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Applications and recent evolutions of the CIVA Simulation Platform

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Abstract
The CIVA platform dedicated to the modeling of NDT techniques is now extensively used in different industrial sectors. This simulation tool is developed by CEA LIST and benefits also from the contribution of numerous partners from industry and universities. The ability to capitalize in a unique platform such developments allows enhancing regularly the fields of applications of CIVA. For instance, some of the latest developments deal with Long Range Ultrasonics using guided waves (LRUT) or Computed Tomography (CT). Used during the design stage of a new component or for the performance demonstration of an in-service inspection method, the simulation tool supports productivity improvement, for instance by reducing the number of necessary mock-ups and experimental trials since it helps to understand what are the influential parameters of an inspection. It also helps to introduce innovative processes such as multi-elements methods. Simulation serves an additional useful purpose by producing realistic inspection results that will confirm or disprove a diagnosis. This article introduces some applications of modeling in NDT as well as some of the latest developments now available in CIVA.

Keywords: Simulation, Modeling, UT, ET, RT, CT, Guided Waves

1. CIVA software Package

The simulation plays an increasing role in NDT, allowing to help the design of inspection methods, their qualifications or the analysis of inspection results.

The CIVA software package can simulate the 3 major NDT techniques: Ultrasonic Testing (UT), Eddy Current Testing (ET) & Radiographic Testing (RT). Moreover, the latest release of the softwate 10.1, also allows to model 2 additional techniques: Guided Waves Ultrasonics also called Long Range Ultrasonic Testing (LRUT) and Computed Tomography (CT).

All these five modules are available in the same environment, bringing to the users a unique NDT oriented Graphical User Interface and some dedicated tools, which make its use quite easy.

The mathematical formulations used in the different modules generally rely on semi-analytical models. This approach allows solving a large range of applications while offering very competitive calculation time compared with purely numerical methods (FEA, etc.).

To summarize the different models, it can be indicated that the UT module relies on a rays theory geometrical approach to compute beam propagation, the so-called “pencil method”. The interaction with defects is calculated using either “Kirchhoff” approximation or the Geometrical Theory of Diffraction “GTD”.

The Guided Waves module uses a hybrid “SAFE” method (Semi-Analytical and Finite Elements), considering a semi-analytical modal decomposition approach for the propagation along the guide, and a FEM approach in the guide section.

The Eddy current module involves a Volume Integral Method which only requires a numerical sampling of the flaw, the electromagnetic field induced in the work piece being calculated analytically.

The X-ray and Gamma-ray tool uses a “rays” approach associated to the Beer-Lambert straight line attenuation model to compute direct radiation. The scattering radiation is solved thanks to a probabilistic approach (Monte-Carlo method) allowing to reproduce photons/matter interaction phenomena.

The CT module calculations relies on the same model than the RT one, including specific tools linked to the tomographic technique. In the present release, two 3D reconstruction algorithms have been implemented: FDB (Feldkamp, Davis and Kress) and PIXTV.
For interested readers wishing to have more information on the models, the following reference papers are available, [1] for the Ultrasonic tool, [2] for the Guided Waves module [3] for the Eddy Current part, [4] for the radiographic one and [5] for the CT module.
One of the main advantages of the semi-analytical approach is to make possible the solving of parametric studies with time compatible with industrial use (sensitivity study, tracking of the best design or of the worst case scenario, etc.). By giving quantitative and numerous results, in a relatively short time and integrated in an intuitive environment, the simulation can constitute a real benefit to optimize performances and cost efficiency in a NDT process.
Extensive validation works of the different codes are performed, and published on the EXTENDE website www.extende.com/validation-2. This validation activity also includes the participation to international benchmarks [6].

2. LATEST MODELING CAPABILITIES

The CIVA platform regularly proposes new releases in which improvements are included. With CIVA 10.1, new capabilities of simulation are being offered : Computed Tomography, and Long Range Ultrasonics.

2.1 Computed Tomography

The CT module relies on the same model than the RT one, but involving several positions of X-ray shots. CIVA will compute all the RT simulations for all the defined projections. Once the computations are done, all the images are available for all the projections. A specific processing is then available to realize the 3D reconstruction. In the current commercial version, two algorithms are implemented:

- The Feldkamp, Davis and Kress better known as the **FDK algorithm** is implemented. This algorithm is a widely used filtered-back projection algorithm for three-dimensional images reconstruction from cone-beam data
- The second method of reconstruction uses the **PIXTV algorithm** based on compressed sensing theory. This is an iterative reconstruction algorithm which minimizes the TV (total variation) norm

Once the processing is finished, CIVA shows the component in 3D. Many tools are then available to represent the reconstructed component: Display of the iso surfaces, Volume rendering, etc.

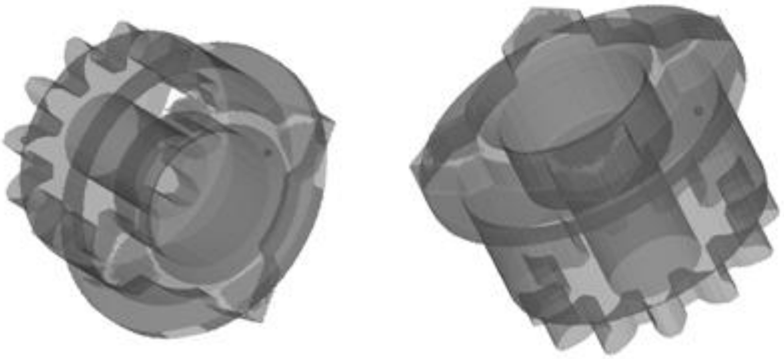


Figure 1. 3D reconstruction of a 3D CAD component in CIVA CT

2.2 *Long Range Ultrasonics Testing using Guided Waves*

2.2.1 The "SAFE" method in a few words

To solve guided waves configuration, CIVA uses a so-called SAFE method, which is a hybrid approach using both semi-analytical and FEM models. Due to the particular multimodal nature of guided waves, a modal decomposition is performed and the model is then solved in the frequency domain, typical waveforms being then synthesized by Fourier transform. The semi-analytical approach is used to solve the guided propagation whereas the FEM is involved in the guide section. Specific FEM models have also been developed to solve the local phenomena (transducer diffraction, defect scattering, guide discontinuities). This hybrid approach allows a very cost-effective simulation time, while both local and non local phenomena can be accounted for [2].

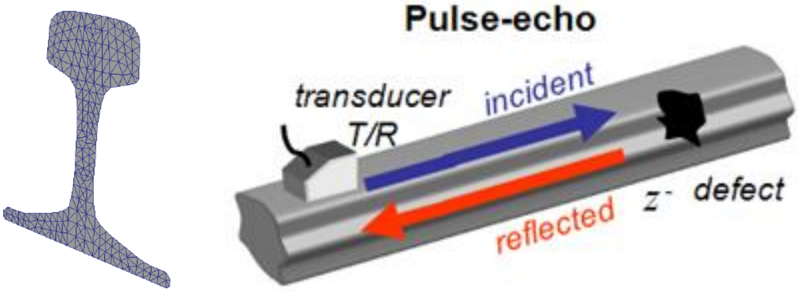


Figure 2. SAFE model: FEM in the guide section, Semi-Analytical for waves propagation

2.2.2 Tools capability

The new tool implemented in the CIVA platform allows to compute dispersion curves, ultrasonic field, and defect response data.
For each mode, the dispersion curves will give the frequency dependence of the phase & group velocities, of the wave number & wave length and of the attenuation. The knowledge of the dispersion curves allows to inform about the potential modes that can propagate in a given wave guide and to predict the order of the modes received in the time domain. The field computation will allow to display the displacement/stress emitted by a given transducer while the defect response will calculate the Ascan at the receiver (including one or several modes) when the specimen includes a notch, perpendicular to the wave guide section.

In the first release, planar and tubular specimen configurations can be addressed, with possibly a coating. Transducer can be contact single element or phased-array probes with a wedge or not and encircling/encircled arrays in tubular configurations. Inspection techniques covered are pulse-echo, tandem and pitch/catch configurations. The SAFE method implemented will allow to enhance this capabilities in future versions.

2.2.3 Application to the inspection of an aluminium plate

The following example simulates the inspection of an aluminium plate of 1.5mm thickness. The transducer is a contact probe with a wedge angle at 60° and an input signal centered around 2Mhz. A pitch-catch symmetrical configuration is performed with a PCS of 200mm:

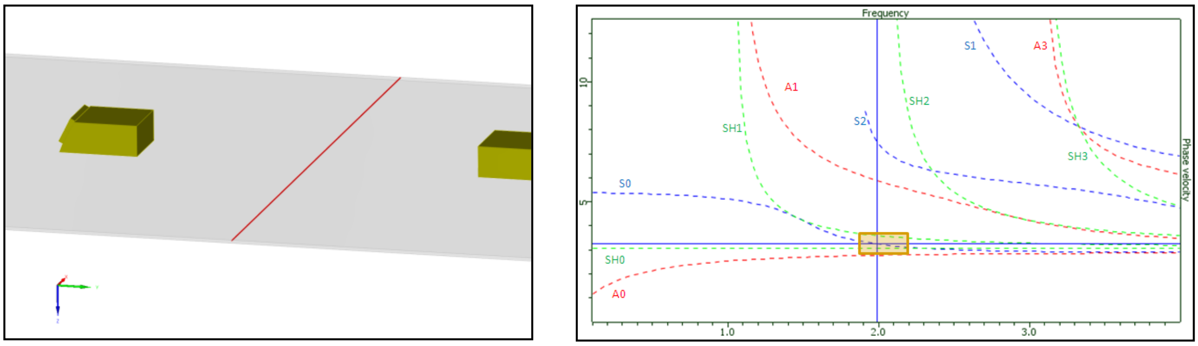


Figure 3. CIVA simulation on a thin aluminium plate, dispersion curve (phase velocity vs frequency)

As shown on the dispersion curves, for this angle and this frequency, the mode involved is mainly the S0 one with also A0. No particular shear solicitations were applied so that shear horizontal (SH) modes are not considered here.

The response of a flaw has been simulated for different heights (0.1, 0.5 and 1mm) and compared to the signal received without any flaw. On the calculated Ascans, the A0 mode and S0 mode are visible, the amplitude of A0 mode being only 10% of S0 as expected.

The influence of the flaw can be evaluated by an additional signal due to a S0-A0 conversion mode, and a decrease of the amplitude of the nominal A0 and S0 echoes observed without flaw. The influence of the height of the flaw can be predicted with a maximum amplitude of -12dB for the signal with the 1mm high notch, compared to the echo of the nominal S0 mode.

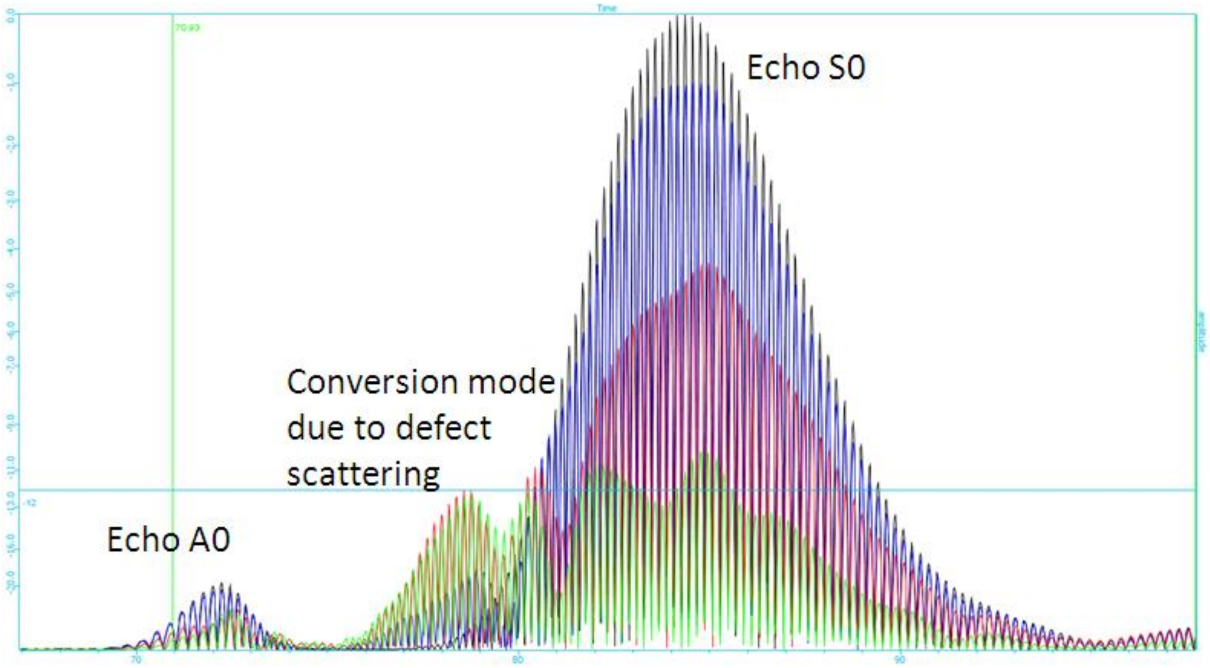


Figure 4. Simulation Ascan obtained in the testing configuration with respectively no flaw (blak curve), 0.1mm notch (blue curve), 0.5mm notch (red curve), 1mm notch (green curve)

3. Application to the inspection of stainless-steel bars with AUT

The following application examples deal with the ultrasonic automated inspection of stainless steel bars in production lines. These works were performed with the collaboration of UGITECH. Subsidiary of the groupe Schmolz & Bichenbach, UGITECH is one of the world leaders for the production of stainless steel long profiles. The products manufactured are bars, wire rods, drawn wires and rebars. Main end users are in various and demanding industrial sectors such as nuclear industry, aerospace, automotives, energy and processing industries, for which a high quality internal health and a good surface state of the raw material is an absolute necessity. Automated UT using phased-array probes is one of the NDT inspection processes installed on the production lines.

A typical inspection set up is presented on the figure 4 below. It consists in an immersed 5MHz encircling array of 116 elements with such a bending radius that natural focusing is reached at the center of the stainless steel bar. The full inspection device involves several arrays circumferentially spread around the bar. On each array, electronic scanning is performed with successive active sequences of 32 elements while the bar is progressing longitudinally so that the full volume of the bar can be inspected. The field calculation tool of CIVA allows to display the beam at any place in the specimen, the figure 5 shows the focal spot at the center of the bar in the perpendicular plane for one active sequence active at the center of the array.

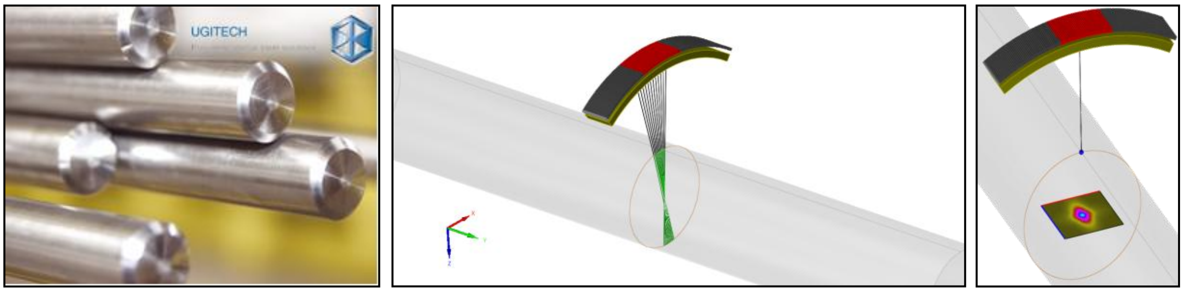
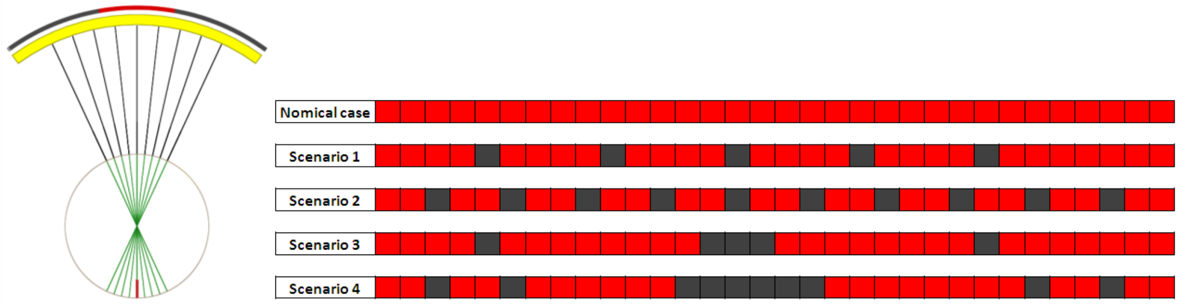
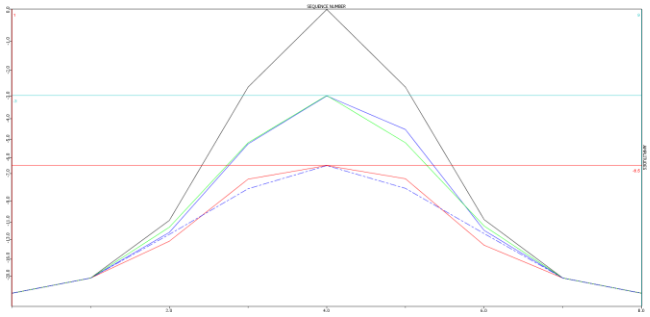


Figure 5. UGITECH stainless steel bars (courtesy of UGITECH), Inspection setup, Image of the focal spot in the perpendicular plane

One of the question addressed during the simulation study was the impact of misfiring element on the detection capacity of the device. For such purpose a Flat Bottomed Hole has been implemented in the bar and several scenarii of misfiring elements were simulated (active elements in red, broken elements in black).





Scenario	Amplitude Loss
Nomical case	0 dB
Scenario 1	-3dB
Scenario 2	-6.5dB
Scenario 3	-3dB
Scenario 4 ---	-6.5dB

Figure 6. Flat Bottomed Hole positioned in the bar (in red), description of scenarii involving misfiring elements (in black) in the array, results (superimposed echodynamic curves), Amplitude loss

The curves displayed show, for each scenario, the amplitude variation versus the different sequences successively enabled on the array (echodynamic). For the given position of the FBH, the maximum is logically obtained at the centre sequence whatever the case but one can noticed a loss of amplitude due to the misfiring elements. In this case, scenarii 2 and 4 lead to a similar decrease of 6.5dB to the sensitivity at the centre sequence. But the change between the 2 echodynamic curves shows that this impact could be different for other positions of the flaw. Simulation tool can allow to describe easily many other scenarii (other flaws position and geometries, non symmetrical arrangements of the misfiring elements).

A similar inspection process is also used, but using shear waves refracted at 42° at 10MHz, thanks to other focal laws. This allows to detect for instance, potential crack positioned as below, with a corner mode.

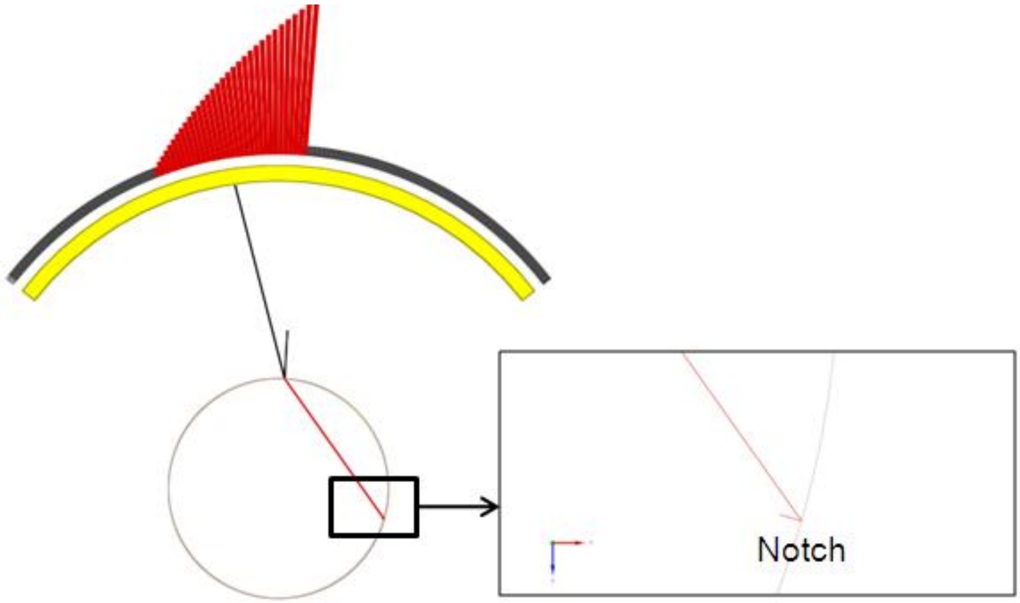


Figure 7. Flat Inspection of a notch with Shear waves refracted at 42° loss

Several scenarii were run with different defect heights. The calculated results below represent a Bscan view reconstructed on the bar profile. It shows that, in addition to the expected corner echo whose amplitude can be correlated to the defect height and its criticity, additional signals are obtained due to creeping waves generated at the reflection of the beam on the bar boundary. This second signal can be sometimes higher than the corner echo or can interfere with it and may disturb the diagnosis, leading to potential false alarms.

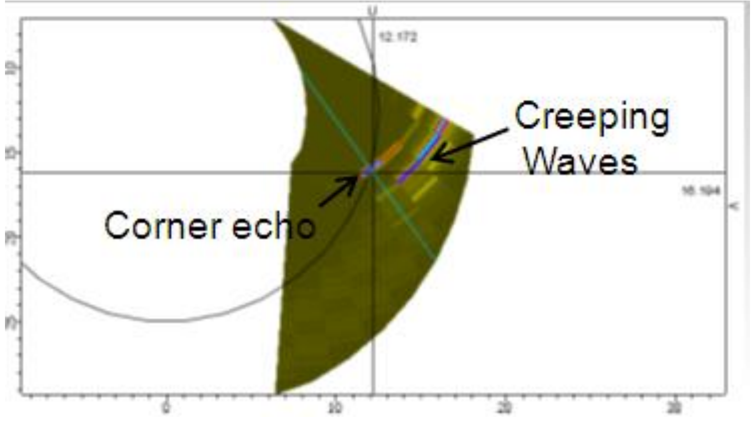


Figure 8. Bscan obtained for the inspection of a 0.1mm high notch

4. Comparison of TOFD and Phased-array performances for the inspection of a heater

The following example deals with the inspection of a heater, located in an EDF French oil-fired power plant, using two different UT techniques: TOFD and Phased array. This study was performed according to the specifications of EDF DTG (Division Technique Générale).
The component to be inspected is visible on the image below. The Region Of Interest (ROI) is the fillet of the heater. A CAD model of this region of the specimen has been defined in CIVA

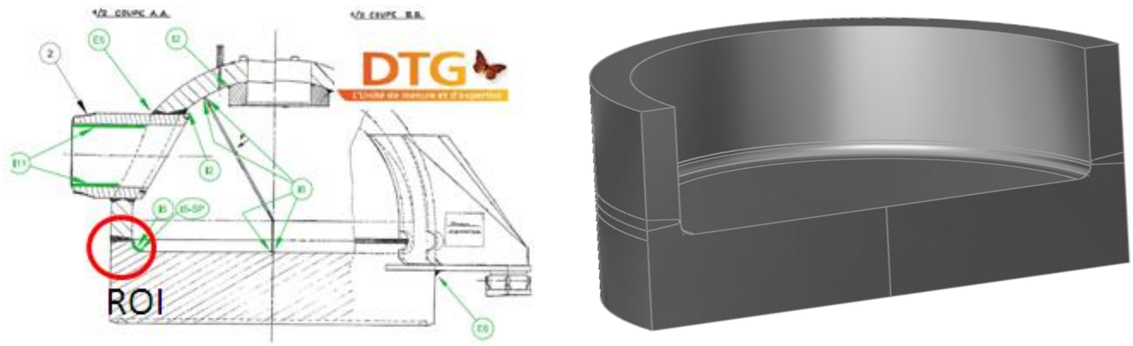


Figure 9. Geometry of the heater (courtesy of EDF DTG)
and CAD representation of the zone of interest in CIVA

Phased-array and TOFD techniques were simulated and compared. The phased-array probe is a 2MHz linear array with 8 elements, 1mm width for each, mounted on a wedge rexolite. The natural angle of refraction for shear waves is 54°, and a sectorial scanning was performed between 35° and 70°. The probe then mechanically scans over the weld side. Both directions of scanning are used to detect different types of defects. The TOFD technique involves two identical 4.2MHz contact probes generating longitudinal waves at 45°, separated by a PCS of 230mm. The elements, mounted on a rexolite wedge, are rectangular single crystals of 4mm*8mm. As for the PA case, the probe similarly moves over the weld side.

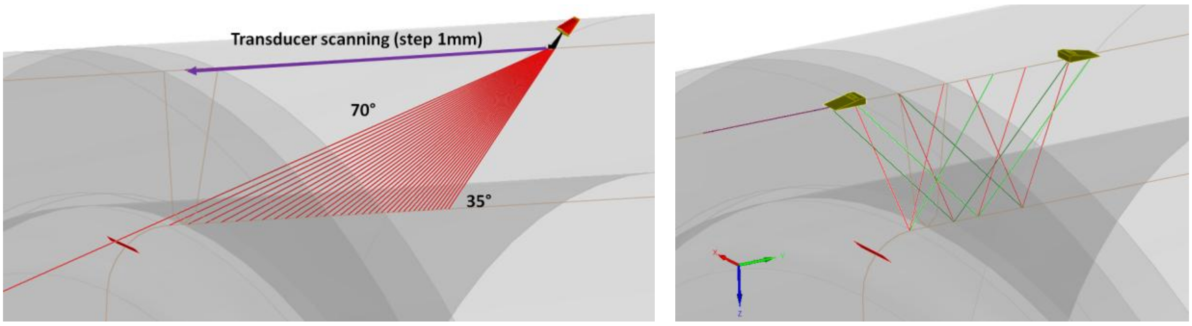


Figure 10: a) Inspection set-up with phased-array probe, b) TOFD case

The simulation were performed with several defects positioned on the fillet. The results below show the case of a 5mm depth notch radially orientated from the centre of the fillet (orientation 45°). The figure 11 presents the angular scan obtained with the phased-array probe, first, for one position, then the cumulated scans over the probe mechanical scanning.
As expected a strong specular reflexion on the flaw is obtained at 45° while the angular scanning allows to reach a similar sensitivity of detection for different positions and orientation of the flaw around the fillet. For instance, it can be seen on figure 12 that a quite strong echo is obtained on another type of defect with the same probe.

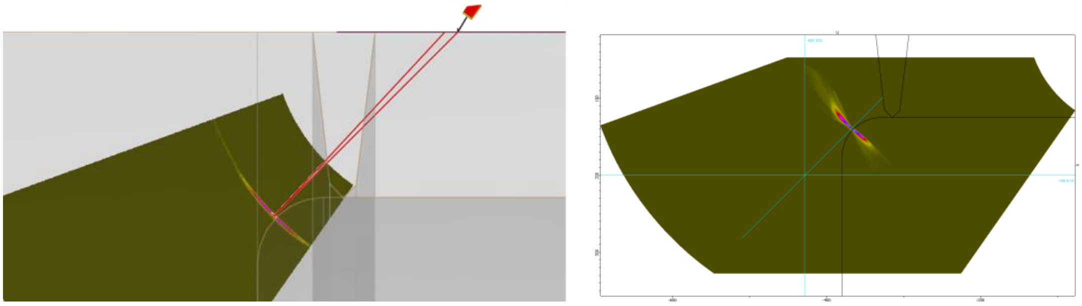


Figure 11. a) Sectorial scan obtained with a 5mm depth notch, b) cumulated S-scan over the probe mechanical scanning

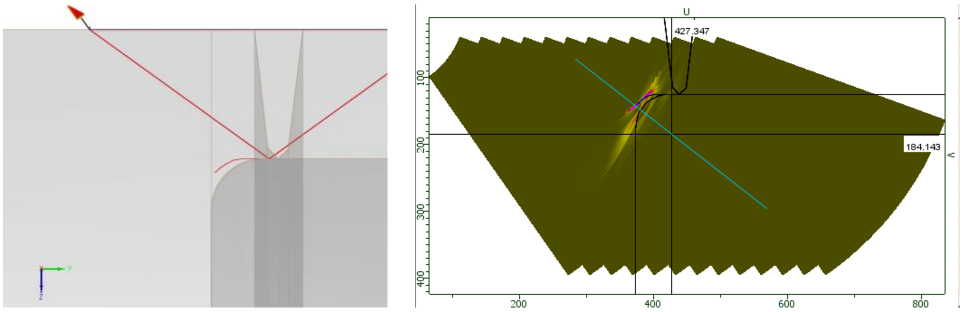


Figure 12. a) Phased-array simulation with a second flaw, b) Cumulated S-scan Obtained over the probe mechanical scanning

The results obtained with TOFD are shown below, first, the Bscan without flaw, then, the Bscan with the 5mm depth notch, orientated at 45°, and then the Bscan with a 10 mm depth notch with the same orientation.

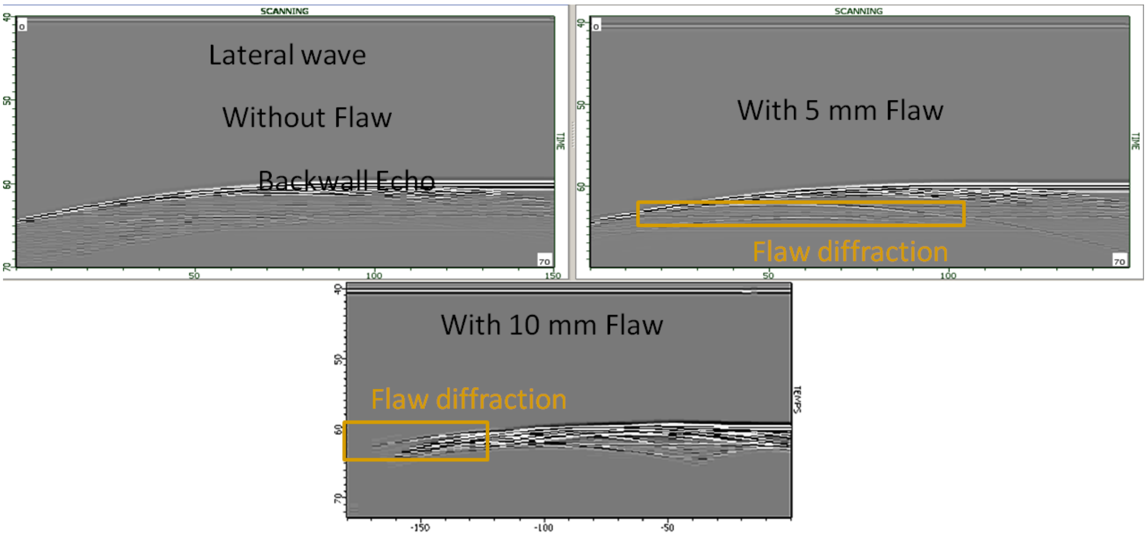


Figure 13. a) Results with TOFD without any flaw, b) TOFD results with flaw #1 (5mm depth, 45° orientation), c) TOFD results with flaw #3 (10mm depth, 45° orientation)

The two methods are quite complementary in this case as the PA allows a quite easy detection of the flaw whatever the case whereas the detection is quite difficult with the TOFD when the flaw size is below 10mm, due to the particular position of the backwall echo on this geometry. However, the existence of the diffraction signal helps to define the depth of the flaw and confirm the characterisation when the size of the flaw is above 10 mm at 45°. From this study, the simulation works continued and allowed to optimize the features of the phased array probe to be used on the field. Different flaws scenarii were simulated allowing to iterate and to improve a first diagnosis that was given from an on-site inspection.

5. APPLICATION TO THE INTRODUCTION OF INNOVATIVE TECHNOLOGIES: EDDY CURRENT ARRAY PROBE

Another benefit of the simulation is the ability to help the introduction of innovative inspection methods. Pre-design tests can be done at a quite low cost which will give the first answers, allowing minimizing the iteration of the prototyping phase. The realization of the prototypes is then faster and more efficient. Earlier in the process, you can also use the simulation to compare the performance of an innovative sensor to a conventional one, before deciding to change and to invest in the new technology.
The design of an Eddy Current array can be an example of such an innovative sensor. On the figure 4, you can see an eddy current array made with a set of micro-coils, designed by the CEA with the help of CIVA. The probe is here composed of 64 micro-coils positioned on 2 layers of 32 elements, separated by a kapton film and assembled on a flexible support.

Figure 14. Flexible ET array probe

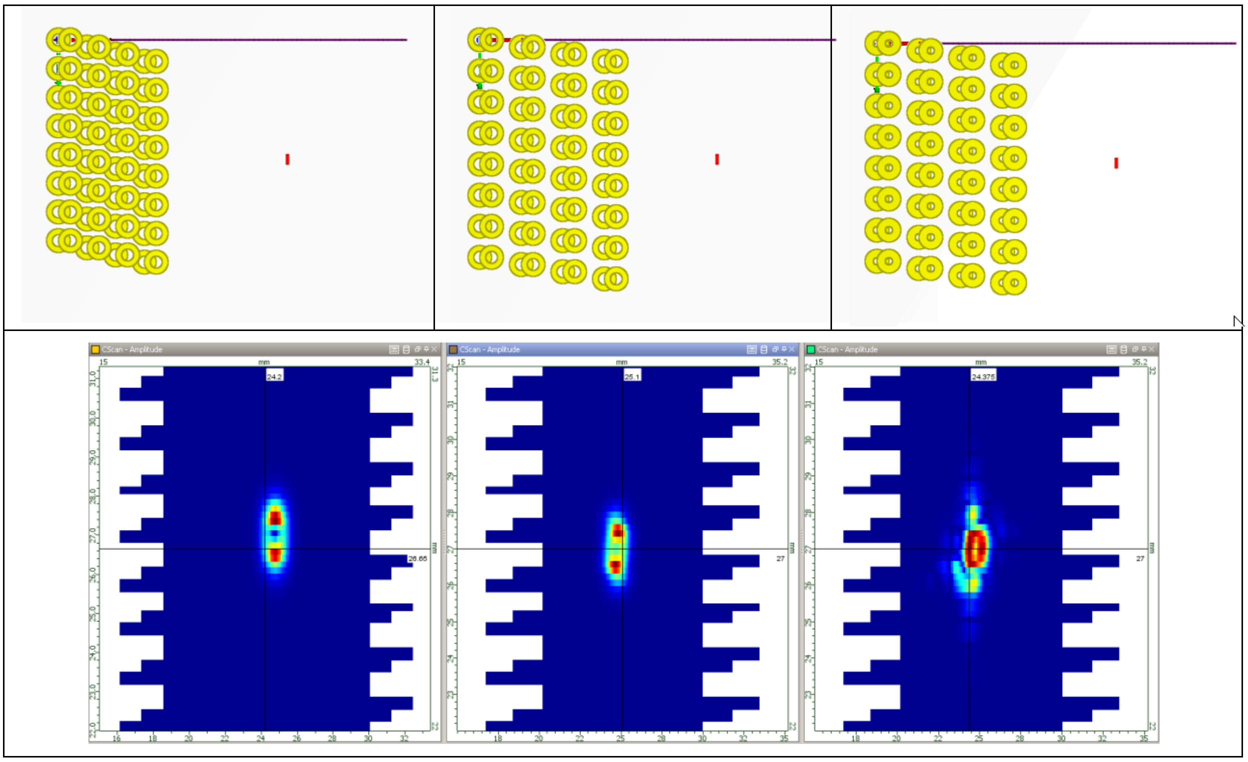


Figure 15. Different designs evaluated by simulation / Cscans of the obtained signal amplitude

This multi-elements technology has significant advantages compared to a conventional one made with standard wounded sensors. First of all, it allows detecting small indications with a very good resolution. Then, the benefit of multi-elements is to require less position of acquisitions and then decrease the mechanical scanning, therefore the inspection time.

Moreover, the electronic management of the arrays allows to benefit from multiple inspection channels. Finally, the flexibility of this probe assembled on a silicon roll ensures a good contact with the work piece, even with an irregular profile, and decreases the level of parasitic signals due to lift-off variation (see [7] for more information on this probe).

For this type of technology, not yet commonly used in the industry, the design process can be quite long, few experiences and few feedbacks being available.

The simulation makes possible to explore the different possibilities at a quite low cost in order to reach a given level of performance (minimum size of flaw to detect, Signal to Noise Ratio, etc.). The size of the elements, the gap between the elements, the operating frequency(ies), the acquisition modes (separate Transmit/Receive, common mode, etc.) are variable parameters that will affect the performance of the probe and that you can define and change very fast in CIVA.

On the figure 15, one can see 3 different set up of matrix arrays of 64 micro-coils with different coils dimensions, inter-coils distances, and acquisition modes. These different solutions are tested on the simulation of the defect response of a 0.4mm*0.2mm*0.1mm flaw, located in an inconel slab. A linear mechanical scanning is performed. It can be noticed on the 3 obtained Cscan that the defect signal significantly changes between each cases.

6. Conclusions

This paper has illustrated some of the latest developments available in the CIVA simulation platform. It can be noticed that Long Range Ultrasonic and Computed Tomography are new techniques that can be addressed. Some application examples of the benefits that can bring such a tool are then described in different industrial applications: Automated UT inspection of stainless steel bars, Phased-array and TOFD inspection of a heater in a power plant, development of an innovative eddy current array sensor.

Acknowledgements

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References

[1] S. Mahaut, S. Chatillon, M. Darmon, N. Leymarie and R. Raillon, “An overview of UT beam propagation and flaw scattering models integrated in the CIVA software” *Review of Progress in QNDE,* these proceedings (2009).

[2] V. Baronian, A. Lhémery, K. Jezzine, “Hybrid SAFE/FE simulation of inspections of elastic waveguides containing several local discontinuities or defects” *Review of Progress in QNDE,* these proceedings (2010).

[3] G. Pichenot, D. Prémel, T. Sollier, and V. Maillot, “Development of a 3D electromagnetic model for eddy current tubing inspection: Application to steam generator tubing”, in *Review of Progress in QNDE*, **16** (2005), pp. 79-100.

[4] J.Tabary, P. Hugonnard, A.Schumm, R. Fernandez "Simulation studies of radiographic inspections with Civa", WCNDT 2008

[5] R. Fernandez, S.A. Legoupil, M. Costin, A. Leveque, "CIVA Computed Tomography Modeling", to be published at WCNDT 2012.

[6] R. Raillon, S. Bey, A. Dubois, S.Mahaut and M. Darmon " Results of the 2010 UT modeling benchmark”, *Review of Progress in QNDE,* these proceedings (2011).

[7] "Flexible and array eddy current probes for fast inspection of complex parts", B.Marchand, J. M. Decitre, and O. Casula, QNDE 2010