APPLICATION AND SIMULATION OF ADVANCED ULTRASONIC ARRAY TECHNIQUES

Laurent LE BER(1), Olivier ROY(1), Frederic REVERDY(2), Steve MAHAUT(2),

(1) M2M, 1, rue de Terre Neuve, F-91940 Les Ulis, France

(2) CEA, LIST, F-91191 Gif-sur-Yvette, France

Abstract. Inspection techniques using ultrasonic arrays are now commonly carried out by industry. They present the advantage of rapidity and flexibility. Their adaptability enables to transmit focused beams in the region of interest of the inspected part by applying suitable electronic delays at transmission and delay + summation processing at reception (phased-array techniques).
In parallel to these industrial implementations, new technical solutions which massively exploit simulation capabilities have emerged. Simulation is used at various steps of the inspection: Conception of the inspection and design of the array; computation of suitable delay laws with a possible consideration of geometrical and materials complexity; performance demonstration and calculation of POD (probability of detection). Also, besides the previously recalled phased array techniques, new techniques have emerged which involve more advanced processing of elementary signals. These techniques implemented on the M2M acquisition systems are proposed to enhance detection and imaging capabilities and exploit the modelling of the ultrasound propagation.
In this communication we present and discuss different advanced array techniques. We describe the array simulation capabilities and give examples of applications of the simulation.

1. INTRODUCTION

The recent developments in commercial acquisition systems and probes have led to a wider implementation of the phased-array technology in various industrial fields. While regular operating modes such as focusing, steering and various electronic scanning or any combination of those have been implemented for a long time, they have been usually limited to 1D probes such as linear or circular arrays. However, the ever-increasing number of UT channels available within the acquisition systems enables the use of these techniques with matrix array probes. In addition besides the classical beam-forming applications of arrays consisting in applying delay laws to the different elements new operating modes have emerged based on the acquisition and processing of elementary signals. To take advantage of these new inspection possibilities and exploit these tools to their full potential, a crucial point is the availability of simulation tools and user-friendly interfaces that will help users. In this objective, the French Atomic Commission (CEA) has developed for years simulations tools dedicated to UT array. These tools are gathered in the CIVA software [1], and some of them are embedded in M2M acquisition systems. Based on semi-analytical models [2] they allow to deal with non canonical geometries, linear and matrix array and a wide range of advanced operating modes. They can be used to compute delay laws, to predict beams transmitted in the inspected area to simulate echoes arising from flaws and to process and image array data.
In the following we present various examples of the use of simulation in the context of advanced array applications. In particular we describe applications of matrix phased-array, and give an example of flexible array. Finally, data reconstruction based on processing the collection of data acquired for each channel of an array is explained.

2. DESIGN OF MATRIX ARRAY FOR 3D APPLICATIONS

The first step when conceiving an inspection based on phased-array methods is to design the array pattern and one important goal is to minimize the amount of grating lobes generated by the array. It is well known that grating lobes occur if the elements are not thin enough to create destructive interferences outside of the desired focusing area.

Empiric rules may be used at first glance to check the validity of the array pattern. The main criterion used is the ratio between the wavelength and the elements "pitch" (distance center to center between two adjacent elements). Any phased-array design stage needs to find a compromise between the number of elements, imposed by the cost of the equipment and the space available to position the probe and the required performances of the inspection (spatial resolution, refraction angles, 2D or 3D steering…). Simulation constitutes the most versatile tool to conceive an array design from scratch and to check its performances.
2 shows some transmitted beams obtained by two 2D-array probes: one 2D matrix array (8x8 elements) and one sectored array (6 rings), divided into 61 elements, each ring being divided by an increasing number of sectors. These probes have the same active aperture (about 256 mm²). They are used at the same frequency of 3 MHz and both share almost the same number of elements. The delay laws are calculated to perform a 3D steering of the beam in a planar specimen. The beam fields are displayed as iso-amplitude 3D curves (from 0 to -20 dB). It is possible to see the main lobe and the grating lobes generated by the arrays. The overall spatial distribution of those grating lobes, as expected, depends on the symmetry of the array showing that arrays with similar aperture, number of elements and central frequency can have totally different performances.

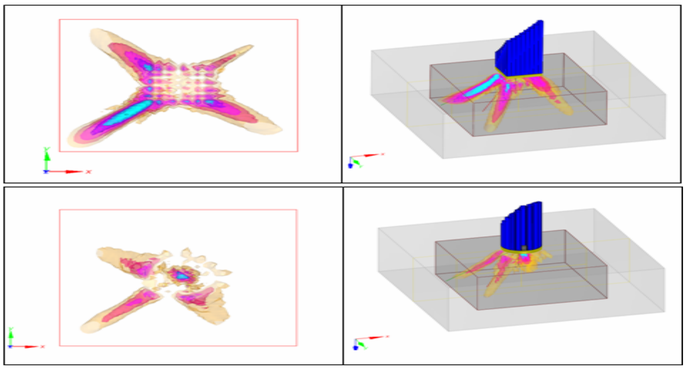

Figure 2: Example of 3D beam computation with 2D array patterns (2D matrix array of 8x8 elements, top view, and sectored arrays of 61 elements, bottom view).

Still, it has to be pointed out that the simulation of the grating lobes through beam simulation is not enough to predict *in fine* the performances of the inspection, as those grating lobes will also be scattered by flaws and boundaries of the specimen. The application of delay laws at reception over the echoes caused by the grating lobes should also be taken into account.

3. FOCUSING AND BEAM STEERING THROUGH A BIMETALLIC WELD

The following example (Figure 3) shows delay law and beam field calculations in a component presenting a complex geometry and structure. The component is a bimetallic weld in a pipe, which can be described by a set of homogeneous isotropic and anisotropic media. The component is defined as a 2.5D-CAD specimen (complex profile and revolution extrusion to form a 3D part). This component is made of two isotropic parts (stainless and ferritic steel), connected by an anisotropic austenitic weld. An anisotropic cladding also lies over the ferritic steel part.
The figure 3 below shows the ray tracing and full beam computation radiated by a matrix array (11x11 elements, 1.5-MHz central frequency, spherically focused) for two different configurations: no delay law (top views) and focalization of a 40°-longitudinal wave inside the weld. The ray tracing tools allow to quickly visualize the concentration of energy in the component by analyzing the concentration of rays. When no delay law is applied the beams seems to concentrate close to the surface, while when the focalization delay law is applied the rays concentrate at the requested focal zone. Although the ray tracing tools may indicate intuitively where the beam would be focused, it cannot be used to quantitatively predict the position and the amplitude of the focal area. A full beam field calculation is then necessary to predict the characteristics of the beam.

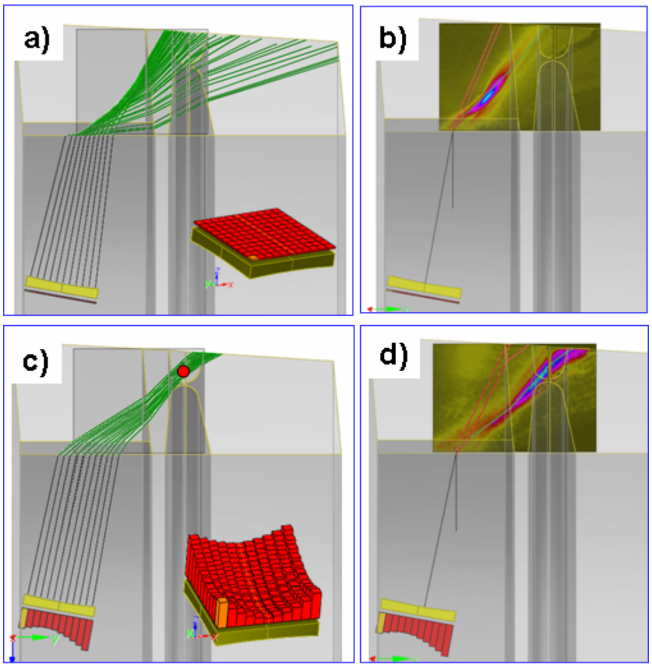

Figure 3: Example of ray tracing and beam computation for a matrix array used to focus through a bimetallic weld.

In this particular example, it is possible to focus the beam at the root of the weld despite the complexity of the structure using a matrix array probe and adapted delay laws to detect potential flaws in this area.

4. INSPECTION OF 3D GEOMETRY WITH FLEXIBLE ARRAY

Ultrasonic inspection of complex geometry components is usually performed with contact methods, using conventional monolithic wedge transducers. The part in contact is adapted to a particular surface but in case of complex and varying geometry, the fixed shape of wedge can not be matched to all inspected zones. Any mismatch between the surface profile under test and the base of the wedge will produce an irregular coupling layer leading to beam distortions which reduce the inspection performance. The development of flexible ultrasonic arrays answers to the lack of adaptability to complex geometry of common ultrasonic sensors. 2D flexible arrays, suitable for 2D or 2.5-D pieces, have been developed and presented previously [3]. 3D flexible phased-array probes have also been developed in order to improve inspections of 3D geometries. These flexible array probes are manufactured by IMASONIC Company. Experiments have shown their ability to focus with longitudinal and shear waves, to measure the emitting surface deformation with a good accuracy, and to calculate delay laws in real-time. The particular operating mode using the embedded calculation functionality of the acquisition system requires the standard Multi-X acquisition system with only updated software which includes a specific library. We illustrate the potentialities of such probes on the example the inspection of a nozzle mock-up with a 3D flexible probe. The mock-up contains a flat bottom hole (diameter 3 mm, height 10 mm) located under the cylinder/cone junction and the acquisition is performed with LW0°. More detailed information on this application is available in this volume [4]. The 3D array composed of 8x8 piezoelectric elements (2.5x2.5 mm^2) moulded in a 50-mm-diameter resin is shown Figure 4. The mechanical part of the probe is composed of 3 by 3 square-matrix pistons which push the array to the surface of the component under test and 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 Multi-X acquisition system is used to monitor, both the UT signals and the voltages coming from instrumentation (deformation measurement). The experimental set-up is also shown

Figure 4. In order to insure 3D complex trajectories, acquisitions were carried out using a robot. The experimental signals can be reconstructed in the 3D view of the nozzle. This representation allows an interpretation of echoes (coming from the flaw and the back wall) and an accurate positioning of the defect (angular position and depth). The results shown Figure 4 illustrate the capabilities of 3D flexible arrays coupled to real time computation of delay laws.

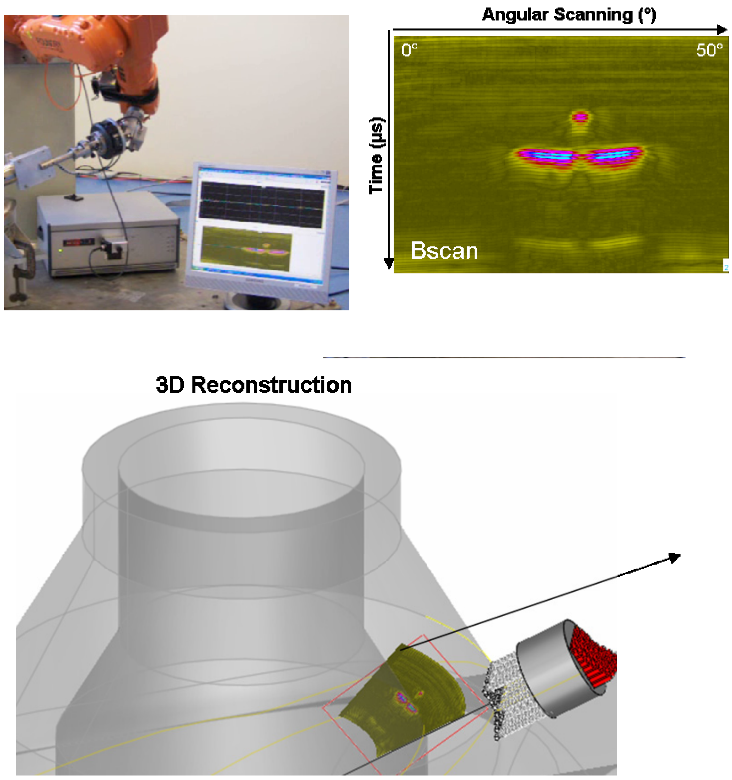

Figure 4. Detection, positioning and sizing of a flat bottomed holein a nozzle with a 3D flexible array.

4. COMBINAISON OF ELECTRONIC AND SECTORIAL SCANNINGS FOR THE INSPECTION OF A TURBINE BLADE ATTACHMENT

The following example (Figure 5) deals with another complex geometry, representative of turbine blade root attachment. The profile, displayed in the figure 4, exhibits a complex geometry, which makes it difficult for a conventional probe to easily scan the component. One way to overcome such restriction is to use a phased-array probe working in a sectorial scanning operating mode. Delay laws are calculated to sweep the beam for a given arbitrary range of refraction angles (the beam may be, in addition, focused). In this example, a flexible matrix array of 8x8 elements is used to sweep longitudinal waves from 30° to 60°, with a reduced number of elements (8 rows, 2 columns). It is combined to an electronic commutation along the direction perpendicular to the complex profile to inspect a full volume of the component without displacement of the probe. During this inspection, seven sectorial scans are recorded to provide a 3D scan of the component. Figure 4 shows the inspection procedure and a superimposition of three simulated sectorial scan upon a 3D view of the specimen. The simulation shows backwall echoes due to the complex profile as well as a corner echo coming from a crack-like flaw.

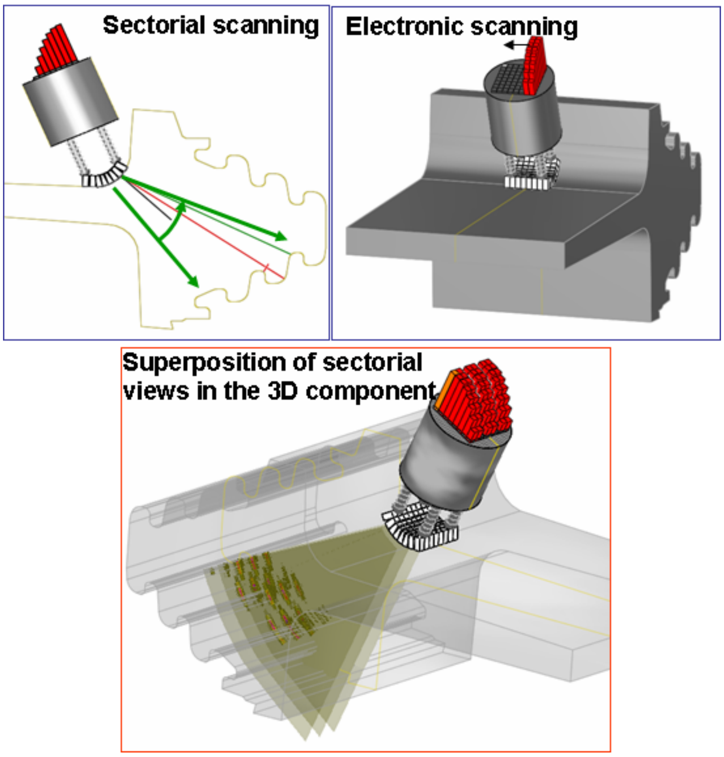

Figure 5: Illustration of a phased-array inspection combining electronic scanning and sectorial scanning of a turbine blade attachment.

5. ADVANCED IMAGING TECHNIQUES

The conventional NDT ultrasonic arrays techniques consists in applying electronic delays at transmission and recording one signal issued from delay + summation processing of the individual signals received on the elements of the array. For such array applications classical imaging principle based on displaying the ultrasonic signals (the A-scans) along "rays" assumed to be representative of the beam axis remain efficient. Besides these applications of array, more advanced operating modes involving the recording of elementary signals are increasingly exploited in NDT field associated to specific post-processing of signals. New processing tools dedicated to such array data (both simulated and experimental using array acquisition systems [5]) have been added to the platform. These tools allow to post-process the data acquired by each channel during a phased-array inspection [6]. The post-processing algorithm considered here basically consists in summing (after application of time delays and amplitude corrections calculated using model-based delay and amplitude laws) the contributions from each element of the array to synthetically focus the energy in various points of a reconstruction area in the component. Basically, the technique relies on the calculation of UT propagation paths from the transmitting element to any point of a reconstruction area to the receiving element. This algorithm, being connected to the forwards models of the platform, is able to deal with ultrasonic propagation through complex (irregular) surfaces as shown in the following example. It may be applied, at least in theory, to any set of recorded signals. Here we present the application to the processing of data issued from the acquisition scheme referred as Full Matrix Capture (FMC) and consisting in acquiring the complete set of signals corresponding to all the pairs of transmitting and receiving elements on the array : an electronic commutation is performed for which each element of the array is successively being used as transmitter while all the elements are used as receivers. A set containing all combinations of transmitter and receiver elements is being stored for post-processing.

An example of application of this technique is shown on Figure 6 and corresponds to the case of a matrix array probe (11x11 elements, pitch 6.5 mm, 1-MHz central frequency) in contact with a ferritic steel specimen (220 mm thick) containing various flat-bottom holes (FBH, 2 mm in diameter) of different height (5 mm to 60 mm). The position of the probe over the flat-bottom holes is shown in figure 6.

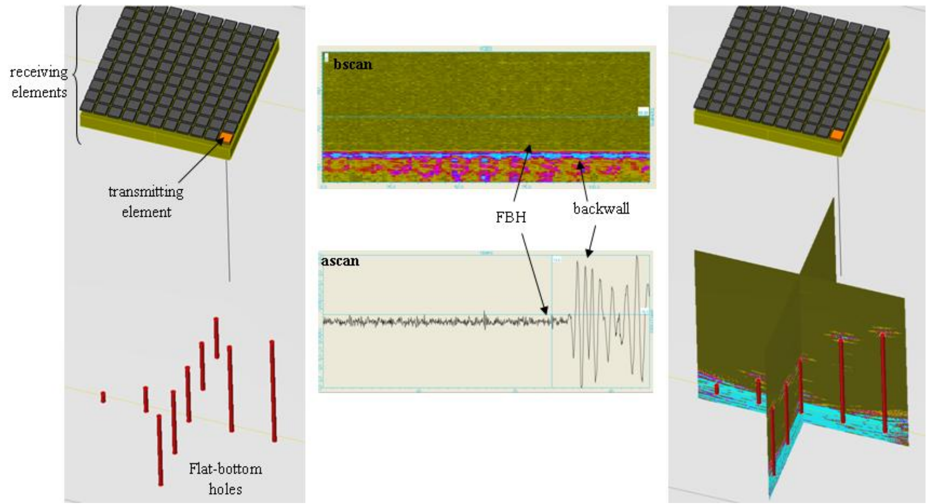

Figure 6 : Inspection configuration, examples of signals acquired during the FMC, and reconstruction result.

The reconstruction algorithm described before is used for experimental data along two perpendicular planes containing the holes. The figure shows the superimposition of the two reconstructions upon a 3D view of the component containing the flat-bottom holes. It is important to notice that despite the poor signal-to-noise ratio observable in the individual Ascans, the reconstruction technique leads to a clear detection of all the holes.

6. CONCLUSION

In this paper we have illustrated on several examples the potentialities offered by advanced applications of array techniques coupled to efficient simulation tools. Simulation is very helpful to design arrays, to optimize and demonstrate the performances of the inspection, to drive the probe (delay law computation). In addition, model-based processing of ultrasonic signal offers the means of imaging data issued from advanced operating modes and positioning echoes in 3D complex geometries. Simulation allows to fully exploit the capabilities of advanced applications of arrays, which will permit to enhance the performances of UT inspections and overcoming some current limitations, especially related to geometrical complexity of inspected components.

7. REFERENCES

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