# SIMULATION OF ULTRASONIC, EDDY CURRENT AND RADIOGRAPHIC TECHNIQUES WITHIN THE CIVA SOFTWARE PLATFORM

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Abstract

The simulation of Non Destructive Testing (NDT) plays an increasing role as it provides an efficient way to conceive and to optimise NDT methods or probes, helps for data interpretation, supports inspection qualifications. This communication aims at presenting an overview of the current simulation capabilities of the CIVA software platform developed by CEA-LIST and partners. CIVA gathers UT, ECT and RT simulation modules. Those modules are mostly based on semi-analytical approaches in order to address fairly complex configurations while keeping reduced computation times. Hybrid methods locally coupling finite elements schemes and semi-analytical techniques may also be carried out in order to assess very complex cases. The different models and techniques shares common GUIs, visualization and CAD tools.
In UT, one can simulate the beam transmitted by the probes (conventional probes, dual probes, phased arrays…) and the echoes arising by defects in possibly complex parts components (described by CAD). The codes rely on integral methods and different approaches for flaw scattering (Kirchhoff, Geometrical Theory of Diffraction, Separation Of Variables) depending on the nature of the flaw and of the technique (pulse echo, TOFD).
In the same way ECT simulation includes both primary field computation and calculation of response of flaws. Single or multiple bobbin coils (with/without ferrite cores) can be used in different operating modes (absolute, differential, Remote Field) over planar or cylindrical conductive or ferromagnetic components. The codes rely on the Volume Integral Method and the Green's dyad formalism.
RT simulation codes allow to simulate X-rays or γ-rays inspections of simple or complex 2D/3D CAD parts. The radiographic images are simulated in the presence of flaws of arbitrary shapes (parametric or 3D CAD flaws or inclusion), for the common radiographic films. Ray casting and Beer-Lambert model are used to simulate attenuation along the path of the photons while the scattered radiation is calculated by Monte-Carlo computational method with a possibility of combining these two methods in an optimal way.
After having briefly recalled these different models, emphasizing on recent developments and experimental validations, we present several applications which illustrate on practical cases the interest of the simulation.

## Introduction

The increasing role of simulation in NDT relies on its potential skills for optimization, qualification or demonstration of techniques. The CIVA software platform [1], developed by CEA-LIST and partners, gathers simulation codes for the three major NDT techniques – Ultrasonic (UT), Eddy Current (ECT) and Radiographic techniques (RT). Dedicated simulation codes, all gathering same GUIs and CAD tools, aim at providing fast and accurate simulated results for a wide range of applications (not only canonical cases) thanks to dedicated codes. Those codes are mostly based onto integral techniques (over the flaw or over the probe) for UT and ECT flaw responses

simulation, while attenuation law (Beer-Lambert) combined to Monte Carlo are used for direct and scattered image of a RT examination.
Validation of those codes is also a major task. In addition to experimental validation, CEA also participates to international benchmarks [2-3]. This paper presents some applications for those three different techniques.

**UT applications**

UT simulation codes allow predicting beam propagation as well as flaw response in echographic mode for various techniques (pulse echo, TOFD, Tandem) and probes (monolithic, dual RT or phased arrays [4]) in arbitrary components (homogeneous/heterogeneous, isotropic/anisotropic, canonical or CAD geometry). Applications discussed hereafter concern a coarse grained structure examination, and multiple skips over a 3D CAD component. Those features are available in the next CIVA version (CIVA10).

<u>Simulation of coarse grained structure</u>

Components with coarse grained structures such as statically and centrifugally Cast Stainless Steel (CSS) materials have been widely used in the primary loops of pressurized water reactors in France, USA and other countries. Cast stainless steels are made of a complex structure possessing several length scales. The large scale component (designated as the macrostructure) consists of equiaxed and/or columnar shaped grains whose sizes may exceed centimeter, larger than typical wavelength inspection. As the ultrasonic wave propagates through the CSS specimen, beam distortions arise and consequently important variations are observed. Depending on the particular part of the specimen that is inspected, the transmitted beam is affected by the macrostructure in a random manner.
Modelling strategies have been developed in the past to deal with complex heterogeneous structures [5], considering a set of homogeneous media of arbitrary geometry defined by CAD. For CSS materials, the proposed approach is based on a geometrical description of the macrostructure using Voronoi diagrams. Examples of Voronoi diagrams for both equiaxed and columnar structures are shown in Figure below. Macrograin to macrograin velocity dispersion is taken into account by picking random velocity values from a uniform distribution. The width of the distribution and thus the velocity dispersion characterizing the material is controlled by the input parameter $\Delta V_L$.

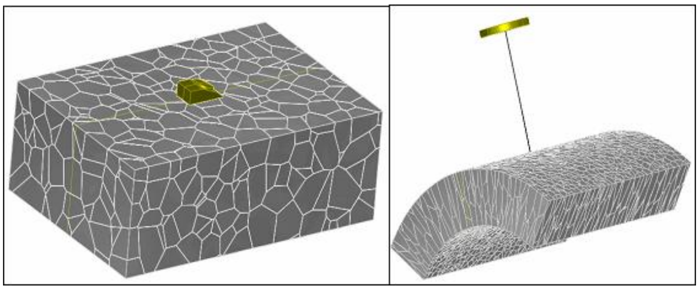

Figure 1: Example of Voronoi diagrams representation for a planar, equiaxed component, and a cylinder with columnar grains

Using this decomposition approach, it is possible to compute the ultrasonic beam and flaw scattering. The example presented below corresponds to the simulation of the back wall echo in a 68.5 mm thick cylindrical part, inspected in pulse echo mode with a focused immersion probe at 1 MHz. A Voronoi diagram characterized by a mean cell size of 12 mm and various values of the parameter $\Delta V_L$ was used. The back wall was computed for several transmitter positions in order to display B-scan images. Fluctuations in amplitude and time of flight can be observed on the experimental data displayed in Figure .These fluctuations reflect the interaction between the ultrasonic wave and the metallurgical structure.. When the computation is performed in a medium with weak velocity fluctuations ($\Delta V_L$ = 3 % of the medium mean velocity), experimental features can be qualitatively reproduced.

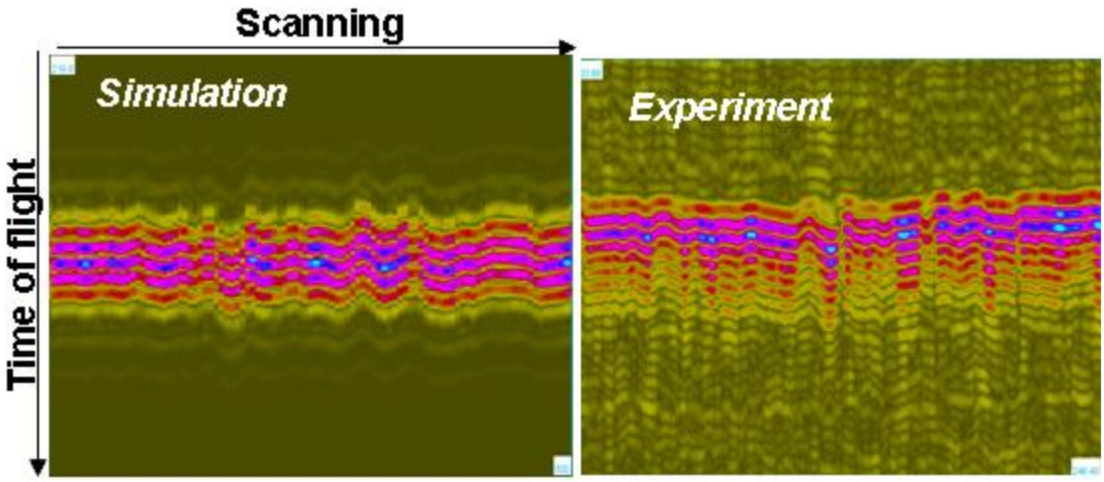


Fig 2: Simulated (left) and measured (right) backwall echo of a CSS cylindrical part.

Simulation of multiple skips in a 3D CAD component

Defect response and beam modeling skills have been extended in the next CIVA version to deal with 3D CAD components (defined by standard iges or step format files). Simulation codes allow to predict response from specimen boundaries and flaws embedded inside homogeneous components. As for other component geometries, mode conversion and corner echoes can be simulated, as well as full skip inspection modes (inspection technique including reflections on both backwall and surface). Figure below shows an example of a 3 MHz phased array probe performing beam steering ,located over a 3D part which gives rise to both complex geometrical echoes and multiple conversions and skips due to a planar (semi-elliptical contour) tilted flaw close to the backwall. On the right side of this figure, echoes denoted as "G" correspond to geometrical echoes, whereas "F" are associated to the flaw. The colormap is saturated so as to display echoes due to the flaw (the backwall echo is much stronger than the echoes due to the flaw). Echoes scattered by the flaw, not discussed hereafter, include mode conversion (longitudinal to shear waves on the flaw surface), tip diffraction, and multiple skips between the flaw and the vertical wall ).

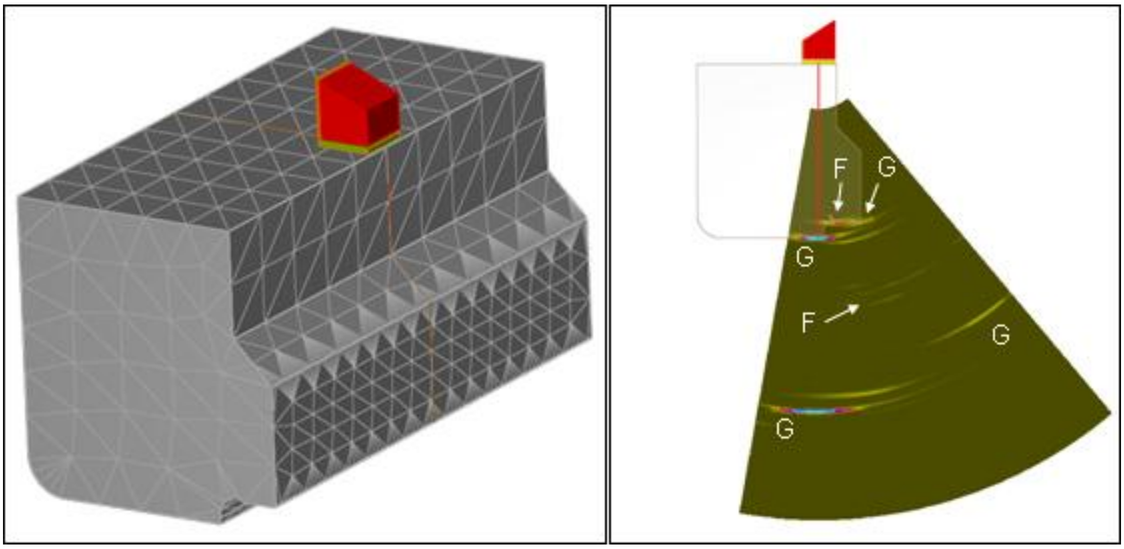


Figure 3: Meshed 3D CAD component (left) and sectorial scan image (right) part.

**ECT applications**

In previous CIVA versions, ECT simulation codes allowed predicting electric fields and ECT signals for planar, conductive (of single structure or stratified parts, including riveted structures) and cylindrical components, conductive or ferromagnetic. One or several bobbin coils (axial, surface riding probes or encircling coils), operating in absolute, differential, or transmit-receive modes, may be used to scan the component, containing one defect; whose geometry depend upon the component (flat bottomed hole, parallelepiped flaw, groove).
Among others, recent developments integrated in CIVA10 version aim at extending simulation skills to multiple flaws configurations [6] as well as new detectors (Giant Magneto Resistances), which have shown high performances for detection of buried flaws and very small flaws, due to high sensitivity and miniaturization of GMR detectors [7].

<u>Simulation of combined flaws.</u>

Modeling ECT signatures due to a set of parametric objects is a generic development allowing CIVA to address several interesting configurations that were up to now too complex to be simulated. Three examples of application of this development are presented in figure 5. The first application (on the left) is the ECT simulation of several flaws: it is now possible to evaluate in simulation the shading effect of one flaw on others located nearby, which provides useful information on the probe capacity to detect flaws with several orientations interacting together. The second application (in the center) is the ECT simulation of flaws with complex shapes. It is now possible in CIVA to introduce more information on the flaw shape (if a general flaw geometry has been observed) in order to reproduce ECT signals due to real flaws. The last application (on the right) is the optimization of interaction calculation between objects like rivets and flaws. Each object considered in simulation has now its own discretization, which leads to faster and more accurate calculations. The theoretical approach used in simulation is the Volume Integral Method [8]: all interactions are modeled using Green dyads for which analytical expressions can be derived in the case of pieces with canonical geometries.

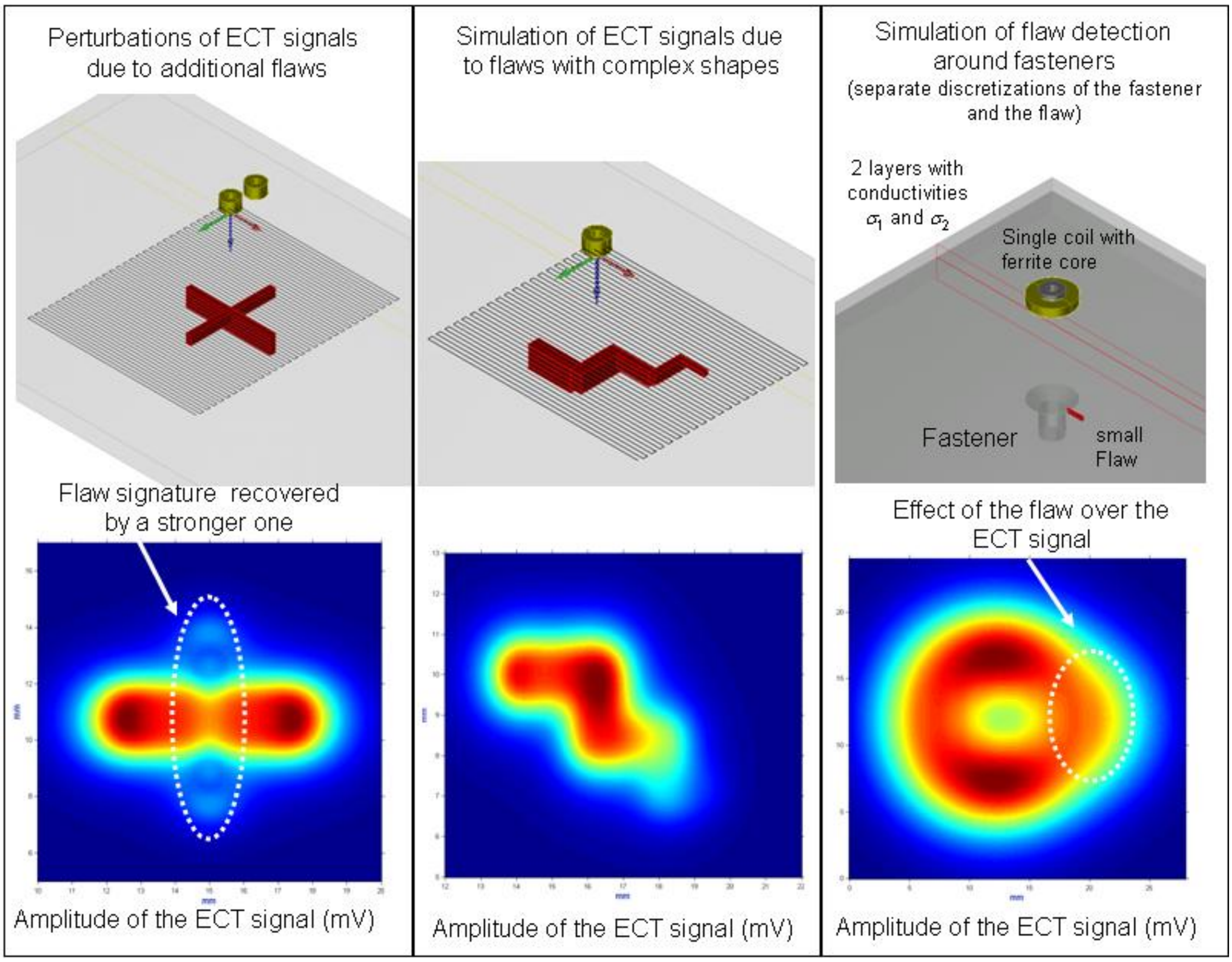


Figure 4 : Three examples of new configurations simulated using multiple flaws. On the left side, modeling of the shading effect of one flaw on one another. In the center: modeling of flaws with complex shapes. On the right side: improvement of interactions calculations between objects like a rivet and a flaw.

Simulation of GMR sensors.

New magnetic sensor technologies using GMRs as receivers are studied and developed at CEA LIST. These sensors show very promising capacities in terms of spatial resolution and sensitivity at low frequencies. In order to optimize the design of such probes, parametric simulation tools have been developed in order to calculate the ECT signal detected by a set of GMRs.

GMR elements are directly sensitive to the component of the magnetic field collinear with their structural orientation. In order to compute the probe response, the perturbation of the volumetric current density induced by the emitting part is first evaluated using VIM, then the resulting magnetic field in the volume of each GMR element is calculated using a Green dyad as a propagation operator. A typical application of this model is presented in figure 6. The emitting part of the probe consists in two rectangular coils plugged in opposition, so that its center induces a large uniform current density. Below this "double D" coil, a small GMR element is characterized by it sensitive axis. After setting up successively this orientation along the x, y and z directions, three c-scans representing the corresponding components of the magnetic field above the piece are obtained.

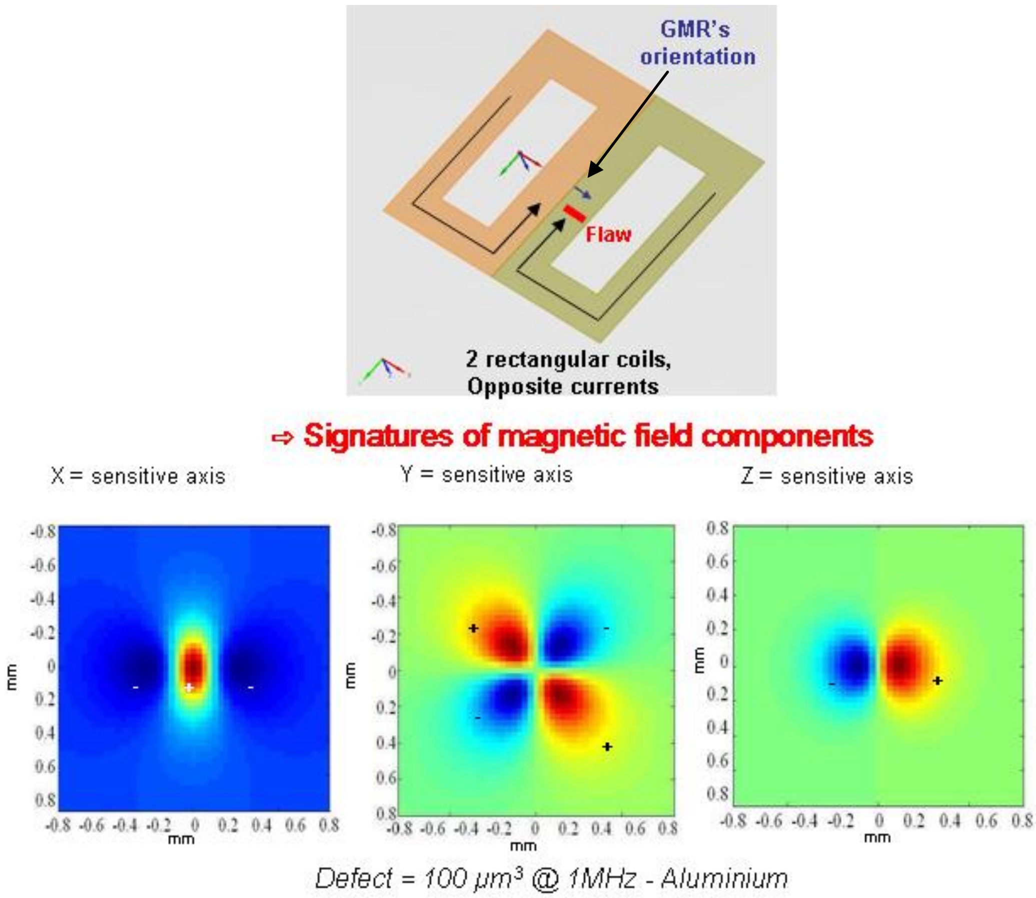


Figure 5: Above: typical probe configuration using a GMR as a receiver. The emitting part consists in two rectangular coils creating a "double D" shape. Below: ECT C-scans obtained for three different orientations of the GMR.

**RT applications**

X-Ray module has been implemented in CIVA since CIVA 9 version. This module is based on a combination of NDT radiographic modules developed at the CEA LETI, in SINDBAD [9], and at EDF R&D, in MODERATO [10]. In this version, simulation with gamma sources was implemented with the MODERATO software, whereas SINDBAD software was devoted to X-Ray sources, which directly means that some options available in one module were not open to the other one [11]. With the view to CIVA 10 release (and supported by the French ANR project RADIOLA), a new architecture has been designed with the different partnership in order to mix both SINDBAD and MODERATO software into CIVA to have access to the best features either in gamma or X-Ray. From a general way, RADIOLA's partners (CEA-LIST, CEA-LETI, EDF R&D and INSA) developed a collaborative plate-form to integrate the new architecture and the development done. Part of this project has been integrated in CIVA 10.0 version, while other improvement will be integrated in further version of CIVA. This new architecture allowed major improvements concerning computation optimization described hereafter, as well as some new features.

<u>Optimization of RT simulations.</u>
Two major improvements have been made in CIVA 10 to make the Monte-Carlo computation faster.

In order to simulate the scattering radiation coming from the interaction of the photons into the part geometry, CIVA uses a Monte-Carlo simulation. For that the user has to define an arbitrary number of photons. For thick specimen (typically for nuclear industry) computation can become very long because of the number of photons. A big work has been achieved to allow parallelisation of the Monte-Carlo computation on the different cores of the machine. For a given number of photons parameterized by the user, the information is simultaneously treated on the different cores. As example, for one hundred millions of photons launched for the Monte-Carlo simulation with a quadric processor the time computation will almost be divided by four, all core taking in charge twenty five millions photons.

A new tool called “import M-C result” is also available in CIVA 10. This option allows the user to load an already achieved Monte-Carlo computation. This option will be very useful to compare for example the effect of the location or size of a defect, the effect of a source blurring, detector blurring or detector noise… without making a complete new simulation. By launching only an analytical computation, loading a Monte-Carlo result and combining both the user will win a significant time computation.

<u>Account of granularity for the film response simulation and options available whatever the source</u>

As mentioned above, the film response describes by the EN581 standard model [12] is now implemented whatever the type of source and takes into account the granularity in terms of diffuse optical density measurements on a zone with constant optical density 2, using a microdensitometer with 100µm circular aperture, and specifies an appropriate measurement procedure.

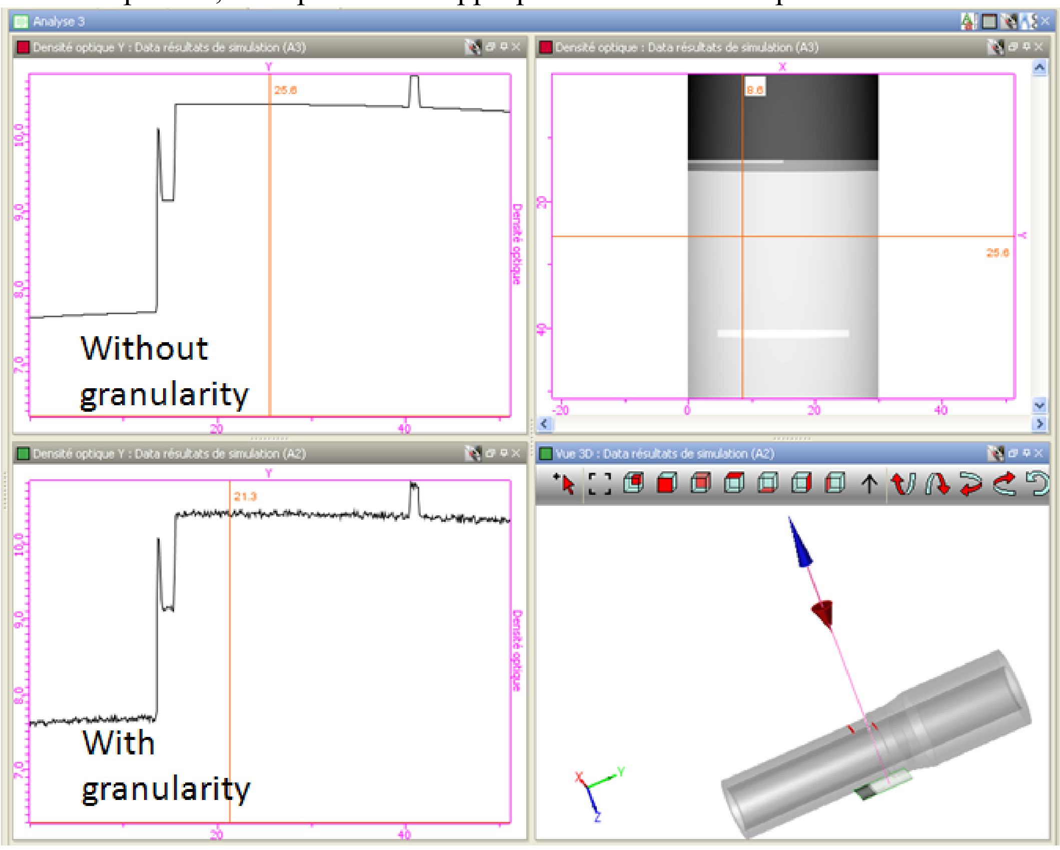


Figure 6: Comparison of two simulations: one taking into accounts the granularity, the other one without granularity

- The detector blur can be described and simulated through its Modulation Transfer Function (MTF). This blur is now authorized whatever the source type.
- The source blurring can be taken into account either from a decomposition of a volume source into small point sources or through a convolution of the image with a kernel corresponding to the size of the source. The last method is quicker and well suited for defects roughly positioned in the same plane (same magnification) whereas the first one is more precise for several defects at different depths in the object. In CIVA 9 the user could only select the first method if a gamma source was selected, and the second one for an X Source. From CIVA 10 both options are available whatever the source.

## Conclusion

Recent advances dedicated to the simulation of NDT (UT, ECT, RT) have been developed and integrated into the CIVA software. This paper has illustrated some of these developments for the three different techniques, concerning new materials, probes, flaws, or computation optimization. UT simulation codes now allows to deal with 3D CAD components as well as multiple skips inspection (not limited to half skip inspection), complex (coarse structures) materials are also dealt with using dedicated tools. ECT simulation now allows to predict responses from a set of flaws, which enables to simulate more complex cases (array of flaws, influence of flaws over others, complex shapes…). New detectors (GMR sensors) have also been integrated, along with new coils (rectangular coils) which allow to deal with new ECT probes designs. RT simulation has also been improved, especially concerning optimization and implementation of the Monte Carlo simulation for scattered radiation, which especially reduces computation times. Other features, not detailed here, concern applications of simulation to statistical tools (POD [13]), visualization and overall ergonomy of the software, as well as different imaging tools, especially for phased array applications.

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