New Possibilities of Simulation Tools for NDT and Applications

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Abstract. Simulation tools gathered in the CIVA platform dedicated to the modeling of NDT techniques are now extensively used in different industrial sectors. This software platform is developed by CEA LIST but also benefits from the contribution of numerous partners from industry and universities which allows capitalizing new developments for the modeling of various NDT techniques in a single environment. Initially based on pure semi-analytical models and thanks to collaboration with other laboratories, the current trend is to merge numerical models to semi-analytical ones in order to benefit from both approach: numerical efficiency and versatility. In this frame, the UT module of CIVA is now integrating several Finite Elements models to account for more complex phenomena in the wave/flaw interactions as well as a Finite Difference model to simulate more realistic composite parts inspections and account for more complex phenomena. The Eddy Current module also integrates numerical tools to give the user the ability to simulate more complex part geometries (CAD shape) or probes (with complex ferrite shapes for instance). One can also mention the ability of simulating high energy source in CIVA RT. 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. This article introduces some applications of modeling in NDT as well as some of the latest developments now available in CIVA.

1. Introduction: General considerations on the CIVA software platform

1.1 Tools to support efficiency in NDT at different stages

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 various modules of CIVA gives access to different NDT methods and techniques Ultrasonic Testing (UT), Guided Waves Testing (GWT), Eddy Current Testing (ET), Radiographic Testing (RT) & Radiographic Computed Tomography (CT). All these 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.). 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.

1.2 Enlarge the application fields

In order to continue the extension of the application fields of CIVA, it is sometimes necessary to rely on more general numerical approaches (FEM, Finite Difference, etc.). To keep the benefits of the semi-analytical strategy, the current trend within CIVA is to build hybrid models, a part of the computation being done by fast semi-analytical models, another part being completed by numerical approach when necessary for the validity of the results. These coupling works involved research within the development team at CEA but also collaborations with external lab, as for the CIVA ATHENA2D module in UT, the Finite Element "ATHENA" code coming from EDF. Another example is the integration of a Finite Difference code from Airbus for composite inspections simulation. An intensive collaborative work has been also performed within the frame of the European project SIMPOSIUM (http://www.simposium.eu/) to enlarge such type of coupling and improve the interoperability between this NDT simulation platform and other types of mechanical models (material characterizations, etc.)

1.3 About validation

As the goal is to help people to use simulation works to replace some tests with mock-ups, a strong effort is put on validation to provide evidence of the validity of the results in various situations, or to show the limits of semi-analytical models when such limits are encountered. In this frame, extensive validation works of the different modules are performed, published on the EXTENDE website http://www.extende.com/objectives-of-the-experimental-validation.This validation activity also includes a lot of publications in international NDT conferences and the participation to international benchmarks [6].

1.4 Simulation and Analysis

As described above, CIVA is a well-known versatile software for the modelling of NDT process. But this platform now also includes an analysis module for UT acquisition data. It can process M2M and OLYMPUS data files and a plug-in is also provided to allow users to develop connections with other UT acquisition data format. The main objectives of this analysis software are to display acquisition data in an easy and understandable way, to extract advanced information in an efficient manner to prepare examination reports and to avoid repeatable and time consuming operations thanks to customization and templates, while keeping traceability for the work that has been done. In addition to these essential tools for the analysis work, this module benefits from the long experience capitalized in CIVA in modelling innovative UT inspection methods in order to provide the users with advanced and easy to use tools (Segmentation, Simulation on Acquisition, Signal processing, Total Focusing Method).

2. Latest Modelling Capabilities

The CIVA platform regularly offers new releases in which numerous improvements are included. With CIVA 2016, new capabilities of simulation are provided in the different modules of CIVA. Some of them are introduced in this section.

2.1 Improvement for Ultrasounds Testing modelling

Due to their lower weight and their mechanical properties, composite materials are more and more widely used in industrial structures such as in aerospace applications. These materials are subjected to specific types of defects compared to metallic structures. For instance, delamination, disbonding, ply waviness are some of the typical flaws that NDT inspections shall detect. A composite material model based on a homogenization algorithm was already available in CIVA for a while but this model was mostly limited to flat components and not really adapted for curved parts whereas CIVA could already address such complex geometries when they were made of metallic structures. The new version includes a set of new capabilities that will enlarge a lot the application fields of composite inspection modelling: A "continuously varying" model allows to correctly describe the fiber acoustic properties in curved parts allowing to simulate more precisely bended area (such as in stiffeners). A coupling with a Finite Difference model developed by Airbus is also implemented which allows to reproduce the interferences occurring between the different plies and that generates a typical "composite" structural noise. This coupling also includes the capability to simulate more complex defects such as ply waviness. For inspection with Phased-Array probes, the "SAUL" algorithm has been also implemented in CIVA. This algorithm allows adapting and optimizing the focal laws when inspecting curved parts. It is based on an iterative process applied to the front surface echo. Finally, some tools are provided in the GUI to easily describe the geometry and the multiple plies material structures of composite assembly.

The "continuously varying" approach has also been applied for the simulation of complex metallic welds such as austenitic welds. Such welds have anisotropic acoustic properties and the direction of anisotropy will depend on the dendrite orientations. CIVA used to ask the user to identify discrete zones (thanks to a macrograph of the weld) where a given dendrite orientation could be assigned. A new model allows a more robust simulation and realistic description of such weld based on a continuously varying dendrite angles. This information can be entered from a parametric description (Ogilvy model [7]).

To compute efficiently the response of a defect, the semi-analytical approach of CIVA generally relies on a simplified formulation of the incident field over the considered flaw surface. In simple words, this simplification consists in considering locally a planar wave approximation. This hypothesis allows a really good numerical performance of the model and is valid in the focal zone and the far field. A new model is now implemented, that gets rid of this planar wave approximation but considers the "full beam", allowing a more precise simulation of the response of defects located in the near field or out of the beam center particularly when divergent probes are involved (such as in TOFD).

2.2 Improvement for Eddy Current Testing

In the Eddy Current modules, some efforts have been put on the capabilities to simulate more complex sensors. Thanks to the implementation of new modelling techniques, sensors with complex ferrite shape can be now simulated, such as +Point sensor (more details in the next part) or the "Rototest" sensor, used for bore inspection. New tools are also provided to define more efficiently Eddy Current arrays which are more and more used in industrial applications for their abilities to increase productivity covering a large surface in a single pass. It can be also mentioned the ability to simulate the response of wear scar which are typical defects encountered in heat exchanger tubes due to fretting with external support structures. Finally, one can also mention the ability to simulate 2D CAD heterogeneous in axisymmetric configurations (bobbin probe). This brings the capability to simulate some types of support plates or deposit layers for heat exchangers applications, or other irregularities in the tube profile.

2.3 Improvement for Radiographic Testing and Computed Tomography

Specific developments were achieved in the Radiographic Testing (RT) and Computed Tomography (CT) modules in order to improve the current models and above all enlarge the capacities of CIVA RT-CT to increase the range of applications. For instance, the CIVA 2016 version proposes a library of different high energy sources such as linear accelerator or Betatron. This new type of source complete the already existing X-Ray sources and gamma Ray sources to perform realistic and accurate simulations with thick components.
This new version also includes a specific option allowing the user to take into account the presence of potential radioactive substances within solids that will have an impact on the darkening of the film. This new model considers the influence of radioactive contamination on a cassette-film being in contact with an irradiating part.
In the CT module a new scanning path is available. Initially only the circular trajectory was modelled in CIVA CT. The circular trajectory provides theoretically exact reconstructions only in the central plane of the object. However, when inspecting a long object, this acquisition geometry leads to severe artifacts in the reconstructed image. Helical or partially helical trajectories allow to handle this problem. This scanning geometry is now available along with a specific reconstruction algorithm.

3. Preparing a UT inspection (scan plan) with more information than a raytracing tool

When preparing an inspection, people generally use geometrical tools to set the main parameters of their inspection and adjust the scan plans. CIVA offers such classical geometrical tools, but it can also provide more information taking into account acoustic phenomenon. This example shows the recent improvements of the latest version and the benefits of knowing more than the classical ray approach.

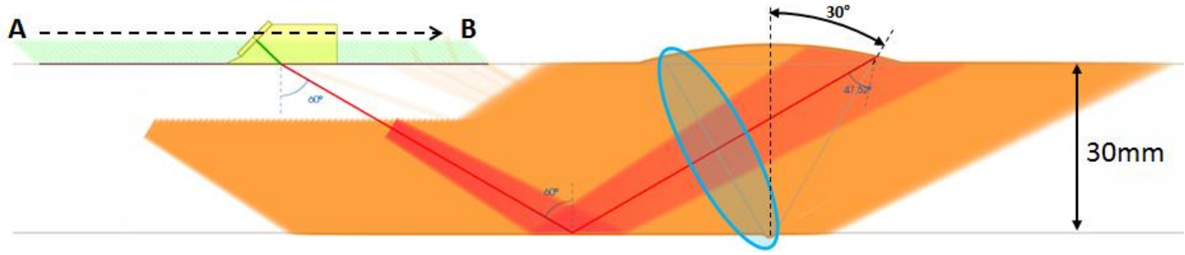

Fig. 1. V-weld inspection with a conventional 60° shear waves probe – geometrical zone coverage

The picture above illustrates the type of zone coverage image you can obtain in CIVA based on pure raytracing and computation of the beam aperture. The red conical envelope corresponds to the estimated beam radiated by the probe at the current position, and orange map corresponds to the coverage obtained taking into account all considered probe positions. No amplitude information is contained in this type of map, but it allows adjusting the scan plan for this probe.
It is possible in the latest CIVA version to add amplitude information to this zone coverage map by considering the actual acoustic beam radiated at each probe position rather than the

ray tracing approach. This type of cartography allows estimating the amplitude drop along the bevel of the weld, which can obviously give interesting information about the variation of insonification versus the depth. On this example, we notice a drop of 12dB on the acoustic beam between the root zone and the cap.

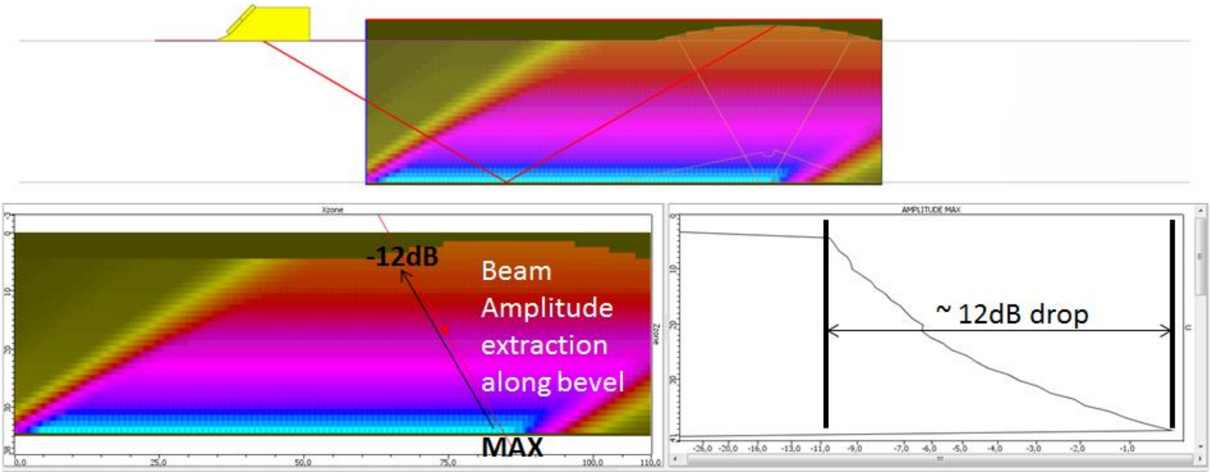

Fig.2: V-weld inspection with a conventional 60° shear-waves probe: acoustical zone coverage

In order to know how this 12dB amplitude drop of the acoustic beam relates to the detection amplitude along the bevel, we can use the Inspection Simulation module of CIVA to calculate the response of a flaw whatever its depth. We consider a Lack Of Side Wall Fusion (LOSWF) defect and use a parametric tool which takes into account a continuous varying depth of the flaw along the bevel. The result shows than as far as detection amplitude of the flaw is concerned, the amplitude drop between the root and the cap zone is around -6dB, with a maximum value when the flaw is close to the root. This type of information is not available when we consider a pure raytracing method.

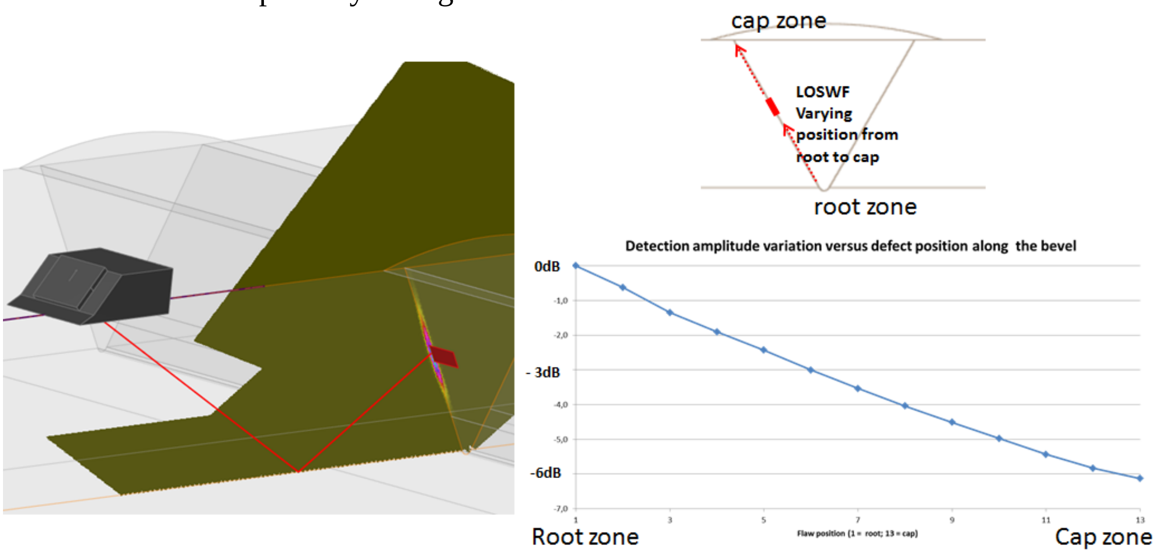

Fig.3: Detection amplitude with regards to the depth of a flaw along the bevel

In this example, the back wall of the component around the flaw was perfectly planar and parallel to the top surface, but this is unfortunately not always so perfect in real testing configuration. For example, the component may exhibit a stripping back, which will obviously affect the detection performances of the probe. Keeping the same probe, the picture hereafter illustrates the acoustic zone coverage of such a component compared to the previous regular one. This image shows that the modification of the back wall orientation in the vicinity of the weld root creates a kind of “pseudo acoustic focusing” area located at the middle of the component thickness. This can lead to more important sensitivity to a flaw at this depth, compared to the cap or the root zones. Again, the inspection simulation module is very powerful in this configuration to quantify the detection performances with regards to the depth of the flaw. It shows that the real detection capability depends not only on the acoustic behavior which depends on the component geometry, but also depends on the incidence angle of the beam with regards to the bevel orientation.

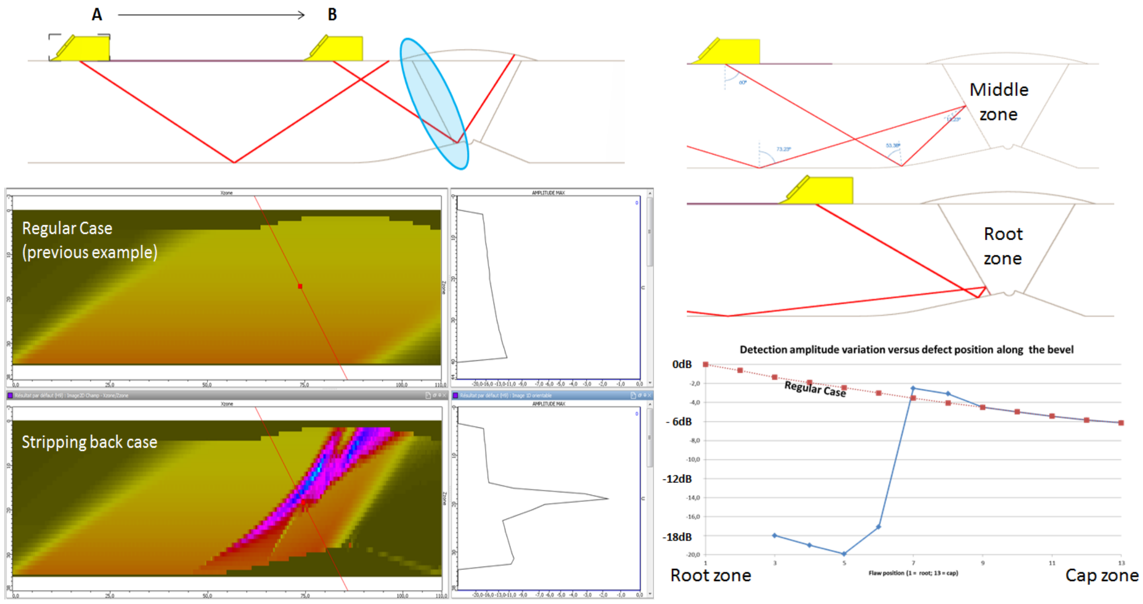

Fig.4: V-weld inspection with a conventional 60° shear-waves probe and a stripping back close to the weld

In conclusion, the recent improvements of the CIVA version give people all the important tools to evaluate accurately the performances of their inspection method, with regards to a single geometrical approach which cannot give any quantitative idea of the weld coverage in terms of detectability.

4. Study the application of an orthogonal cross wound sensor for different types of defects

Orthogonal cross wound sensor, also called "+Point" type sensor, refers to a family of eddy current probes based on 2 interlaced coils, and orientated parallel to the inspection surface in two perpendicular directions. The 2 interlaced coils can be mounted on a ferrite core (with a "+" shape) to maximize the induced field in the test piece. The 2 coils generally work as a combined transmit-receive mode and the reception is then processed in differential mode. Other designs can use a driver pick-up mode. This probe technology is naturally less sensitive to lift-off noise as the 2 receivers in differential mode are located at the same position. As lift-off variations along the scanning path of the sensor is one of the most disturbing parameter in an ET inspection, such probes provides a significant advantage to improve Signal to Noise Ratio. An image of such sensor design is shown below. Due to the complex ferrite shape, the modelling of this probe type in CIVA software involves a combination of Surface Integral Equations (SIE) (to compute the field of the sensor) with a semi-analytical calculation of the field in the conductive specimen and the defect response (more details in [8]). This type of sensors including the ferrite core can now be defined in CIVA. A simulation of the eddy currents induced by such a sensor (operating at 100 kHz) in a stainless steel slab computed in the field computation module of CIVA is shown below: The amplitude of eddy currents is shown in 2 sections (YZ plane in the depth of the component, and XY plane at the top surface of the slab) and then the other image shows the directions of eddy currents.

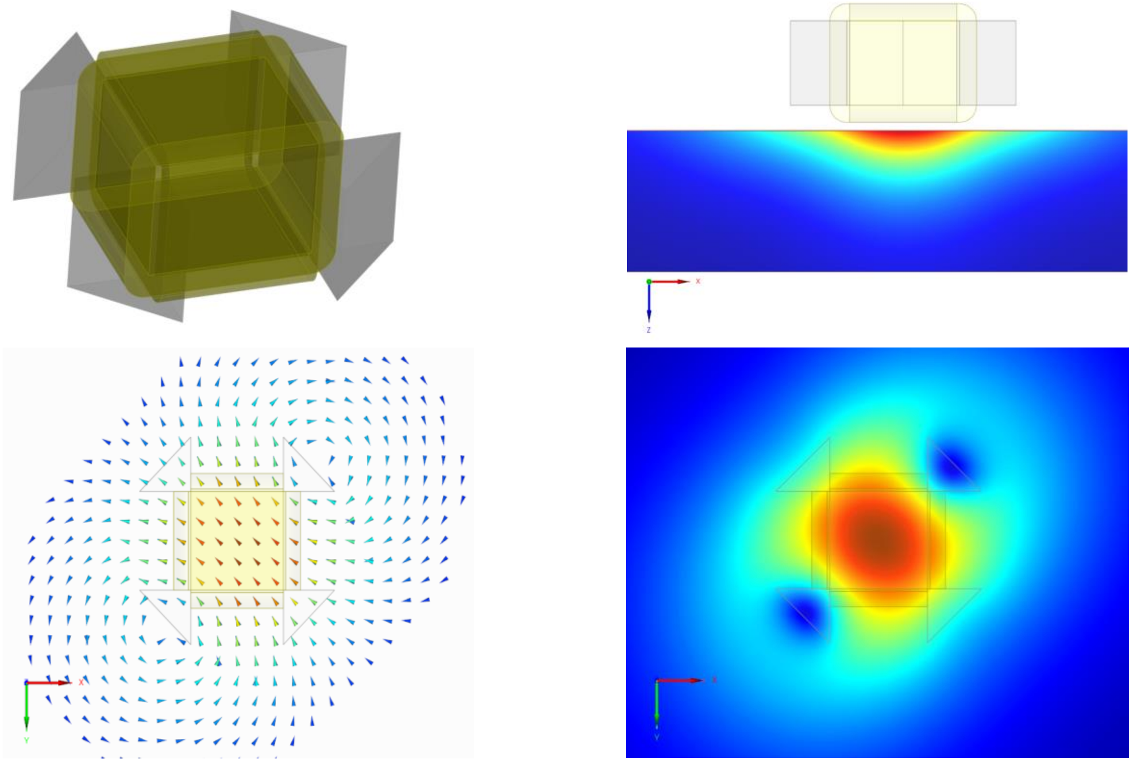

Fig.5: +Point like sensor image then and Eddy Currents amplitude and directions induced by the +Point sensor and simulated in CIVA

The field induced by this sensor reveals some particular points compared to a classical cylindrical coil: First, the maximum of eddy current density is obtained below the centre of the sensor location whereas a classical coil would exhibit maximum densities directly below the winding. Then, the field induced is highly directional. Combined with the direction of sensitivity in reception. This results as a higher sensitivity for this probe for either longitudinal or transverse defects but less for other defect directions such as 45°. The simulation of the response of a longitudinal surface breaking notch of 5mm length obtained with this sensor and then with a cylindrical coil with the same external diameter is shown and compared below.

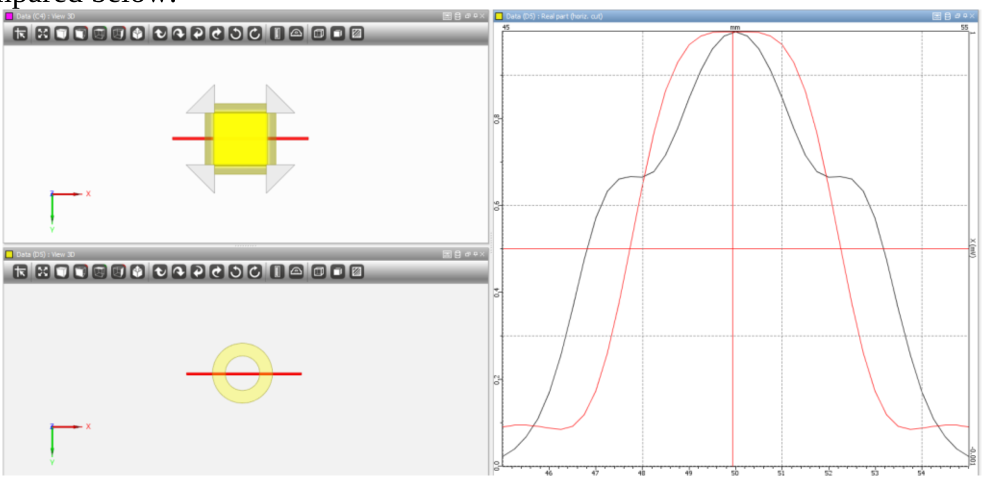

Fig.6: Response of a longitudinal notch with a +point sensor and a classical cylindrical coil of the same outer diameter. Comparison of signal amplitudes along the scanning (+Point response: Red curve, cylindrical coil response, black curve)

The signal obtained with the +Point sensor looks to have a better resolution along the length of the defect. Indeed, if the flaw length is estimated by the signal length above -6dB, the

+Point sensor would give here 4.6 mm (red curve) while the cylindrical coil (black curve) would give 6.5mm (for a defect length of 5mm).
The response of a complex defect exhibiting different directions of propagation is now calculated. The defect is shown below, as well as the C-scan obtained when a +Point sensor performs a raster scan over it. The C-scan shows that the 2 branches of the defect orientated longitudinally and transversally to the sensor produces the hottest spots. When the probe scan overs the other parts of the defect (some of them having a 45° orientation) the amplitude is much lower and even produces a higher signal when the sensor goes out of the defect. This is because the current lines that will be more sensitive to non-transverse and non-longitudinal defect directions belong to the current loops located at the “external side” of the sensor. This results as a defect much less easy to characterize (C-scan difficult to analyse) and even to detect (maximum amplitude obtained on this defect is 6dB less than the 5mm longitudinal notch seen above whereas its overall dimension is larger). The ability to simulate such probes and other types of sensor and compare them quickly and easily allows to prepare inspection method and procedures, study the limit of performance of a given one and also to help to interpret results that can be sometimes quite complex.

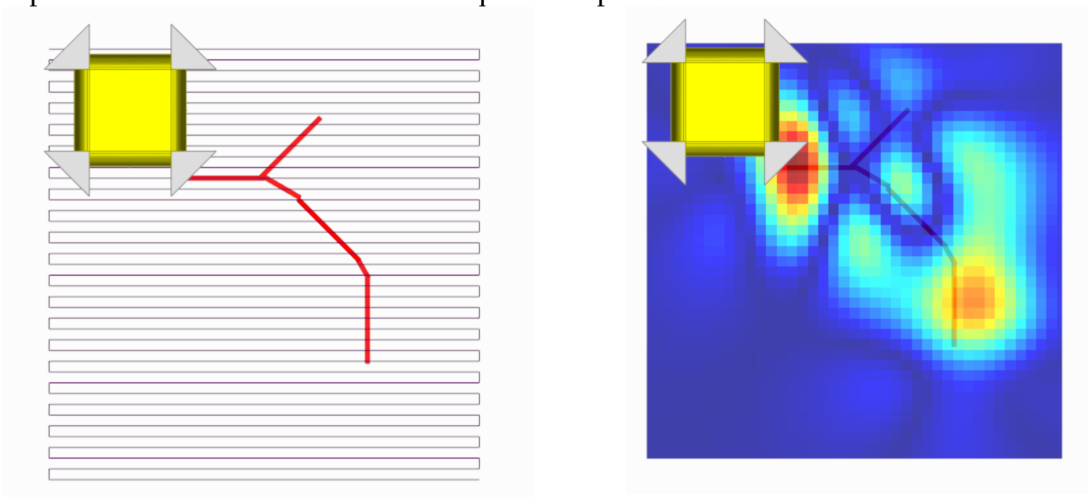

Fig. 7: Response of a complex crack with a +Point sensor simulated in CIVA

5. Impact of radiating specimen during RT inspection in nuclear plants

When doing an inspection in a nuclear power plant, important rules must be respected to avoid any contamination. Strict requirements are asked by the safety and regulation authorities to avoid any human contamination and radiation exposure for a too long period of time. To be located in an environment exposed to important radiations is not only a human problem but can also affect the radiographic testing inspection. Indeed, this technique involves the use of penetrating gamma or X-ray radiation to examine parts. An X-ray generator or radioisotope sealed source is used as a generator of radiation. In this context, the inspection of a contaminated part producing additional radiations may affect the radiogram by adding a non-wanted dose on the film. This radiation must be measured and considered to avoid an over exposure of the film leading to a non-interpretable radiogram.
In this context, and for nuclear applications, in order to consider the potential presence of radioactive substances within solids that will have an impact on the darkening of the film a new functionality has been developed and integrated in the latest version of CIVA. This new model considers the influence of radioactive contamination on a cassette-film being in contact with an irradiating part. By activating the option “contact dose rate”, the user can enter a “parasite” dose rate in contact of the film. This additional dose will be taken into

account in the computation and in the final conversion of the dose to optical density on the radiogram.
The example below illustrates the impact of a radiating specimen. The inspection is performed with a 73 Ci Iridum192 source with a panoramic exposure in order to perform a single wall RT shot. The component is a 50 mm thick pipe made of ferritic steel where a crack of 3 mm height by 20mm length with an aperture of 0.2 mm is located in the centre of the weld.

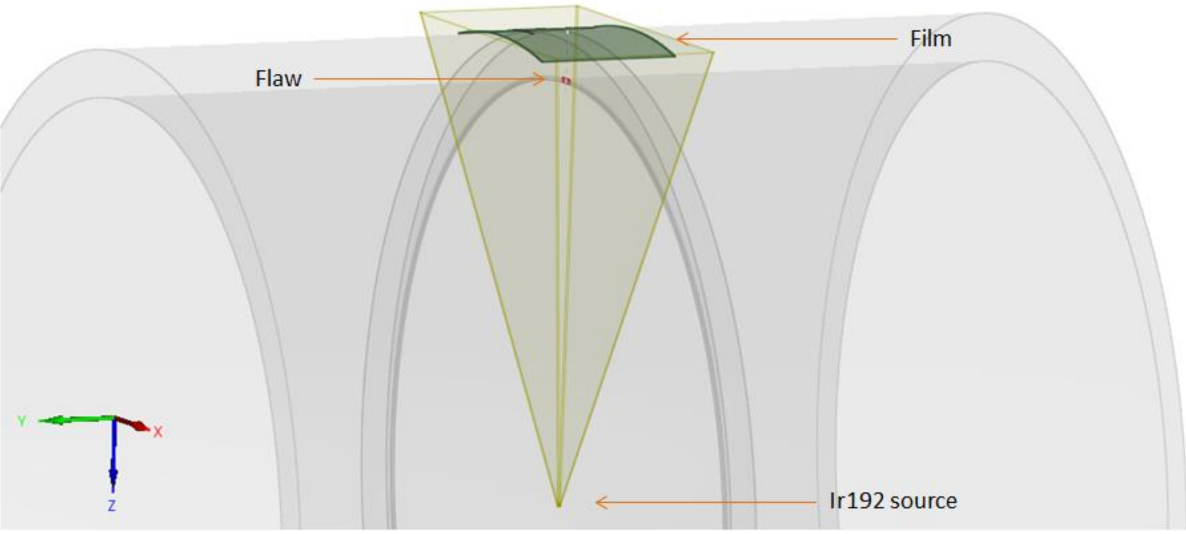

Fig. 8: 3D view of the initial configuration free of parasite radiation

For the first case, for a given exposure time and the configuration free of parasite radiation, the optical density (OD) obtained on the film at the position of the flaw is equal to 2.9 and the results shows that the defect is clearly detected. In the second case, we considered a dose rate of 12.1 mSv/h for the parasite radiation. For the same exposure time, if we account for an equivalent dose rate of 12.1 mGy/h, the optical density at the position of the flaw is around 4.3 leading to a global increase of the density of about 45%.

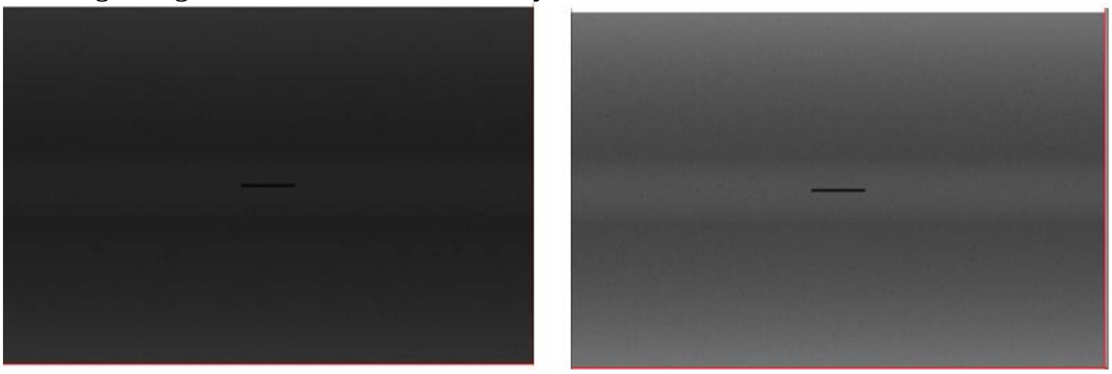

Fig.9: Comparison of simulated radiogram with a part contaminated and an OD of 4.3 (left image) and a free of contamination part with an OD of 2.9 (right image).

The measurement of this potential parasite radiation is therefore important to perform a correct RT shot meeting with the requirements of the procedure in regards to the desired optical density. To compare the impact of the parasite radiation on the detectability of defect, the time of exposure has been reduced in the second configuration in order to obtain the same incident dose on the detector as for the first case. The profile lines below extracted on the optical density images compare both results and shows the difference of contrast between the two configurations (with or without parasite dose). It can be seen on these profile lines that the detectability of defect can be affected by this parasite dose.

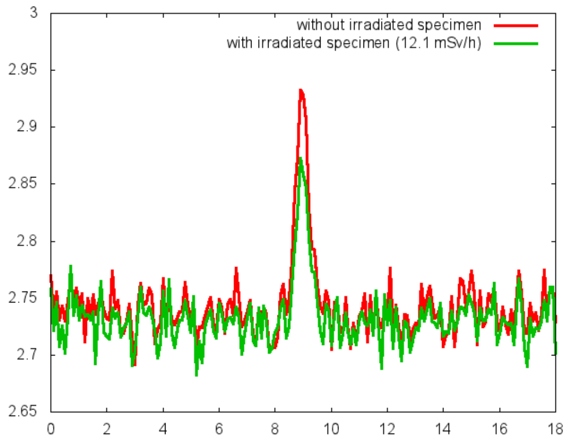

Fig.10: Profile lines extracted on the optical density images for a configuration without irradiated specimen and a second one with an irradiated specimen

6. Conclusion

This paper has presented some of the latest development of the CIVA modelling platform opening new applications. Three examples are then described where the capabilities are shown and the benefits of using simulation in NDT are highlighted: Accurately evaluate detectability when preparing scan plan of a UT inspection, Compare different Eddy Current probes performances including complex ones (such as orthogonal wound design), account for radiating components to correctly predict exposure time for a RT shot. These are some cases among others showing the increasing usefulness of simulation in NDT, other ones can be mentioned such as the study of influent parameters, the support to POD campaign and more generally to qualification and inspection reliability studies, or the help to automate diagnosis.

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