6th International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurized Components
October 2007, Budapest, Hungary
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Developments in Ultrasonic Phased Array Inspection II

Advanced Matrix Phased Arrays Settings for Inspection

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ABSTRACT

Phased arrays are now widely used in ultrasonic non destructive testing, as they provide improved versatility with comparison to conventional monolithic probes. Apart from the intrinsic abilities to steer and to focus the beam through planar, curved or irregular profiles, specific phased arrays acquisition schemes can also be applied. Electronic commutation (a group of elements over a large array transmits the ultrasonic beam, then neighboured elements are activated) allows very fast inspection times – this may be performed, for instance, for pipes inspections using circular arrays -, while sectorial scanning (several delay laws are applied to sweep the beam at different refraction angles) allows to inspect a given area without mechanical motion of the probe, which may be applied for access-limited components (turbine inspections for instance). Although these techniques are quite well known in the NDT field, most applications have been carried out with linear phased arrays (1D phased arrays). More complex applications now require advanced phased array techniques based on matrix array design, which imply increased number of elements and improved phased arrays driving software and systems. Developments carried out at CEA and M2M aim at providing user-friendly tools to conceive and to fully exploit electronic commutation and scanning features over matrix arrays (2D phased arrays), for which one can easily define groups of transmitters and receivers, draw their electronic scanning trajectories in the full array pattern, and modify their active aperture as well as applied delay laws at transmission and/or reception. The collected data may therefore be displayed in the real component frame thanks to 3D CAD features based upon paths associated to each ultrasonic shots carried out during the acquisitions. Several simulations of inspection configurations performed over complex components (nozzles, CAD specimen…) are presented, which illustrate some potential applications of matrix array settings

INTRODUCTION

The application of phased arrays techniques in ultrasonic non destructive testing (UT) are now commonly used in various industrial fields, thanks to their intrinsic versatility, combined to increased performances of commercially available acquisition systems and array probes. Those skills allow carrying out inspections of complex components with new operating modes, which may combine basic advantages of phased arrays, as electronic commutation, sectorial scanning, focusing… Those techniques are usually carried out using 1D array patterns (linear arrays), however the ever increasing number of UT channels available with acquisition systems, now enable to perform such techniques using matrix arrays, which allows to exploit 3D focusing or beam sweeping, while linear arrays applications are limited to the array splitting plane. The application of 3D beam sweeping, focusing, electronic scanning in a 2D aperture way, data reconstructions, over matrix arrays requires advanced settings and simulation tools to conceive inspection procedures and to predict their performances.

Designing matrix array patterns and predicting their performances and related limitations due to physical restrictions imposed by the array splitting pattern (amplitude loss, array lobes generation) is a primary step for inspection procedure qualification. To assess such performances prediction, the French Atomic Commission (CEA) has developed for years semi-analytical models dedicated to UT. These simulations tools, which are gathered in the CIVA software developed by CEA [1], allow computing delay laws, beam propagation, flaw scattering, as well as imaging tools. Those different features are available for simple (circular, linear) or more sophisticated (1.5D or 2D matrix arrays, sectorial arrays) patterns.

This paper is organised as follows: the simulation tools used in CIVA and their related available configurations are briefly introduced in the first part. In the second part, various applications of simulations using matrix phased arrays are presented. The third part presents some data reconstruction based on processing the collection of data acquired for each channel of the array (weighted and time shifted summation of the elementary signals using model-based UT paths from the array elements and each computation point of a region of interest). Those different examples illustrate some potential applications of matrix arrays.

MODELING OF PHASED ARRAYS TECHNIQUES IN CIVA

Beam propagation and flaw response computation

UT semi-analytical models developed in the CIVA platform aim at fully predicting an inspection. In order to simulate the inspection, various flaw scattering approximations may be involved [2-4], depending on the configuration cases (type of inspection : pulse echo, tandem or TOFD technique) and on the flaw type (volumetric void flaws, crack-like flaws, solid inclusions), while the field incident over the flaw is modelled using a surface integral aperture over the transducer aperture [5]. Finally, the synthesis of the signal at reception is computed using an argument based on Auld's reciprocity [6]. This calculation is achieved for each scanning position of the probe and each applied parameters (delay and amplitude law) over the array, and for each elementary mode contribution: direct specular echoes in longitudinal and transverse modes, corner echoes with or without mode conversion occurring over the flaw or over the backwall, then the overall echo at reception is the summation of all these elementary modes.

Delay laws and operating modes

In addition to beam and flaw scattering calculations, advanced delay law settings are available for various array patterns designs (linear, matrix, circular, sectorial, encircling or encircled arrays) and various operating probes (contact, immersion, flexible, dual T/R probes). Those delay laws aim at focusing and/or deflecting the beam in 2 or 3 dimensions according to the symmetry of the array, for arbitrary components shapes (canonical or CAD defined) and structures (homogeneous or heterogeneous, each propagation medium being isotropic or anisotropic). Those delay laws are applied over all the elements of the array or for varying commutation trajectory patterns (successive groups of elements in transmission and/or reception, allowing scanning a virtual probe inside the aperture of the array). Standard commutation patterns are applied with linear arrays (for tube inspection using full circular arrays and complete electronic scan, for instance), however advanced patterns may also be defined (manually or with user-defined rules) thanks to recent developments in CIVA. Finally, multiple delay laws at reception for homogenization of the beam spot within a desired inspection range of depths may also be applied, with fixed or optimal aperture of the array pattern.

Imaging and reconstruction tools

The application of delay laws to drive the beam leads to a collection of different UT paths (for instance: multiple angles in sectorial scanning techniques) and potentially large amount of data collection (acquisition and storage of elementary signals received by each channel of the array for post-processing). For each applied delay and amplitude laws, it is possible, thanks to previously presented simulation tools, to determine the UT paths, time of flights or the amplitude of the radiated or scattered field inside the component. The knowledge of these allow to build true scan image (display of ultrasonic echoes according to the specimen frame coordinates) as well as post-processing summations of elementary signal to map a region of interest. Figure below shows some of these tools for measuring the focal spot dimensions of a circular array using different focal laws, evaluating the actual refraction angles (both features relying on a complete beam propagation), as well as a more simple (and very fast) ray tracing tool showing the UT paths used for focusing over a side drilled hole.

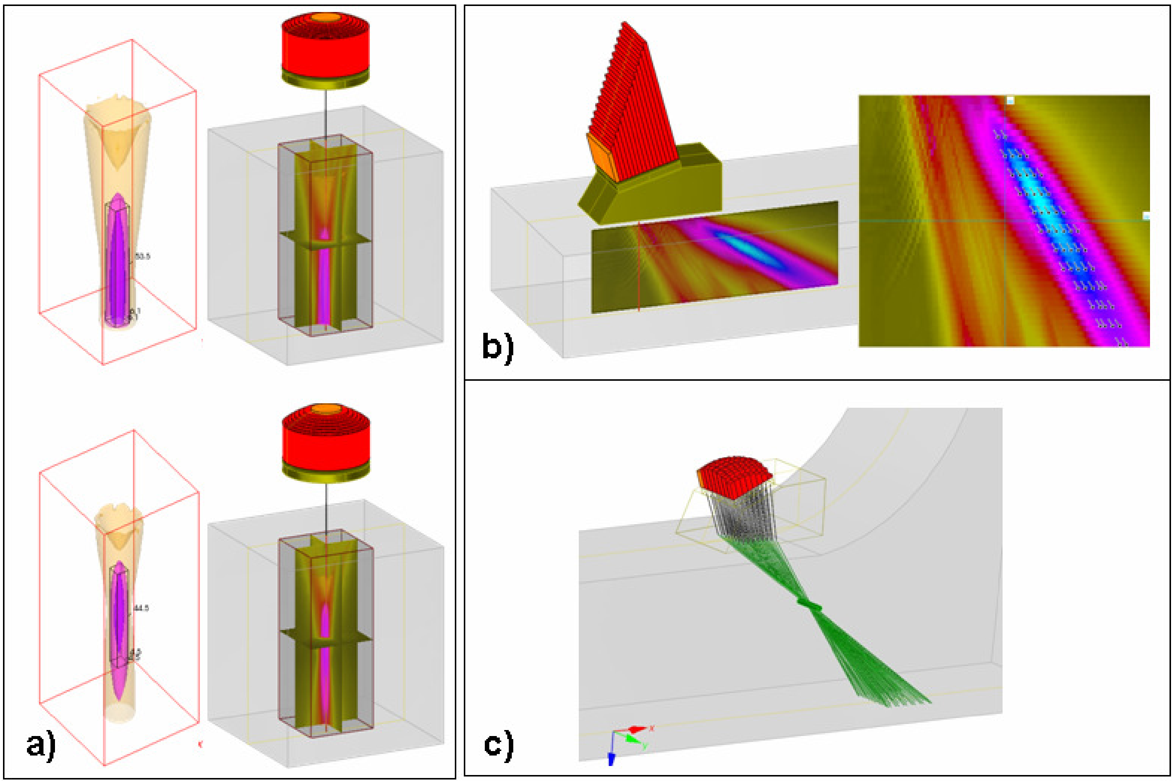

Figure 1 - Tools for evaluating phased arrays techniques: a) measure of the focal spot, b) estimation of the actual refraction angle, and c) ray tracing tool.

EXAMPLES OF SIMULATION OF PHASED ARRAYS TECHNIQUES

The following examples refer to simulation of phased arrays features, including beam propagation, flaw scattering and data reconstruction.

Designing matrix arrays patterns for 3D applications

The first step for conceiving phased arrays techniques is to design the array patterns. One obvious interest of the beam simulation is to predict the amount of grating lobes which may arise using a phased array for demanding applications. It is well known that grating lobes occur if the array splitting is not thin enough to create destructive interferences of all elements contribution outside of the desired focusing area.

Empiric rules may be used at a first glance to check the validity of the pattern of the array. The main criterion used is the ratio between the wavelength and the elements "pitch" (distance between the centres of two adjacent elements). One usually considers that:

- if the pitch is lower than half a wavelength, no grating lobes occur.
- If the pitch is between half a wavelength and one wavelength, grating lobes occur, their amplitudes and positions varying upon the applied delay law and the symmetry of the array design.
- If the pitch is higher than one wavelength, grating lobes, superior to the main focusing lobe, may be generated.

Any phased array design stage needs to fix a compromise between the number of elements, which is mostly depending upon economic constraints (cost of the probe and driving acquisition system, assuming that technological probes manufacturing processes and acquisition systems performances are now available) and the desired performances of the inspection (required spatial resolution, refraction angles, 2D or 3D steering…). Some simple solutions exist to reduce the amount of elements needed, for instance the use of a wedge to limit the actual steering range of the probe, or a "preliminary" geometrical shaping of the probe if one needs very high focused beam. However, simulation probably constitutes the most versatile tool to conceive an array design from scratch and to check its actual performances.

Figure below 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 increased number of sectors. These different probes have the same aperture active area (about 256 mm²) and are used at 3 MHz frequency, and both share almost the same number of elements. These arrays aim at performing 3D volumetric steering over a planar specimen. Beam transmitted using one delay law computed in order to focus at positions in mm (X, Y, Z)= (25, 25, 20) are reported. Those beam simulations were carried out over a 3D computation area parallel to the surface of the specimen, at 20 mm depth. The beam fields are displayed in iso-amplitude 3D curves (from 0 to -20 dB). On these pictures, one can observe the main focusing lobe as well as some grating lobes. The overall spatial distribution of the grating lobes, as expected, also depends upon the symmetry of the array.

Still, it has to be pointed out that the simulation of the potential 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 the flaws and the boundaries of the specimen, and the application of delay laws at reception over the echoes due to grating lobes shall also be taken into account.

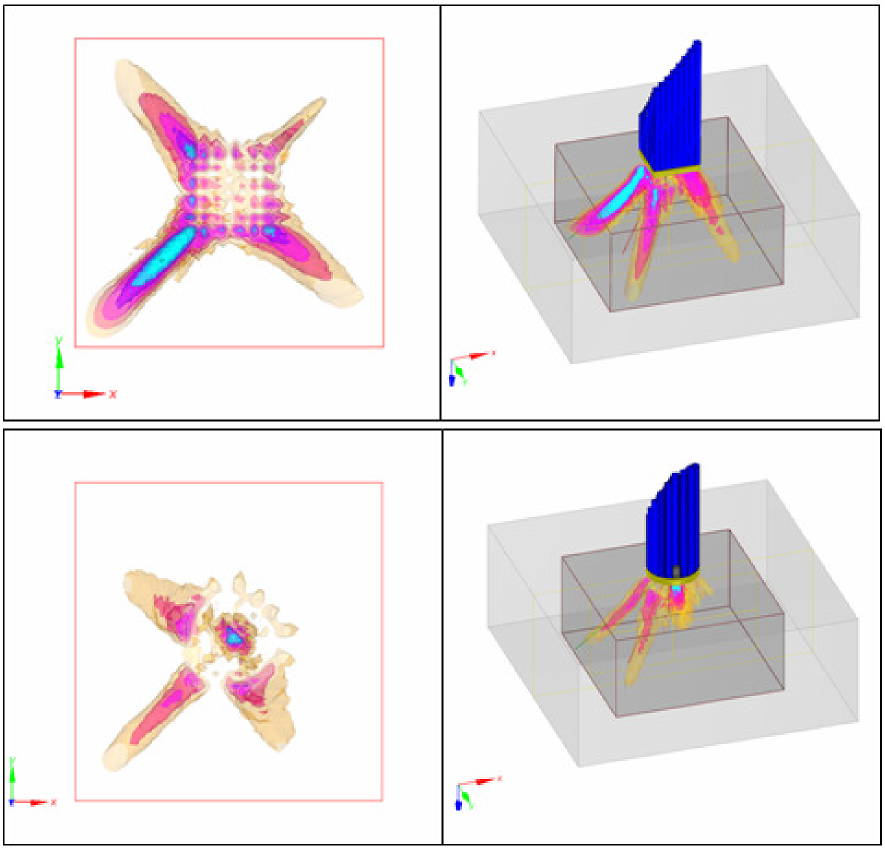

Figure 2 - Example of 3D beam computation with 2D splitting array patterns (2D matrix array of 8x8 elements, top view, and sectored arrays of 61 elements, bottom view).

Focusing and deflection through a bimetallic weld

In the previous example, beam computations were achieved through a planar component. The following example refers to delays and beam calculations over a more complex component: a bimetallic weld in a pipe, described as a set of homogeneous isotropic or anisotropic media. The component is defined as a 2.5D CAD specimen (complex profile and revolution extrusion to form a 3D piece). This component is made of two isotropic parts (of stainless and ferritic steel), linked by an anisotropic austenitic weld. An anisotropic cladding also lies over the ferritic steel part.

Figure below shows ray tracing and full beam computation radiated by a matrix array (of 11x11 elements, 1.5 MHz central frequency) for two different configurations : without any delays (top views) and with delays computed to focus inside the weld, with 40° Longitudinal waves. This probe also has a spherically focused shape. It can be pointed out that the beam is focused close the surface if it is used without delays. The ray tracing tools may indicate, intuitively, that the beam would be focused close the surface (as most rays converge in this area), however it cannot be used to quantitatively predict the position and the amplitude of the focal area. Using delay laws computed to focus inside the weld (the focal spot is displayed in red on the figure), one may master the beam to concentrate the energy on the weld root in order to detect flaws in this area.

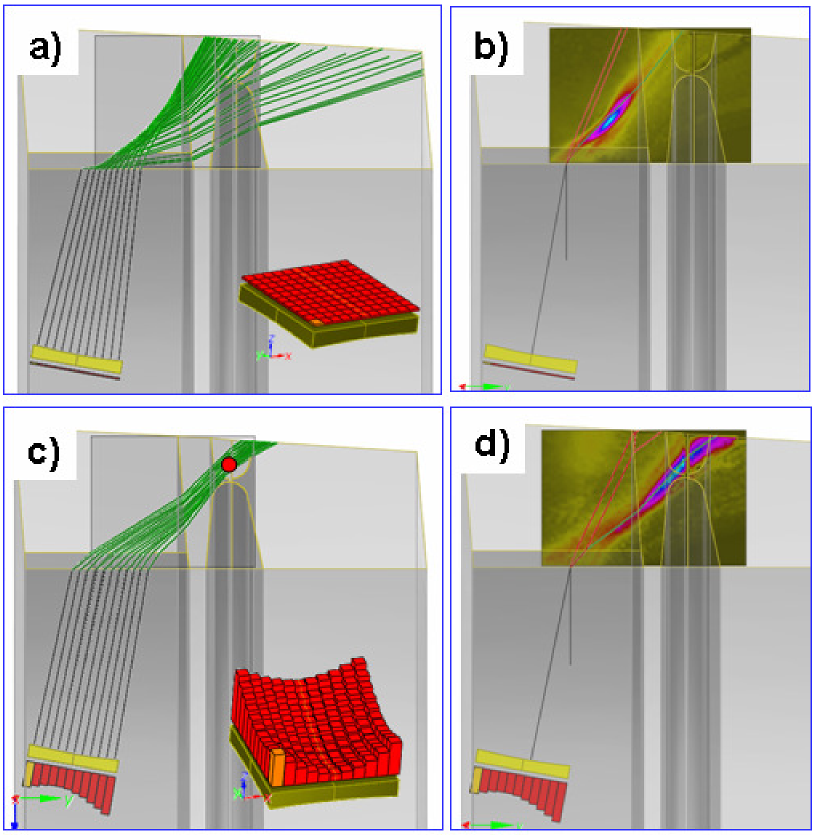

Figure 3 - Example of ray tracing and beam computation for a matrix phased array used to focus through a bimetallic weld.

Combination of electronic and sectorial scanning for inspection of turbine blade attachment

Previous examples were dealing with beam computation through a planar or a more complex (bimetallic weld) component. The following example concerns another CAD component, with a complex geometry, representative of turbine blade root attachments. Such a profile, as displayed on figure below, exhibits a complex geometry which prevents a conventional probe to easily scan the component. One way to overcome such scanning displacement restriction is to use the so-called sectorial scanning technique, which consists in sweeping the beam in a given arbitrary range of refraction angles using delay laws (the beam may be, in addition, focused). In the example reported hereafter, a flexible matrix array of 8x8 elements is used to sweep the beam from 30° to 60° in longitudinal mode, with a reduced number of elements (8 rows, 2 columns) and using electronic commutation in the direction perpendicular to the complex profile, in order to inspect a full volume without displacement of the probe. With such an inspection procedure, 7 sectorial scans are formed to provide a 3D scan of the component. The inspection procedure is schematically illustrated on figure below, as well as the superposition of three simulated sectorial scan views displayed in the specimen coordinates. These views show backwall echoes due to the complex profile, as well as a corner echo provided by a crack-like flaw at the backwall.

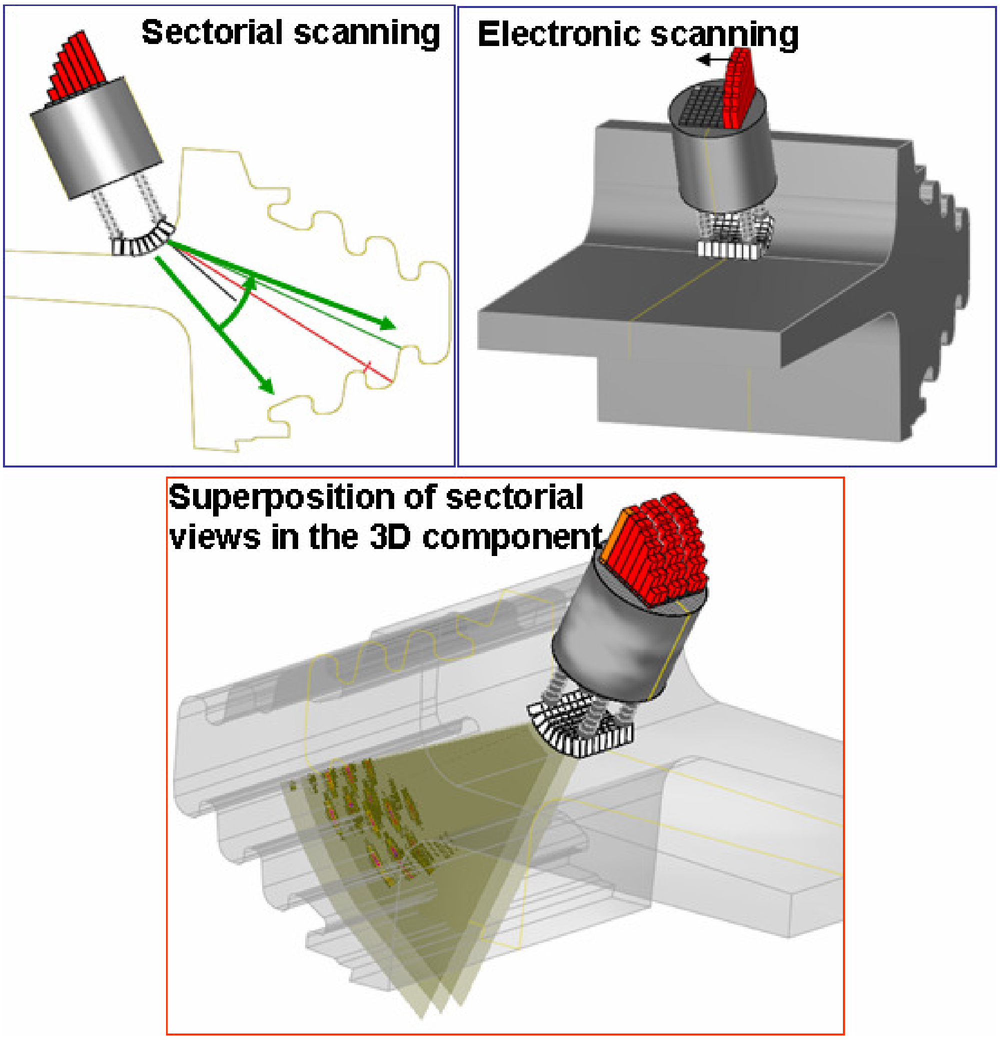

Figure 4 - Illustration of a phased array inspection technique combining electronic scanning and sectorial scanning over a turbine blade attachment and display of three simulated scans.

DATA RECONSTRUCTION OF PHASED ARRAYS DATA OVER COMPLEX PROFILE

New tools dedicated to the management of phased arrays data (both simulated and experimental using phased arrays acquisitions system developed by M2M [7]) have been added to the CIVA platform since version 9. These tools allow to post-process the data acquired in a phased array inspection by each element of the array[8]. The post-processing technique consists in summing the elementary contributions time shifted and weighted using model-based delay and amplitude laws. Basically, the technique relies on the calculation of UT paths propagations from the transmitting element, a supposed point source scatterer lying in any position of a reconstruction area, and the receiving element. Those paths are modelled using the previously detailed simulation tools for beam computation and flaw scattering. The application of such reconstruction technique is illustrated hereafter for an experimental tests carried out over a complex profile component, representative of irregular state of surface that may be observed in the vicinity of welds. A linear array of 64 elements lies over a ferritic steel of complex profile, containing 8 side drilled holes (4 side drilled holes are located below a planar part, while the 4 other reflectors are located below a complex part). The acquisition is carried out as follows: the first element is used as a transmitter, and signals received by each element of the array are picked and stored, then the second element is used at transmission and all echoes are stored. Finally the complete set of transmitters and receivers (64x64 signals received for one position of the probe) are used to form the collection of UT data. This technique is sometimes referred as the full matrix capture or transfer matrix by different authors. Figure below shows the ascans received on the array, as the first element is used for transmission. The four echoes scattered by the side drilled hole are clearly observed by the array, although this configuration is somewhat unfavourable, as the array aperture is shifted with respect to the flaws position (one also has to note that the first element is the element closest to the side drilled holes). The observed echoes correspond to smooth hyperbolic curves, as this series of side drilled hole is located below the planar part of the component.

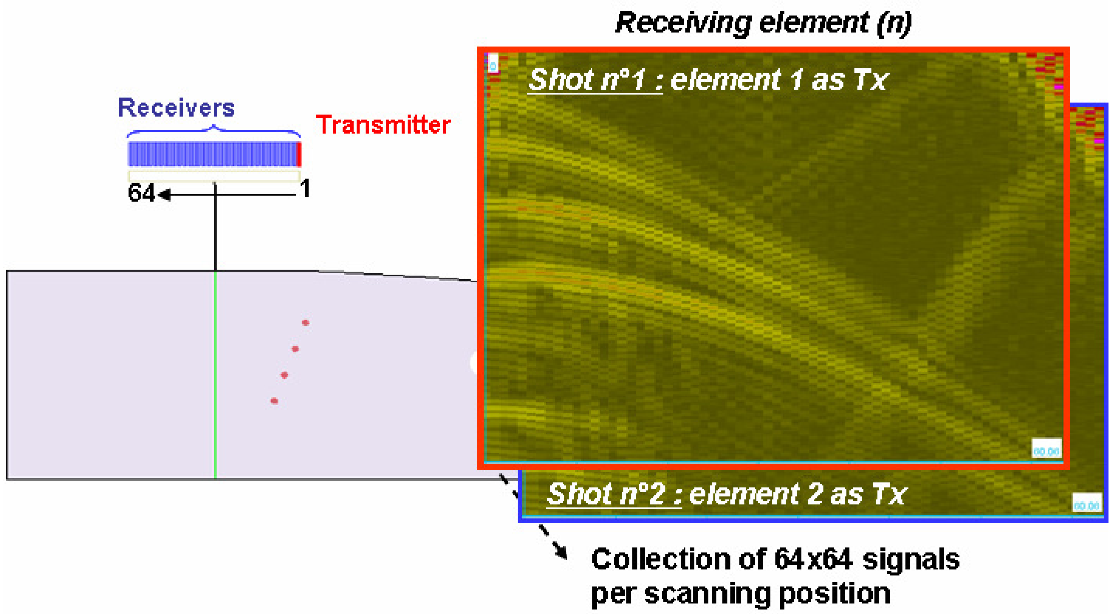

Figure 5 - Examples of signals acquired by the array, using the full matrix capture acquisition.

Using the collection of signals received in the full matrix capture acquisition, the summation of echoes is performed in a region of interest in the component. The results obtained for two positions (the first one corresponding to the previous figure, and the second one corresponding to the axis of the array probe aligned on the second series of side drilled hole, that is to say in front of the complex part of the component) are displayed on the figure below. It can be seen that both reconstructions give excellent results in terms of positioning of echoes (the reported circles correspond to the exact positions of the side drilled hole in the component), resolution, and signal-to-noise ratio.

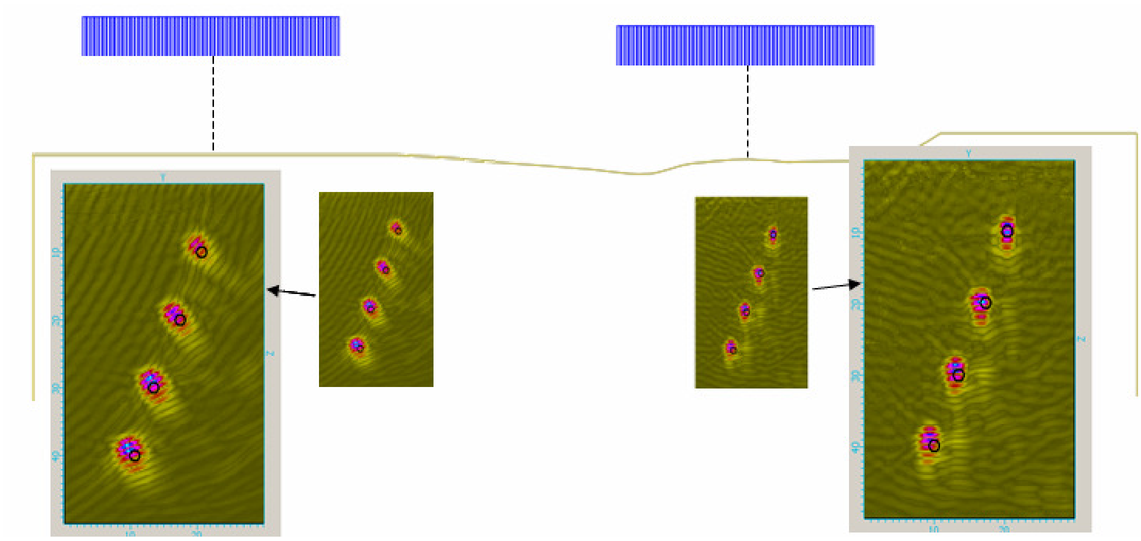

Figure 6 - Reconstruction over planar and irregular parts of the component.

CONCLUSIONS

This paper has presented some illustrations of the simulation tools for simulation of phased arrays techniques, gathered in the CIVA platform. Those tools include delay computation, ray tracing, beam computation, flaw scattering and post-processing reconstructions, based on semi-analytical approach to obtain fast and accurate results. Detailed examples include beam computation, flaw scattering and data reconstruction over complex components. Most recent developments in CIVA9 deal with applications of these features for matrix arrays, including complex settings (combination of electronic scanning with arbitrary patterns and trajectories, fixed or variables patterns apertures along the trajectory…) which allows the user to fully define and to simulate arbitrary inspection techniques.

REFERENCES

1) More details may be found at http://www-civa.cea.fr.
2) Raillon R and Lecœur-Taïbi I, "Transient Elastodynamic Model for Beam Defect Interaction. Application to NonDestructive Testing", *Ultrasonics*, 2000, Vol 38, 527-530.
3) Chaffaï S, Darmon M, Mahaut S, Menand R, "Simulation Tools for TOFD Inspection in CIVA Software", *in these proceedings*.
4) Darmon M, Calmon P, Bèle B,"An integrated model to simulate the scattering of ultrasounds by inclusions in steels", *Ultrasonics,* 2004, Vol 42, pp. 237-241
5) Gengembre N, "Pencil method for ultrasonic beam computation", in *proceedings of the 5th World Congress on Ultrasonics*, 2003, pp. 1533-1536.
6) Auld B, *Wave Motion* **1**, 3 (1979).
7) O. Roy, M. Bouhelier,*"3D beam steering for improved detection of skewed crack"*, EPRI Piping & Bolting/Phased Array Inspection Conference, 2005
8) Calmon P, Iakovleva E, Fidahoussen A, Ribay G, Chatillon S, "*Model based reconstruction of UT Array Data"*, to be published in proceedings of the 34th Review of Progress in QNDE, 2007