NEW FEATURES FOR PHASED ARRAY TECHNIQUES INSPECTIONS : SIMULATION AND EXPERIMENTS

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Abstract: Ultrasonic NDT techniques based on phased array technology are more and more applied in various industrial contexts, as they provide improved adaptability to different inspection configurations. Such techniques include conventional or advanced inspection modes, as electronic commutation, sectorial scanning, adaptive beam forming, multi-channels data reconstructions… All those features shall be performed over canonical or complex profile specimen. These techniques rely on the application of delay and amplitude laws to all, or to groups of, elements of an array. Within the CIVA software developed by CEA are included a set of tools based on modelling and developed specifically for phased array applications. Delay laws computation tools are the first of them. Indeed as soon as complex structures are dealt with (complex profile, non homogeneous and/or anisotropic materials…) the laws have to be optimised in order to compensate phase aberrations due to geometrical or material properties variations and this is done within CIVA by applying suitable modelling based algorithms. The second application of modelling concerns the simulation of the inspection by predicting either the beam transmitted beam in the part or the echoes arising from flaws. These simulations allow to evaluate the performances of methods and/or interpret experimental results. At last modelling based reconstruction algorithms can be applied to the experimental results in the aim of accurately locating the ultrasonic echoes inside the part. In this paper we present some applications over canonical and complex structures showing the capabilities of phased array techniques and associated simulations. Experiments and simulations carried out over complex mock-ups (in terms of entry profile geometry) with embedded reflectors show that these tools allow to efficiently conceive phased array methods and to predict their actual performances.

Introduction: Significant technological advances have been made over last years in phased arrays techniques, mostly in terms of acquisition systems (versatility, miniaturization) and transducers technology (piezocomposite probes with highly reduced acoustical cross-talk). Such progress makes the phased array technology seen as a very powerful tool in terms of adaptability and versatility for a wide range of industrial applications. However, as a wide range of complex applications – beam-steering and electronic commutation, multiple parameters settings -, can be performed with such systems, an optimal utilization requires modeling- based conception and exploitation. Modeling is applied to compute suitable delay laws, to simulate the inspection, allowing feasibility study or performance demonstration and reconstruction of acquired data. In this paper, we will briefly present the UT simulations codes developped at the French Atomic Energy Commission (CEA) for several years, then we will present some validation examples as well as simulated applications of them for different phased array inspection techniques. Although conventional techniques may be readily simulated most examples will deal with so-called "dynamic inspection modes", which postulate that for each scanning position (if any), multiple settings may be applied to the phased array probe.

Modeling tools allow to simulate realistic NDE configurations inspections. These models (for ultrasonic as well as eddy current techniques), gathered in the Civa software [1-2], aim at being able to conceive, optimize and predict the performances of various NDE methods. Such models may also be used for experimental data inversion [3] or complex results interpretation.
A very broad range of realistic configurations has to be dealt with, in terms of :

- Specimen (isotropic or anisotropic, homogeneous or heterogenous, of simple or complex – possibly CAD – geometry)
- Probes : standard or advanced, e.g. phased arrays
- Scatterers : calibration defects or complex shaped defects, solid inclusions

- Inspection method : pulse-echo, TOFD, tandem applications
- 3D and broadband regime for realistic echo simulation

Such configurations also need to be modeled with high speed computation codes for parametrical studies. Semi-analytical models have therefore been developed : they include the simulation of the beam propagation as well as defect scattering.

The computation of the beam radiated by the transducer through the specimen relies on the summation of every elementary contributions over the surface of the probe. Each elementary contribution is evaluated by means of a pencil method [4]. The "pencil" term corresponds to a collection of rays emanating from the point source, which will then diverge during the propagation. The central ray of this pencil lies over a geometrical path between the source point and the computation point, which respects Snell-Descartes 's laws for refraction/reflection at any interface. The divergence factor, which takes account of the beam spreading over the propagation is evaluated using the energy conservation over the envelope of the pencil. Once all of the contributions have been evaluated, the wave field transmitted is synthesized and expressed in the pulse response formulation, which enables to predict the acoustic behavior of the probe for any arbitrary waveform. For phased array computations, such a formulation allows to take account of arbitrary delay and amplitude laws applications over the array without any need of new calculations : the pulse responses of all elements of the array are individually computed and stored. Therefore the beam radiated by the array may be readily synthesized as the sum of individual pulse responses, time shifted and weighted according to the delay and amplitude laws [5].

Different defect scattering computations approximations may be used, depending on the type of method and on the defect. As long as void cracks are dealt with, the Kirchhoff approximation is used for the defect scattering computation [6]. This method assumes that the echoes generated by an insonified defect are obtained from the sommation of contributions from each elementary surface of the defect. Those contributions may be seen as scattered wavelets. Their relative amplitudes are calculated using the incident wave field distribution – computed using the pencil method described in the previous paragraph - , and the complex diffraction coefficient at the defect. Finally, an argument based on Auld's reciprocity is used to predict the sensitivity at reception, that-is-to-say the signal observed by the receiving probe. Each possible echo formation, in Longitudinal (L) waves mode, Transverse (T) wave mode or using mode conversion at the backwall or at the defect are individually computed. The overall response obtained for the inspection simulation results from the sommation of these individual echoes. It may also be mentionned that some developments have recently been performed to deal with solid inclusions [7] – for which the Kirchhoff approximation is not valid anymore - , as well as complex scattering effects which may occur on non smooth defects (multiple paths over a ramified defect, etc...). For this latter case, an hybrid method was used to couple a finite element code for scattering around the defect and the pencil method carried out for the long range propagation modelling [8].

Results: In the following, we present some examples of comparison between simulations and experiments concerning both the field computation model and the defect scattering model, prior to specific simulations that illustrates some skills of phased array techniques in terms of phase aberration correction abilities, electronic commutation performances assessment and dynamic tandem inspection with phased arrays compared to a classical tandem inspection with a pair of probes.

Validation of beam and defect scattering models

Figure 1 below shows an example of comparison between simulated and measured beam profiles radiated by a circular arrays used in immersion mode (made of 11 rings, and with a central frequency of 1 MHz). Measured and simulated profiles are located at 20 and 50 mm depth, along aline perpendicular to the probe axis. The transducer radiates longitudinal waves focused at 50 mm depth in a ferritic steel block.

Fields profiles measurements are obtained with an electromagnetic probe (EMAT) in through transmission tests over a stepped block. Simulations are carried out with a reference waveform corresponding to the ascan obtained at the focusing point. The use of an experimental signal as the reference waveform allows to take account of the acquisition system characteristics as well as the bandwidth of the receiving probe. The very good agrement between simulations and measurements both validates the model and the manufactured probe. It also allows to show that the electrical and acoustic cross-talk between elements of the array are very low, otherwise they would have led to additional contributions.

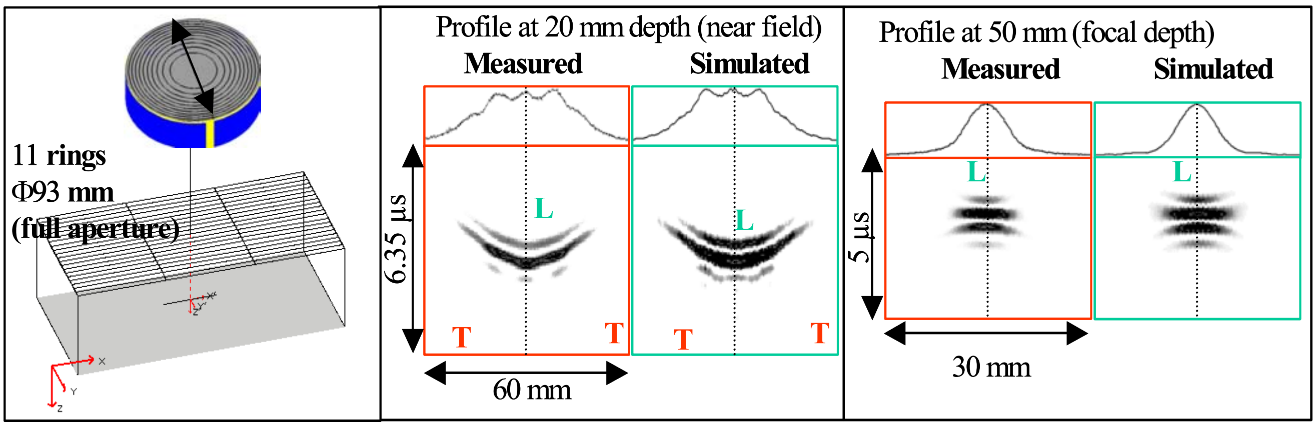

Figure 1: Comparison between simulated and measured beam profile transmitted by a circular array

Figure 2 presents another example of simulation tools validation, dealing with the application of sectorial scanning technique over a calibration block (containing 7 side drilled holes, from 72mm to 48 mm depth, with a 4 mm depth step). A contact linear array made of 32 elements (overall aperture of 16x15mm²), at 5 MHz frequency, steers a longitudinal beam from 0° to 75°. The simulation result of this configuration is shown on the figure. One can observe echoes from the side drilled holes and from the backwall reflection. On this figure, ultrasonic echoes obtained for the various refracting angles are displayed in a so-called "raw" Bscan, coordinates being each refraction angles and time of flight.

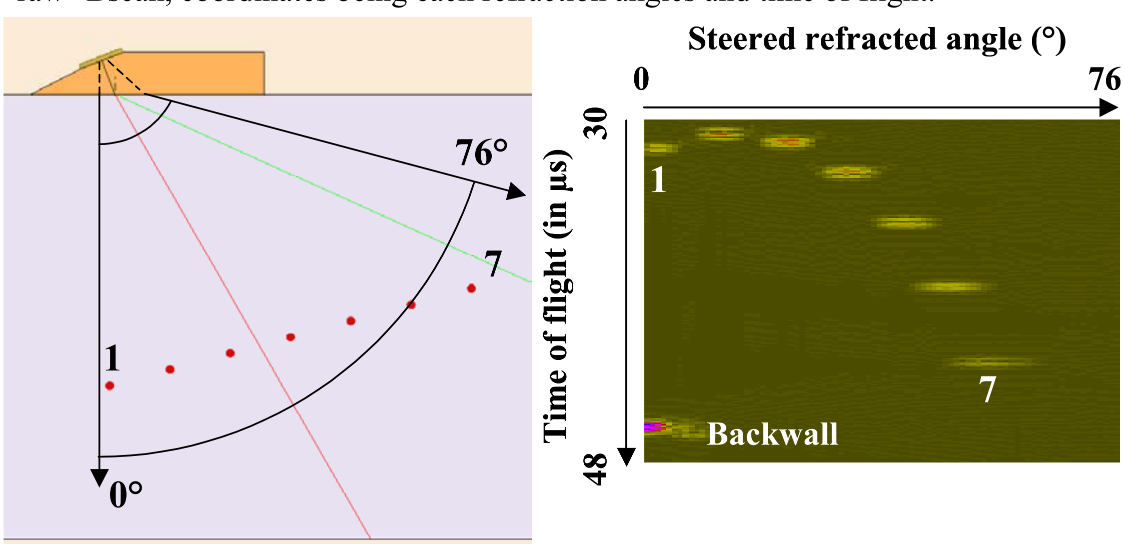

Figure 2: Simulation of sectorial scanning technique over a calibration block

From this Bscan image, one can create the sectorial scan image which allows to display the echoes in spatial coordinates related to the component referential axis, as illustrated on the figure 3 below. On the same figure, the experimental result is also displayed as a sectorial scan image. This experiment was carried out using a phased array equipment - Multi 2000 system - , developed by M2M [9], for which Civa simulation tools for phased arrays settings are integrated. Here again, a good agreement is obtained between simulation and experiments (slight differences are observed because the acquisition time windowing are different from simulated and experiment images).

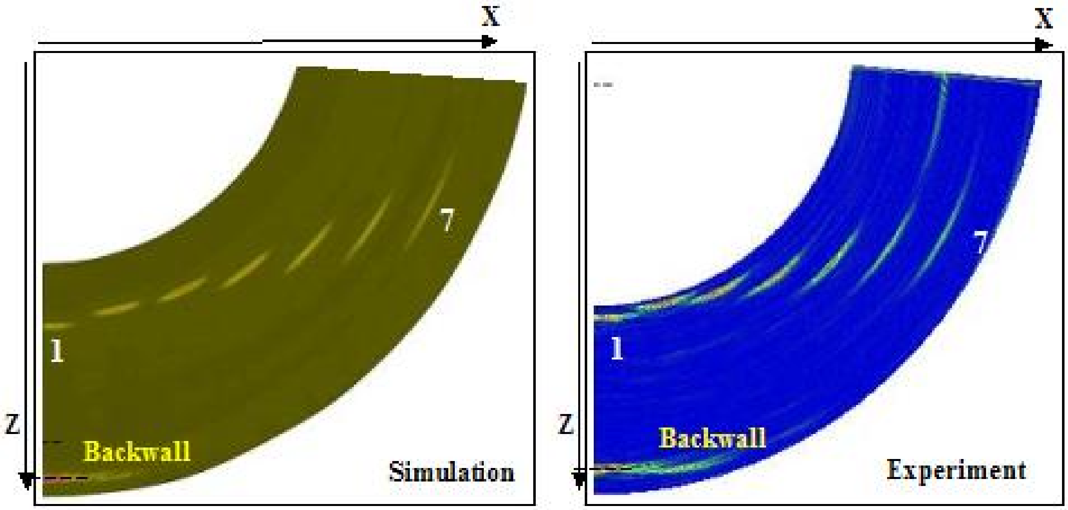

Figure 3: Comparison between simulated and measured sectorial scanning technique over the calibration block

Simulation of phase aberration correction

The following example demonstrates a compensation of aberration effects due to an irregular profile. A linear array is used at immersion over a specimen made of an irregular profile. It can be observed that, in such a configuration, strong effects may occur even in the case of slight aberrations (on the irregular profile, the altitude variations are about +/-1 mm over a 40 mm distance, within slow slope variations (see figure below). On the figures simulated beam profiles have been reported, for two different materials : plexiglass and ferritic steel, with respective sound celerities in Longitudinal mode 2720 m/s and 5900 m/s, for each following labelled configuration : "no delays" (all elements are simultaneously shot), "phase compensation" (delays are optimised to recover a planar wave front in the material), and "phase compenstion+focusing" (delays are optimised to focus the beam at the profile depth, taking account of the irregular profile) . If no delays are applied, the profile variation clearly leads to distortions of the beam, both in terms of amplitude and arrival time, and these effects are obviously stronger for the water/steel interface than for the water/plexiglass interface. Adapted delays allow to compensate these aberrations, whether the aim is to transmit planar waves or to focus the beam.

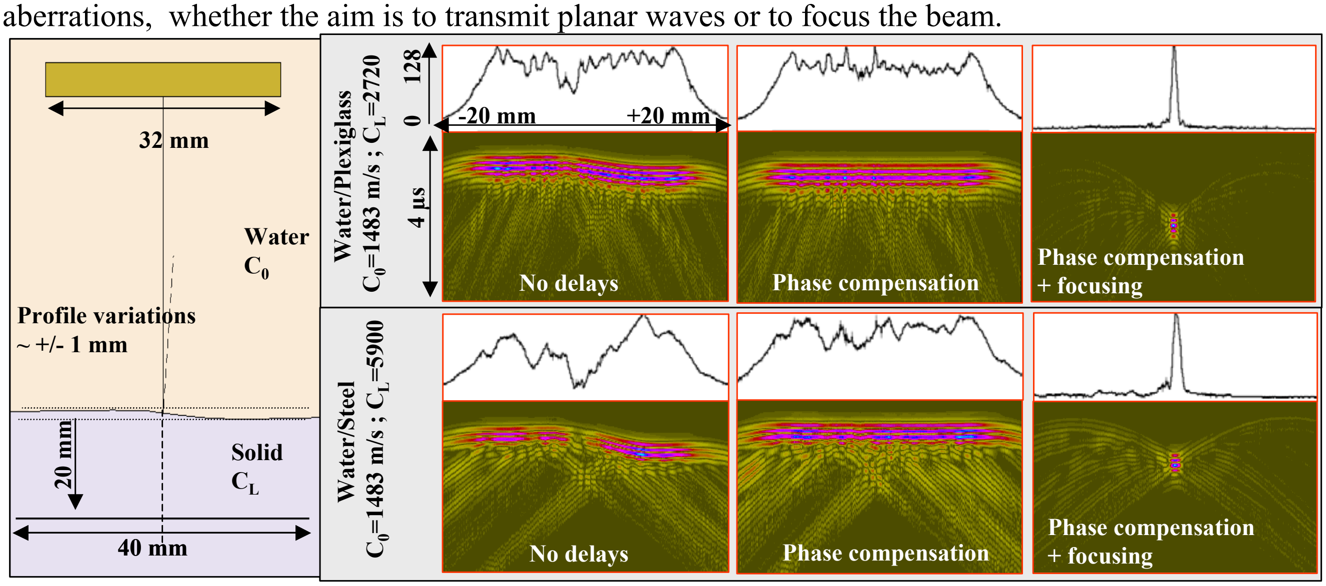

Figure 4: Simulation of phase aberration effects due to an irregular geometry and their compensation using a linear array with adapted delay laws

Electronic commutation simulation

The electronic commutation technique is one of the most usual application for phased arrays techniques : it consists in using a limited number of active elements (at Transmission and Reception) multiplexed over a large array. For instance, a frequently encountered configuration is a 16x64 channels/elements pattern, which means that 16 elements may be fired over an overall aperture of 64 channels. The first 16 elements are used at transmission and reception, then this aperture of 16 elements is successively translated with a step of one element until to cover the whole array. This technique is classically apply to reach very high acquisition rates with a simplified mechanical device, since one of the displacement direction can be replaced by an electronic commutation. However, the limitation of this technique is that the inspection resolution depends both on the beam spot and the distance between two adjacent elements. An accurate estimation of the resolution is to be assessed to predict the actual performances of the technique. This can be experimentally carried out using a redundancy technique : the linear array performs both an electronic commutation and a mechanical displacement along the array splitting [9]. The example described hereafter illustrates theses skills using the simulated inspection of a parallepipedic steel block containing an hemispherically bottomed hole inspected with 0° longitudinal wave beam beam focused at the calibration reflector depth (25 mm), by a linear array of 48x20 mm² aperture, of 32 elements (the pitch being 1.5 mm), and with a 3 MHz central frequency. The array has a cylinder focusing pattern on the perpendicular plane (radius of 150 mm). In the example displayed on figure below, the linear array is moved above the flaw, from -10 to +10 mm, with a 0.15 mm step displacement. For each scanning position, the electronic commutation is performed using 16 elements over 32, 1 element step (thus 17 sequences are applied over the array aperture). The ultrasonic data collected using such an inspection can therefore be seen as a Cscan image, displaying the waveforms received for successive sequences, and for all scanning positions. The mechanical displacement being much smaller than the electronic commutation step (equal to the phased array pitch), the variations observed for two successive commutation patterns correspond to the variation losses due to the fact that the flaw is not exactly aligned to the axis of the radiated field. As an illustration of this, 11 successive electronic commutation results are superposed : these sequences correspond to an overall displacement of 1.5 mm, which is the array pitch. Therefore the first and the last sequence are strictly identical, except that they are spatially shifted by 1.5 mm. Both sequences are related to cases where the flaw center is exactly aligned to the field radiated by one sequence of the electronic commutation. Between both sequences, other electronic commutation patterns do not exhibit a perfect alignment of the flaw center with respect to the beam, thus the response of the flaw is discreased. The overall discrepancy is about 1.8 dB, which would therefore be a limitation that has to be taken into account in the performances assessment of the technique.

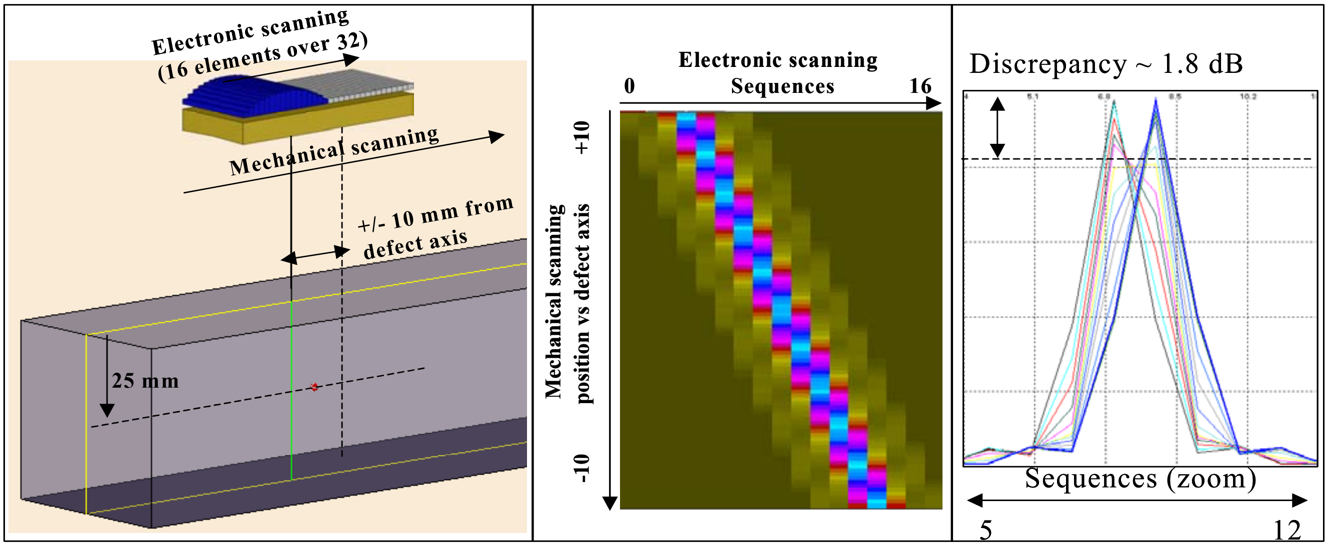

Figure 5: Simulation of combined electronic commutation and mechanical displacement

<u>Tandem inspection over a pipe using phased arrays or a pair of probes</u>

The following example deals with another application of electronic commutation. The aim here is to exploit phased arrays skills for improved flexibility in terms of tandem applications. Such inspection techniques may be carried out to detect midwall defects in noisy materials, as they provide a way to assess flaws in specular reflection (as a contrary a pulse echo inspection with one single probe cannot be used for an optimal corner echo as soon as the defect is not emerging at backwall or frontwall).

In most cases, a pair of jointed probes is used to scan the specimen, one transducer for transmitting waves, the other one for receiving scattered echoes. The distance between both probes and their characteristics (refraction angle and generated modes - L or T beams -) allow to master the inspection characteristics (mostly in terms of defect detectability over depth).

Figure 6 below shows a simulated inspection carried out using a pair of probes over a cylindrical mock-up (external diameter of 400 mm, and 50 mm thickness) containing three planar defects of 10x5 mm² (height and extension) which ligaments (distance from the lower extremity of the defect and the backwall) are 7, 17 and 27 mm. The gap between both probes - contact planar probes of 18x15 mm² aperture radiating 45° shear waves - as well as the refraction angle lead to an optimised inspection for the planar defect related to the medium ligament, as displayed on the figure. As a result, the simulated inspection of the different defect obtained over a cylindrical scanning shows that this defect exhibits the stronger amplitude response.

An alternative way to perform such a technique relies on the selection of different groups of elements over an array, some elements being in transmission mode, other elements in reception mode. As those elements may be arbitrarily selected, and, in addition, with arbitrary delay laws applied, phased array allow a significantly more flexible tool for tandem inspections. Figure 7 illustrates an example of simulation with the same mock-up, to improve defect detection over other defects. A contact phased array made of 48 elements is used with separate elements at transmission and reception, to replace the pair of probes. Inspections have been simulated for three different settings of the phased array probe, each setting designed to optimise the inspection of one defect. The delay laws are computed to focus shear waves at the selected defect depth, in direct mode for elements used at reception, and focusing after backwall reception for elements used at reception.

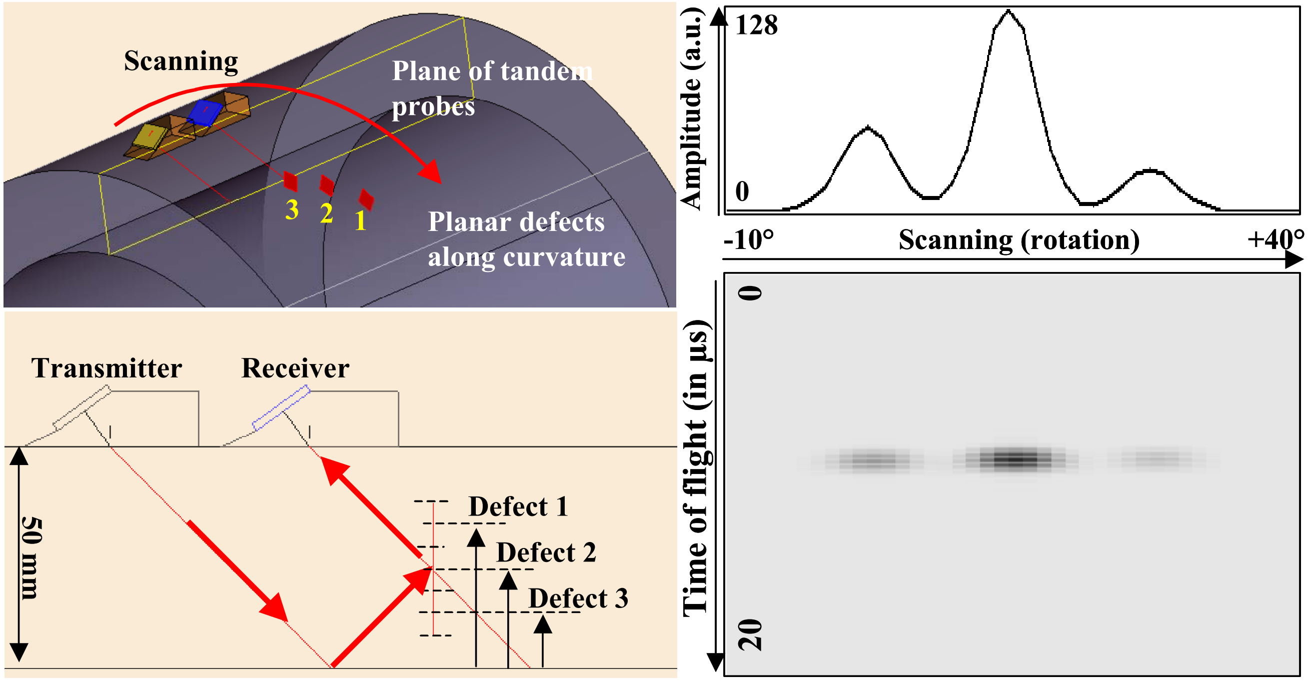

Figure 6: Simulation of Tandem inspection over a pipe with a pair of contact probes

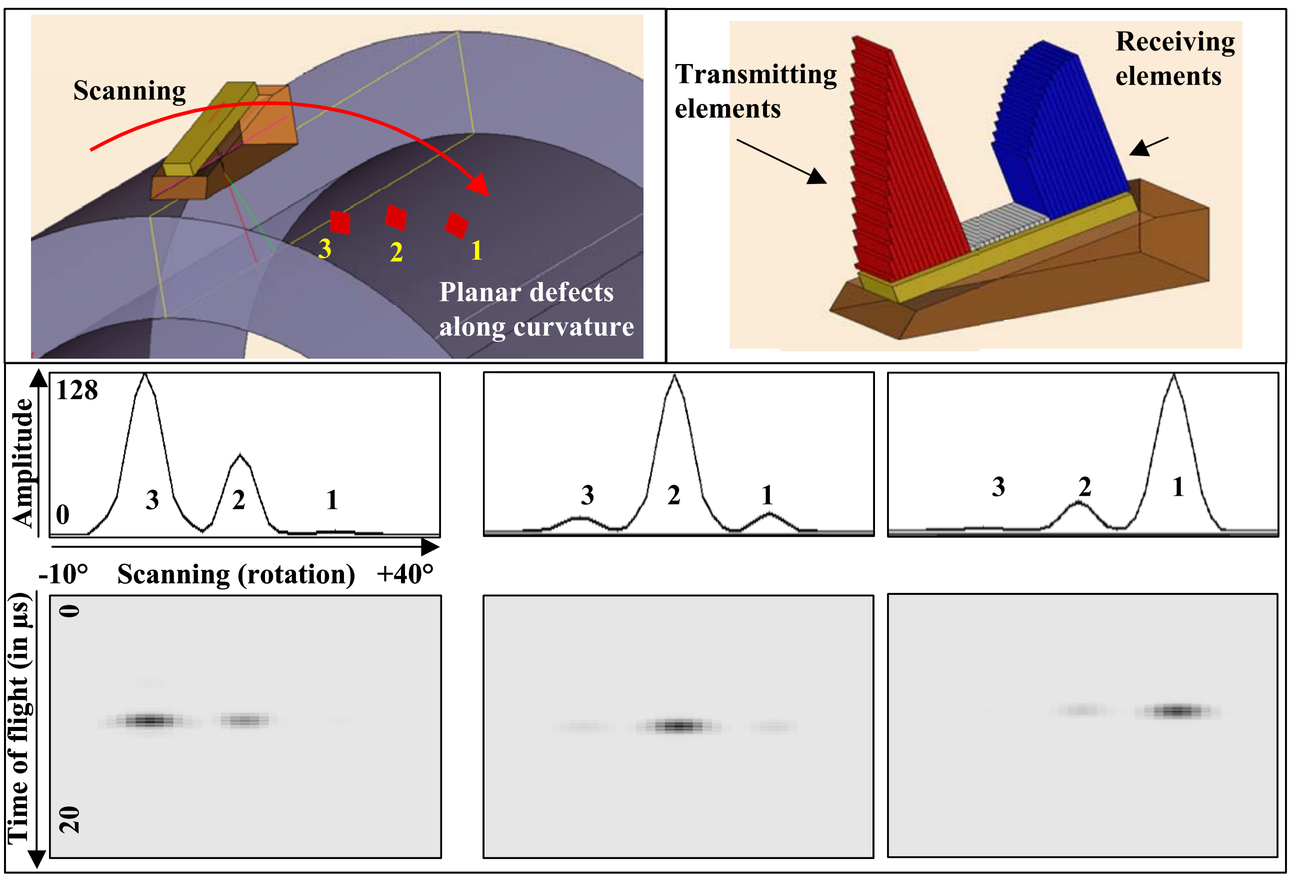

Figure 7: Simulation of Tandem inspection over a pipe using a phased arrays and settings for each defect

Conclusions: Modeling tools developed at CEA, in terms of wave propagation and echo formation simulations, allow both to optimise and predict performances of phased array techniques. Examples of experimental validation for simulation of radiated beam by annular arrays, as well as inspection in sectorial scanning mode have been shown. Simulation tools have also been used to illustrate the ability to predict and to compensate beam distortions or deviations which may occur through a complex shaped specimen. Electronic commutation techniques have also been simulated, which shows that one can use simulation to predict the performances of such techniques in terms of amplitude losse due to lateral resolution. At last, an example of electronic commutation technique using different groups of elements at transmission and reception has been simulated, which illustrates the ability of phased arrays to improve the flexibility of tandem-like inspections. This latest application has also been compared to an inspection carried out with a pair of standard contact probes.

References:

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