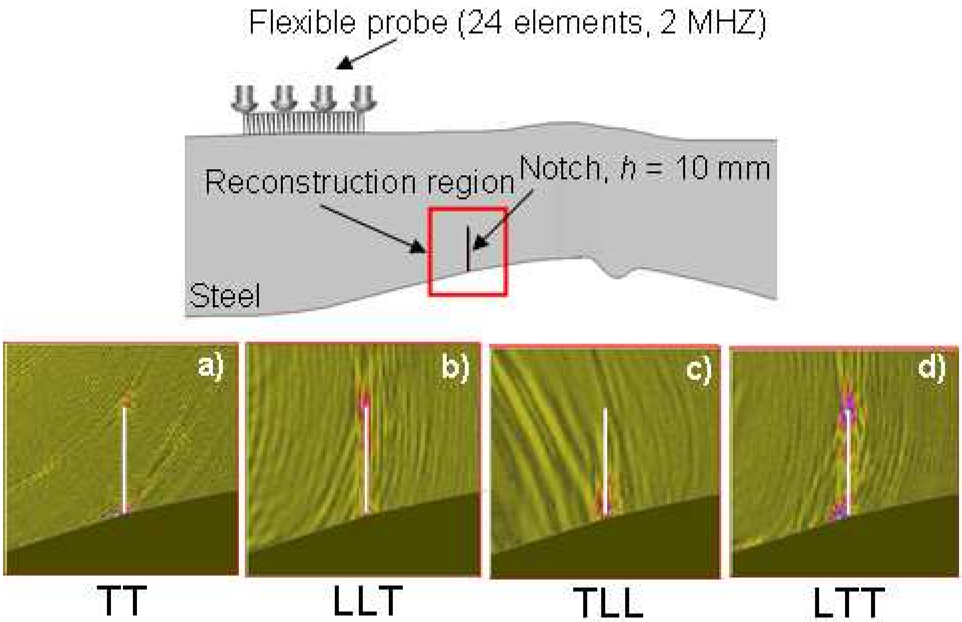

Figure 10: Imaging a vertical 10 mm breaking notch in a complex part.

As expected, the image (a) emphasizes the two spots corresponding to the two tips of the notch. More interesting are the images (b) and (d) corresponding to the LLT and LTT reconstructions. Using these corner modes, the notch is imaged along its entire length. This is a quite valuable result unreachable with classical inspection techniques. As the position of the probe corresponds to a focusing LW45° on the bottom tip of the notch, the notch is better imaged for modes involving an incident longitudinal wave on the back-wall (the reconstruction fails for the TLL mode).

Conclusion

2D and 3D smart flexible phased-array transducers were developed to improve ultrasonic inspections of complex geometry components. For 2D or 3D geometries, the experimental results carried out on realistic components have shown their abilities to detect different type of defects with a good SNR. Moreover, the embedded functionalities of the acquisition system offer many perspectives of development for real time interfacing of phased-array sensors, which will be easily implemented since no hardware modification is needed. For instance, a new real time functionality allowing to reconstruct the external and internal profiles of a complex component has been presented.
In the last part of this paper, the FTP reconstruction algorithm has been applied to a FMC acquisition carried out with a 2D flexible phased-array. For of crack-type defects near the back-wall of a component, the experimental results have demonstrated the interest of involving in the algorithm more complex wave paths than direct echoes to improve the imaging of this kind of defects.

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