ABSTRACT

The piping inspection in nuclear power plants is mainly performed with ultrasonic wedge transducers in contact with the component. The control is efficient, and the transmission is maximized when the wedge of the transducer is adapted to the surface of the part. However, some parts of circuit pipes have variable geometries (variable radius of curvature, irregular surface conditions), which may limit the efficiency and the accessibility for wedge transducers. In that case, the transmitted field is disturbed and can lead to missed detection, wrong echo localization and characterization. To optimize the contact with these kinds of geometry, smart 2D and 3D-flexible phased-array probes have been developed and are manufactured by IMASONIC Company. These transducers integrate an embedded instrumentation measuring in real time the actual shape of the emitting surface. Then, the software of the M2M acquisition system including a specific library is able to calculate the new delay laws taking into account the current shape of the array. The first part of this paper presents the recent results obtained for the inspection of 2D realistic mock-up including artificial defects. Performances are evaluated using a multi-shots configuration with several delay laws calculated in real time with the embedded process. The second part shows two examples of 3D mock-ups inspections using a flexible array transducer. In the first application, the 3D probe is driven by a robot in order to follow complex trajectories. Reconstructed data in the 3D-geometry are then presented using reconstruction tools of the CIVA software. The second application presents a 3D weld inspection.

Keywords: Non Destructive Techniques, Ultrasonic Methods, Flexible Phased-Array Transducer, adaptative methods.

INTRODUCTION

Ultrasonic inspection of complex geometry components is usually performed with contact methods, using conventional monolithic wedge transducers. The active aperture in contact is adapted to a particular surface but in case of a complex and varying geometry, the fixed shape of wedge can not be matched to all inspected zones. Mismatches between the surface profile under test and the base of the wedge produce 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]. 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 (embedded process with a repetition rate of 1000 times per second). 3D flexible phased-array probes have also been developed in order to improve inspections of 3D geometries.

The first part of this paper presents recent examples carried out with the 2D flexible phased-array transducer. A first application presents a multi-shot configuration to inspect a 2D realistic profile mock-up containing artificial reflectors. The 2D flexible probe and the acquisition system are described and also experimental results obtained on the mock-up are presented.

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 one, another 3D-flexible phased array is used to control a complex 3D component containing flaws around a weld.
2D FLEXIBLE PHASED-ARRAY TRANSDUCERS

The flexible array transducer is composed of 32 linear piezoelectric elements, mechanically assembled to obtain a structure able to deform its shape with a radius of curvature up to 15 mm. This ultrasound sensor integrates two other systems: a mechanical device pushing the elements on the surface and an instrumentation measuring the irregular profile fitted by the transducer. Such a profilometer is driven by a self-adaptive process, which measures the actual position of each element on a complex profile, computes the adapted delay laws, applies them and stores the reconstructed waveforms. The method insures to monitor the beam’s characteristics (orientation, focusing depth, steering). This probe is manufactured by IMASONIC Company who owns its commercialization license.

The transducer is fixed to a mechanical 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. The delay law takes into account the focus characteristics and the actual deformation of the emitting surface given by 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 standard hardware Multi-X acquisition system with only updated software which includes a specific library.

![Figure 1 - 2D flexible phased-array and the acquisition system MultiX 128 parallel channels.](image)

EXPERIMENTAL DETECTION UNDER A 2D IRREGULAR GEOMETRY

In order to validate the ability of the flexible probe in real time adaptative mode with a multi-shots configuration, experiments have been carried out in a complex profile mock-up containing artificial reflectors.

Acquisitions have been performed on a steel mock-up representative of a welded component with an irregular surface (measured on a realistic profile component). The mock-up 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 planar extrusion so the validation had been done using the 2D flexible transducer.

In order 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.

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 mastering the characteristics of the different focused beams below the plane surface as well as below the irregular profile (orientation, focusing depth, steering…).
3D FLEXIBLE PHASED-ARRAY TRANSUDCERS

In order to extend the application field of the flexible phased-array presented previously, limited to 2D irregular profiles, 3D flexible phased array transducers have been developed in order to conform 3D geometries such as elbows. The aperture is now a matrix distribution of piezoelectric elements moulded in a soft resin.

The 3D array plotted in Figure 3 is composed of 12x7 piezoelectric elements (1.8x2.5 mm²) moulded in a 50-mm-diameter resin. This probe presents an effective aperture of 32.6x26.5 mm². The mechanical part of the probe 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, thanks to displacement sensors. Like 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). In this 3D configuration, the repetition rate of the embedded process is higher than 150 Hz for the application of one delay law.

Experimental detection of a 3D geometry using a robot

Mock-up Description and Inspection Configuration

The nozzle mock-up displayed in Figure 4 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. Figure 4 summarizes a flat-bottom hole (FBH), distant of 40 mm from the surface and located where the internal profile is conical (limited angular sector).

In order to insure complex trajectories in 3D-geometry components, acquisitions were carried out using a robot, equipment supplied by the federative platform GERIM [2]. The acquisition is carried out with LW0° (from the local normal direction) for the detection of the flat-bottomed hole FBH located under the cylinder/cone junction.

Figure 4 - Nozzle mock-up and inspection configuration.

Inspection from the cone/cylinder junction

Figure 5 presents the experimental detection of the defect performed along the circumference using an angular scanning of 50° around the nozzle. Experimental results can be represented as raw B-scan (Figure 5-a), but can also be reconstructed in the incidence plane defined by the orientation of mean beams for each position. Figure 5-b shows the experimental result reconstructed in the 3D-geometry with LW mode on the flat bottomed-hole (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). This 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.

Figure 5 - Detection, positioning and sizing of a flat bottomed hole: raw Bscan (a), reconstructed Bscan in the 3D CAD mock-up (b), 2D view (c).

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

Mock-up Description and Inspection Configuration

The mock-up displayed in Figure 6 reproduces a part of the mixing zones present in circuits of nuclear power plants. Here, a 3D flexible phased-array is used for the inspection of a welded junction between two nozzles. 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 6 also illustrates the mismatches between a probe with solid wedge and the complex surface of the testing area.

To evaluate the performances of flexible phased arrays to inspect this geometry, 4 notches had been machined on the mock-up Figure 7. They are located 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. All 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. These acquisitions were carried out using an axial scanning 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. Moreover, the acoustical unit had been modified in order to generate shear waves with large angles. So, this probe presents an effective aperture of 12 x 12 mm². The mechanical part of the probe is composed of 3 by 3 matrix pistons which push the array to the surface of the component and measure its deformation thanks to displacement sensors.

![3D Flexible phased array transducer](image)

**Standard wedge transducer (6x35 mm)**
- **Limited accessibility**

**Figure 6. Problematic and Inspection configuration with the 3D flexible phased-array.**

**Figure 7 - Experimental configuration with the 3D flexible phased-array.**

*Experimental results of detection*

Figure 8 presents the detection 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. 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 -9dB 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 -10dB compared to the reference. Moreover, acquisition results emphasize the tip diffraction echoes so that can be used to characterize their height (2 mm).
Figure 9 presents the detection of the two notches located near the weld. Experimental results show that detection is optimized with a SW-55° regarding the E3 notch and with a SW-60° regarding the notch E4. Detection levels reach -13dB compared to the detection of a notch under a plan surface with SW-45° while the closest notch from the weld (E4) is detected at 20dB compared to the reference. The lower detection level regarding E4 can be explained by the surface which strongly disturbs the transmitted field with this refraction angle.

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.

CONCLUSION

Flexible phased-array transducers were developed to improve ultrasonic inspections of complex geometry components. The development of 3D flexible array follows the one of 2D array, which has been already validated on 2D and 2.5-D geometries. A such device can be used to inspect a wide range of geometries.
The piping inspection offers a realistic situation to illustrate the performances of this technology. The experimental results have shown its ability to detect different type of defects with a good SNR. Moreover, the embedded functionalities of the acquisition system offer numerous perspectives of development for real-time interfacing of phased array sensors (autofocusing technique, synchronized sum, focusing after surface learning…), which will be easily implemented since no hardware modification is needed.

Recent developments have been done on the embedded algorithm in order to inspect components with a multi-shots configuration. The result obtained on 2D irregular profile shows that the self-adaptive process allows to master the characteristics of the different focused beams in the specimen (orientation, focusing depth, steering…).

Inspection results performed with the flexible phased-array coupled with the reconstruction functionalities of CIVA show the ability to locate and to accurately size flaws under a 3D complex geometry component.

REFERENCES
