# An overview of validation campaigns of the CIVA simulation software

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**Abstract**

Numerical modelling is widely used in the frame of inspection qualification process, since it offers the capability to study a wide scope of configurations, and at a lower cost compared to a full experimental campaign. In this context, the reliability of simulation models is of the highest importance. Validation works related to the CIVA software simulation modules have been carried out each times new models are developed, from the origin of their development in the nineties. One has also to mention other validation works that are managed in the frame of various industrial collaborations and also the participation to benchmarks such as those proposed annually by the World Federation of NDE Centers. However, some of these results are not publicly available. That is why, to provide a better overview and determine the field of application of CIVA simulation tools, a long-range collaboration work has been engaged since 2010 by the CEA-LIST & EXTENDE around CIVA validation campaigns, based on comparisons (available on the EXTENDE website) between experimental results and CIVA predictions on configurations representative of industrial NDT applications. This paper gives an overview of the different works performed and focuses on several examples.

## 1. Introduction

The simulation plays an increasing role in NDT, allowing helping the design of inspection methods, their qualifications or the analysis of inspection results. Sometimes a qualitative result is enough, for instance to quickly prepare scan plans, at the pre-design stage, or to understand the main physical phenomena involved in a given situation. However, an industrial use of the simulation will often require a more accurate and quantitative information to really support decision making. For instance, the optimisation of a probe or of an inspection method needs reliable data to be used for determining probe specifications and inspection procedures. Simulation is also widely used in the context of inspection qualification as it helps to reduce the number of physical mock-ups (and thus cost and time) to assess essential parameters influence. In these contexts, simulation tools have first to give evidence of models validity to be fully considered as a reliable element for technical justifications. For instance, the recommended practice #45 from the ENIQ (European Network for Inspection Qualification) which is dedicated to the use of modelling in Inspection Qualification (1)

mentions that *"the availability of validation data is a key aspect for using simulation for technical justification".* That is why a lot of validation efforts have been put around the CIVA software, since the origin of their development in the nineties.
An evaluation of models accuracy can involve a comparison with theoretical formula or a comparison with other modelling package, but above all, and as mentioned again in the ENIQ document, *"Validation of models is typically performed by comparison of their predictions with the results of experiments".*
Another key issue is that experimental measurement should be conducted with care, as it is subject to variability induced by the inspection system parameters as well as human factors. For instance, in the different validation campaigns of CIVA regarding the ultrasonic module, the experimental uncertainty, is generally estimated around +/-2dB, sometimes +/-3dB, through reproducibility and repeatability tests, and automated inspections are carried out to reduce experimental uncertainties and human factors.
Finally, the use of the simulation also requires a competent user, trained to the use of the software, and aware of its capabilities and limits.

## 2. Models implemented in the CIVA simulation platform

### *2.1 Overview of the CIVA software*

The development of CIVA software started in the early 90s, first for ultrasonic application. Then, this package became commercially available and has started to be widely and even extensively used by the NDE industrial community from the years 2000s, in different industrial sectors such as power industry, aerospace and transportation, oil & gas, mechanical or steel industry.
The various modules of CIVA give access to different NDT 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. The mathematical formulations used in the different modules often 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.). 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. A brief description of the simulation models is given below. For interested readers wishing to have more information on the models, the following reference papers are available, (2) and (3) for the Ultrasonic tool, (4) for the Guided Waves module (5) for the Eddy Current part, (6) for the radiographic one and (7) for the CT module. Besides the simulation part, this platform now also includes a versatile analysis module for UT acquisition data.

### *2.2 A brief description of models implemented in CIVA UT*

The UT module relies on a geometrical approach (the so-called "pencil method") to compute beam propagation, while the interaction of this beam with discontinuities

involves several models depending on the context, mostly with semi-analytical or analytical formulations such as Kirchhoff or GTD ("Geometrical Theory of Diffraction"), "SOV"(Separation of Variables) and "Specular" models. More recently, hybrid models have been implemented using local Finite Element method for the beam/defect interaction while the incident beam around the "zone of interest" still relies on the "pencil method" quoted above. For instance, the ATHENA2D FEM code from EDF is implemented in this way, and another in-house FEM code ("Transient FEM") is available for some configurations in the latest release CIVA 2017.
The Ultrasonic Guided Waves module uses a hybrid "SAFE" method (Semi-Analytical and Finite Elements), considering a semi-analytical modal decomposition approach for the propagation along the canonical guide, and a FEM approach in the guide section (containing complex flaws or guide singularities).

### *2.3 A brief description of models implemented in CIVA ET*

Several models are available in the Eddy Current module of CIVA. The main part involves Volume Integral and Boundary Element Methods to compute the field/Flaw perturbation phenomenon, which only requires a numerical sampling of the flaw. The electromagnetic field induced in the work piece is calculated based either on analytical expressions, model approaches based on truncated regions, or more numerical Surface Integral Equations, depending on the complexity of the eddy current probe and the component geometry. For some configurations, CIVA ET also relies on a 2D Finite Integration Technique.

### *2.4 A brief description of models implemented 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 a probabilistic approach (Monte-Carlo method) allowing reproducing photons/matter interaction phenomena (Compton diffusion, Rayleigh diffusion, Photo-electric absorption, pair creations) based on the knowledge of cross-section data, available thanks to an extensive material database. Based on a set of RT projections, CIVA also includes Computed Tomography 3D algorithms such as FdK, PixTV and SART. Finally, models dedicated to films and detectors are used to predict the actual RT image.

## 3. Different means/strategies of validation

Models validations in CIVA take place at different stages. Validation works are usually performed to establish the field of validity of new feature or model (comparison with experiments, with other models available in the platform, with literature, etc.). For instance, some papers dealing with complex flaws and/or materials, as well as statistical approaches (PoD curves) have been published (8-14).
The CIVA development team also participates to the international UT and ET modelling benchmarks proposed annually for more than 10 years by the World Federation of NDE centers and published in the QNDE conference, which aims at comparing different simulation codes to experimental data provided to all participants (see wfndec.org).

Numerous validations are also performed in the frame of industrial collaborations, or by the users themselves. In these cases, the validations are targeted to specific industrial inspection configurations. Some of them lead to communications (15-17), but in most situations validation results and applications cannot be publicly available.
As said above, because validations are performed all along the development of new models or really targeted to an application, and as a lot of data cannot be published, it is difficult to capitalize all these set of works in an organized way clearly presented to the user. That is why a specific effort has been put on validation to provide evidence of the modeling results validity in various situations, or to show the limits of semi-analytical models. These validation campaigns, funded by EXTENDE, have been performed since 2010 and published on the EXTENDE website (http://www.extende.com/objectives-of-the-experimental-validation-ut). The experimental measurements have been performed at the CEA facilities. The physical basis of the model are considered to define their domain of applicability and the reliability of its predictions. The limit and approximations of the models and its implementation are also discussed and shown on the website to help the user to use simulation with confidence.

Due to the very large variety of industrial cases and the need for a quantitative validation of the signal amplitudes, a lot of efforts have been put on the UT module. However, validation works relative to the Eddy Current and Radiographic module can also be found on the EXTENDE website, where a similar approach has been employed, in addition to the validation references regularly published in international conferences.

## 4. An overview of CIVA validation cases published on the EXTENDE website

### *4.1 Conditions to perform "good" validation campaigns*

Several conditions need to be gathered to perform a fruitful validation campaigns as shown in the following graph:

**Table 1. Some conditions for a good and fruitful simulation software validation campaign**

| | | | |
|---|---|---|---|
| Exhaustive and accurate knowledge of input parameters | Reliable reference measurements | Estimation of the measurement uncertainty | Similar simulation and experimental procedures |
| Trained and experienced user of the simulation software | Choice of relevant output data to establish the validity | Separated investigations of influent parameters | Well-documented report for every steps |

Regarding the operating conditions, sources of uncertainty can come from the integrity of the specimen material (presence of inhomogeneities), unknown transducers parameters, the mechanical adjustments of the translation system, the quality of the coupling, the uncertainties relative to the artificial flaws machined in the mock-up, or other parameters. To minimize these sources of uncertainties, a clear procedure must be defined and followed including a calibration on a reference reflector. In some cases, the characterization of the probes shall be required (with reverse engineering process for instance). Immersion testing might also be preferred as it eliminates the source of variability encountered with contact probes due to the coupling quality (but of course, validation of contact probe testing is also important as this a very common inspection mode). Finally, whatever the precautions taken, the measurement variability shall have to be estimated through repeatability and reproducibility tests. As said before, even in good lab conditions, the experimental uncertainty is often at least of +/-2dB. Of course, the simulation works shall follow the same procedure: similar input data for specimens, probes, defects and mechanical scanning or electronic set up (for phased-array probe), calibration on the same reference defect, and the same way to analyse the output signal. This output can be based on the amplitude of an echo, but also on the temporal wave-form, the echodynamic curve or images such as B-Scan, S-Scan or C-Scan ones. Finally, it is advised to perform variation of each parameter under study separately, to be able to discriminate their contributions and the potential sources of discrepancy with experiments.

### *4.2 An overview of UT validation cases for different techniques*

Many inspection configuration and set-ups exist (Pulse-Echo, Tandem, straight or angle beam, etc.) using different transducers (Single Element or Phased-Array), different types of defects (volumic or planar defects…) so that an exhaustive and comprehensive table of existing validation cases is quite difficult to be provided. The EXTENDE website sums up the available validation cases description. Tables 2 and 3 illustrate some validation works performed and published on the EXTENDE website during the latest years.

**Table 2. Examples of scattering phenomena involved according to inspection modes and reflectors**

| Inspection mode / Reflectors | Pulse echo mode | Tandem mode | ToFD |
|---|---|---|---|
| (Reference reflectors)<br>Side Drilled Hole<br>Flat Bottomed Hole | (Mostly) specular echoes<br>L, T modes | Specular or corner echoes | Specular echoes |
| Notches | (Mostly) corner echoes in L, T, including mode conversion.<br><br>Single element and phased array settings | (Mostly) Corner echoes with pair of probes or Phased arrays settings (ZDM) | (Mostly) tip diffraction echoes in L mode |
| Geometry (specimen boundaries) | (Mostly) specular echoes (surface or backwall echoes) | Corner echoes (side wall echoes) | Backwall echo<br>Lateral wave echo |

It can be noticed that both conventional and phased-array probes (linear or matrix arrays) have been tested. A majority of immersion testing has been done but numerous contact testing cases as well. TRL Dual element probe, Tandem technique, and TOFD also belong to the scope of these validation campaigns. Regarding defects, a lot of efforts have been put to verify the accuracy of Flat Bottom Holes and Side Drilled Holes responses as such defects are used as reference ones for calibration. A lot of situations implying rectangular notches have also been tested (including vertical orientation, horizontal one to model delaminations, or also with various tilt angles), which are used as representative defects for ensuring performances of cracks detection.

For each configuration, a lot of situations have been studied (for instance different transducers at different central frequencies and/or with different crystal size). This paper will not of course detail the results, as the EXTENDE website gives many details (http://www.extende.com/objectives-of-the-experimental-validation-ut). Some papers have also been published after some of these validation works (18-20).

**Table 3. List of influent parameters investigated and phenomena encountered through multiple variations, tests, and comparisons**

| Example of parametric variations and phenomena influence on | |
|---|---|
| **Relative to the :** | **Parameter:** |
| Defect | Height |
| | Length |
| | Aperture |
| | Tilt angle |
| | Depth position (--> for instance DAC and DGS curves) |
| Probe or system set-up | Frequency range (generally from 2 and 5, also from 1 to 10 MHz) |
| | Crystal size |
| | Refraction angle |
| | Focused or Flat |
| | With/Without focal laws for PA probes (focal depth, sectorial scanning) |
| | Influence of the tilt of the probe (immersion testing) |
| | Varying PCS for TOFD |
| Component | Flat, cylindrical , irregular surface |
| | Attenuation effect due to microstructure (sensitive often for probe frequencies >=5MHz) |
| Other | Impact of mode conversions if any (particularly with L waves angle beam probe) |
| | Comparison between several models available in CIVA (semi-analytical ones or numerical methods) |
| | Impact of creeping waves if any |

It can be underlined that the website provides both well predicted results (signal amplitudes being predicted with a +/-2 or 3dB gap from reference measurement, within measurement uncertainty interval), but also cases showing higher differences. In these cases, the origins of the discrepancies are discussed. An example is given hereafter.

## 5. Example of validation campaign: Corner echoes on vertical notches

### *2.1 Overview*

One of the validation campaign dealt with the modelling of the corner echo (18), commonly used to detect vertical breaking planar indications with angle beam probes. Both immersion and contact testing were performed for various refraction angles of longitudinal and shear waves, various probe size and frequencies, and various defect sizes (see full description at http://www.extende.com/ultrasound-corner-echoes).

### *2.2 Corner echoes with shear waves: Influence of the notch height*

In one part of this work, the impact of notch height variation was studied, based on shear wave probes in immersion testing. The mock-up is a ferritic planar steel specimen of 30mm thickness containing backwall breaking notches (15 mm long and variable heights: 0.5, 1, 1.5, 2, 3, 4, 5, 7.5, 10, 12.5 and 15 mm). To check the specimen homogeneity and the measurements reproducibility, the inspections are performed in two scanning directions, using three immersion probes (table 4). The calibration has been performed on the response of a Side Drilled Hole of 2mm diameter at 20mm depth in a similar ferritic steel block. The amplitudes of the corner echoes obtained with the 3 probes and for all defect heights are shown on the figure below:

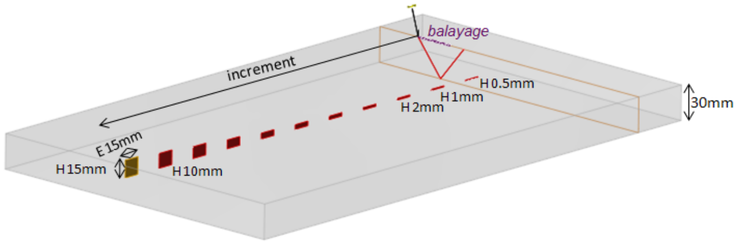


**Figure 1. Ferritic steel mock up including vertical notches with various heights**

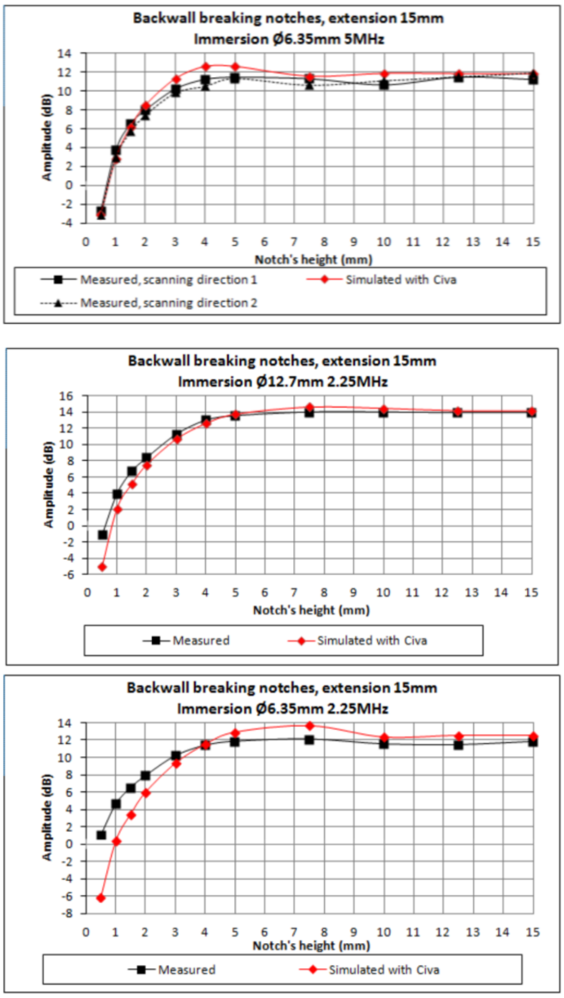


**Figure 2. Graphs of the simulated and experimental amplitude measured on the corner echoes as a function of the flaw height and for 3 immersion probes (from top to bottom: 5MHz Ø6,35 mm probe, 2.25MHz Ø12.7 mm probe, 2.25MHz Ø6,35 mm probe)**

**Table 4. Probe properties**

| **Central Frequency (MHz)** | **Crystal size** | **Refraction angle in steel** | **Water path** |
|---|---|---|---|
| 5MHz | Ø6,35 mm | Shear Waves 45° | 25mm |
| 2.25MHz | Ø12.7 mm | Shear Waves 45° | 25mm |
| 2.25MHz | Ø6,35 mm | Shear Waves 45° | 25mm |

### *2.3 Discussions and models evolution in the CIVA platform*

The simulation results are in an overall good agreement with the experimental ones. For the 5MHz probe, the agreement is really good for all flaw heights, with less than 2dB difference. For the 2.25MHz probes, the agreement is also really good but only for flaws equal or higher than 1mm for the Ø12.7 mm probe and higher than 2mm for the Ø6.35mm. These cases have been run with the Kirchhoff semi-analytical model and these results highlight 2 limitations of this model. One is linked to the size of the defect: when the flaw size gets close or smaller to the wavelength, the accuracy of the Kirchhoff model decreases. When you compare the results obtained with the Ø6.35mm probe at 2.25 and 5MHz, it is clear here that for the 5MHz probe where the wavelength is smaller, the results remain accurate for the 0.5mm defect while this is not anymore the case at 2MHZ where the discrepancy amounts to 7dB. A second point is also that the model accuracy is more affected when probes divergence is higher. Indeed, the results obtained with the Ø12.75mm is better for the 0.5mm and 1mm defect heights than with the smaller and more divergent Ø6.35mm probe. A more divergent beam includes a wider range of incidence angles that affects the beam/flaw interaction phenomenon.

Since this validation campaign was done, major improvements or alternative models are now available for the users in CIVA. First, a « Full Incident Beam » model has been released in CIVA 2016 and allows a higher accuracy in the computation of the incident beam on the defect, especially when the beam is quite divergent or when the defect is located in the near field. Then, FEM models are now available to simulate the beam/defect interaction and overcome the limitation with « small defects » of the Kirchhoff one. In the latest release CIVA 2017, a transient FEM model is directly embedded in the same module as the Kirchhoff one, just as a simple option. Even if of course it has a cost in terms of computation time compared to Kirchhoff, it gives the ability to the user to improve the simulation accuracy when it is relevant in a given context.

## 6. Conclusion

This paper aimed at giving an overview of the large effort that has been put around the validation of the CIVA simulation software, especially regarding the Ultrasonic Inspection Simulation module. The results of these validation campaigns are widely detailed in the EXTENDE website. The results obtained are often very consistent and provides a good basis to help end-users to justify the relevance of using simulations to support NDT qualification studies (or design studies) with a more cost-efficient methodology. But let’s also remind that cases where discrepancies obtained are also published and explained as much as possible, which helps both the users to know the limits of validity of the models, and the development teams to optimize models to overcome them, as shown in the example of corner echo validation campaign where 2 major models improvement have been realized since then. As this is a good way to benefit from each other’s experiences, EXTENDE would be also very pleased to receive more users contributions to these validation works. If you have some validation cases and/or papers you’d like to share with the CIVA users community, please do not hesitate to contact us so that we will upload them on our website.

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