Validation of CIVA Simulation Tools for Ultrasonic Inspection in Realistic Configuration

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Abstract. Ultrasonic simulation tools have been gathered in the Civa software developed at CEA (the French Atomic Energy Commission), in order to conceive, optimise and predict the performances of various inspection techniques. Those models are based on semi-analytical kernels and numerical integration, so that realistic 3D and time transient configurations may be dealt with, and specific emphasis is made to optimise time computations, so that these models can be used for parametric studies in spite of potentially complex configurations. These simulation tools include beam propagation and defect scattering models, thus the whole inspection performances may be predicted for a wide range of applications (phased arrays, complex specimen geometry and/or materials, various flaws). This paper addresses some experimental validations of those models, in the frame of collaboration with the French Institute for Radiological Protection and Nuclear Safety (IRSN). Applications concerned include validation of inspection predictions over realistic configurations in terms of probes, specimens, and flaws, for which developments have been achieved to deal with complex shapes (planar flaw with a contour defined by CAD and multi-facetted flaws). This paper addresses some experiments carried out with mock-ups containing calibration reflectors (side drilled hole, flat bottomed holes) or artificial complex shaped defects, for which complex phenomenon may occur in the echo formation. Comparison with simulated results is presented and discussed in order to assess the validity range of the simulation models.

Introduction

Ultrasonic modeling tools have been developed and integrated in the CIVA software platform for NDE [1], dedicated to simulation and processing of various techniques (UT and ET, while RT modules integration is in progress). Those tools aim at providing fast and accurate predictions of inspection techniques for a wide range of configurations (in terms of probes, specimen, structures, flaws) in order to assess real industrial needs. Since the beginning of the CIVA software project in the early nineties, the simulation codes have been continuously extended to take account of increasing complex configurations so as to fulfill realistic inspection problems. The main strategy of modeling development is based on semi-analytical approaches to maintain reduced computation times while being able to get quantitative predictions for complex configurations. For ultrasonic inspections, the modeling codes allow to simulate the response of arbitrary flaws (various shapes : calibration reflectors or more complex shapes, arbitrarily located and oriented) inside components (of canonical or complex shape, CAD defined for instance, and materials : isotropic or anisotropic, homogeneous or heterogeneous), being inspected with arbitrary

probes (contact or immersion, pulse echo or dual RT, single crystal or phased array probes) which radiates Longitudinal and/or Transverse bulk waves, with or without mode conversions occurring at the specimen boundaries or after reflection on the flaw. Flaws responses are synthesized for 3D and transient configurations, and the simulated data may be displayed using the same format as the UT acquisition data files for comparison and/or inversion schemes.
The basic hypothesis and modeling approaches for beam propagation and flaw scattering are briefly presented in a short introduction, then some applications and experimental validations of those simulation tools achieved in the framework of collaborations with IRSN (Institute for Radiological Protection and Nuclear Safety) about realistic configurations are presented. These configurations include :

- Prediction of flaw and backwall orientation over the corner echo formation of backwall breaking flaws inspected with contact probes. It is well known that vertical flaws lying at the backwall of a specimen are detected using the classical corner echo arising after beam reflection over the flaw and the backwall. However, such an echo path is obviously affected by misorientations of the flaw or the backwall : as soon as the flaw is tilted (or if the backwall is not horizontal, for instance). A parametric study over the influence of flaw and backwall orientations has therefore been carried out to predict the amplitude losses of corner echo.
- Assessment of canonical and complex shaped flaws (planar flaws which contour is defined by CAD, and complex shape – for instance ramified flaws). This study shows the influence of complex phenomenon which may occur in terms of local interaction over the flaw.
- Prediction of backscattered noise (due to the structure of the material) for the inspection of a bimetallic dissimilar weld. The prediction of the backscattered noise allows to predict the signal-to-noise ratio for a given component inspected with a given probe : therefore one can conceive and optimise inspection techniques to ensure the detectability of reference flaws.

These applications show that the simulation tools allow to predict, and therefore to conceive and to optimise inspection techniques in realistic configurations.

1. CIVA tools dedicated to ultrasonic inspection

CIVA tools include beam propagation and flaw scattering codes which allow to predict inspection techniques. These tools are based onto semi-analytical approach (see §1.1) in order to optimise computation times, as most industrial studies require the modification of one or several parameters for techniques optimisation, flaw classification/identification, or, obviously, flaw diagnostic using inversion schemes. However, the codes also need to account for realistic configuration; therefore numerical integration is also made to deal with 3D and transient propagation and scattering. Finally, any semi-analytical approach is valid for its own validity range, so that validation of codes (and knowledge of intrinsic limitations) is a key factor of the confidence of the codes. In order to fulfil these requirements, experimental validations of the codes, as well as return of experience from CIVA users, have to be carried out.

1.1 Semi-Analytical Modeling approach

The ultrasonic inspection simulation requires the following steps :

- Simulation of the ultrasonic beam incident over the flaw : CIVA allows to compute bulk Longitudinal (L-) and Transverse (T-) beams radiated by arbitrary probes through arbitrary specimen (see §1.2 for available configurations). This beam is computed using the synthesis of impulse response achieved via a “pencil method” applied to elastodynamics [2-4]. The field is calculated using the summation of all contributions from source points distributed in the aperture of the probe: UT paths are calculated and summed, taking into account their different time of flights, amplitude spreading and attenuation.

- Simulation of flaw scattering : Once the beam is calculated, the response of the flaw is calculated using specific algorithms, depending on the type of the flaw and of the inspection technique, which is an efficient and rather classical way to proceed [5]. The Kirchhoff approximation stands for “void” flaws, as volumetric flaw (side drilled holes) or planar cracks, which assumes that the wave does not propagate into the defect [6]. For planar cracks, the edges diffraction are simulated thanks to GTD (Geometrical Theory of Diffraction), either in pulse echo or TOFDT inspection. A modified version of Born approximation [7] is used to deal with solid inclusions (volumic flaws made of solid material inside a host medium).
- Computation of the signal at reception: Once the incident beam and the flaw response have been computed, it is needed to predict the signal at reception. Within CIVA, this is achieved thanks to a reciprocity argument based on Auld’s theorem [8]. Assuming this reciprocity principle, one can directly calculate the forward/backward beams (which may be identical or distinct: for instance within a UT path related to a corner echo with mode conversion) as well as the flaw scattering response).

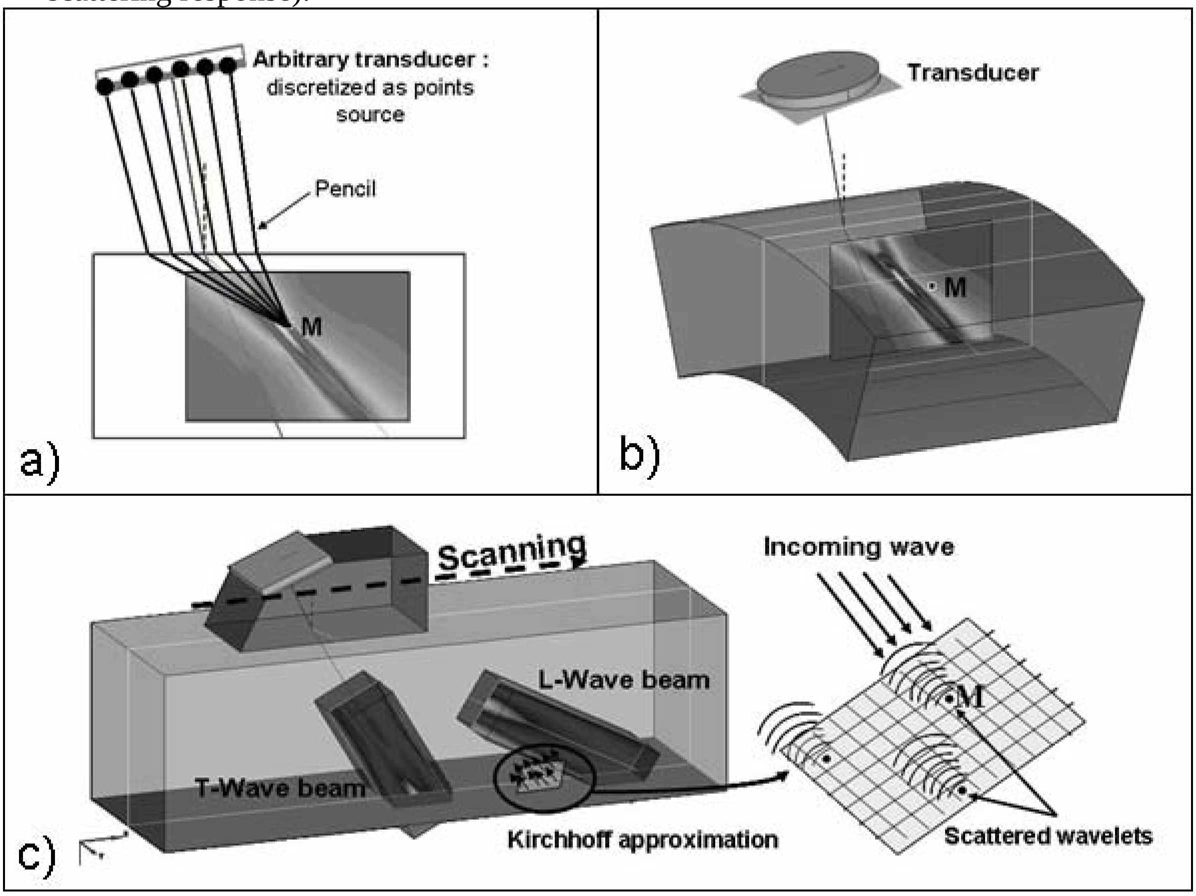

Figure 1. Schematic illustration of CIVA ultrasonic simulation tools : a) principle of beam synthesis, b) : example of computed beam, c) flaw scattering with Kirchhoff approximation

1.2 Available configurations

CIVA tools, as already pointed out, aim at predicting ultrasonic responses for a wide range of configurations. The current version of CIVA (CIVA8) allows to deal with :

- Arbitrary probes :
  - i. Contact, immersion, dual RT, flexible probes (direct contact)
  - ii. Single crystal or phased arrays (linear, annular, matrix or sectorial patterns)
  - iii. Planar or focused probes
- Arbitrary components :
  - i. Parametrical shapes (planar, cylindrical, elbows, nozzles)
  - ii. 2D or 3D CAD designed components
  - iii. Homogeneous/heterogeneous, each constitutive medium being isotropic or anisotropic
  - iv. Structural noise (see §2.3)
- Arbitrary flaws :
  - i. One or several flaws, arbitrarily located and oriented
  - ii. Calibration reflectors (side drilled holes, hemispherically or flat bottomed holes)
  - iii. Rectangular or 2D contoured planar cracks
  - iv. Multi-facetted flaws

For these various configurations, one calculates flaws responses to bulk longitudinal and/or transverse waves, including backwall and flaw reflection, with/without mode conversion.

2. Simulation application and experimental validation with IRSN

In the framework of collaboration with IRSN, a CIVA strategy of validation has been conducted. This strategy of validation has been carried out using a large data set of measurements (see Table 1) acquired on several mock-ups representative of the main In-Service inspection techniques. For each available configuration, simulation results obtained with CIVA have been compared to these experimental data.

	Simple vertical defect	Simple defect with Tilt/Skew angle	Complex defect
Thick parts (with cladding)	Completed: Immersion	Completed: Immersion	
Canonical specimen (planar)	Completed: Contact single element		In progress: Contact single element, Immersion
Canonical specimen (with tilted backwall)	Completed: Immersion, Contact single element, Contact dual element, Phased-Array		
Complex specimen	Completed: Contact single element, Contact dual element		
Complex materials (noise prediction)	In progress: Contact single element, Contact dual element		
Complex materials (Bi-metallic welds)	Completed: Phased-Array	Completed: Phased-Array	

Completed
In progress

Immersion
Contact single element
Contact dual element
Phased-Array

Table 1. Description of the complete data set for Civa validation strategy

The complete data set offers a large variability of the encountered situations in terms of specimen geometry (thickness, shape…), material (ferritic, cladding, stainless steel…), defects (shape, orientation, location to the surface…) and transducer (immersion, contact, phased-array, TOFD…). In the following, some configurations among these data are presented in order to illustrate CIVA performances.

2.1 Influence of flaw and backwall orientation over corner echo detection for a surface breaking notch

This study aims at predicting inspection performance losses for backwall breaking planar flaws, with respect to the orientation of the flaw and the backwall. Experiments were carried out in immersion mode with focused probes radiating 45° T-waves over a thick planar component of ferritic steel (representative of a vessel wall), including a set of electro-eroded notches of respective heights 6, 12 and 25 mm. Figure 2 below show two couples of simulated and experimental results, displayed as rectified Bscan images : the first configuration is related to vertical flaws, for which the corner echo assessment is optimal due to the geometrical path, whereas the second one leads to degraded performances because of a 10° tilt over the flaws.

For both simulation and experiment, the amplitude of the corner echo of each flaw is reported in dB range, the reference echo used for normalization being related to the specular reflection over a side drilled hole (close to the backwall). It can be pointed out that for both configurations a good agreement is observed between simulated and experimental results.

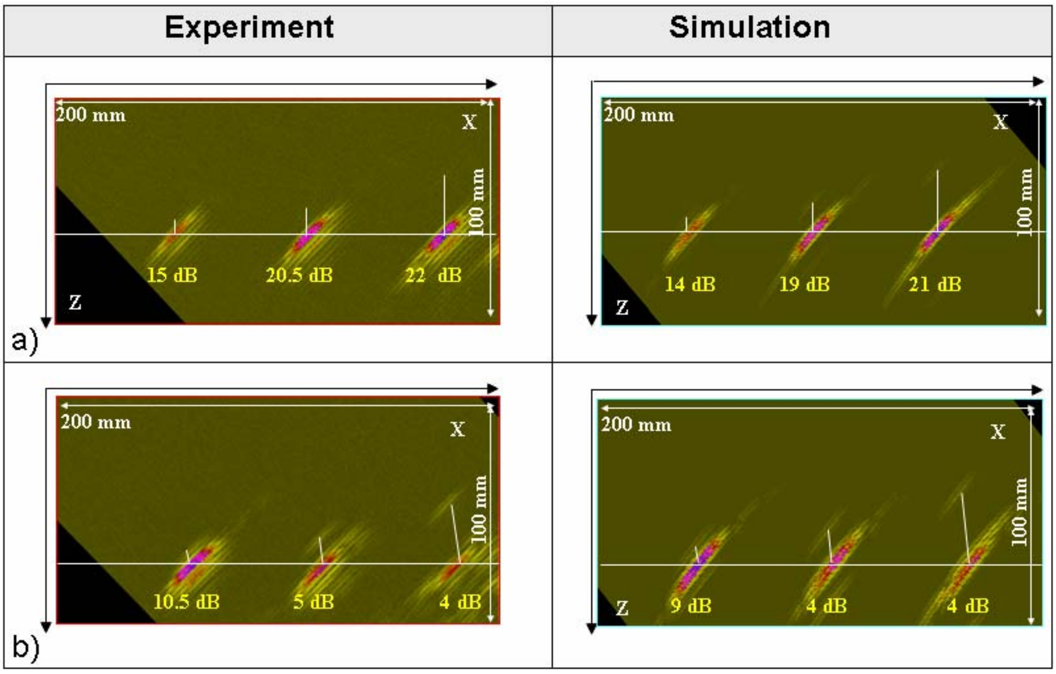

Figure 2. Simulated and Experimental results for corner echo inspection of backwall breaking flaws inspected using 45° T-waves : a) vertical flaws, b) 10° tilted flaws.

A second set of experiments has been reported on Figure 3, which represents a 45°T-waves inspection using a standard contact probe (Krautkramer WB45 probe) of a mock-up containing one backwall vertical flaw and different backwall slopes orientation (from 0° to 20°). Simulation and experiments have been carried out using this probe, with an inspection carried out towards the “negative” slope of the backwall. A good agreement is observed between experimental and simulated results for the behaviour of corner echo variations as a function of the slope (see Figure 3).

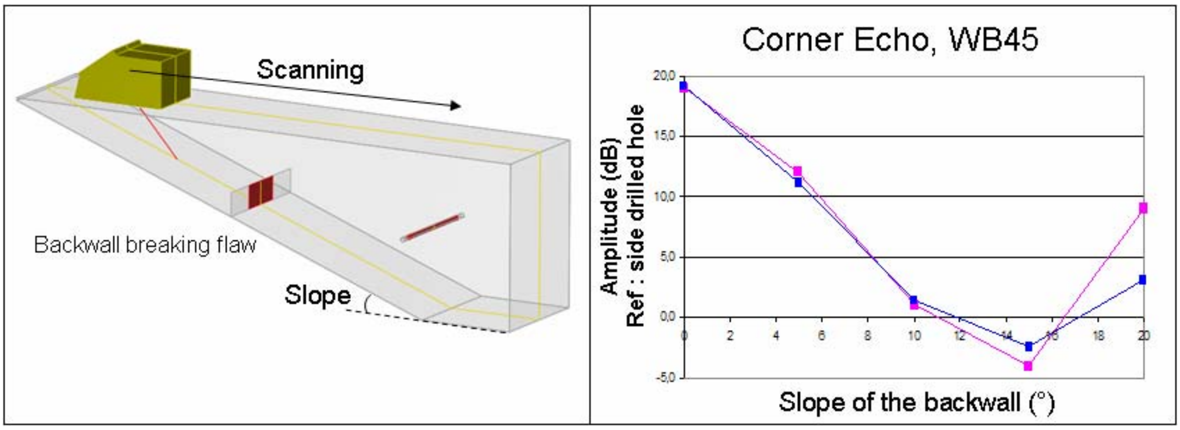

Figure 3. Simulated and Experimental results for corner echo inspection of variable slopes backwall breaking flaws inspected using 45° T-waves : a) configurations, b) report of simulated and experimental corner echo amplitude (vs side drilled hole) as function of the slope of the backwall

2.2 Comparison of canonical planar flaws and more complex shapes

Studies have also been carried out in the framework of CEA and IRSN collaboration, to deal with more complex shaped flaws, as it is readily known that natural flaws are not perfectly planar neither smooth (in terms of sharp, regular edges, non branched, non ramified types). In order to predict the response for irregular cracks, developments made (and integrated in the CIVA8 version) allow to deal with multi-facetted flaws, made of several segments linked to form one homogeneous flaw. As illustrated on Figure 4 below, a multi-facetted flaws is made of several parts (segments) which can be extruded in the perpendicular direction to form a “2.5D” CAD flaw, or extruded with a more complex polyline to from a 3D multi-facetted flaws.

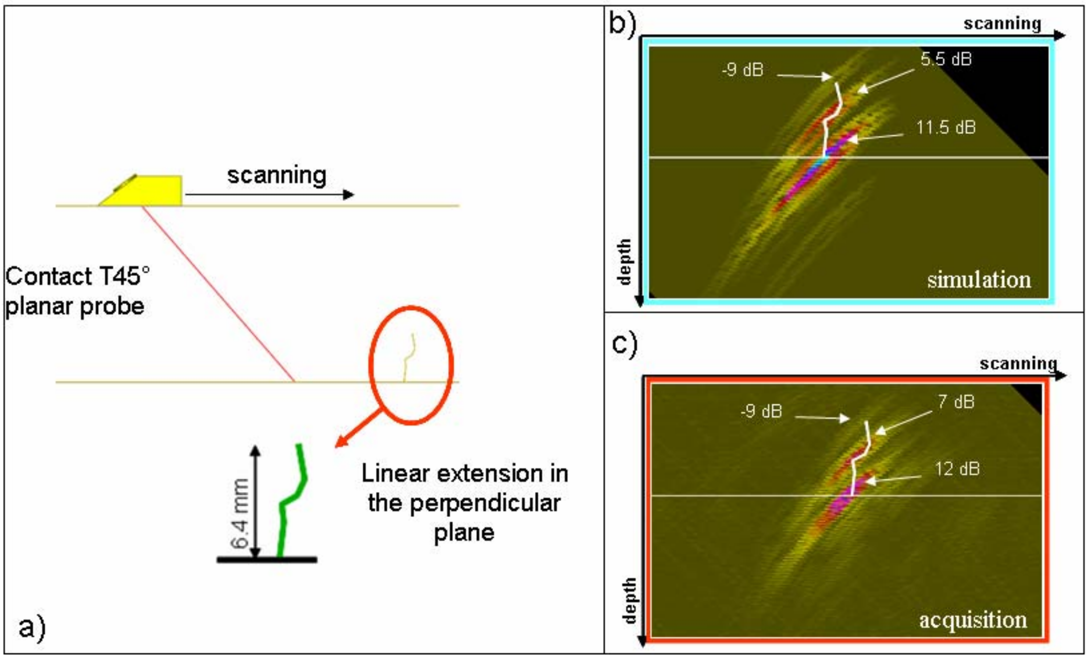

Figure 4. Simulated and Experimental result for a CAD multi-facetted flaw inspected using a 45° T-waves probe : a) configuration, b) simulated result, c) experimental result

Figure 4 shows the comparison between simulation and experiment for such a flaw, inspected with a 45° T-waves probe. One can observe the corner echo, diffraction echo, as well as a “local” specular echo resulting from the complex shape of the flaws, both for experimental and simulated image. The amplitude of these echoes are reported, with respect to a side drilled hole used as a reference, which exhibits a good agreement between simulation and experiments, in terms of flaw response and overall amplitudes.

2.3 Backscattered noise simulation to assess defect detectability in a dissimilar bimetallic weld

Developments have been carried out in previous years to deal with structural noise radiated by coarse grained structures [9]. The main purpose of this tool is to predict a realistic signal-to-noise ratio that can be used to conceive/optimise inspection techniques to ensure the detectability of potential flaws for a given material. As soon as one can predict a realistic level of noise for a given structure inspected with a given probe, one can optimise probes and/or inspection techniques (in terms of waves polarity, frequency, incidence angle, focusing pattern and probe aperture) in order to get an optimised signal-to-noise ratio for the desired defect assessment. The structural noise model used is based on a random distribution of point-like scatterers inside the material, of arbitrary density and reflectivity. Multiple diffraction effects are neglected, considering there's no interference between contributions of individual scatterers. The density and reflectivity parameters, for one given material, need to be adjusted via a calibration procedure. Once this calibration step has been fulfilled, those parameters (density and reflectivity of scatterers) can be maintained and different inspection procedures (other probes, apertures…) may be simulated to predict the signal-to-noise ratio for those various probes using the same flaw and same material structural noise properties. Recent developments in CIVA8 now allow such features with arbitrary noise parameters for each constitutive medium of an heterogeneous structure. Thus this tool can be used for complex structures as welds for instance, as illustrated below for a dissimilar bimetallic weld inspected with two different probes (not detailed here). For both probes, simulated and experimental images displayed as rectified Bscan images, with superposition of the CAD description of the mock-up, show that one can correctly predict the structural noise for both configurations (using the first configuration as the reference one, the performances improvement observed for the second configuration in the experiment is also addressed on the corresponding simulation result).

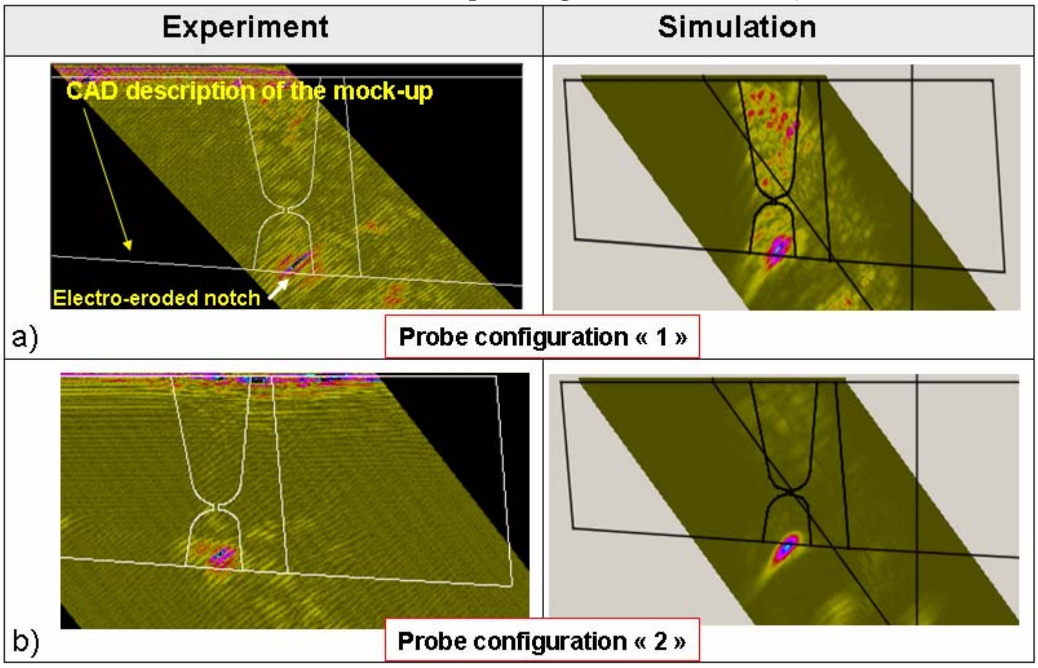

Figure 5. Experimental and simulated result for a dissimilar bimetallic weld inspected with two different probes : rectified Bscan images on configuration 1 a) and 2 b).

3. Conclusion

Ultrasonic simulation tools gathered in the Civa software have been briefly presented. Those models, based on semi-analytical formulations kernels and numerical integration to deal with generic applications, include beam modeling and field-to-flaw interactions. A whole inspection (prediction of scattered echoes received by the probe, for each scanning position) can therefore be simulated using the incident field and the defect scattered echoes, using an argument based on the Auld's reciprocity theorem. Three different applications have been presented, the first one concerning corner echo detection for vertical or tilted notches at backwall (with variable slopes). The second one concerns an ultrasonic inspection over a planar specimen containing a complex shaped defect with a contact non-focused probe. The last configuration deals with the prediction of a dissimilar weld inspection containing a notch, taking account of the structural noise. For all cases, a fair agreement is observed between simulations and experiments, especially in terms of amplitude echoes level with comparison to the reference calibration reflector. These simulation tools therefore demonstrate their ability for quantitative prediction of inspection performances.

References

[1] More information about CIVA may be found at http://www-civa.cea.fr

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