

New applications of the NDT Simulation Platform CIVA

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ABSTRACT

The CIVA platform dedicated to the modeling of NDT techniques is now extensively used in different countries worldwide including Brazil and in different industrial sectors: Power industry, Aerospace, Oil and gas, etc. 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 this tool. The software can address several NDE methods: UT (conventional, phased-array, TOFD, Guided Waves), RT, CT and ET. Used during the design stage of a new component or for the performance demonstration of an in-service inspection method, the simulation tool allows reducing costs by decreasing 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 and develop new inspection techniques with fewer prototypes. Finally, simulation can also serve as an expertise purpose by producing realistic inspection results that can confirm or disprove a real diagnosis. The latest release CIVA 11 brought some advanced features, for instance, the possibility to deal with really complex and realistic geometries of work pieces or for instance the ability to simulate Digital Radiography and not only conventional films. The software can also help to predict POD curves in UT, ET or RT. 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, GWT.

1. INTRODUCTION ON CIVA SOFTWARE PACKAGE

The simulation plays an increasing role in NDT, allowing helping the design of inspection methods, their qualifications or the analysis of inspection results. The CIVA software package can simulate the major NDT methods: Ultrasonic Testing (UT) including conventional UT, Phased-array UT, TOFD or Guided Waves Testing (GWT), Eddy Current Testing (ET), Radiographic Testing (RT), and Computed Tomography (CT). All these NDT techniques are available in the same simulation environment, bringing to the users a unique NDT oriented Graphical User Interface and some dedicated tools, which make its use quite simple. It is therefore also quite straightforward to compare these methods together or to compare simulation with experimental results since Omniscan Olympus® and M2M acquisition data files can be imported and analyzed inside CIVA environment. Simulation aims at helping people reducing costs induced by mock-ups and prototypes involved in the development and qualification of an inspection. Of course, some physical tests remain absolutely essential but many unnecessary trials could be avoided if simulation tests are performed preliminary, thus, time and money can be saved. By the way, by producing results in a comprehensive and user-friendly imaging environment, simulation allows to help dramatically the understanding of physical phenomena and therefore to ease technical discussions between experts, inspectors, customers, contractors and suppliers.

Simulation can also serve as an expertise purpose by producing realistic inspection results that can confirm or disprove a real diagnosis. 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.). CIVA 11.0 is the latest release available.

2. MODELS AND LATEST CAPABILITIES IN CIVA UT

As indicated above, the mathematical models involved in the simulation are mostly semi-analytical. The UT module relies on a ray 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” for crack-like flaws. In CIVA 11, a mixed-up “Kirchhoff and GTD” model has been developed in order to allow a precise prediction of both reflection-like and diffraction-like echoes in a single calculation. For volumetric flaws, other models are used (SOV, Born). For some configurations, in order to address critical phenomena or to account for interactions between several flaws, a coupling between semi-analytical and FEM methods has been developed (CIVA ATHENA2D module). The Guided Waves Technique simulation is available in a dedicated module, using a hybrid “SAFE” modeling 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. For interested readers wishing to have more information on the models of the ultrasonic tool, the following reference papers are available [1], [2]. Some extensive validation works are continuously performed in order to demonstrate the models consistency. A lot of validation evidence can be found on the EXTENDE website (www.extende.com), but also in conference papers [3].

One of the main new features now available in CIVA 11 is the possibility to import 3D CAD heterogeneous geometries (i.e. a set of different volumes or solids) for the test piece. Up to now, only 3D homogeneous components were available. This greatly expands the potential applications: Assembled structures, welds in complex components, clad 3D geometries, accounting for change of acoustic properties due to heat-treatments, simulation with multiple objects, etc. From now on, interior interface echoes from the geometry can also be calculated in such structures. Also available in the new release, EMAT probes can be simulated based on a coupling between CIVA UT and CIVA ET (in non-ferromagnetic materials). Aiming at getting closer to acquisition systems, another major new capability is to define one or several gates in CIVA UT as you would do in a real system. Olympus® data files can also now be read with CIVA. Finally, the possibility to automatically identify the nature of each wave modes on scan views in UT inspection simulation will help a lot the analysis and understanding of UT signals.

3. APPLICATIONS OF CIVA UT

In the following application, a step wedge made of aluminium and including Flat Bottom Holes is modelled. A Glass plate is positioned next to the block, the whole elements being set in immersion. This device aims at replacing a classical transmission configuration with only one transducer. The new ability to define several solids allows simulating such configuration in CIVA11. A focused probe operating at 3MHz scans this block. The results of the simulation are given hereafter. Both A-scans and images (B-Scan, C-Scan, and D-Scan views) are available to display output signals. On the following image, the echoes reflected by entry and bottom surfaces of the 2 blocks, as well as the ones reflected by the Flat-Bottom holes can

be seen. When preparing an inspection, probe performances can be predicted and compared to another candidate transducer, DGS curves can be plotted.

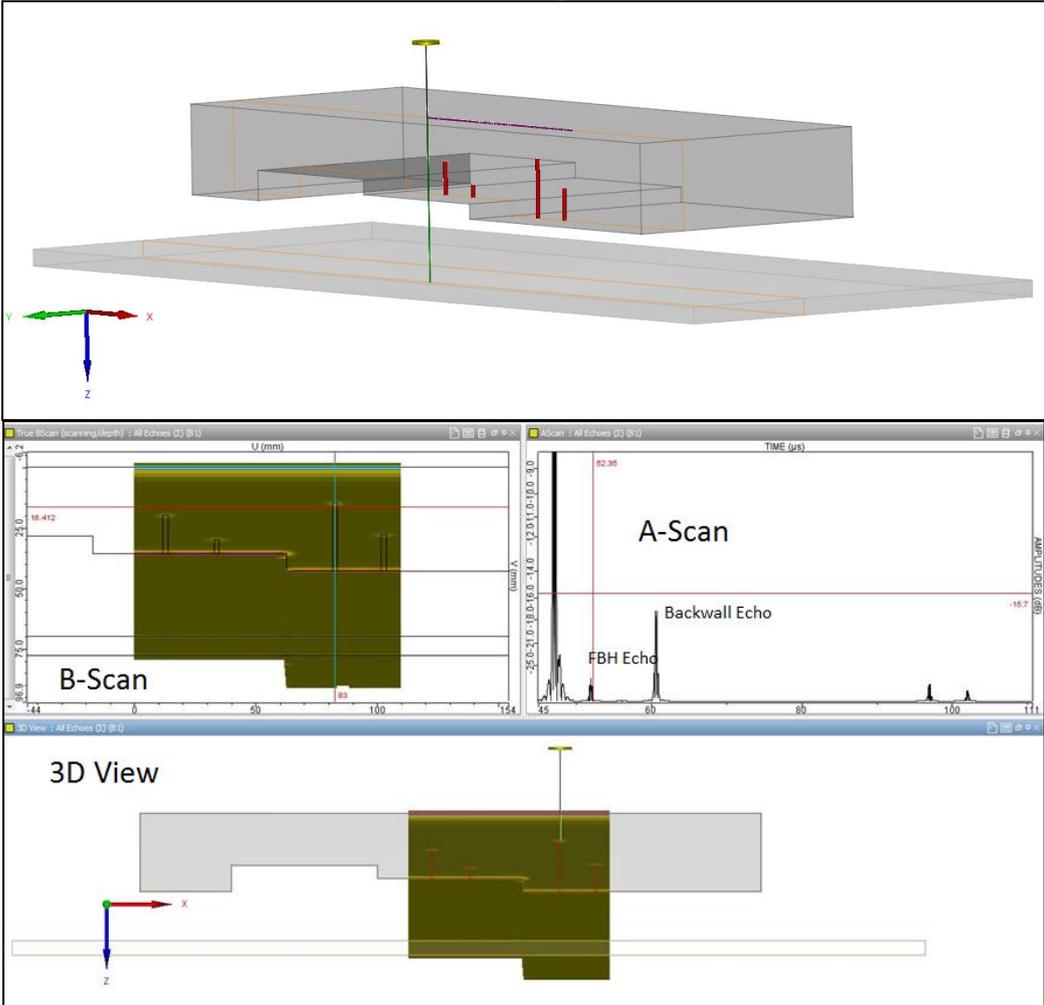


Figure 1: Simulation of a test setup involving several solids (aluminum block and glass plate) and obtained results

Acquisition gates can also be applied and tested in simulation before doing the real test. Gates can be synchronized which gives the possibility to define starting and ending times versus signals received in another gate. This point is being discussed in the next example where another step wedge block simulation is defined. This second block is made of carbon steel and inspected with a dual element probe operating at 4 MHz

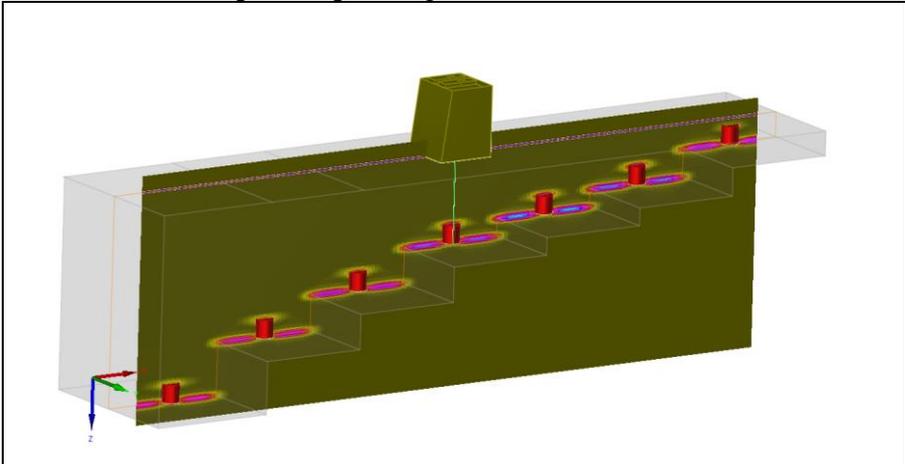


Figure 2: Carbon Steel Step Wedge, Results obtained without applying acquisition gates

The initial results exhibit both backwall echoes and FBH echoes. As the block thickness is not constant, you cannot define a unique relevant time in order to locate acquisition window around FBH signals. But, with the capability to synchronize gates, you can refer this acquisition window versus the backwall echo. On this second image the “FBH” gate (pink color) is defined from $-2.5 \mu\text{s}$ to $-0.8 \mu\text{s}$ versus the last maximum of the main window (red cross). Doing that, only the FBH echoes are kept.

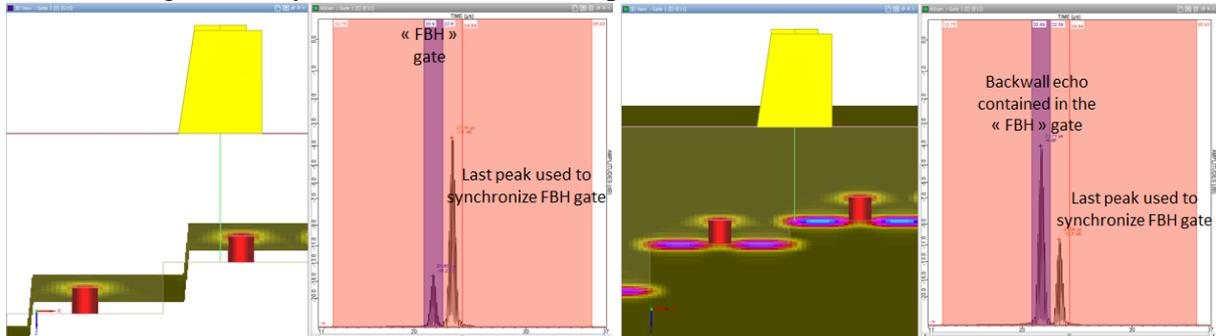


Figure 3: Gate definition versus backwall echo: Left image: FBH echo isolated, Right image: Additional backwall echo “trapped” in the gate

But it appears that, at some positions, the backwall echo is still visible in this new gate. This is due to the fact that at the positions between 2 steps, 2 backwall echoes overlap so that the first one is kept in the “FBH” gate. These phenomena can happen in a real inspection and can produce unexpected signals or unstable gate. A better “design” of the step wedge would avoid this and simulation can help for defining such block. On the following case, a calibration block with smoother steps is simulated and the same acquisition gate is applied to isolate FBH echoes. It can be verified that only FBH echoes are kept and the DGS curve can be easily deduced from the echodynamic curve obtained in this gate:

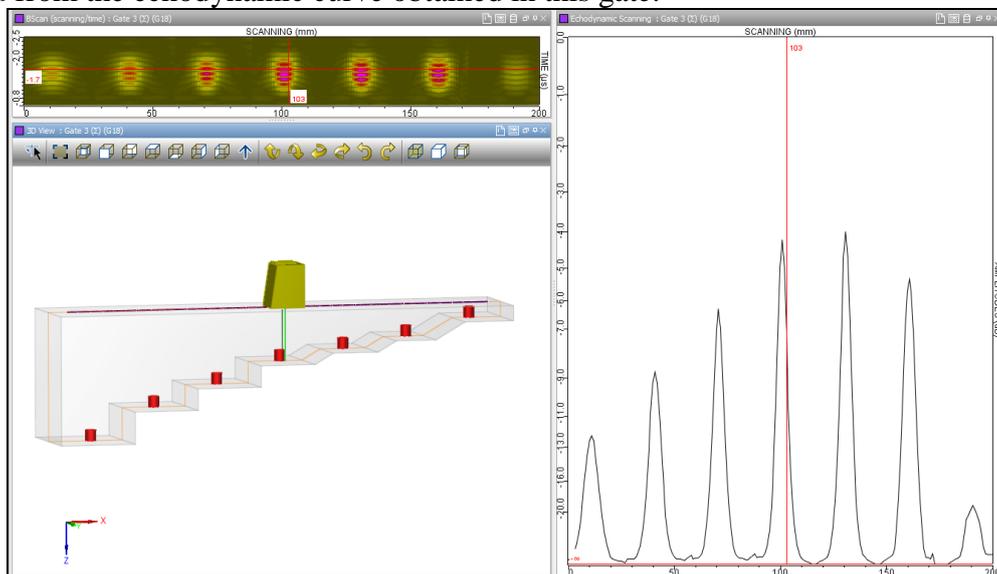


Figure 4: DGS curve obtained thanks to the application of a relevant acquisition gate in a modified step wedge block

Another common use of CIVA deals with phased-array probes where CIVA gives the possibility to introduce all the existing common designs of industrial PA probes (linear arrays, matrix probes, etc.). In the new CIVA 11, custom phased-array probe with random arrangements of elements can be assessed. One the main advantage of this type of probe is to avoid grating lobes while keeping a reasonable number of elements. Today such transducers

are mostly limited to R&D but are promising for future industrial applications. Interested readers can refer to the following paper [4].

Apart for the probe itself, CIVA also allows to compute focal laws and electronic settings of the probe (electronic scanning, probe focusing, beam steering, sector scan, etc.), and is of great help when having to define the best settings for a given control. Among many others, one application of PA probe is the automated inspection of pipeline girth welds for which one of the most commonly used method is the so-called “zonal discrimination” approach. This is based on the division of the weld into different zones of inspection of about 3mm maximum in height (see figure 1). Basically, the fundamentals of this method are:

- To focus the UT beam so that the beam spot size is the same as the inspected zone
- To set temporal acquisition gates to reduce the volume of data and support interpretation, especially in the root area (see figure 2 with the example for the inspection of a fusion line).

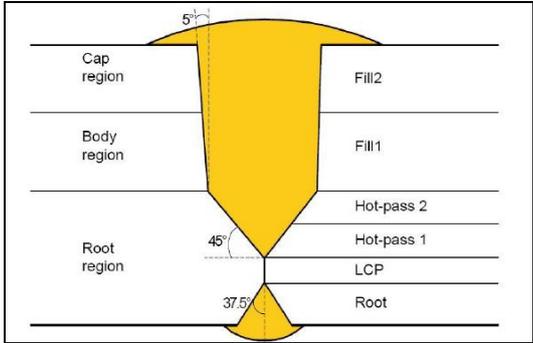


Figure 5: Zonal subdivision of the weld

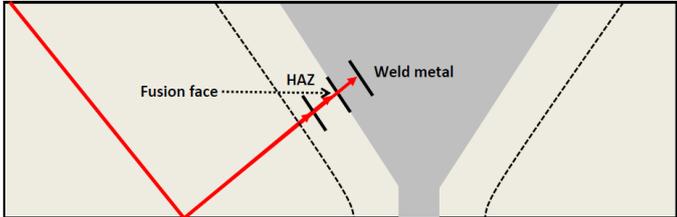


Figure 6: Acquisition gate adapted to fusion line region inspection

Several probes and/or several electronic settings of a PA transducer are defined on the inspection system so that different acquisition channels are created, each of these aiming at inspecting a given zone. In order to ensure that required inspection performances are met, oil & gas companies require that the AUT equipment and procedure go through a qualification process before using it for girth weld inspection. After a calibration stage, a performance demonstration test involves the inspection of several welds in which realistic flaws have been artificially produced by deliberately deviating from optimal welding parameters. AUT is then used to detect and size these flaws. Macrographs are finally performed on salami cuts at different increments of the welds. The macrographs help to verify the performance of the AUT system as well as to determine PoD (Probability of Detection) and sizing accuracy curves. This qualification process is cost and time consuming (costs of the mock-up, costs of the macrographs, time spent to realize the tests, etc.) and the results obtained for the PoD and sizing accuracy curves are strongly dependent on the size and orientation of the defects that have been created in the weld. Moreover, some of the influential parameters of the inspection cannot really be evaluated. With only few inspections, it is not possible to have flaws covering all possible skew, tilt, position and size. It is also difficult to evaluate the impact of other parameters such as the variations related to the system positioning on the pipe, the

uncertainties on the probe settings, the metallurgical noise of the work piece or the human factor. For these reasons, introducing modeling into the qualification work to replace part of the tests currently performed and add other relevant tests that would otherwise be excluded brings added value to the qualification process. On the following image, one channel simulated in CIVA is displayed. The elements of the active array for this channel are displayed in red. This one targets the upper part of an X-bevel weld profile where a flaw representing a lack of fusion has been simulated. The corresponding B-Scan is displayed. Other channels will scan the other zones defined along weld thickness while the mechanical body will rotate around the pipeline circumference to cover the whole weld. In usual PAUT inspection systems, the maximum signal obtained at each location is plotted (echodynamic curve) and each channel is represented in different lines as shown below. Weld profile can be defined from CAD files or, in CIVA 11, from parametric geometries, as predefined standards templates of most Bevel types are now available in a library.

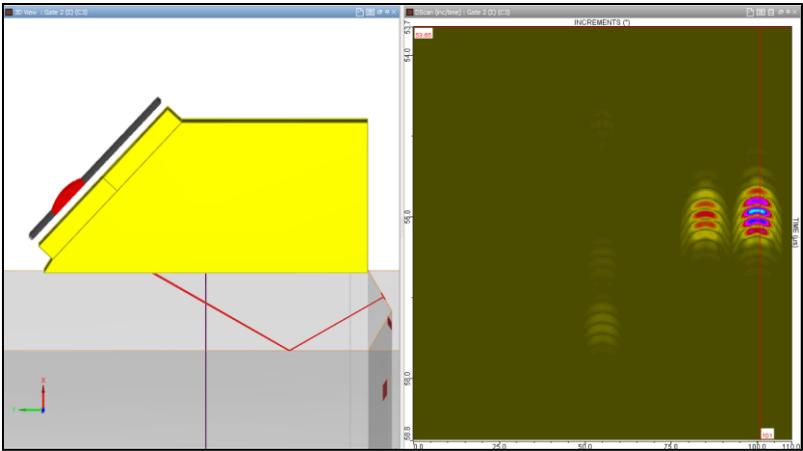
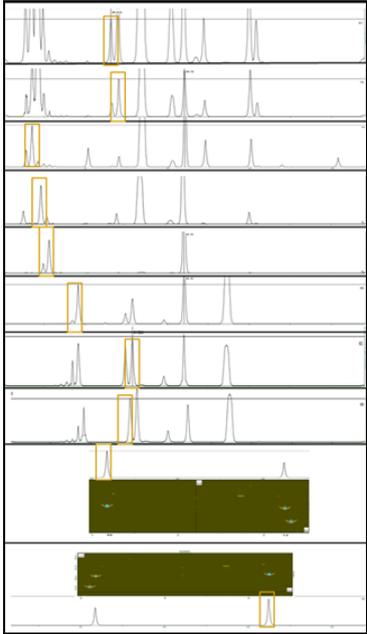


Figure 7: X-Bevel AUT inspection – B-Scan obtained with one channel (Lack Of Fusion echo) –
 Right image: Typical presentation of girth-weld PAUT results



CIVA allows to predict the expected echoes and to plot the echodynamic for the different channels and to study the sensitivity of this process to influential parameters. Based on this, data necessary for the process qualification can be established and potential improvement of the inspection process can be evaluated and proposed. More information on this application can be found in the following paper [5] where a study performed with TOTAL, and aiming at validating the use of CIVA for such application is discussed.

4. Models and latest capabilities available in CIVA ET

The Eddy current module mainly involves a 3D Volume Integral Method which only requires a numerical sampling of the flaw, the electromagnetic field induced in the work piece being calculated analytically. The following reference paper is available [6] to have more information regarding the mathematical models. The latest release also implements BEM approach (Boundary Elements), more precise to simulate narrow cracks. Both electromagnetic field calculation and inspection simulation can be performed in this tool, with different probes, whether it be conventional ones (contact probe, bobbin coil, rotating probe) or innovative sensors: Eddy Current Arrays, GMR, EMAT probes (coupling with the UT module). In the latest release, new coil shapes are available in the library (D-Coil, Pancake coil, Racetrack coil, Meander coil). The electric parameters of the ET generator system can also be accounted for (resistance, stray capacitance or inductance, etc.).

In addition to the 3D VIM/BEM module, CIVA 11 brings a new module in CIVA ET based on Finite Difference Method allowing solving 2D axisymmetric configurations. This module allows simulating some defect response configurations in tube transition zones with tube sheet (heat exchangers), or tubes with an irregular profile defined by a 2D CAD sketch. An example of such configuration is shown hereafter.

5. Applications of CIVA ET

In the following example a heat exchanger tube made of Inconel is described in the CIVA ET module. This tube has a nominal inner radius of 9.84 mm and a thickness of 1.27mm. At the basis, a ferromagnetic tubular plate surrounds the heat exchanger tube, and the tube has been expanded to fit the inner side of tubular plate. This expansion leads to a tube transition zone where the tube inner diameter reduces from typically a few of mm.

This tube is inspected with a bobbin differential coil operating at 200 kHz. An axisymmetric inner flaw, 1mm wide and of about 20% thickness with respect to the tube thickness is simulated at different locations in the tube, far from the transition zone (25mm) then closer to it (1mm). On the following graphs, the simulation results are displayed. In these simulations, the tubular plate is ignored in order to visualize only the effect of the variation of diameter in the transition zone. On the first case, it can be seen that the flaw signal is clearly separated from the tube transition signal (black curve). But, when the flaw gets closer to the transition zone, the flaw signal is becoming mixed up with the geometrical signal and more or less affects it (red then blue curve).

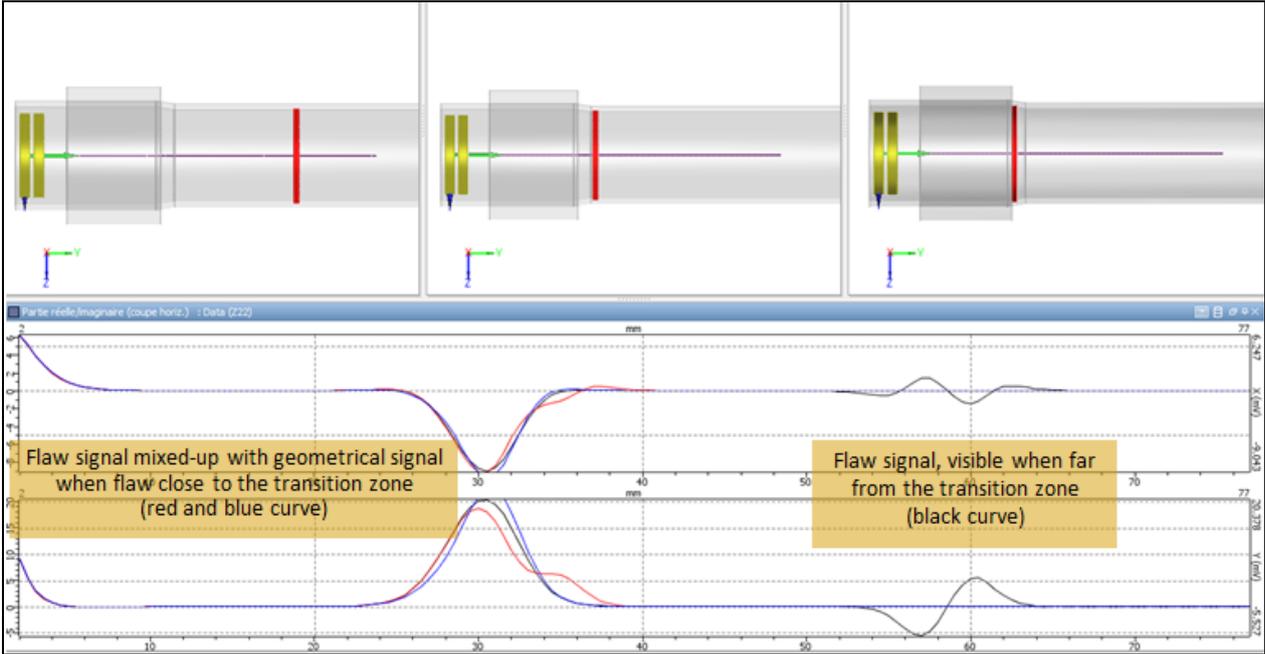


Figure 8: Tube transition zone inspected with a 200 kHz bobbin differential coil, axisymmetric flaw respectively located at 25 mm (black curve), 5mm (red curve) and 1mm (blue curve) from the starting of the tube transition zone

Some post-processing is then required to separate flaw signals from geometrical signals. For instance, frequency mixing technics are sometimes used for this purpose. A lower frequency signal is acquired, more sensitive to conductivity and permeability variation at the outer side. This second signal is subtracted by matrix combination (complex coefficients) from the main one in order to extract the flaw signal. This kind of post processing feature is also available in CIVA platform.

6. Models and latest capabilities available in CIVA RT-CT

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 probabilistic approach (Monte-Carlo method) allowing reproducing 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: FDK (Feldkamp, Davis and Kress) and PIXTV. The CT module also proposes now the ability to import CT acquisition files, meaning that you can simulate and try various 3D reconstructions from real data. The following papers [7], [8] give more information on the models implemented respectively in RT and CT simulation modules.

Regarding the latest CIVA11, as for the UT module, 3D CAD heterogeneous specimens are now available in CIVA RT. Another major improvement is the possibility to introduce image plate digital detectors in the simulation. With such detector model, simulation also accounts for the effects of a reinforced screen. It can be also mentioned that the Monte-Carlo solver has been improved in order to account for pair creations, leading to a better accuracy for high energies, especially for X-Ray accelerators. The pair production can only occur if the photons have an energy exceeding twice the rest energy of an electron (1.022 MeV) but becomes quite important (in steel) for energy level above several MeV.

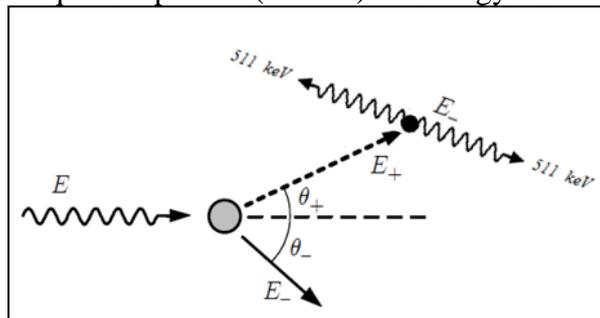


Figure 9: Pair production phenomena

Thus CIVA RT has now a very accurate Monte Carlo engine to simulate all the scattering effects in the whole energy range used in NDE. Since the implementation of the pair creation phenomena in CIVA, some validations have been made to ensure the good prediction of the scattering effect for high energies. The figure below shows a comparison between CIVA and Penelope (PENetration and Energy Loss of Positrons and Electrons [9]) of the scattering effect in a 100mm thick steel block at 10MeV (deposited energy along the detector length):

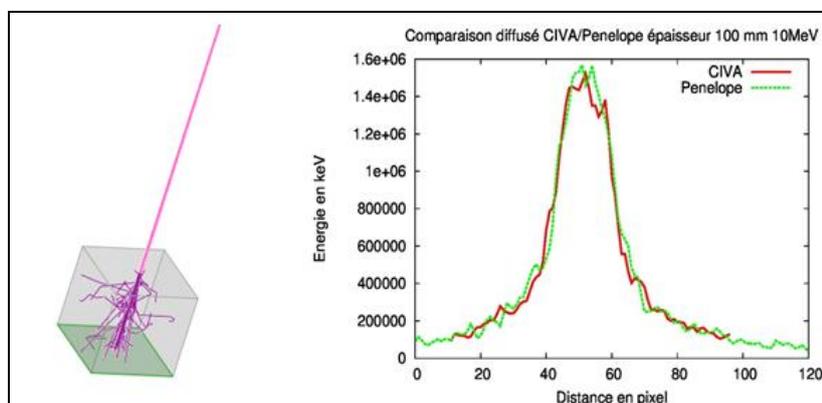


Figure 10: Validation of the scattering effect for high energy in CIVA

7. Applications of CIVA RT

Benefitting from the new capabilities of CIVA RT allowing simulating 3D CAD heterogeneous geometries and also several components in the global environment, this example evaluates the impact of the backscattered on the final radiographic image.

To be able to evaluate the impact of the backscattered from the photons that pass through the detector and interact with a part of the environment, two simulations were performed:

- The first one with only the specimen to inspect
- The second one with a lead block positioned after the detector

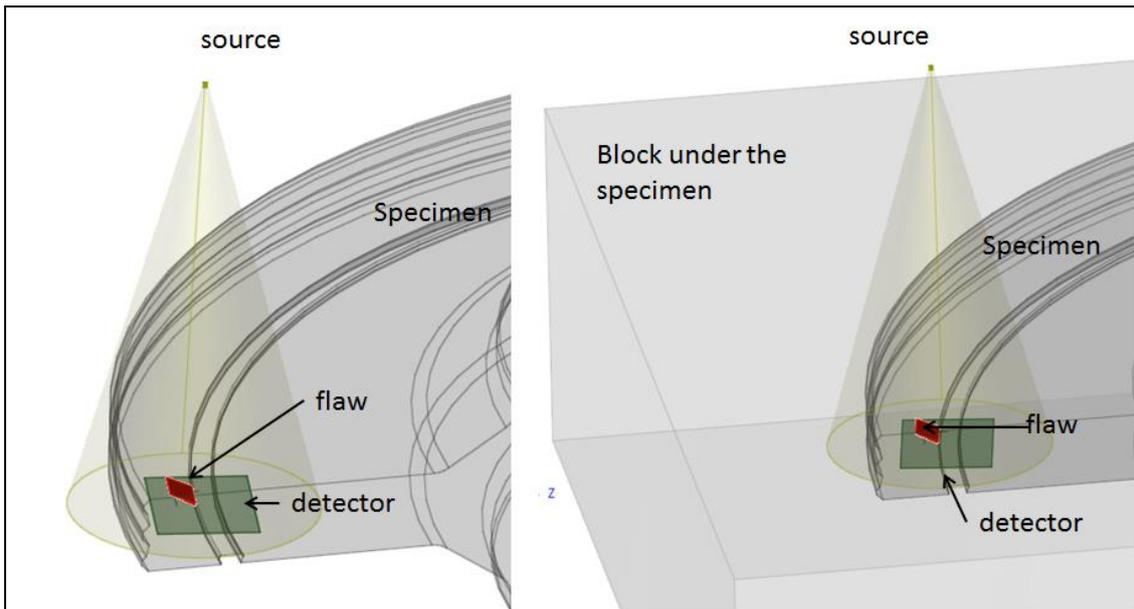


Figure 11: visualization of the configurations

The specimen is a 60mm thick steel part inspected with an Ir192 source. CIVA is able to extract for any RT simulation the so-called “Build-Up” factor cartography ($BU=1+\text{scattered/direct}$). The scattered radiation contributes to the image in a destructive manner, adding noise and reducing the image contrast. Then, closer the BU factor is to 1, better the detection of a defect is. The BU factor can be considered as an indicator of the “quality” of the radiography. A too high BU factor will hide a possible crack indication.

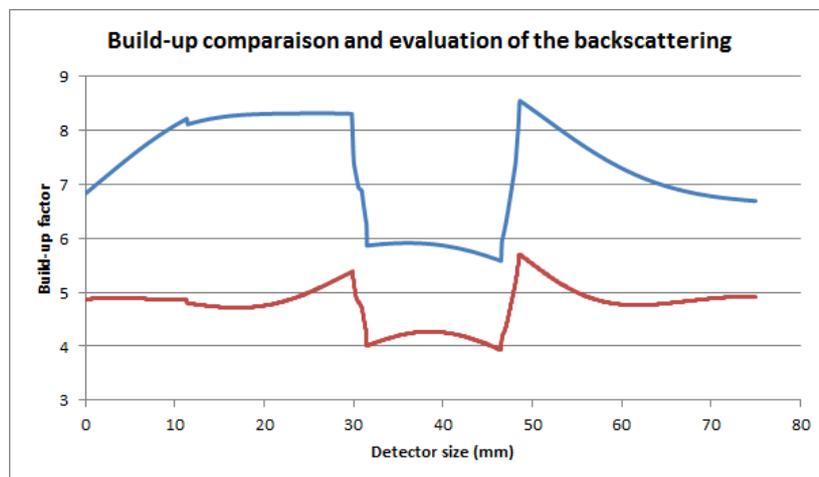


Figure 12: Comparison of the Build-up mapping on the two configurations (Blue curve: Back scattering accounted for, Red Curve: Backscattering ignored)

In this specific example, a simple evaluation of the Build-up values along a profile of the detector (around the crack) reveals that the effect of the backscattering is non-negligible and has a strong impact on the total scattering effect and will impact negatively the flaw detection.

8. Conclusions

This paper has illustrated some of the latest developments available in the CIVA simulation platform. Applications of modeling are discussed such as the use of CIVA to predict signals received in calibration blocks and how it can help to set acquisition gates, the use of CIVA to support qualification process for PAUT girth welds inspection, the simulation of heat exchangers eddy current inspection where complex profiles can produce disturbing signals, and finally the modeling of RT inspection with several parts geometries that allow to evaluate the backscattering effect on the final image.

The capabilities now offered by simulation tools as well as the improvement of software and hardware calculation performances opens a lot of potential applications for modeling platform such as CIVA. If experimental verifications remain absolutely essential, many unnecessary trials could be avoided if simulation can be introduced at the appropriate level and relevant stage of a NDT process (design, qualification, expertise, etc.) and simulation can bring cost-efficiency to the process.

9. References

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