CIVA, AN INTEGRATION SOFTWARE PLATFORM FOR THE SIMULATION AND PROCESSING OF NDT DATA

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Abstract: In the early 90's CEA (the French Atomic Energy Commission) launched the development of an expertise software for NDT named CIVA. The idea was to gather within the same software, processing, imaging and simulation tools in order to be able to directly and easily compare experimental and computed data. Over the years, the project have gained in importance and with successive versions of *CIVA*, the results of latest modeling research have been being integrated into the software. In parallel the connexion of CAD tools allowed to perform simulation of CAD designed components. At the beginning limited to ultrasonic applications and models issued from CEA laboratories, CIVA now includes Eddy current simulation tools while work is in progress in order to make easy the integration of algorithms and models developed by different laboratories and to include Xray modeling. In this communication we give an overview of the existing CIVA capabilities and describe this evolution towards an integration platform.

Introduction:

Simulation and data processing plays an increasing role for analysing results and providing help to experts. Simulation is also commonly used to conceive methods and demonstrate their performances at a low cost, and also to teach and train operators. Since more than one decade the CEA (French Atomic Energy Commission) has been contributing to this evolution by developing the *CIVA* software. In the early nineties, with the first version of CIVA the idea was to gather within the same software, processing, imaging and simulation tools in order to be able to directly and easily compare experimental and computed data [1] and the first applications were dedicated to the interpretation of ultrasound signals acquired during inspections of nuclear power plants [2]. For fullfilling the requirement of computation times compatible with practical use in industrial context A twofold strategy was put forward: the choice of semi-analytical methods rather than fully numerical methods (finite elements, finite differences, etc.), and the development of models integrated into software modules usable by operators who are not simulation specialists.

Since then, the use of numerical modeling has been constantly gaining in importance, and its applications have become increasingly diverse. In this context, the CEA has been strongly involved in NDT modelling with the constant objective of extending the range of applicability of realistic and reliable simulation to more and more complex engineering studies. Over the years the results of this R&D activity have been being integrated in successive versions of *CIVA* in the aim of fulfilling requirements of users which belong now not only to nuclear industry but also to various industrial sector and especially aircraft industry (see for example [3,4]). In the first versions limited to ultrasonics, CIVA since several years contains also Eddy current modeling tools.

In parallel strong efforts have been put on the development of a generic and versatile graphic user interface system and on the simulation to CAD connexion allowing to deal with realistic and complex NDT configurations. Since a few years, a new phase began and in the framework of collaborative works several models and data processing algorithms developed in other laboratories or universities in France and Europe have been connected or integrated in CIVA. Now, to generalize and facilitate such integrations, specific software developments are in progress in CIVA which is becoming an integration platform for NDT. After having described the main existing simulation capability in CIVA we discuss this evolution.

Ultrasonic tools in CIVA:

*The simulation modules***:** The objectives pursued when using ultrasonic modeling may be very different from one application to another. The first objective is obviously to help the UT operator to analyze the results of an inspection and therefore to improve the identification, location and characterization of defects. But since several years simulation tools are also very used in the aim of performance demonstrations of methods (see for example [5]): The computations are used to evaluate the capability of a given method and to identify its limitations. Another very common application of simulation is the design and optimizations of inspections methods. It is particularly true for phased-arrays methods. In that case, to compute delays laws applied to the array, taking into account the whole configuration, may be very helpful [6]. To fulfill the requirements of these different objectives, various modeling-based modules have been developed within CIVA. Below, we will focuse on the two main modules respectively dedicated to the computation of ultrasonic fields for one position of the probe, and to the prediction of the echoes received during the probe displacement. Besides these two modules and using the same calculus kernels other modules are developed which allows the computation of delay laws, of focalizing surfaces, the display of coverage rates, etc. At last other models, based on alternative approaches are connected to the plat-form.

The CEA models: We give here a brief description of the CEA models used in *CIVA* to simulate radiation and propagation of ultrasounds. Interested readers will find complementary information in the papers given as references. The prediction of the contribution of one echo requires the modeling of: i) the radiation of the wave and its propagation from the transmitter to the area being inspected, ii) the interaction (scattering) with acoustic discontinuities within this area (defects or boundaries) and finally iii) the propagation to the receiver and reception. To deal with the point i), the applied method is the so-called "pencil method". The transducer is considered as a distribution of particle velocity source over the emitting surface, each source radiating an hemispherical wavelet. Along its propagation, in the coupling medium and in the solid, each wavelet is distorted and attenuated. These effects are due to the propagation itself but also to refraction (and/or reflection) through the different interfaces encountered during its path. The pencil method is used to model these effects by considering the geometric path linking the source and the calculus point. This method consists in describing the evolution of a pencil of rays emitted by the source and centered on the geometrical path. The model allows to compute the ultrasonic field within the component for wedge coupled or immersed probes of arbitrary shapes, for monolithic or phased-array transducers. Firstly developed for homogeneous and isotropic materials [7], it has been extended to deal with anisotropic and heterogeneous cases [8]. To deal with the point ii), namely the wave scattering, the different classical approximations are applied [7] depending of the scatterer. In the case of boundaries, calibration reflectors (side drilled hole, flat bottom hole, etc…) or voids, the high frequency Kirchhoff approximation is used. In the case of cracks, depending on the situation, the Kirchhoff approximation or GTD (Geometrical Theory of Diffraction) are used. At last, to predict the response of solid inclusions a slightly modified form of the low-frequency Born approximation has been proposed and implemented [9]. Finally, the signal received by the probe (point iii) is obtained by summing up the contributions of all these sources. The amplitude of one source is proportional to the probe sensitivity at this location called "reception field". The model in *CIVA* assumes a reciprocity between the field emitted by the probe acting as transmitter and the reception field of the same transducer acting as receiver. At last to predict the echoes structure received by the probe the contributions of each possible ultrasonic paths are successively computed as explained above and then summed up at every probe positions.

Examples and illustrations: Figure 1 shows the visualization window of CIVA which is common to all the ultrasonic and Eddy current simulation codes. We can see here an example of simulation concerning a nozzle inspection. The nozzle is specified by a few parameters (diameter, depth and

orientation of the two pipes) and automatically a CAD designed nozzle is built. On the presented example, a wedge coupled transducer has been located outside the secondary pipe and the field computation module has been executed. We can see here the result of the computation. The display is a cartography of the amplitude of the velocity potential within the component. It can be noticed that, on this example, the field computation accounts for reflections on the internal surface of the nozzle.
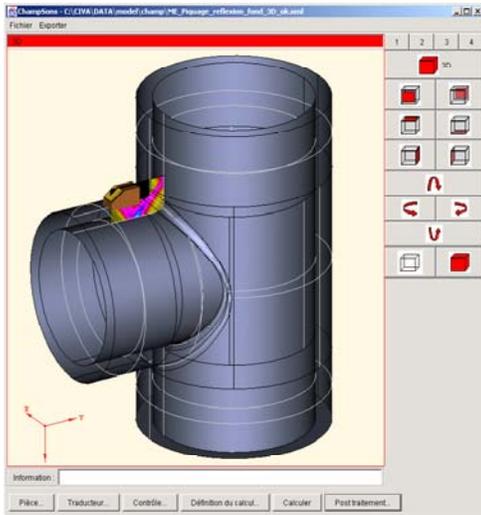
Figure 1 : Example of a simulation result: The ultrasonic field transmitted by a wedge coupled probe within a nozzle. The display of the module is visualized within the main window of CIVA.
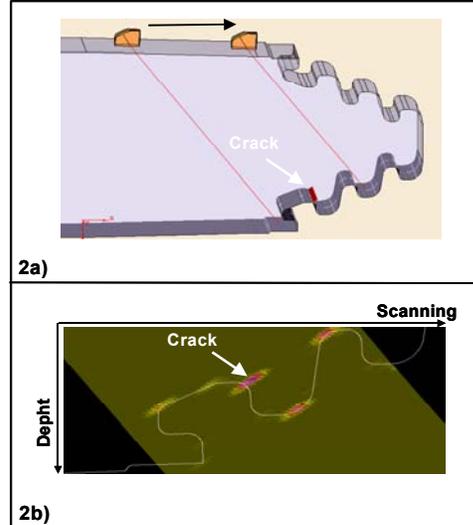
Figure 2 : Simulation of the inspection of a CAD designed component. a) Simulated configuration;
b) Simulated rectified Bscan and superimposition of the CAD profile

The figure 2 shows an example of application of the ultrasonic simulation module. The simulation concerns the inspection of a pressure turbine's blade roots performed with a T45° wedge coupled transducer. The researched defects are stress corrosion cracks located in disk rim attachment. On figure 2a we can see the configuration being simulated. The probe is visualized both at its initial and final scanning positions. A surface breaking crack has been inputted in the inspected area. On figure 2b is shown the simulated result of the simulation. The received echoes are displayed in a rectified Bscan (scanning/depth) view. The superimposition of the CAD profile describing the geometry of the component within the plane of incidence is a functionality of *CIVA* which allows a better understanding of the different echoes. Here, in addition to the echo generated by a corner effect mechanism on the defect, we can see various echoes resulting of reflection on the component surface itself.

The example of figure 3 illustrates the different applications of numerical modeling for phased array applications: i) computation of delay laws, ii) simulation, and iii) reconstruction. It concerns a sectorial scanning inspection performed on a 60 mm thick planar specimen containing a narrow Electron Beam Weld. Because of geometrical constraints, the probe cannot move backward to scan the lower part of the specimen, while the irregular profile in the neighborhood of the weld does not allow to inspect flaws close to the surface. A contact linear array of 48 elements is used here to steer the beam from 0 to 60° and to focuse within the weld from 10 to 60 mm depth. To reach this goal, suitable delay laws are computed with *CIVA*. The quality of the computed delay laws can be appreciated on figure 3 which shows the computed corresponding beams.

In order to validate the ability of this technique to inspect a real weld, experiment has been carried out on a part containing two side drilled holes and an embedded notch. On figure 4, the experimental results are presented and compared with simulated ones. The echoes are visualized

on a sectorial Bscan view which is built by applying a modeling-based reconstruction algorithm implemented in *CIVA*. The quality of the reconstruction as well as the detection performances of the method can be seen on figure 4.
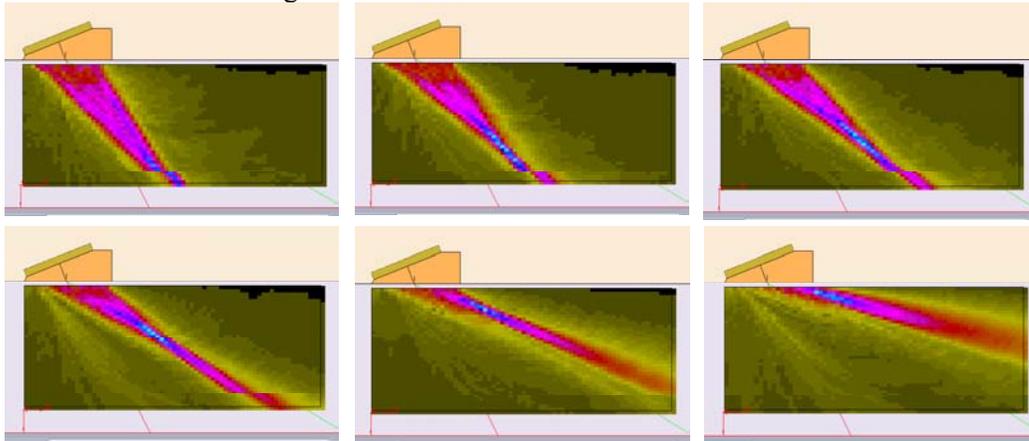
Figure 3 : Example of a phased array sectorial scanning application. Results of field computations corresponding to the application of different computed delay laws.
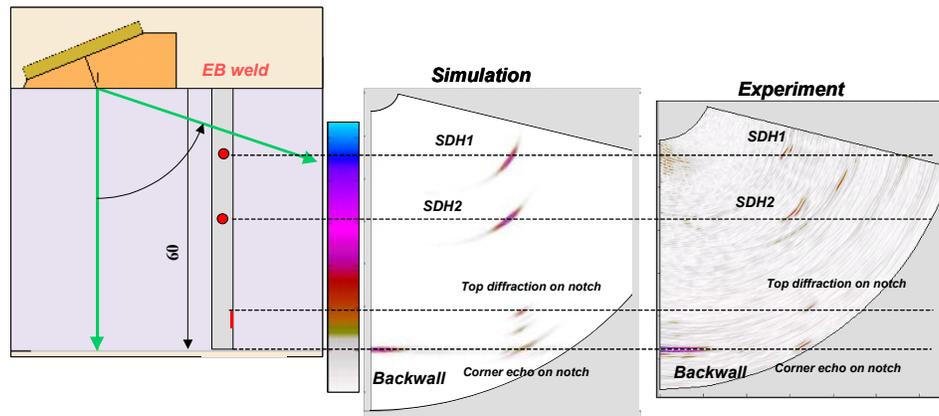
Figure 4 : Example of a phased array application. a) The sectorial scanning configuration; b and c) Simulated (b) and experimental (c) reconstructed Bscans.
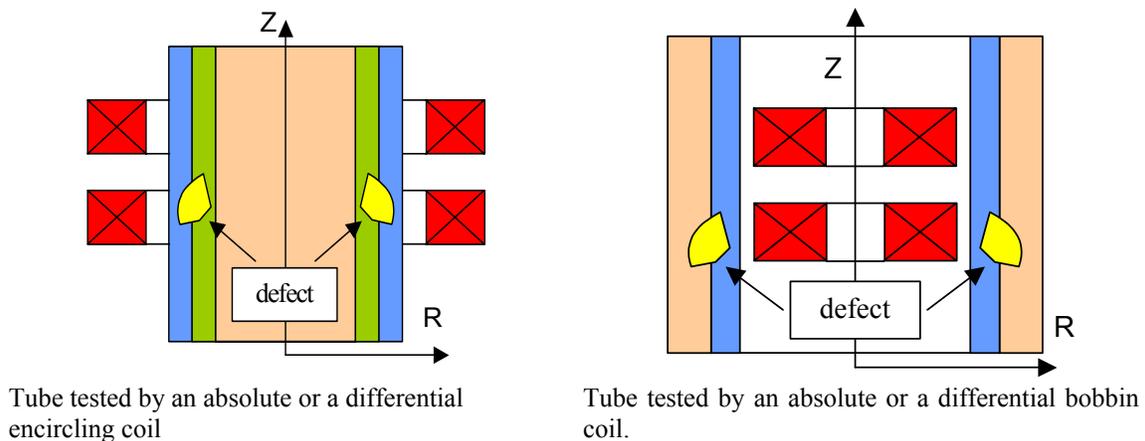
The data processing tools: Besides the simulation modules CIVA software includes ultrasonic imaging system connected to a wide range of data processing tools. Advanced signal processing algorithms are available such as split spectrum processing, time frequency analysis (wavelet transform), Wiener, and number of deconvolution algorithms. Image processing have also been implemented in CIVA, with a connection to CAD descriptions of components allowing to positioning echoes thanks to reconstruction algorithms.

Eddy Current simulation tools in CIVA:
The main problem in Eddy Current Non Destructive Evaluation consists to predict the effects due to the interaction of eddy currents with defects within a conducting material. The theoretical model often called the forward problem is tackled by a semi-analytical approach based on the volume integral equations. The main advantage of this approach is the reduction of unknowns because it is only necessary to construct a grid over the flaw and to compute the fields in the flaw. The dyadic Green's functions take into account all regions outside the flaw, in particular the boundary conditions at the planar interfaces. This approach avoids all requirements about boundaries conditions and one user can easily set up his test configuration. The Eddy Current

simulation module of CIVA can provide accurate probe responses in a few time and a lot of simulated experiences may be carried out very easily for testing a great number of parameters that are of interest in non-destructive testing. Today, CIVA deals with a range of practical configurations, which are of interest in non-destructive evaluation. For example the simulation of the inspection of a tube by an absolute or differential probe allows the prediction of the signal arising from a circumferential flaw. Another functionality concerns the computation of Eddy Current density in a conducting tube inspected by any arbitrary probe located outside the part. Some recent works [10,11] consider the Eddy current problem of a conducting tube excited by a bobbin coil and affected by a 3D Flaw which may vary by the size and the place within the tube's wall. The probe may be an axial probe or a differential probe. The model has also the capability to take into account the tilt of the exciting coil and the misalignment of the exciting coil.

Application to tubing inspection: The inspection of steam generator tubing is a critical issue for the nuclear industry. CIVA offers the possibility to simulate the response of an encircling coil or a bobbin coil for any configuration of tubes (simple or double wall) and axisymmetrical flaws such as grooves (figure 5). The number of conductive walls and flaws is not limited. In the example given in figure 6, one considers a tube made of Inconel 600 (σ=1 MS/m) with an outer diameter of 22.22 mm and a wall thickness of 1.27 mm. Two flaws are introduced in the tube wall: an outer diameter groove 40% trough wall (tw) and a 10% tw inner diameter groove. Both flaws have a width of 1 mm. One can clearly see the 90° phase shift between the inner and outer flaws and the equivalent amplitude of the signals despite a great difference in volume. This simple example of response for a bobbin coil is well known by ECT users but more complex configurations can be easily addressed. For example, one can consider the interaction of several flaws in the area covered by the bobbin coil. The effect of copper deposit on EC signals can also be analysed. This model runs much faster than a FEM solver and can also be used as a training tool

Tube tested by an absolute or a differential encircling coil

Tube tested by an absolute or a differential bobbin coil.

Figure 5: Flawed axisymmetrical configurations for testing

The simulation of EC signals for 3D flaws in tubular geometries is also addressed. An example of a signal obtained with a differential bobbin coil is given in figure 7 for a longitudinal notch at 100 kHz. This flaw is a 54% tw outer notch of 10 mm length and of 0.1 mm opening. The simulation result is the dashed line and the experimental data is the solid line. The agreement, as one can see, is excellent.
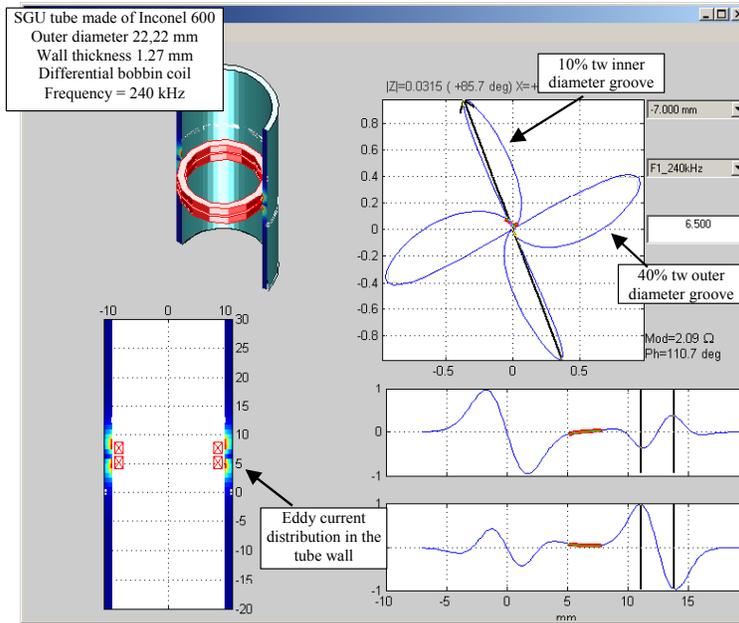
**Figure 6:** simulation of EC signals for a bobbin coil in a tube with 2D flaws

Application to planar geometries: A number of EC inspection configurations can be modelled as the displacement of a coil along a surface. For many applications, the surface curvature is low and can be locally considered as planar. The response of a surface riding coil to a 3D flaw in a slab can be computed with great time efficiency and accuracy with the semi-analytical model based on the Volume Integral Method (VIM).
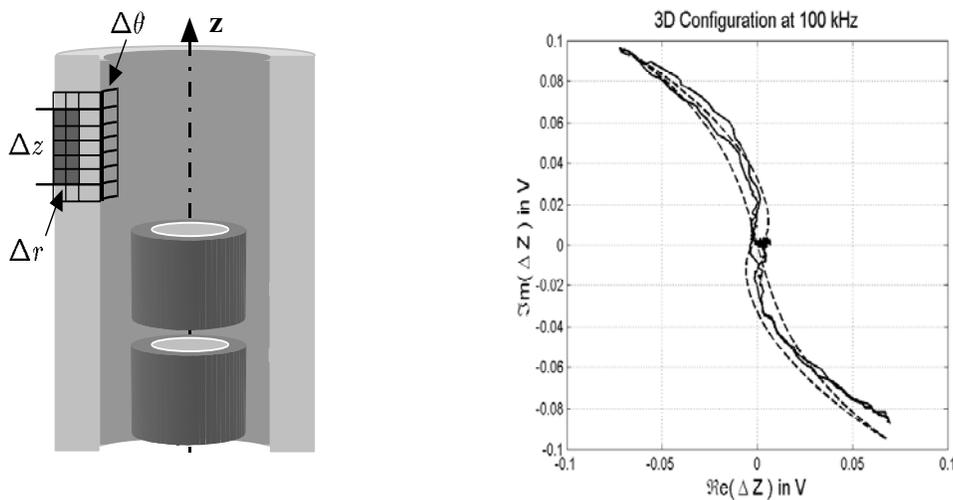

Figure 7: simulation of EC signals for a bobbin coil in a tube with a 3D flaw

Let's consider for example the simulation of the inspection of a titanium-based or nickel-based alloy with very small breaking flaws. This configuration is typical of ECT for engine in the aerospace industry. The slab and probe specifications are given by: the coil has an inner radius of

0.4 mm, an outer radius of 1 mm, a height of 1 mm, contains 70 turns, and the exciting frequency is 6 MHz. The lift-off is 0.1 mm. The length of the notch is 2 mm, its width is 0.1 mm and its depth is 0.2 mm. The probe is scanned over the slab with a sampling pace of 0.1 mm in both X and Y directions. The geometrical configuration is illustrated by figure 8 and the CSCAN is given in figure 9. The model gives to the user the opportunity to optimize the parameters of the inspection or to quantify perturbations factors (selection of the frequency, effect of a ferrite-core or a cup-core, lift-off, tilt…).
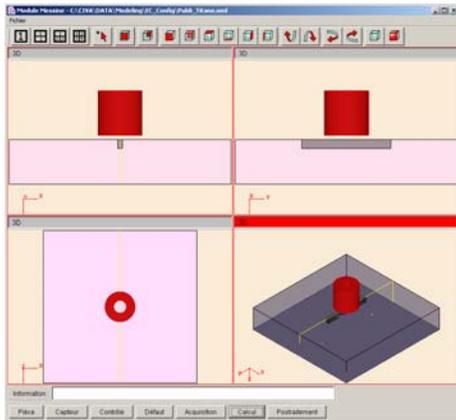
Figure 8: EC inspection configuration of a titanium slab
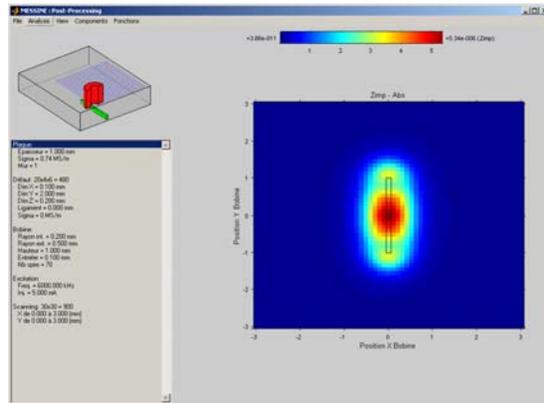
Figure 9: EC CSCAN of a titanium slab with a rectangular notch .

Graphic Users Interfaces (GUIs) and CAD connexion: In order to make easier the use of the different NDT simulations modules, all are connected to a common GUIs environment. The inspection scene is visualized in a 3D display window and a different set of windows is available depending on the NDT technique (ultrasonics or Eddy current) and the simulation module. As an example, in all the cases the operator has to define the component being inspected (its geometry and the constitutive materials) and one or several probes. The GUIs dedicated to the component is common to all the modules while thee GUI dedicated to the probes differ from one technic to the other.se two objects are therefore common to the different modules. In addition to this common kernel, the software includes GUIs specific to each module.

One key problem in ultrasonic NDT simulation is the capability of codes to deal with very different geometries of components, sometimes complex, and often described by CAD [12]. To provide simulation tools in virtual CAD environment is indeed of great practical importance especially specially for aircraft industry, since it should allow to take into consideration components controllability as early as at the design stage. Since several years *CIVA* has been connected to a CAD library. This connection makes possible ultrasonic simulations on non canonical geometries: Besides parametric components such as planar, parts, tubes, elbows or nozzles, the *CIVA* user can load a 2D or 3D CAD file in a standard format (STEP, IGES).

CIVA, an integration software platform: Since several years in the framework of collaborative works several models and data processing algorithms developed in other laboratories or universities in France and Europe have been connected or integrated in CIVA. To generalize and make easier such connections a collaborative project named MUTSIC and supported by the French ministry of industry have been lauched this year with the aim of proposing a software platform allowing to integrate, in a convivial way, different NDT simulation codes. The final objective of this project is to give to industrial users access to different simulation codes in a same environment. Such a platform will make easier and simpler the use of simulation and also will be helpful for validation and code benchmarks. Under this project software engineering

works are in progress in CIVA. These developments will make possible and easy the connection of modeling programs, developed by R&D laboratories partners of the project, on CIVA graphic user interface. To reach this goal, independent software components are going to be created on which simulation codes will be plugged. The project includes simulation of ultrasonics, Eddy Current and X Ray techniques and in this context the integration of Xray modeling tools in CIVA is in progress.

Conclusions: In this paper we have briefly presented the capabilities of the CIVA software. Emphasis has been put on the major ultrasonics and Eddy current simulation tools existing in the plat-form. For both the two techniques, the semi-analytical modeling approach has been chosen at CEA in the aim of minimizing numerically costs for an industrial use of the codes. With successive versions of *CIVA*, the last results of research are integrated in order to improve the software capability and to widen the domain of applications. Efforts are now made in the framework of a project supported by French ministry of industry in order to make easy integrations of different modeling codes developed by other R&D laboratories and to provide a plat-form gathering a set of UT, EC and XR NDT simulation tools covering in the best way the requirement of industries.

References:
[1] Ph. Benoist and al in Review of Progress in QNDE, **14**, op. cit. (1995), 2353.
[2] P. Calmon and O. Roy, "Ultrasonic measurements and modeling of cracks and ligaments using corner effect" in Review of Progress in QNDE, **11** (1992) 2123
[3] N. Gengembre, P. Calmon, O. Petillon and S. Chatillon, "Prediction of ultrasonic fields in multi-layered structures" in Review of Progress in QNDE,**22**, op. cit. (2003), 957

[4] S. Lonné A. Lhémery and F. Thévenot, "A simulation study to explain the variability of ultrasonic attenuation measurements in RTM composites" to be published in Rev.of Prog. in QNDE **23**, op. cit. (2004)
[5] L. Le Ber, R. Raillon, P. Calmon and E. Abittan, "Contribution of UT simulation to the qualification dossier of a PWR secondary loop nozzle examination", in the Proc. of the 3rd Int. Conf. on NDE in relation to Structural Integrity for Nuclear and Pressurized Components (2001)

[6] Mahaut S., Calmon P., Chatillon S. and Raillon R., "Ultrasonic NDT simulation tools for phased array techniques", in Review of progress in QNDE, 22, op. cit. (2003), 777
[7] P. Calmon, A. Lhémery, I. Lecoeur-Taïbi, R. Raillon, L. Paradis, Models for the computation of ultrasonic fields and their interaction with defects in realistic NDT configurations, Nucl. Eng. and Design (1998)

[8] Gengembre N. and Lhémery A., "Calculation of wideband ultrasonic fields radiated by water-coupled transducers into heterogeneous and anisotropic media", in Review of progress in QNDE, 19, (2000) 977

[9] M. Darmon, P. Calmon, B. Bele, "Modelling of the ultrasonic response of inclusions in steel"in Review of Progress in QNDE, **22**, op. cit. (2003)
[10] G. Pichenot, D. Prémel, T. Sollier, V. Maillot "Development of a 3D electromagnetic model for eddy current tubing inspection: Application to steam generator tubing", Review of progress in Quantitative Nondestructive Evaluation. (to be published), (2003).

[11] D. Prémel, G. Pichenot and T. Sollier, "Development of a 3D electromagnetic model for eddy current tubing inspection: application to the simulation of probe eccentricity", International Conference on Applied Electromagnetics and mechanics, 12-14 of May 2003, Versailles, France. (submitted to International Journal of Applied Electromagnetics and Mechanics)

[12] L. Le Ber, S. Chatillon, R. Raillon, N. Gengembre and P. Calmon, "Simulation of the ultrasonic examination of CAD designed components",