PipING Inspection using A Smart Flexible Phased Array

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Abstract. The inspection of piping in nuclear power plants is mainly performed in contact with ultrasonic wedge transducers. Some areas of circuit pipes have variable geometries (variable radius of curvature, irregular surface conditions) which may limit the efficiency and even the accessibility for wedge transducers.
A prototype of smart flexible probe was developed with the support of EDF in order to improve such inspections. The phased array is flexible so as to fit the variable surface. A profilometer, embedded in the transducer, measures the local surface distortion allowing the computation, in real-time, of optimized delay laws and compensate the surface aberration. Those delay laws are transferred to the real-time UT acquisition system, which applies them to the piezoelectric elements. This self-adaptive process preserves, during the scanning, the features of the focused beam (orientation and focal depth) in the specimen. This paper presents results obtained with the prototype on realistic pipes configurations. The inspected configurations were also simulated with the CIVA Software. The good agreement between experimental and simulated results validates the acoustical behavior of the probe and confirms the accurate control of the beam focusing during the tests.

Introduction

If ultrasonic contact conventional transducers are well suited to the inspection of a large panel of components, the quality of the coupling between the array and the part under test remains a major limitation of such methods. This needs necessary to design sensors adapted to each situation or geometry. The development of flexible ultrasonic arrays answers to lack of adaptability to complex geometry of common ultrasonic sensors. 2-D flexible arrays, suitable for 2D or 2.5-D pieces, have been developed and presented previously [1]. The experiments have shown their ability to focus with L and T waves, to measure the emitting surface deformation with good accuracy, and to calculate delay laws in real-time (embedded process with a repetition rate of 250 Hz). A prototype of 3-D smart flexible probe has also been built with the support of EDF in order to improve inspections of 3-D geometries.

The first part presents the 3-D flexible array, the acquisition system and the mock-up containing machined flaws such as notches and holes. Different operating modes are possible using delay laws calculated by the embedded algorithm and executed by the MultiX apparatus from M2M or computed by the CIVA software and applied by the UT-system. Comparisons between theoretical and experimental delay laws are shown.

The second part exposes examples of the CIVA software computation used to design the array and to evaluate its detection performances.

Finally experimental results are presented and compared to simulation. This last part details:

- the validation of the different operating modes, and in particular the real-time instrumented acquisition method.
- the presentation of the CIVA software reconstruction functionalities and the application of such tools to flaws positioning and sizing
- the evaluation of the geometry influence on detection performances.

3D Flexible Phased Array, acquisition system

The 3-D array plotted (Figure 1) is composed of 8x8 piezoelectric elements moulded in a flexible matrix of resin. This disk of diameter 50 mm presents an effective aperture of 27x31 mm². Pistons push the array to the surface of the piece under test, 9 of them (3 by 3 square-matrix) are used to measure the deformation of the surface, thanks to displacement sensors. Each of the 64 piezoelectric elements is linked to his own independent emission-reception channel. The MultiX UT acquisition system (128 parallel US channel, emitting pulses up to 200 Volts and receiving with 10bits ADC, sampling up to 100MHz) is used to monitor, both the US signals and the voltages coming from instrumentation (deformation measurement).

The M2M system allows two operating modes. The first one uses a software calculation of delay laws, included in the M2M interface software. The calculation takes into account the geometry of the specimen, the position of the array and the whished focal spot position. Then this “ideal” delay laws is transferred to the UT acquisition system and applied to the phased array. In this mode the repetition rate can be chosen up to 30 kHz.

The second way to perform the same experiment is to use the embedded calculation functionality of the MultiX acquisition system: the real time calculation of the delay laws is performed by the FPGA circuitry of the system. With this mode, the real time delay law takes into account the focus characteristics and the actual deformation of the emitting surface given by instrumentation. In this mode, the repetition rate is up to 100 Hz, but will be increased by algorithm optimization.

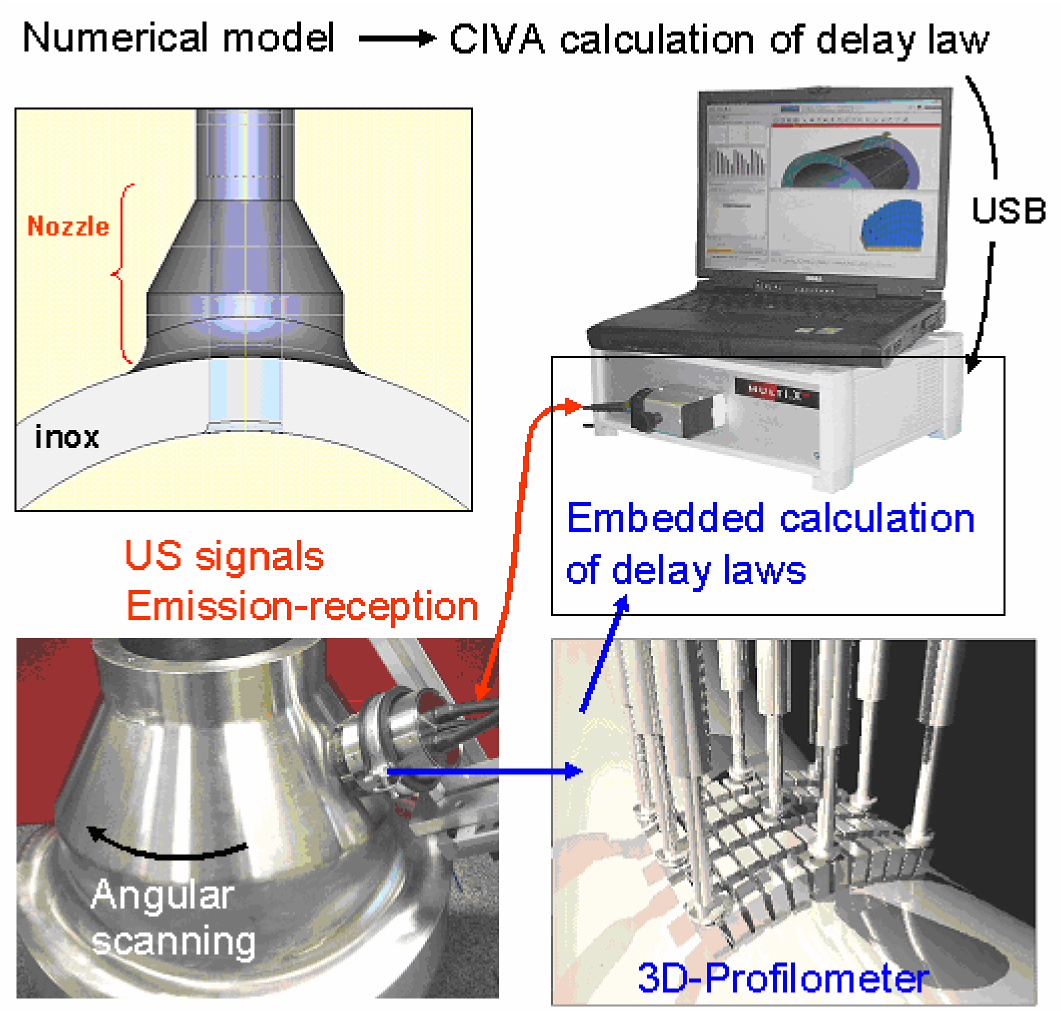


Figure 1: 3-D flexible 8x8 elements array and the acquisition system MultiX 128 parallel channels

Pipe nozzle mock-up description

The nozzle mock-up presented Figure 1 reproduce the upper part of pipes junctions present in circuits of nuclear power plants. The defects machined in the mock-up are summarized on Figure 2. The CIVA graphical tools allow to draw the complete specimen: the flaw and the array positions for each detection. The detections are performed along an angular scanning of 50° around the piece, but a scan along the generatrix is also possible.

For notches (N) and side drilled holes (SDH), the incident angles of detections are chosen at LW45° (angle between the ultrasonic beam and the radial direction of the defect) and LW0° for flat bottomed holes (FBH). The focusing features used for each defect are indicated in blue. The depth is defined as the projection of radius vector on the radial (perpendicular to the revolution axis). The notches are placed from the bottom surface, the side drilled holes are parallel to the top surface (cone and cylinder) at 40 mm-depth. The top of the flat bottomed hole is located under the cylinder-cone junction with a 40 mm-ligament. In order to detect the notch corners located under the cone, the beam has to be perpendicular to the axis of the secondary pipe. So, in the case of N2, the beam has to be tilted 22° in the incidence plane and skewed 30°.

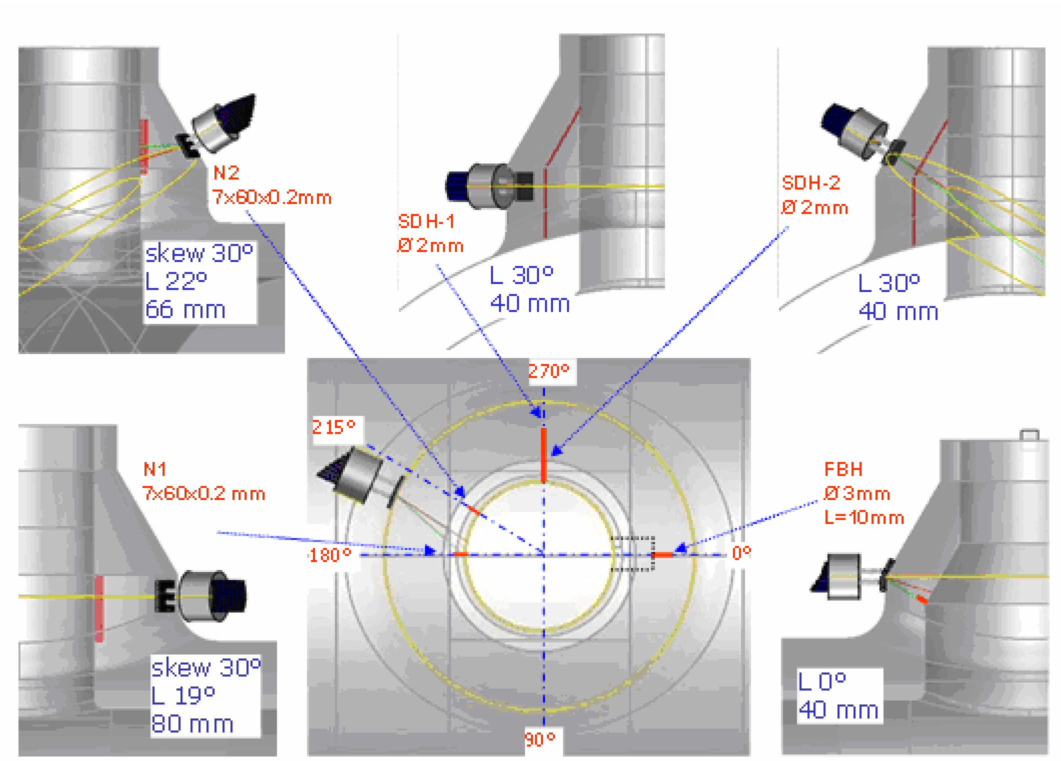


Figure 2: Mock-up summarizing the positions of the defects and the array. Angular positions of the flaws are shown on the central view and details are schematized on lateral views.

Field Calculation using CIVA software

The CIVA software computes the ultrasonic field propagation transmitted through the surface and the delay laws according to the deformation of the phased array. The represented positions are chosen to detect notches and side drilled holes with longitudinal waves. The Figure 3 presents the focus beams obtained in the same plane corresponding to the notches plane for three positions of the probe on the cylinder and the cone. The focusing characteristics are calculated to focus LW45° in this plane. Those geometries show that no skew angle is needed for the detection from the cylinder and from the cone the beam is 30°-skewed. The results of ultrasonic field calculations show that the shape and size of the spot are satisfying in regard to the aperture of the array, and the deformation of the surface does not degrade focusing. The Table 1 summarizes the focal sizes and the detection levels. These results allow to predict the spatial resolution and to verify the good positioning of the focal spot and also the capabilities of the flexible phased array to control a 3D-geometry. Similar calculations have shown that the whole aperture is not necessary for focusing depth smaller than 100mm, and experiment have shown that the maximal depth of focusing is greater than 150mm.

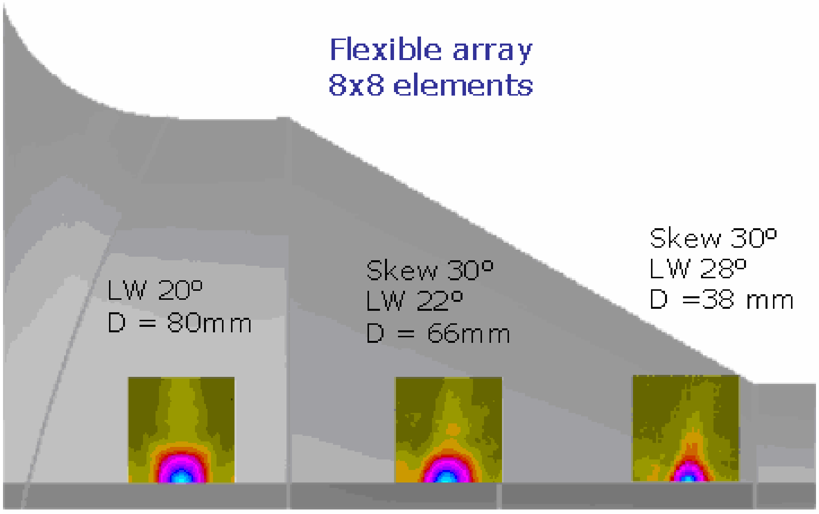


Figure 3: Field calculations with the flexible phased array.

	Skew 30°, L 28°, depth 38 mm	Skew 30°, L 22°, depth 66 mm	Skew 0°, L20°, depth 80 mm
Focal area	4 x 2 mm²	6,5 x 3,5 mm²	7 x 4 mm²
amplitude	0,1 dB	-3,5 dB	0 dB

Table 1: Focal spot size and maximal amplitude of the ultrasonic field (the level obtained on the cylinder is chosen as reference).

Experimental results

This experimental study presents the performances of the flexible array and in particular the embedded functionality and some comparisons with the previous simulation results. The five defects are detected using 50° degrees angular scanning presented Figure 2. All experiments have been performed using longitudinal mode with incident angle between 0 and 30° (relatively to the array normal).

Instrumentation: validation of the embedded mode

We compare the theoretical delay law to the values calculated with the instrumentation, in the most unfavourable situation, i.e. the transition cone-cylinder (detection position for the flat bottomed hole FBH-1).

First, the altitudes of pistons are in reasonable agreement with theoretical values. The figure 4 presents the superimposition of delay laws computed by the embedded algorithm and the theoretical values from the CIVA. The slight differences correspond to the elements located on/and around the cylinder-cone junction; but, the good fitting of curves validates the good behaviour of the embedded real time process of reconstruction. The delays are very close which insure correct angles and focusing depth.

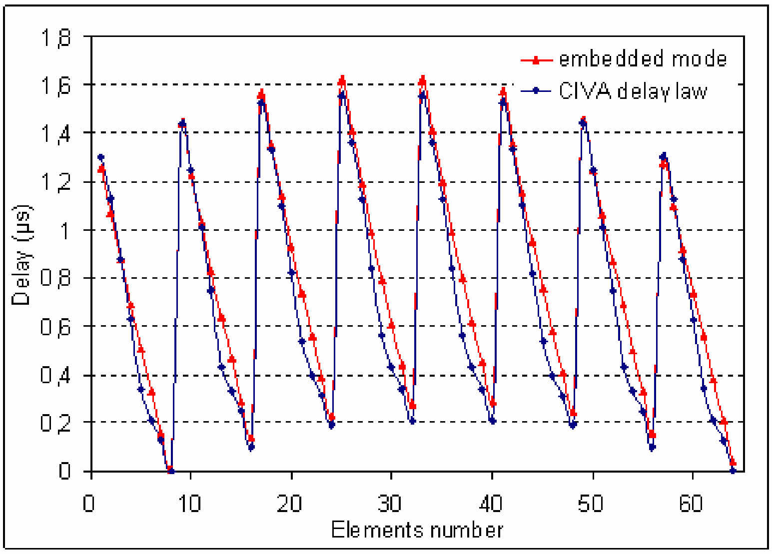
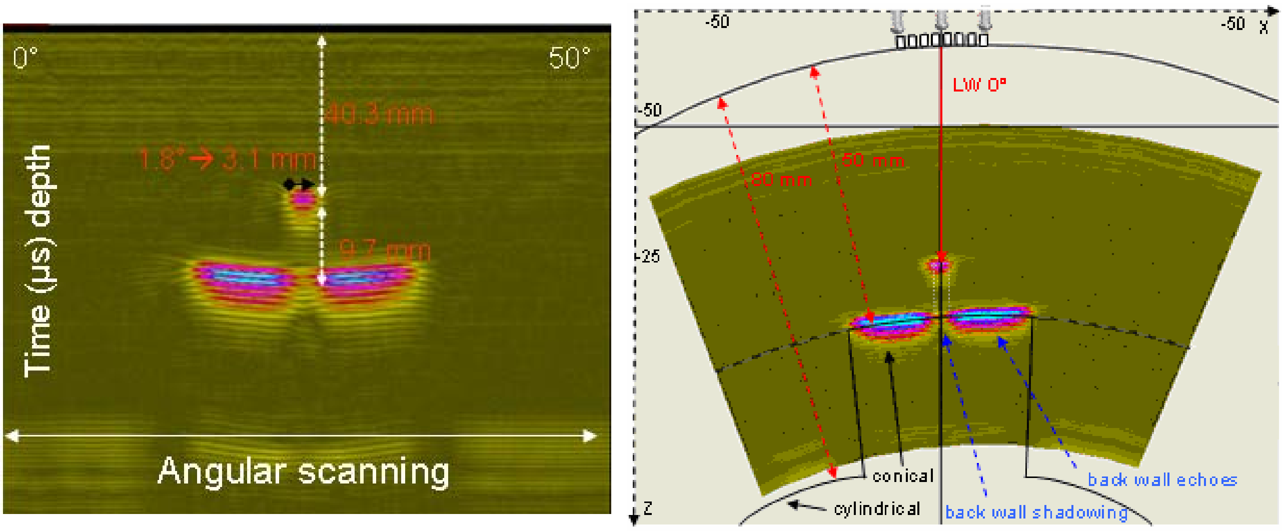


Figure 4 : Delay laws calculated by CIVA on the nominal profile and by the embedded algorithm.

The probe is fixed to an arm and move along the circumference. The embedded process computes the delay laws with a 50Hz-repetition rate. The acquisition is carried out with LW0° (from the local normal direction) for the detection of the flat bottomed hole (FBH-1) located under the junction.

Experimental results can be represented as raw Bscan (fig.5-a), but can also be reconstructed in the incidence plane defined by the orientation of mean beams for each position.



(a) raw Bscan (b) Reconstructed Bscan

Figure 5 : Detection, positioning and sizing of a flat bottomed hole.

The **Fehler! Verweisquelle konnte nicht gefunden werden.**5-b gives an example of such reconstruction with LW mode, incident at 0° on the flat bottomed hole (diameter 3 mm, height 10 mm). This representation allows an interpretation of echoes (coming from flaw, back wall) and an accurate positioning of the defect (angular position and depth).

These results show the good performances of the device on strongly distorted surface and validate the mechanical part of the flexible phased array, the efficiency of the acoustical matrix aperture and the whole embedded process which reconstructs the 3D-surface and computes in real time the adapted delay laws.

Detection of a side drilled hole

The figure 6 presents the SDH-2 detection located under the cone with a 20° angular scanning performed along the circumference. The incidence angle is 30° from the probe to insure a LW45°-detection. We note the signature of the SDH on the raw B-SCAN view presented on the fig.6-a. The signal to noise ratio may be estimated from the A-SCAN stored at the max of detection. The SNR level is bigger than 20dB. With the graphical tools of the CIVA, the data may be reconstructed in the 3D model of the acquisition. The result is presented on the fig.6-c where we note the repositioning of the flaw which is superimposed with the white circle corresponding to the perimeter of the flaw.

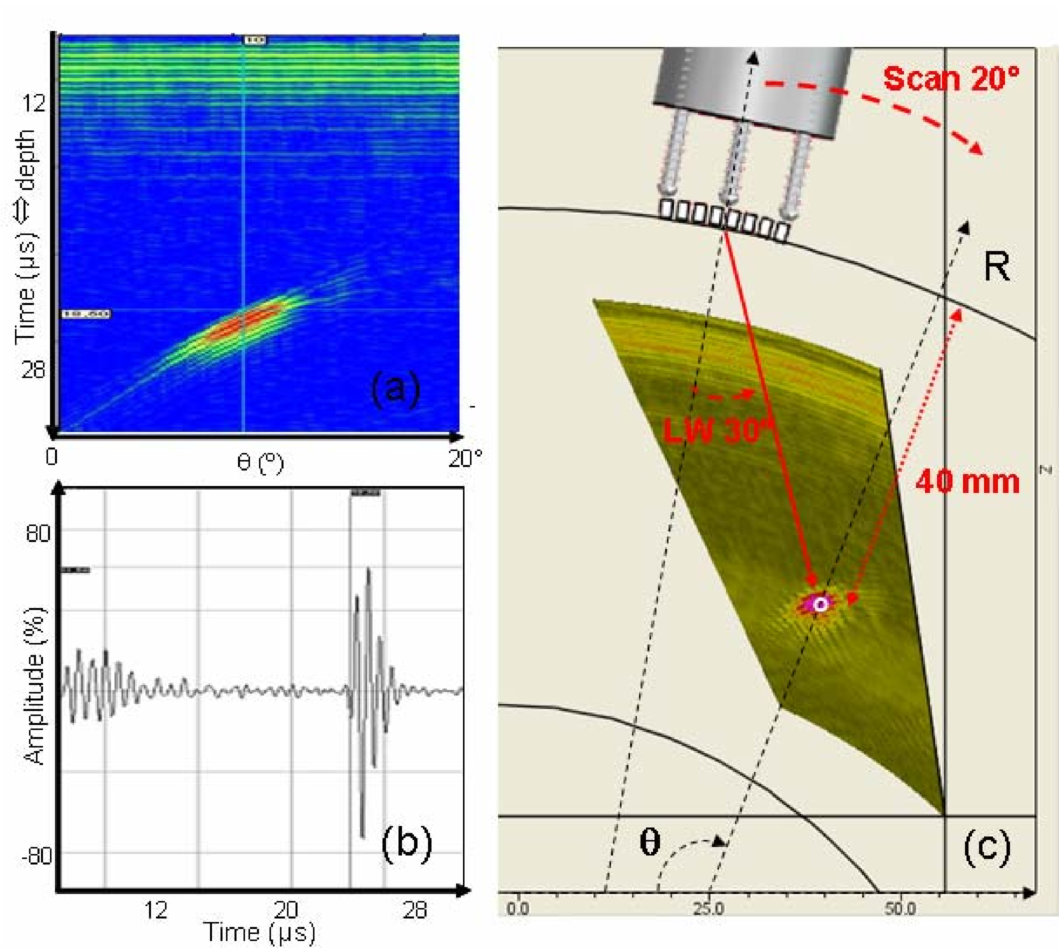


Figure 6 : detection of SDH-2 : presentation of the raw Bscan (a), Ascan (b) and the reconstructed in 3D CAD mock-up

Conclusion

A 3D-flexible array has been developed and driven by the UT-acquisition system. The presented prototype is a 3D-extension of the linear distribution of the 2D-flexible array, which has been already validated on 2-D geometries. Such devices allow to use the same sensor to inspect a wide range of geometries. The piping inspection offers a realistic situation to validate this technique and show its potential applications.

This technique has shown its ability to detect the different type of modelled defects with good SNR. In particular, detection and sizing of notches can be achieved using corner and tip diffraction echoes. Delay laws calculated in real-time (embedded mode using instrumentation) give the same results as the theoretical delay laws. The embedded functionalities of the acquisition system offer numerous perspectives of development for real-time interfacing of phased array sensors, which will be easily implemented since no hardware modification is needed.

The CIVA software allows to evaluate the flexible array performances on realistic nozzle geometries. Numerical results are validated by experiments. Defects signatures and detection levels are in good agreement with the simulation. Positioning and sizing is accurately achieved using the reconstructions processing.

Reference

[1] S. Mahaut, O. Roy, O. Casula and G. Cattiaux, "Pipe Inspection using UT Smart flexible Transducer", 8th ECNDT, Barcelona proceedings 2002.

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