Simulation of Complex Configurations

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Abstract. Simulation is more and more widely used by the different actors of industrial NDT for a great variety of applications (help for diagnosis, data reconstruction, performance demonstration, probe design and inspection parameters settling, virtual testing etc…) and the requirements in terms of reliability, accuracy, and complexity of the simulated configurations are always increasing. CEA contributes to this evolution by developing the CIVA expertise plat-form which gathers in the same software several modeling tools dedicated to different situations and applications and makes possible simulation of realistic NDT configurations. In this communication we present a state of the art of the simulation capabilities, describe some recent advances and give several examples of applications.

Introduction

In all the industrial sectors which require high-level inspection methods (aeronautics, transportation, energy, steel industry, etc…) the role of the NDT simulation is continuously increasing and diversifying. The applications are numerous and show a great variety (see for example [1-3]): help for diagnosis, performance demonstration, probe design and inspection parameters settling, virtual testing, data reconstruction, etc… The development at CEA of the CIVA software platform has accompanied this evolution over the years [4,5]. Resulting of an intense research activity in the field of ultrasonic and electromagnetic modelling, efficient simulation tools are implemented in CIVA and today are widely used in various industrial contexts. The models developed at CEA are based on semi-analytical approaches, this choice being motivated by the sake of finding a good compromise between accuracy of quantitative results, complexity of the simulated configurations, numerical efficiency and easiness of use. In parallel, these last years software engineering work have been done in CIVA which became an “integration plat-form” allowing easy connections or integration of complementary models developed by partners.

Over the years, to increase the complexity of the configurations addressed to the simulation is motivating and accompanying the progress of the models and of the available codes. This complexity concerns the geometry and the materials constitutive of the inspected components and the characteristics of the researched defects. It concerns also the inspection method itself. In particular, the sophistication and the generalization of the phased arrays inspection techniques have induced strong evolutions for the simulation tools. To ensure the reliability of generic simulation codes dedicated to complex and varied situations and used by different actors with sometimes very different purposes requires an intense activity of validation. At CEA, one laboratory is entirely dedicated to this purpose, achieving both “theoretical” (comparison inter-models, benchmarks) and experimental validations (see for example [6] in this volume).

In this paper we briefly recall the theoretical basis of the semi-analytical models appealed by CIVA. We show on different examples how complex configurations are addressed, and also we present some example of validation results. In general the reader interested by more details on such and such item will find suitable references to other CEA contributions in this volume. At least we conclude giving elements about new trends and perspective.

1. Modelling approaches

1.1 Numerical and semi-analytical approaches

The purpose pursued by all the modelling approaches is finally to resolve the equations governing the physics of the phenomena (respectively the wave equation of elasticity and the Maxwell equations for UT and ECT applications) but the adopted strategies differ. The approaches are generally divided in two main classes called respectively "fully" numerical and semi-analytical methods. The first ones (finite elements, methods, finite different methods, etc…) aim at resolving the governing equations without making any physical approximations concerning the form of these equations and reach this objective by a spatial sampling of the media separating the probes and the inspected area. The second class of methods, the semi-analytical ones, aim at solving (numerically) approximated analytical forms of the governing equations, the applied approximations being different and chosen depending on the situation. The advantages of the numerical methods are mainly the high accuracy of the provided results and the versatility of addressed situations but they suffer from requiring important computation times and memory and a somehow complexity of use. For these reasons the choice has been done at CEA to develop semi-analytical methods. Nevertheless since several years software engineering work is made in CIVA in order to connect codes developed by CEA partners and especially to take advantage of the complementarity of numerical and semi-analytical approaches. For instance, in the framework of a French government collaborative project, a connexion has been created between the electromagnetic finite element code Flux3D [7] and CIVA, and in the case of ultrasonic applications, a hybrid model involving the finite element code Athena of Electricité de France has been developed [8].

1.2 The CIVA ultrasonic models

Detailed descriptions of the models developed at CEA for the radiation, the propagation and the scattering of ultrasound have been given at different occasions and can been found elsewhere (see for example [9] and [5]). We just recall briefly the main features of the approach.

Let us consider the general issue of the prediction of the response some flaw. Firstly, the incident ultrasonic field impinging the flaw is obtained by applying the so-called *pencil model* [10] which provides a high frequency asymptotical solution of an integral form of the wave equation: The transducer surface is discretized and the field is obtained by summing up the contributions of all the sampled infinitesimal sources. Each contribution is calculated by considering the evolution of the wave front along the ray path linking the sources and the calculus point. Then, the scattering of the wave by the flaw is modelled by applying, one suitable approximation depending of the defect (type, geometry and size vs wavelength) and of the inspection configuration. Thus for instance, the response of a crack-type flaw in pulse-echo configuration is usually calculated by applying Kirkhhoff approximation while the Geometrical Theory of the Diffraction is used in TOFTD configurations. A slightly modified form of the Born approximation is appealed to deal with small solids inclusions. Lastly the Auld transmission-reception reciprocity theorem [11] is applied to account for the reception.

As illustrated below by various examples, this integrated modelling approach allows to deal with a large range of complex situations: Concerning the inspection technique itself pulse-echo, tandem or TOFTD configurations can be simulated. The models apply for monolithic, dual probes or phased arrays, both wedge coupled or immersed. The materials constitutive of the inspected components may be anisotropic and heterogeneous. The geometries may be complex (defined by CAD) and non regular. Echoes involving reflections on the part boundaries (corner echoes, "indirect" tip diffractions, backwall echoes…) can be predicted.

1.3 The CIVA electromagnetic models

The electromagnetic modelling approach is based on the so-called *Volume Integral Method* [12] and the calculation of Green's tensors in order to solve Maxwell equations. The first step of the simulation consists in calculating the primary electric field created by the probe in the inspected area. The electric-electric Green's tensor modelling the contribution of an infinitesimal current source at the calculus point [13] is computed and integrated over the emitting coil. In case of ferrite-cored probe, the calculation of the primary magnetic field has to be added to this step [14]. The presence of the flaw is described by a local variation of the conductivity in the inspected area and modelled by a fictitious current source density. The numerical computation of this current source density is the second step of the simulation. It uses the primary field previously obtained and requires the evaluation of the electric-electric Green's tensor inside the inspected material. Finally, the ECT output signal which is generally the variation of the electromotive force is evaluated either analytically or considering separately each discretized element of the receiver, through the resolution of an observation equation derived from the reciprocity theorem [15]. The main advantage of this approach is to only require the fields computation in the flaw. The physics outside the flaw and in particular boundary conditions at the part surfaces are integrated in the expression of the Green's tensors.

This approach allows to deal with a wide range of configurations involving single probes or arrays working in different modes (absolute, differential, transmit-receive mode, etc…). Multi-layered components can be modelled and assuming a locally canonical geometry (planar or cylindrical) the models can been applied on parts of complex geometry defined by CAD.

1.4 Models implementation in CIVA

To deal with the different purposes pursued by operators, different modules have been developed, based on the previous models: Modules for computing primary field in ECT and transmitted beams in UT, modules for predicting the signals or echoes arising from flaws, module for driving phased arrays (ultrasonic delay laws computation), "zone coverage module" which allows to determine which areas in the component are really insonified and efficiently inspected during an ultrasonic examination. All these modules are connected to the same GUIs (Graphic Users Interface) and CAD library. CAD functionalities make possible the simulation on non canonical geometries: Besides parametric components such as planar, parts, tubes, elbows or nozzles, the user can load a CAD file in a standard format (STEP, IGES) or directly define a 2D CAD profile in order to build a axi-symmetrical or translation invariant geometry. The CAD tools can also be used to define complex-shaped defects (see below).

With successive versions of CIVA new functionalities are added extending the range of applicability of the simulation tools. These evolutions may imply only software or algorithmic works (connection to the existing models to new configurations) but often require specific modelling advances. In ECT applications these modelling advances mainly consist in expressing Green's tensors in new and more complicated configurations. In UT the models are improved to deal with phenomena not yet taken into account.

3. Examples of simulations on complex configurations

In this section we present some examples illustrating the capability of the simulation tools to deal with complex configurations. Some of the given examples are the subject of a dedicated paper in this volume where the interested reader will find more details .

3.1 Simulation of ultrasonic inspection of heterogeneous parts

It has been already mentioned that the pencil method used to model the ultrasonic propagation allows to deal with heterogeneous and anisotropic parts. By heterogeneous we mean here a part which is constituted by various homogeneous volumes whose sizes are large relatively to the central wavelength. In these cases, the pencil method predict the effect of internal refractions and mode conversions on the transmitted wavefronts [10]. The simulation in CIVA of ultrasonic inspection of austenitic welds is based on this principle. The weld is modelled as a set of volumes in which the crystallographic orientation is assumed to be constant. The internal boundaries can be directly inputted in the software thanks to the CIVA CAD facilities. It can be made easier by the possibility of superimpose to the CAD description of the part a micrograph of the weld. Figure 1 presents an example of application concerning an austenitic steel. A mock up containing three side drilled holes is inspected with a 2.25 MHz L45 wedge coupled transducer. On figure 1a), b) can be seen the description of the part as a set of homogeneous regions and the location of the defects. The simulated results, visualized on figure 1c) are compared to experiment (figure 1d).

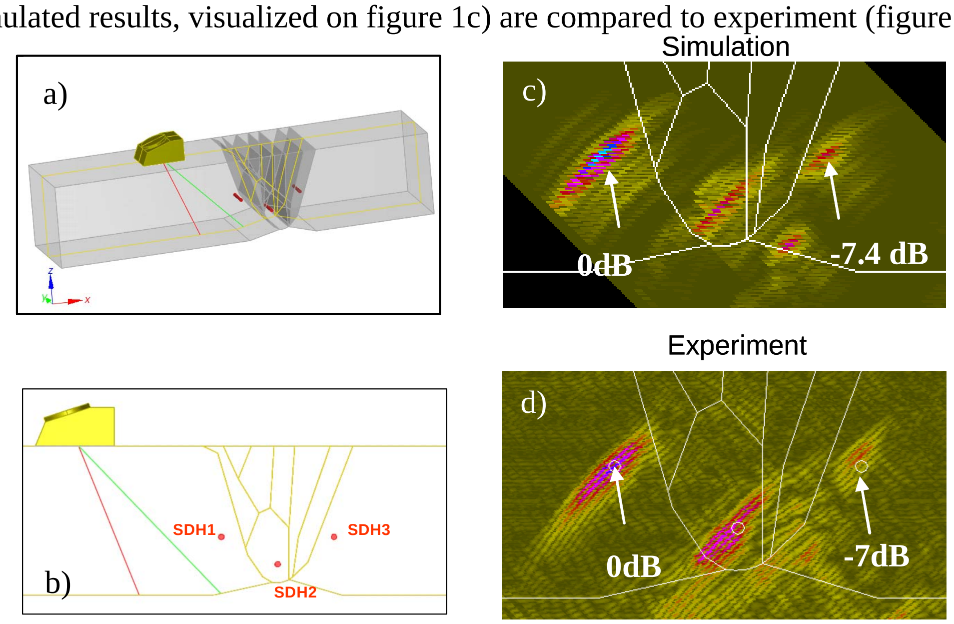

Figure 1. Simulation of the ultrasonic inspection of an austenitic weld; a and b) Simulated configuration; c) Simulated true Bscan; d) Experimental true Bscan

As in the following of this paper, true Bscan views are used to visualized ultrasonic echographies. These views are obtained by applying a reconstruction algorithm which consists to display each signal along a line (which may be a polyline) calculated from the knowledge of the media encountered by the wave during its propagation. These views may be superimposed to the CAD description of the part making easier the interpretation of echoes.

3.2 Simulation of ECT encircling Probe configuration

The electromagnetic models can be used to simulate tubing inspection with an encircling probe and take into account perturbation factors such as a tilt or the eccentricity of the probe (see figure 2a) due to the fast displacement of tubes. On figure 2b) is illustrated for example the effect of the eccentricity on the signal obtained from a longitudinal notch. One can see a comparison between two computed signals, obtained with a centered and a non-centered coil. The effect of the eccentricity can be easily identified and quantified on this example. Such result could of course be obtained experimentally but at greater expenses.

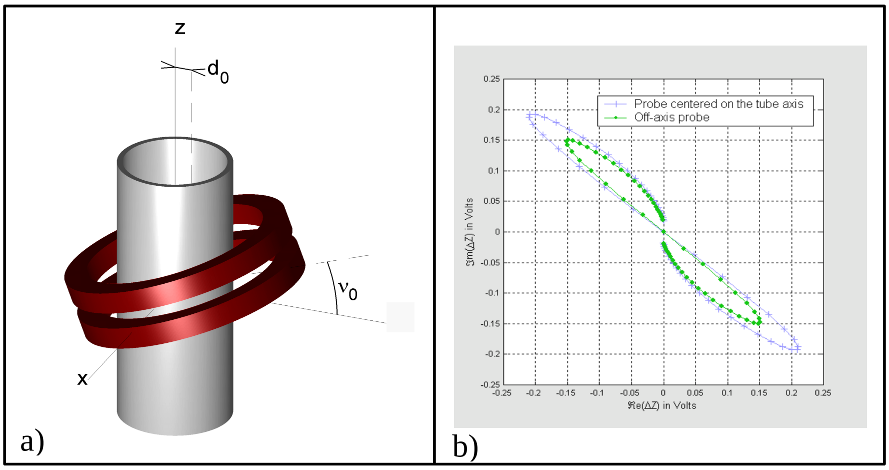

Figure 2. a) Tubing inspection configuration; b) Effect of a probe eccentricity: Computed signals arising from a longitudinal notch for both centered and off-centered probes

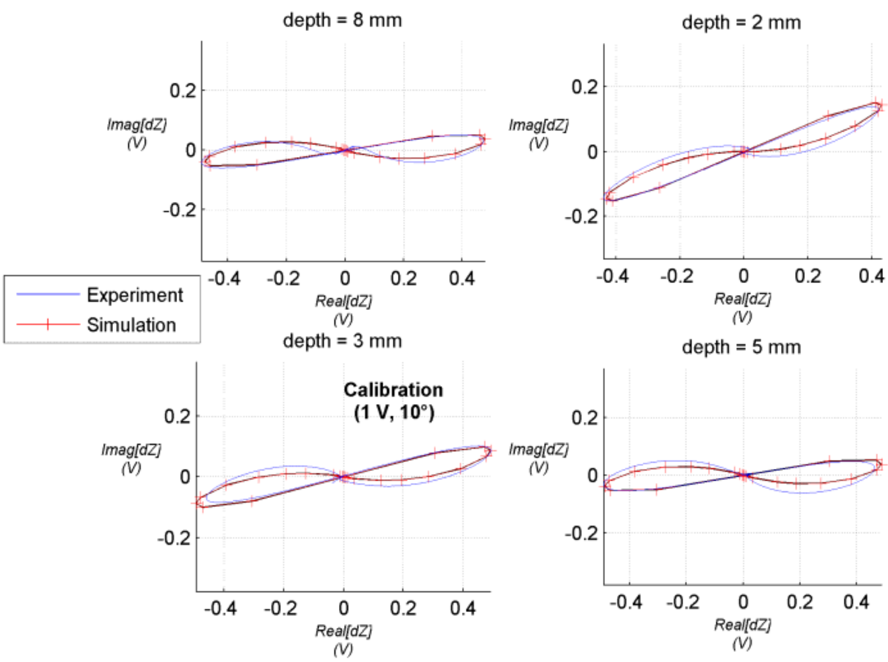

Figure 3. Experimental and computed signals obtained on the four holes tested with an off-centered probe

In the framework of a collaborative work with the Vallourec group, modelling and experimental work has been done [16]. The predictions of the simulation have been compared with experimental data acquired on rough industrial tubes in conditions close to industrial ones. On figure 3) are shown some results obtained on a stainless steel tube (inner and outer radius: 8 and 16 mm) containing four holes (diameter 3.5 mm) at different depths (2, 3, 5 and 8 mm). The probe which consists in one emitting coil and two identical receiving coils is off-ceneterd (d_0 = 2mm). A very good agreement can be observed confirming the ability of the models to account for this complex 3D configuration.

3.3 Simulation of the ultrasonic inspection of a nozzle with a flexible array

One of the major field of application of the ultrasonic simulation concerns phased-array. Phased arrays provide increased versatility and adaptability for a broad range of applications. Simulation tools are requested to get an optimal exploitation of the capabilities offered by phased array at the different stages of the inspection from the probe design to the excitation of the array (computation of delay law) and the data interpretation.

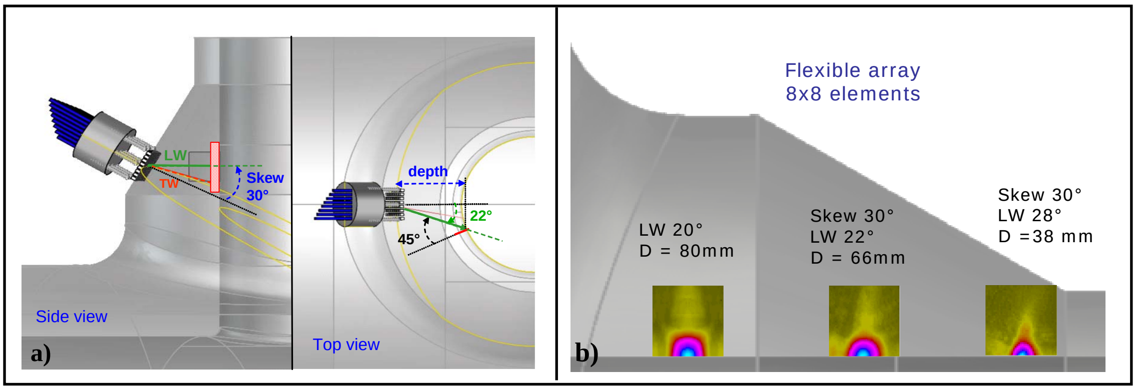

Figure 4. a) Visualization of one inspection configuration; b) Some results of field computations for different probe positions, the array being excited with optimized delay laws computed.

CIVA allows to simulate in a very versatile way usual and advanced phased array functionalities. We present here an example of application illustrating the capability of simulation tools in a complex configuration which concerns the inspection of a nozzle with a flexible matrix array. This work [17] has been done in collaboration with Electricité de France. The development of flexible arrays aims at providing an efficient solution for the inspection of complex geometries. In the present study a 3D flexible array has been designed, by simulation, specifically for nozzle application. Simulation has also been used for theoretically evaluating the performances of the probe. These predictions have then been experimentally validated on a representative mock-up containing several defects. On figure 4a) can be seen the inspection configuration. The represented defect is one longitudinal notch breaking the internal surface of the pipe. The flexible probe is scanned on the external side of the conical part of the nozzle. The figure illustrates the fact that the beam axis has to be electronically deviated in 3D in the aim of making possible detection and sizing of the notch. This deviation varies with the notch location and the correspondent delay laws are to be computed taking into account the full 3D geometry. In the case of the notch of figure 4 a) a 22° steering is required for generating L45° waves and a skew angle of 30° is needed for ensuring a plane of incidence normal to the defect. On figure 4 b) are presented some results of beam computations obtained for different probe positions which show the capability of the method for different defect locations. The amplitude cartographies lie in the plane of researched defects and it can be seen that the application of optimized delay laws ensures a proper focalisation and orientation of the beam. The performances are confirmed by simulations including the defects responses. On figure 5a) the result of such simulation achieved with the same notch as figure 4 a) (height 7 mm) is presented and compared with experiment (figure 5 b). As in the previous example, the images are true Bscans applying a reconstruction algorithm which takes into account the geometry at the probe position. These images can be included in the 3D view of CIVA as shown in Figure 5c, making easier the interpretation of the echoes.

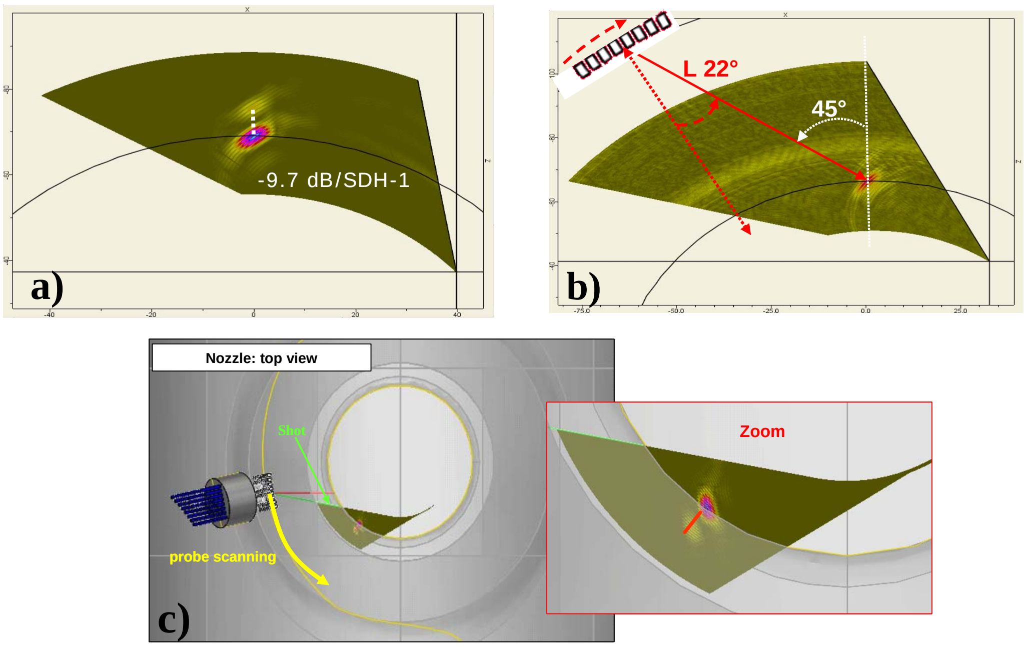

Figure 5. Simulation of the response of the notch of Figure 4; a) Simulated rectified Bscan ; b) Experiment; c) The simulated Bscan of a) visualized in the 3D view of CIVA

3.4 Simulation of ECT on CAD specimen

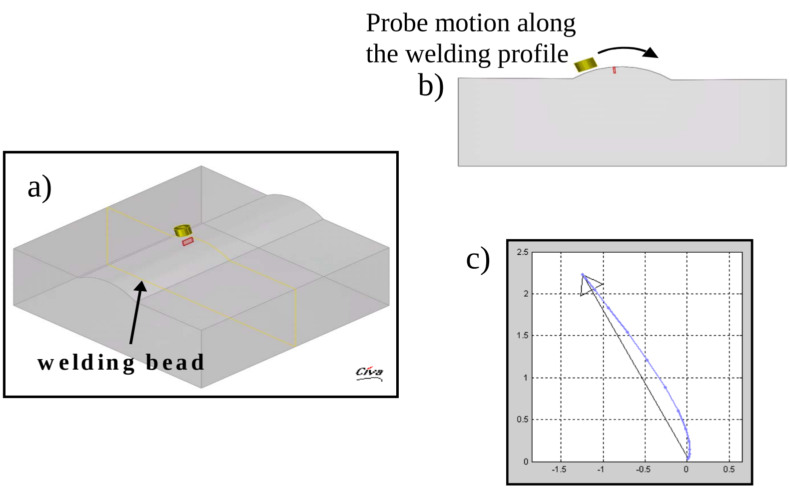

Figure 6. Welding inspection of a repaired Inconel area with a surface ridding probe; a) Configuration; b) extracted profile and c) simulated flaw response

The CAD facilities of CIVA can also been used in a ECT context and the models allow to predict the signals received from small defects located in a part of complex geometry with a surface riding probe. The example illustrated figure 6a) concerns the detection of small defects in the welding of a repaired Inconel area. From the knowledge of the CAD geometry and of the probe motion, a profile of the piece is automatically extracted (figure 6b) on which is applied performed the computation of the ET signal (shown figure 6c) assuming a locally canonical geometry (planar or cylindrical).

3.5 Simulation of the ultrasonic response of complex-shaped defects

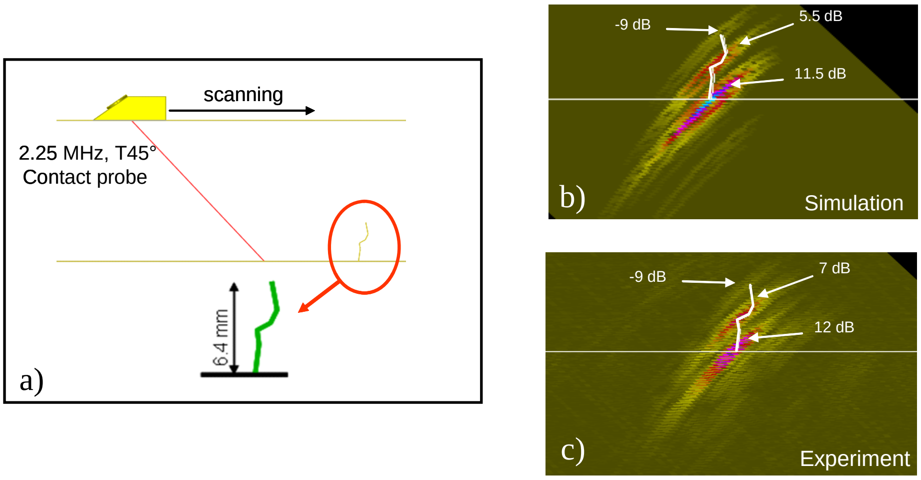

Figure 7. Simulation of the response of a multi-faceted defect; a) Simulated configuration, b) Simulated and c) experimental rectified Bscans.

One important and classical issue is to evaluate the representativity of ideal defects for predicting the response of natural ones. In CIVA, the scattering model based on the Kirkhhoff approximation has been extended in order to deal with multi-faceted defect defined by CAD in order to simulate irregularities observed on natural cracks. The response of the defect is computed by summing up the response of all the facets. This approximation can be considered reasonable as far as multiple reflections on the defect itself and shadows effects can be neglected. In order to experimentally confirm this hypothesis experiments have been performed in the framework of a collaboration with French Safety Authorities (IRSN). A mock up containing an artificial electro-eroded breaking notch with controlled multi-faceted shape has been made and inspected with a 2,25 MHz T45° wedge coupled transducer. The simulated configuration is schematized on Figure 7 a). Experiment and simulated rectified Bscans can be seen on Figure 7 b) and 7 c). The amplitudes of the different echoes, calibrated on a side drille hole are in a good agreement.

Nevertheless, in other situations, as mentioned above, approximated theories as Kirchhoff approximation will fail. It will be the case as soon as complex scattering mechanisms (multiple scattering, interaction between closed defects, surface echoes) cannot been neglected. To deal with such complex situations a hybrid model has been developed in collaboration with Electricité de France based on the FEM code ATHENA and the pencil model described above. This model tends to combine the advantages of the twoth methods: application of the pencil method for the propagation along long distances between the probe and the region containing the defect, FEM resolution in a small region surrounding the defect. The coupling between the two computations is realized through an integral formulation derived from Auld's reciprocity principle. The interest of this hybrid approach is to provide an accurate description of complex scattering mechanisms while minimizing the computation time. Figure 8 illustrates the application of the model in the case of a branched crack and shows a comparison with an experimental result. The inspection is done with a 4MHz T45° immersed transducer on a steel mock-up containing a electro-eroded breaking notch modeling a Y–shaped crack. The images present multiple echoes due to the complex shape of the defect and the good quantitative agreement between experiment and simulation can be noticed. On figure 8 c) are reported some snapshots provided by the FEM computation whose analysis makes easier the identification of the echoes.

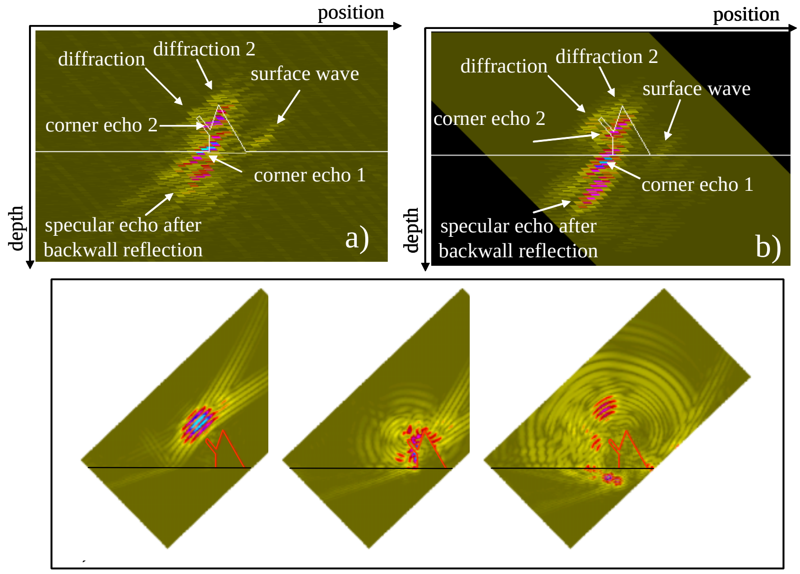

Figure 8. T45 Simulation of the inspection of a branched breaking crack; Experimental (a) and simulated (b) rectified Bscan images c) Successive snap-shots provided by the FEM computation

Conclusions

In this paper we have tried to give a comprehensive overview of the present capabilities of the simulation tools based on semi-analytical approaches and implemented in the CIVA plat-form. Through several UT and ECT examples, we have shown that today quite complex and realistic situations can be simulated. We have underlined the importance of the experimental validation realized in the aim of ensuring the reliability of the models. Combined with the good numerical performances of the codes, it appears that these tools are now mature for advanced applications such as resolution of inverse problems or simulation-helped evaluation of probability of detection (POD). We also have underlined the complementarity between the different modelling approaches and the interest of hybrid models. Thanks to the plat-form architecture of CIVA, various codes developed by other groups have been already connected to the CIVA plat-form in the framework of collaborative work.

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