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A FLEXIBLE PHASED ARRAY TRANSDUCER FOR CONTACT EXAMINATION OF COMPONENTS WITH COMPLEX GEOMETRY

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Abstract: The inspection of cooling circuit components of French pressurized water reactors is mainly performed with contact ultrasonic transducers. The surfaces of components involve that the shapes of the solid wedges are not matched to the irregular surface or to the shape of components (butt weld, nozzle, elbow). This mismatch creates an irregular coupling layer between the wedge and the local surface, and can lead to beam distortions and losses of sensitivity. These two phenomena contribute to reduce the inspection performances. To improve such controls, a new concept of contact “smart phased array transducer” has been developed with the support of the French safety authorities (IRSN). The phased array is flexible to fit the complex profile and to minimize the thickness of the coupling layer. The independent piezoelectric elements composing the radiating surface are mechanically assembled in order to build an articulated structure. A profilometer, embedded in the transducer, allows to compute in real-time the optimised delay laws to compensate the distortions of 2D or 3D profiles. 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.

Two prototypes are presented and inspections of realistic irregular profiles of 2D and 3D geometry mock-ups, including artificial flaws, have been carried out, to estimate the enhancement performances of the "smart phased array transducer" compared to conventional contact probes.

Introduction: The cooling circuits of French pressurized water reactor include many welded pipes with complex geometries as nozzles, elbows. The ultrasonic inspections of those components are mostly performed in contact with conventional monolithic wedge transducers. In case of complex and varying geometry, the fixed shape of wedge can not be matched to all inspected zones. The consequence on the transmitted wave strongly depends on the thickness of the coupling layer. These effects can lead to wrong flaw localization and characterization.

As illustrated on the figure 1-a, the plane shape of the wedge fits the flat surface of the component. The regular thickness of the coupling layer is slight and the characteristics of the focused beam (energy and tilt) are optimised (the transmitted ultrasonic fields are computed using simulation tools gathered in the CIVA software developed at CEA [1, 2]). However, when the transducer is located on an irregular surface, the shape of the wedge is not matched to this realistic surface (fig. 1-b). The computed field shows that the energy is interfering in the irregular coupling layer, disturbing the transmission in the specimen. This effect leads to a shadow volume without any possible detection. To minimize the coupling layer, the monolithic transducer is replaced with a flexible phased array (fig. 1-c).

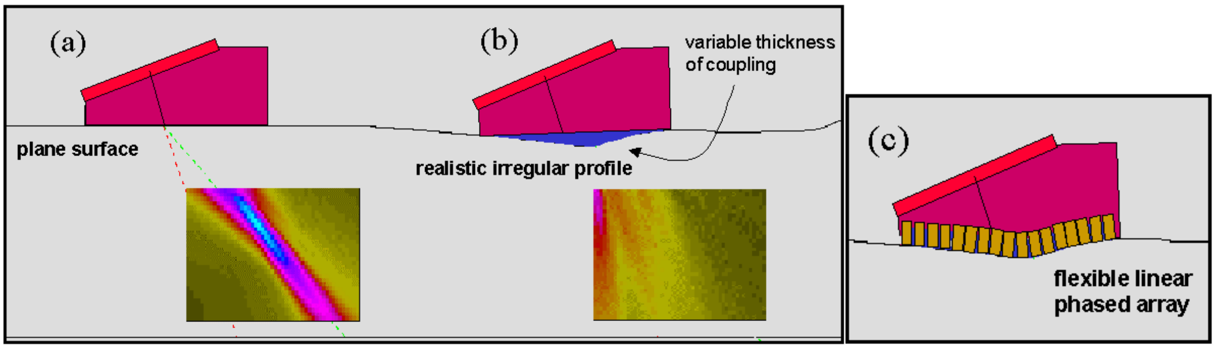

Figure 1 : Simulation of focused beam transmitted through plane interface (a) and a realistic irregular interface (b) and optimisation of the coupling layer (c)

Principle

To illustrate the coupling improvement, we compute the field (longitudinal and shear waves) radiated in the specimen when the phased array is located at the plane and the irregular surfaces. First, the transducer is located on the plane and the delay law is computed to focus 45° longitudinal waves (LW) at 35mm depth. The result has predicted characteristics (fig. 2-a). Then, the transducer is located on the irregular surface and the previous delay law is applied. The field is splitted on several beams (fig. 2-b) because the delay law is not adapted to the shape of the flexible transducer. The delay law algorithm is modified to take into account the deformation of the transducer. The new delay law, computed with the local shape, is applied to the phased array. The resulting field plotted in the figure 2-c, show that the characteristics of the transmitted beam are mastered.

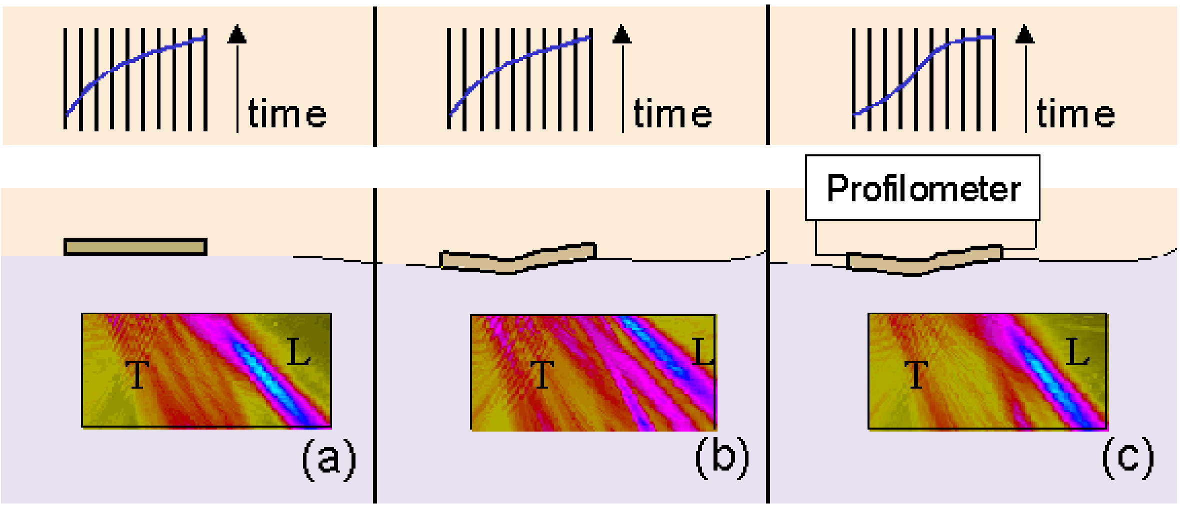

Figure 2 : Simulation of the acoustic field focussed through a plane surface (a), an irregular surface with a delay law adapted to the plane (b) and an irregular surface with a delay law adapted to the irregular surface (c)

Results: A linear array prototype has been made to validate the inspection performances. The flexible array transducer is composed 24 rigid piezoelectric elements, mechanically assembled to obtain a structure able to deform its shape up to a fixed bending radius. This ultrasound sensor integrates two other systems: a mechanical device pushing the elements on the surface and an instrumentation measuring the irregular profile met by the transducer. This profilometer is driven by a self-adaptive process: measurement of the actual position of each element on a complex profile, computation of adapted delay laws, application of delays and storage of the reconstructed waveforms. This method insures to monitor the beam’s characteristics (orientation, focusing depth, steering…).

The transducer is fixed to a mechanical arm, which is driven by stepping motors. The set-up is driven by a real time UT acquisition system, which controls the scanning, the electrical excitation of each element, the adaptive process and the data storage. A typical overall repetition rate for this system is about 150 Hz. The transducer is composed with 24 independent linear elements of 1.3 x 20 mm². The pitch and the area dimensions respectively are 2.0 mm and 48 x 20 mm² [3]. The central frequency is 2-MHz.

Some tests have been carried out on a mock-up with a realistic irregular surface. Figure 3 below shows three different positions from a scanning displacement of the probe and the deformation of the active surface reconstructed by the self-adaptive process.

Measured profiles obtained from the instrumentation system show that the probe preserves optimal fitting to the specimen profile. Some comparisons with the actual shape prove that the deformation measurement system accurately determines the specimen profile and elements positions.

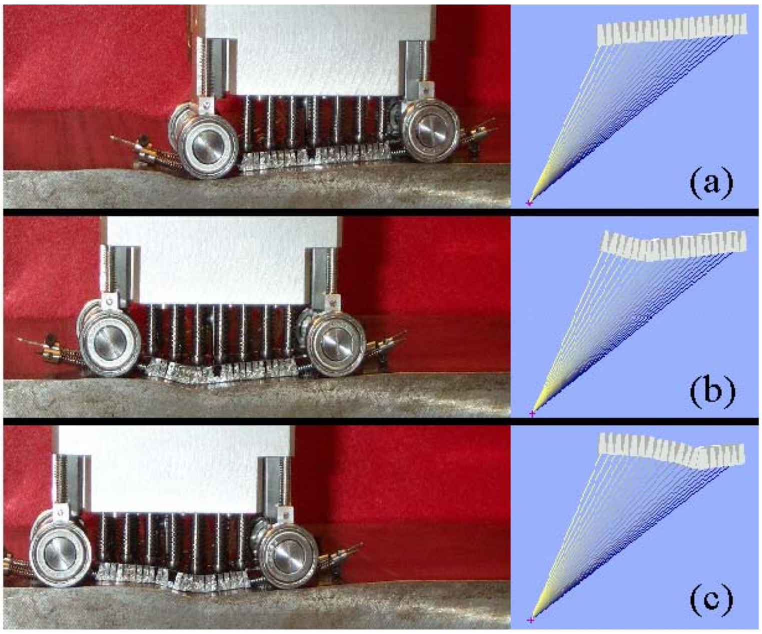

Figure 3. Mechanical and measurement tests carried out with the flexible array prototype with integrated deformation measurement system.

Validation of improvement performances in pulse-echo mode

Inspections of complex profile mock-ups containing artificial reflectors have been carried out to confirm the ability of this probe to improve the testing performances. Acquisitions have been performed on a steel mock-up representative of a welded component with an irregular profile (measured on PWR auxiliary circuit).

The mock up contains two identical series 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 under a flat interface - as reference reflectors -, while the second set is placed under an irregular profile.

Acquisitions have been performed in pulse echo mode using 45° longitudinal waves with the smart array transducer and a conventional contact transducer (planar probe of 8x9 mm² active surface, coupled to a wedge, of 20x22mm² size, 2 MHz frequency).

In both cases, the SDH located below the flat surface are detected and accurately positioned.

Figure 4 shows detections with both probes located on the complex profile.

The True Bscan view (in spatial coordinates related to the specimen) carried out using the wedge transducer shows that some flaws may not be detected (SDH numbered 2), not accurately located (SDH numbered 4) or detected with a very low sensitivity (SDH numbered 3). Only the first side-drilled hole is accurately detected and located, because this scanning position of the probe is located on a quite planar and regular surface.

It can be pointed out that the standard contact probe cannot be mechanically adapted to the inspected specimen. Indeed, an important water layer separates the wedge from the inspected specimen (about one wavelength maximal depth) and multiple reflections arise in the coupling layer between the wedge and the irregular interface. Energy is not well transmitted into the piece and the holes are not correctly detected and positioned, which is also due to the transducer rotation over the irregular surface.

We note that the phased array transducer correctly detects both sets of side-drilled holes.

These results show that the self-adaptive process allows mastering the characteristics of the focused beam in the specimen.

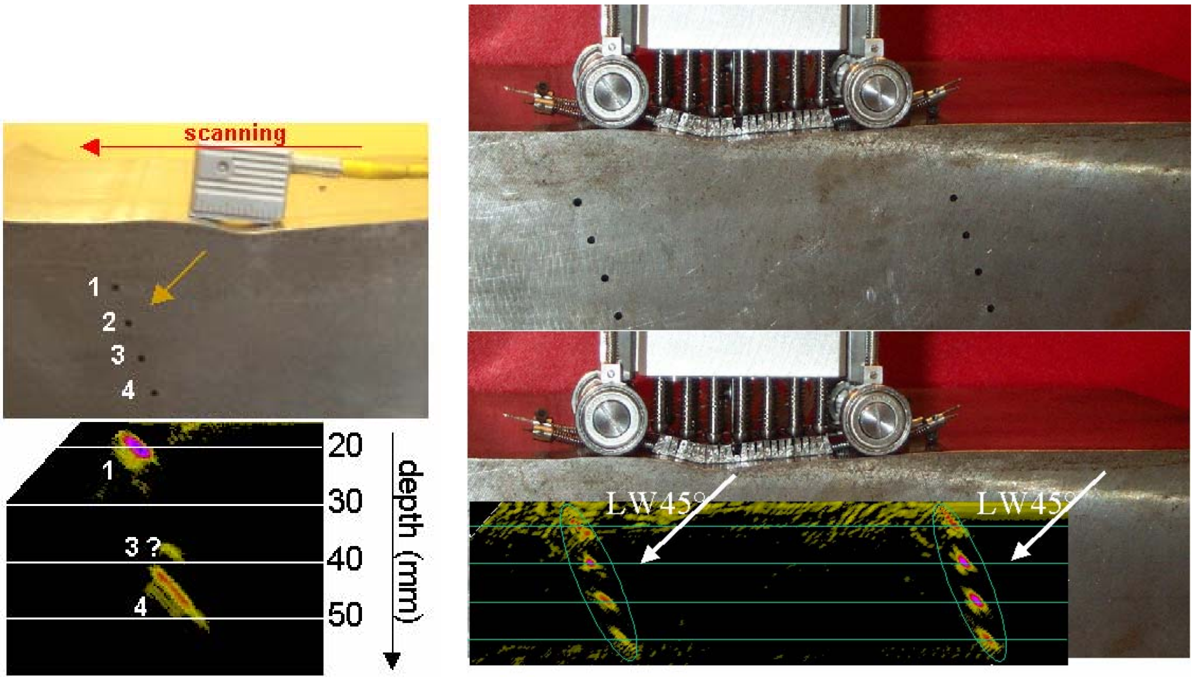

Figure 4. Detection of a set of side drilled holes in pulse-echo mode with the monolithic wedge transducer (left) and the smart phased array transducer (right).

<u>Extension of the flexible linear phased-array concept to 3-D geometry component</u>

The previous part has shown the improvement of the flexible phased array coupled to a self-adaptive instrumentation for the control of wavy, rugged surfaces or more generally with an unknown irregular 2D profile, which cannot be fitted with a classical monolithic transducer.

The whole inspection of elbow (intrados, extrados…) cannot be just performed by one monolithic transducer because of the continual evolution of the coupling layer thickness.

The previous transducer can be used on a specimen with a plane extrusion. But, the cooling circuit of power plants is made with many welded pipes such as elbows (fig. 5-left), nozzles (fig.5-right) and others 3D geometry components.

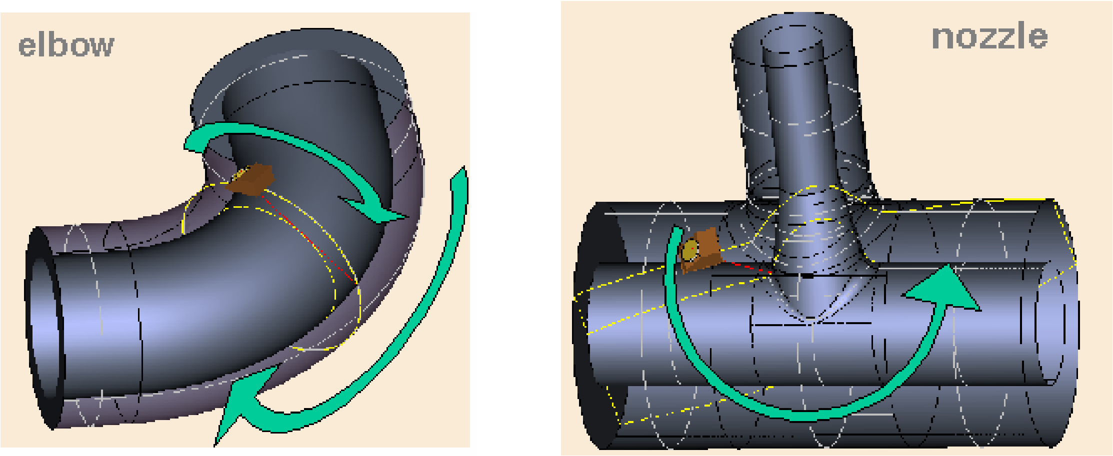

Figure 5. Typical 3-D geometry of complex components

To perform the control on these components, the phased array transducers have to be flexible in the incidence lane and out of it. So the principle of the smart phased array transducer extended to 3D-components needs a 3D flexible piezoelectric area, which can be realised by many processes [4, 5], and a 3D-profilometer.
We present, in figure 6-a, a matrix of independent elements moulded in a soft resin. This matrix is composed by 60 rectangular elements of 1x2mm². The pitches in and out of the incidence directions respectively are 0.5 and 1mm. The piezoelectric aperture is about 16x14mm². On this photo, the deformation, applied to the mock-up, denote the good bonding between elements and the sufficient flexibility of this solution.

About the 3D-profilometer, the principle is an extension of the 2D flexible instrumentation described in figure 3. This sensor measures the 3D-deformation of the active area. An interpolating algorithm computes the coordinates of each element to provide the adaptive delay laws. The figure 6-b shows the reconstructed shape of the matrix phased array. The global repetition rate of the reconstruction process is about 100 Hz.

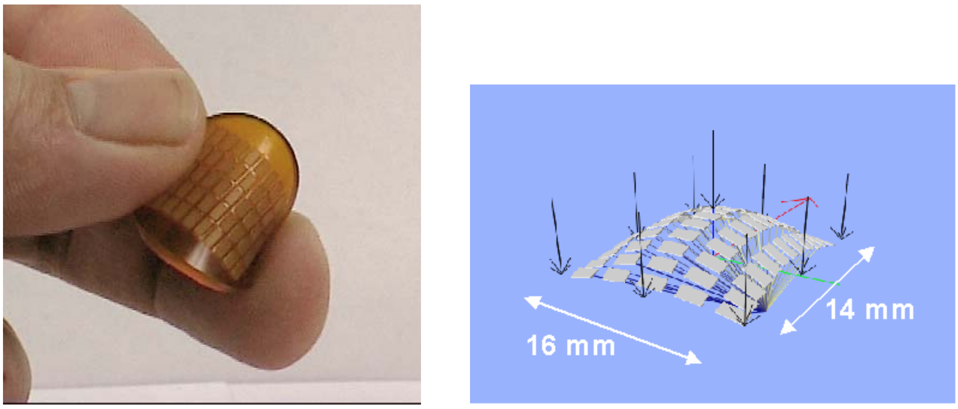

Figure 6. Principle of the flexible matrix phased array transducer: Matrix of element molded in soft resin (a), view of the reconstructed flexible matrix transducer (b)

This 3D phased array, composed by the 12x5 independent elements, has been designed to focus 45° shear waves in steel specimen with thickness about 10mm. The central frequency is 3MHz.
To evaluate the performances of the matrix phased array, we use the CIVA software [1] to compute the transmitted ultrasonic field. The matrix phased array is excited with a delay law computed to focus 45° shear waves in steel plate at 10mm depth. The C-SCAN view (fig. 7), shows the efficient focused beam in the incidence plane and the weakness of grating lobes induced by the design of the phased array.

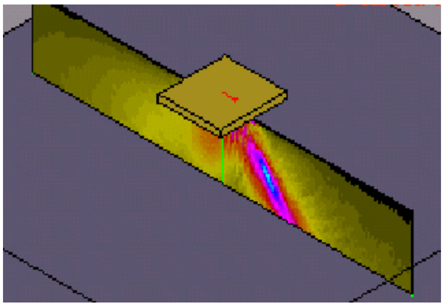

Figure 7. Computed shear waves focused to 45° in a plate.

Results :

A prototype has been made with the previous design, by the French manufacturer Imasonic. Above the phased array, springs push the elements on the surface to ensure the coupling during the scanning and the local deformation is measured in real time by the 3D-profilometer. These two devices are integrated in a handle. The external dimensions of the 3D smart transducer correspond to a cylinder with 50mm-diameter and 100mm-length. This prototype is fixed to an arm, which is driven by stepping motors. The UT acquisition system used with the 2D smart transducer has been modified to manage the parameters of the 3D smart transducer.
To validate the flexibility of the device, the smart transducer is located on the intrados of an elbow with 70mm-diameter and 60mm-bending radius. The photograph in fig. 8, shows the handle embedding the instrumentation and the mechanical device. We note that the coupling between the flexible phased array and the torus surface is correct.

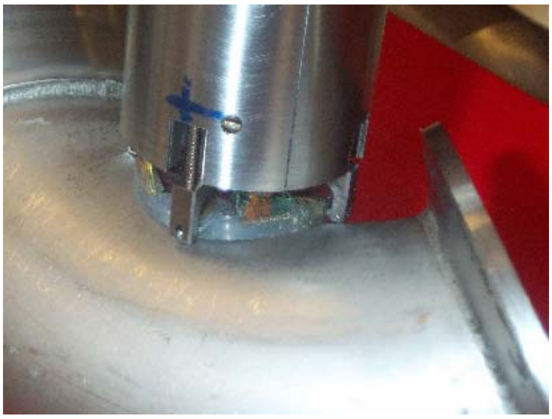

Figure 8. Smart phased array transducer located on the intrados of an elbow with 70mm diameter and 60mm of bending radius.

To evaluate the performances of detection with shear waves, the smart transducer inspects a part of a steel cylinder with 100mm diameter. The maximum thickness is about 15mm. On the plane surface, a vertical notch with 3.5mm-height has been machined.
The adaptive delay law is computed from measurements performed by the 3D-profilometer. These results are secondly treated by the whole instrumental process and applied to piezoelectric elements. Because of the cylindrical configuration, the transducer has to focus the SW30° at 15mm depth. In the notch's reference, this corner detection is performed in pulse echo mode with SW45°. The 3D-smart transducer is moved on the cylindrical surface and the scanning is 40° around the detection position.
The figure 9 presents the outline of the machined specimen superimposed to the reconstructed Bscan view of the detection.

We note that the signal corresponding to the notch is detected with a 12dB signal-to-noise ratio and well located (depth and position). Indirectly, this detection shows that the elements are well coupled to the specimen.

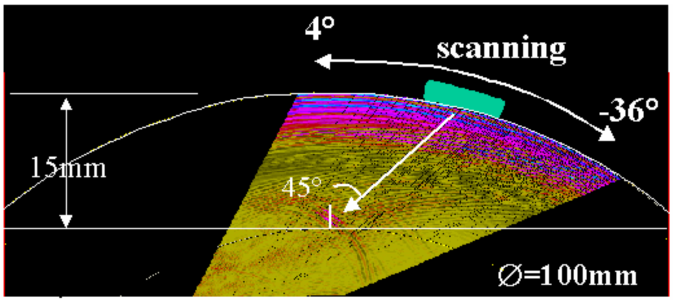

Figure 9. Reconstructed Bscan view of the detection in pulse echo mode with SW45° of vertical notch located below cylindrical part using the 3D smart transducer.

This control is the first performed with the flexible transducer. Other tests are in progress with more complex 3D-geometry such intrados and extrados of elbows.

Conclusion: A new concept of phased array transducer has been developed to improve the contact inspection of pipes and complex geometry components. The principle is based on the use of flexible phased array to fit irregular surfaces and the deformation of the active surface is measured by a profilometer located above the phased array. A self-adaptive process computes, in real time, the reconstructed surface, the coordinates of elements and the adaptive delay laws. Two specific prototypes have been performed to inspect specimens with 2D and 3D-shapes.

Experimental results obtained in transmission with the 2D-transducer validate the mechanical and acoustical behaviours of these probes. The use of optimised delay law ensures the transmission of a homogeneous and controlled beam during the scanning along complex geometry.

Inspections on samples with realistic irregular profiles and containing artificial reflectors have been carried out using the flexible array probe and a standard contact probe. Inspections performed with the conventional contact probe failed to detect and characterize most reflectors, while inspections performed using the flexible array show the efficiency of the system to detect, locate, and characterize side drilled holes. Experiments were performed using a linear scanning of the specimen; the transducer being moved over the complex profile with a controlled homogeneous beam preserved thanks to optimised delay laws.

The detections of a notch performed on a part of cylinder have shown the flexible capacities and the acoustical performances of the flexible matrix phased array.

These works have fully validated the ability of such a system to inspect complex and unknown specimen using a mastered UT beam preserved through the whole scanning pattern. These potentialities make it a powerful tool for complex inspection configurations that may be encountered in many industrial fields, like nuclear, aerospace and aeronautic industries. Also, the linear and matrix array design allow inspecting a wide range of specimen geometry.

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