SIMULATION OF COMPLEX ULTRASONIC NDT CASES USING COUPLED ANALYTICAL-NUMERICAL METHOD: THE MOHYCAN PROJECT

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ABSTRACT

The simulation of Non Destructive Testing (NDT) plays an increasing role as it provides, for instance, an efficient way to conceive and to optimize NDT methods or probes, helps for data interpretation, supports inspection qualifications. In order to assess such ambitious objectives, different modeling strategies may be involved: analytical, semi-analytical (namely, integral techniques), numerical techniques (finite elements, finite differences…). Although semi-analytical techniques lead to accurate results within reduced computation times and memory burden, their application is somewhat restricted within their range of validity. Usually, semi-analytical techniques aim at predicting specific phenomena involved in the NDT response, which both allows to get accurate and fast results. Pure numerical techniques offer a wider range of applications, as they solve the exact wave propagation equations within the whole space of the NDT configuration. But those techniques exhibit more important computation times and memory load, which may be a limitation, especially for 3D applications.

In order to get advantage of both approaches (computation efficiency of semi-analytical techniques and genericity of numerical techniques), the MOHYCAN project (Hybrid MOdeling and Coupling Analytical/Numerical method for ultrasonic NDT simulation), supported by the ANR (National Research Agency in France) aims at extending the features of ultrasonic NDT simulation tools to deal with 3D industrial, potentially complex configurations.

In order to assess such configurations, the MOHYCAN project is based on a coupling method between a semi-analytical code (developed at CEA LIST) to predict the radiated field, and a numerical method (Finite Element: ATHENA Code, developed at EDF) performed in a restricted area around the flaw. This hybrid method is based on coupling conditions boundaries modified with respects to prior studies. The modification of the coupling conditions, as proposed by POEMS, allow to greatly reduce the size of the FEM box, which may be as close as possible to the flaw, which was not possible with previous coupling conditions.

In the second part of the paper, several examples of application of the simulation tools described in the first part will be given for illustrating their capabilities. Simulation results shown will address both standard and more complex cases, as well as experimental validations upon 2D representative industrial configuration cases.

INTRODUCTION

Simulation plays an increasing role in NDT, as a tool for probe or methods designing, performance demonstration and qualification of techniques, as well as diagnostic help. In order to fulfill those objectives, simulation must deal with realistic industrial configurations, in terms of structures, flaws, probes, techniques… More particularly, simulation codes needs to take account of the flaws characteristics:

- Geometry of the flaw : ramified flaw, irregular (rough) profile …
- Arbitrary positions and orientations inside the component, close to specimen boundaries or embedded …
- Arbitrary number of flaws: arrays of flaws, combined flaws…

Complex interaction phenomenon between the ultrasonic wave and the flaw and/or the inspected part lead to a complex acoustic signature (reflection, conversion modes, scattering in bulk or surface waves…) have to be simulated in order to get an accurate response of the actual signal received by the probe. This response has to be quantitatively predicted with respect to industrial calibration and sizing reference procedures, so that the user may determine the actual size of the flaw.

Such a need drives the MOHYCAN project, which aims at developing an efficient tool, accessible for NDT end-users, to handle complex cases by using all the CIVA capabilities concerning specimen or probe parameterizations. This tool is based on a hybrid method, coupling semi-analytical codes (SA) and Finite Element (FE) codes in order to combine the advantages of both methods, thus providing fast and accurate simulation results.

DESCRIPTION OF THE COUPLING METHOD

The MOHYCAN project lies on the coupling between semi-analytical and numerical techniques, main techniques used in simulation. Semi-analytical techniques, as integrated in the CIVA software platform [1], allow to predict beam propagation and flaw scattering for various configurations within reduced computation times, within the range of validity of the semi-analytical modes (mostly, integral techniques). Alternatively, numerical techniques (finite differences, finite elements), like ATHENA code, fully solve the propagation equations inside a meshed configuration, without approximations related to the nature of waves or scattering process involved in the echo formation. But such techniques may lead to large numerical schemes (high computation times and memory burden), especially for 3D cases.

The idea of the MOHYCAN project, supported by the French research agency (ANR), thus, is to provide an efficient tool to combine the advantage of both semi-analytical and numerical techniques, using a coupling method with a FE box limited to the area for which complex interactions occur, i.e. very close to the flaw, whereas the propagation (forward and backward) is dealt with semi-analytical computation (very efficient to handle large propagation paths, typically tens or hundreds of wavelengths).

Semi-analytical computation of beam propagation

As mentioned in the previous paragraph, the beam propagation is computed using a semi-analytical code in CIVA. This simulation is based on an integral technique (integration of contributions arising from point sources distributed over the surface of the probe), which allows to synthesize the impulse response of the probe. The contribution of each point source to the computation point (in terms of amplitude, time of flight, polarization) is evaluated thanks to the "pencil method", which is an extension of ray approximation techniques [2].

This code allows to predict bulk waves (Longitudinal or Transverse) in homogeneous/heterogeneous, isotropic/anisotropic components.

Finite Element computation of flaw scattering

The ATHENA code, developed by EDF/R&D, allows to simulate propagation of elastic waves in arbitrary heterogeneous and anisotropic components, radiated by contact or immersion probes, as well as its scattering by arbitrary flaws, using a FE method [3].This code, initially developed by EDF in collaboration with INRIA [4], uses a regular mesh for propagation, whereas flaw scattering is performed using the fictitious domains technique, which allows to separate both meshes and adapt the mesh dedicated to the flaw to any arbitrary defect shape. Other developments include attenuation by grain scattering [5], and ramified and multi-facetted defects [6].

Coupling method between CIVA and ATHENA

The coupling method between the beam computation (SA) and flaw scattering (FE) is based on Auld's reciprocity principle [7]. This principle considers two "states" (with and without a flaw lying inside a closed volume), for which one needs to calculate the elastic fields at the frontier, computed by the SA code (without flaw), and computed by the FE code (with the flaw) in stress and velocity component. This coupling method was carried out within previous works by CEA and EDF [8], the coupling being limited to one frontier of a parallelepiped box surrounding a flaw. During the MOHYCAN project, the coupling method has been modified (in terms of boundary conditions), using the same reciprocity principle, so that one may now use smaller FE box in order to speed up computation times.

To study realistic 3D cases with a large number of unknowns and a high memory burden, the parallelization of the FE ATHENA code had to been carried out. The FEM volume is decomposed into distinct domains equal to a fixed number of processors, one processor being dedicated to the flaw mesh. This decomposition is straightforward on the regular structured mesh grids. Due to the good scalability of this parallelization process, numerical (computation and memory load) performances are largely increased with respect to single processor computation. In order to perform FE parallel calculations on multicore clusters from a personal computer with the coupling method, developments have been carried out to allow remote FE computations and data exchange between the local computer (running CIVA, beam computation and synthesis of the response) and the remote machine (running 3D FEM).

EXAMPLES OF COMPLEX FLAWS SIMULATIONS

Array of cracks (Thermal fatigue case)

The application described hereafter deals with thermal fatigue cracking, which may lead to an array of small cracks lying at the bottom of the component. The influence of a network of secondary cracks on the detection of a propagated crack has been experimentally studied in previous works [9]. Thus, an array of small cracks (typically lower than 2 mm height), it may drastically prevents a corner effect echo of a larger crack located inside the array. Simulation should therefore be useful to perform any parametric study with a view to evaluate the influence of the array of cracks on the detection of the large crack.

Figure 1 below shows three simulations carried out using the coupling method. A vertical notch of 4 mm height is located at the inner surface of a planar steel component, inspected using a 4 MHz focused probe radiating 45 transverse waves, scanned along the axis of the planar block (as illustrated on the figure). The rectified scan image (cross-section image displayed in the specimen coordinates), displayed on top of the figure is related to the response of the notch without any crack, which can be used as the reference. One can clearly see the corner echo response, superposed along the backwall of the component, as well as a weak diffraction echo due to the upper flaw tip scattering, aligned with the corner echo (in abscissae coordinates). The second image (middle of the figure) corresponds to the simulation of the notch with two small cracks (2 mm height, 4 mm spaced along the backwall) located in front of the larger crack. One may see that the response of such an arrangement is just the summation of individual responses (one may see the corner echoes and tip diffraction echoes for each crack).

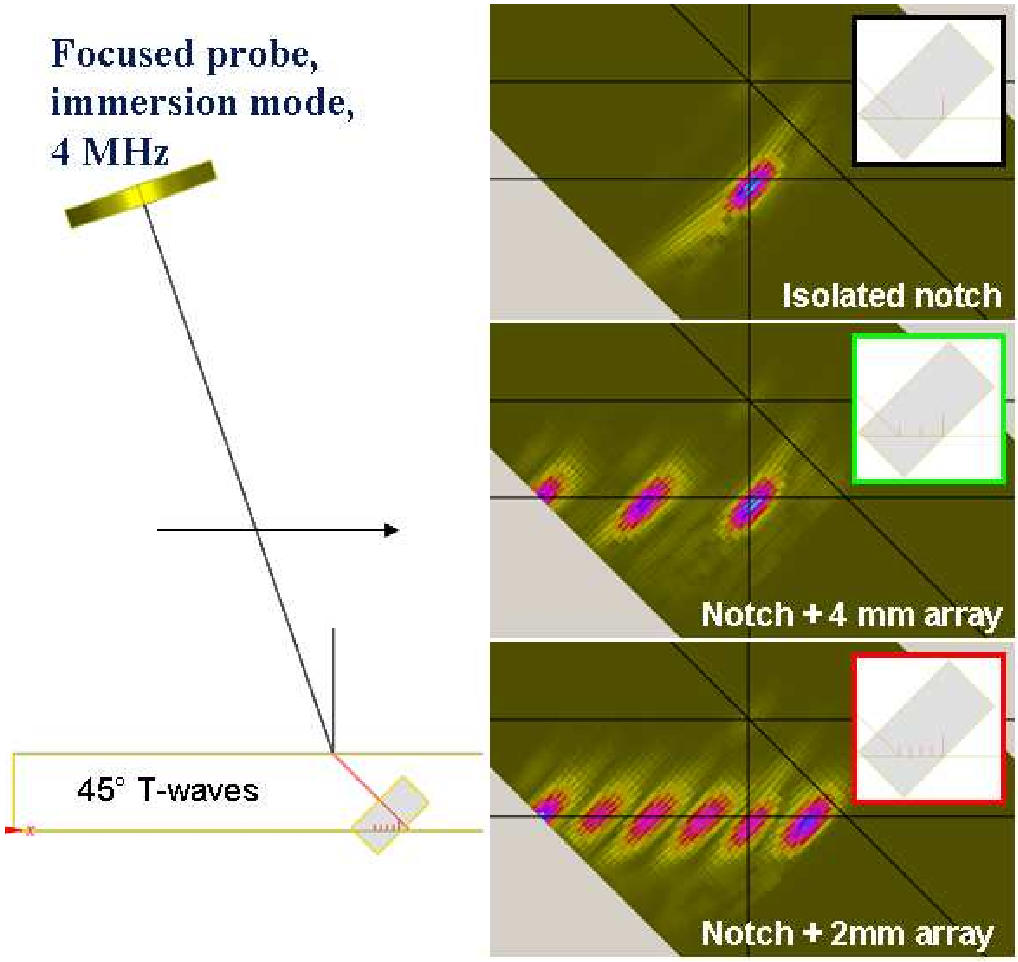

Figure 1: Simulation of a 45° T inspection in pulse echo mode for detection of a vertical notch surrounded by an array of small cracks.

The third simulated image (bottom of the figure) is related to a denser array, with 4 small cracks (2 mm height, 2 mm spaced) in front of the notch. For such a configuration, more complex interactions occur, as one may observe that the tip diffraction echo of the larger crack is not aligned anymore with a classical corner echo. The last echo observed on the right side of the scan view corresponds to a multiple corner echo "trapped" between the large notch and the neighbouring crack: this echo is obtained by successive reflection of the wave toward the large crack, the backwall, and the side of the small crack, as detailed in Figure 2. On this figure, the snapshots of the elastic fields propagated at different transient times inside the FE box are displayed (from 1 to 8), which show the multiple reflections. These images were obtained for one scanning position of the probe, as reported on the figure.

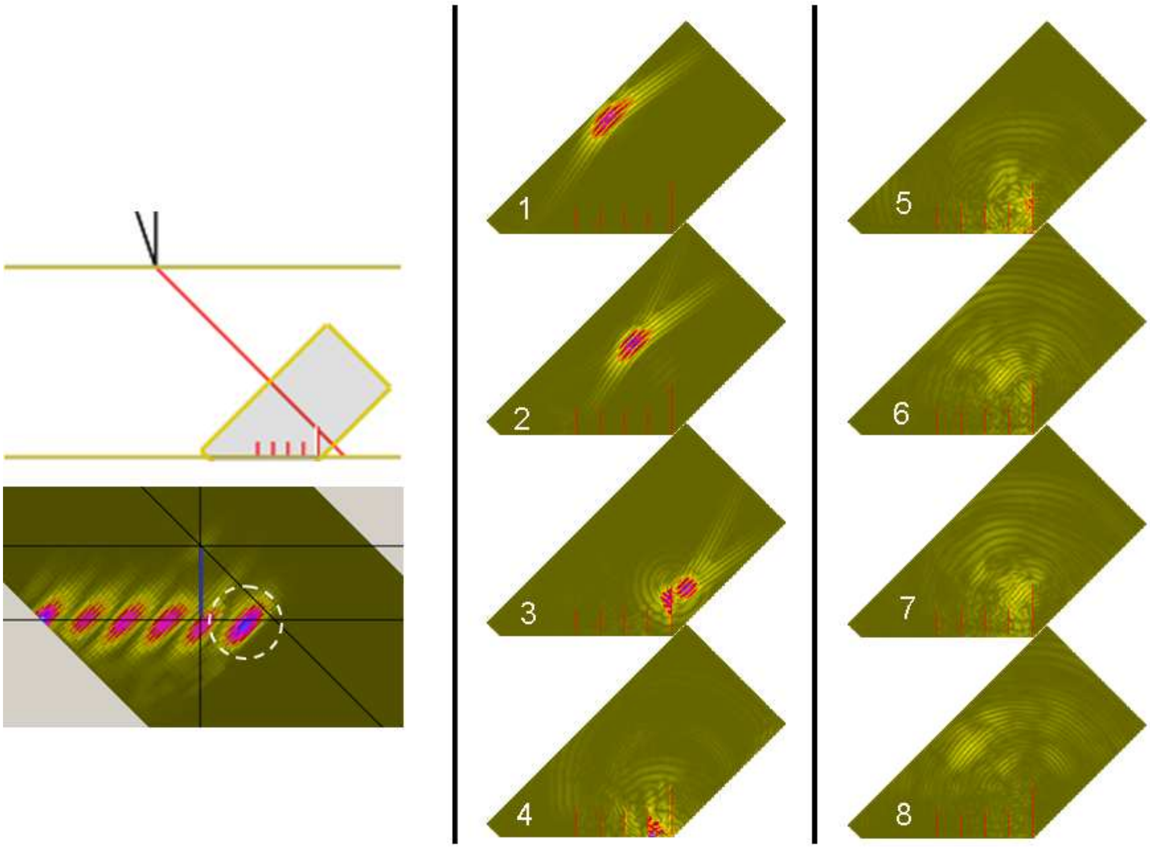

Figure 2: Detailed view of the simulation with the 2 mm spaced array configuration, with snapshots (numbered 1 to 8) displaying the propagation and scattering inside the FE box.

Ramified and rough cracks (stress corrosion cracking case)

Stress corrosion cracking is a potential risk for different components of Pressure Water Reactors. The inspection of such flaws is therefore a main safety issue. Unlike other fatigue cracks, stress corrosion cracks usually exhibit complex morphologies (roughness, branching). In order to evaluate the influence of such morphologies over the inspections, studies have been carried out, both experimentally over mock-ups with 2D electro-eroded notches of complex shapes (multi-facetted flaws mimicking the roughness of cracks, and ramified cracks), and with simulation tests [6].
The influence of roughness is illustrated on Figure 3. Cross-section views are reported for four different cracks (all cracks are 10 mm height, defect « A » is the reference vertical flaw, whereas defect « B », « C », and « D » are made of, respectively, 5, 10 and 20 facets) inspected with 45 L-waves beam with a 2.25 MHz contact probe. One may observe tip diffraction echoes as well as the corner effect echo. Moreover, one may point out the influence of the number of facets towards the amplitude of corner echoes, as well as « intermediate » diffraction echoes between the corner echo and the tip diffraction echo. Those echoes appear for the defect made of 5 facets, become important for the 10 facets defect, while the 20 facets defect gets a response very similar to the reference.

Simulations related to those different flaws were carried out with the hybrid coupling code. Figure 4 displays the comparison for the 5 and 20 facets defects, which shows that simulation accurately predicts the influence of the roughness of such flaws.

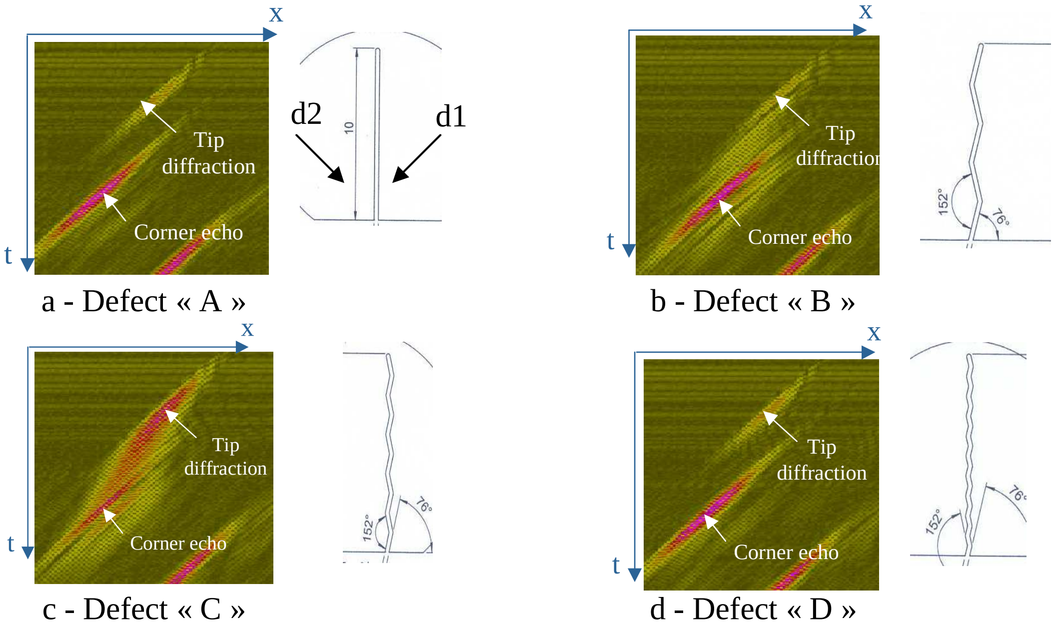

Figure 3: Experimental cross-section views of 4 defects made of different facets inspected using 45° longitudinal waves [6].

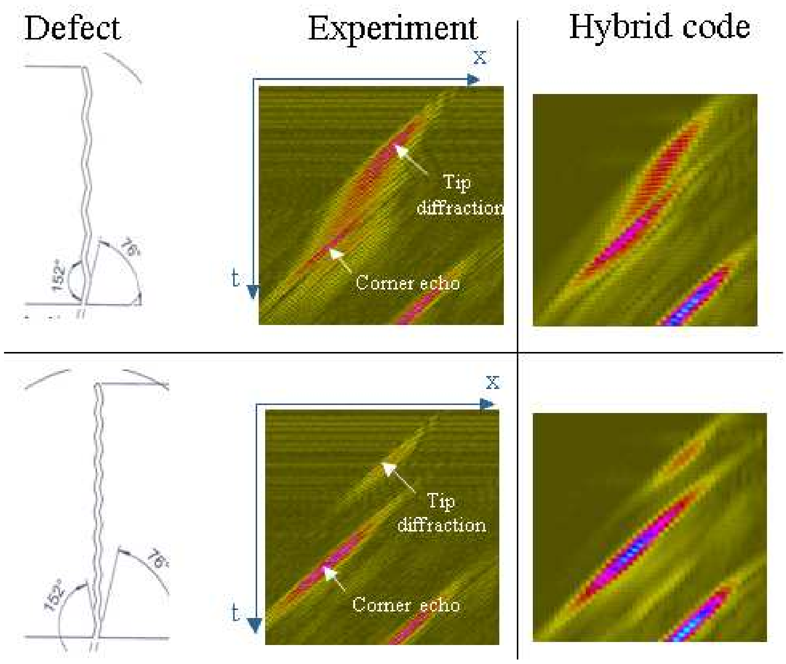

Figure 4: Experimental and simulated cross-section views of the 5 and 20 facets flaws.

The last example concern flaws with ramifications ("Y" shape flaws), as illustrated on Figure 5. The interaction of oblique waves over such flaws may lead to additional echoes arising between the branches of the flaws, thus complicating the interpretation of the inspection results. In addition to diffraction echoes (potentially each branch of the ramified cracks may give rise to diffraction echoes) and corner echoes, corner effect can be generated between branches (this is the case for the third –bottom – defect displayed in Figure 5), and indirect echoes (reflection on the backwall before to specularly interact with the branch, the backward path being identical to the forward path). Here again, comparison between experimental and simulated results show that the simulation accurately predicts complex interaction phenomenon. This result confirms that the coupling approach doesn't introduce any error compare with results obtained with the ATHENA 2D code [6], all the beam propagation being also performed by FEM model

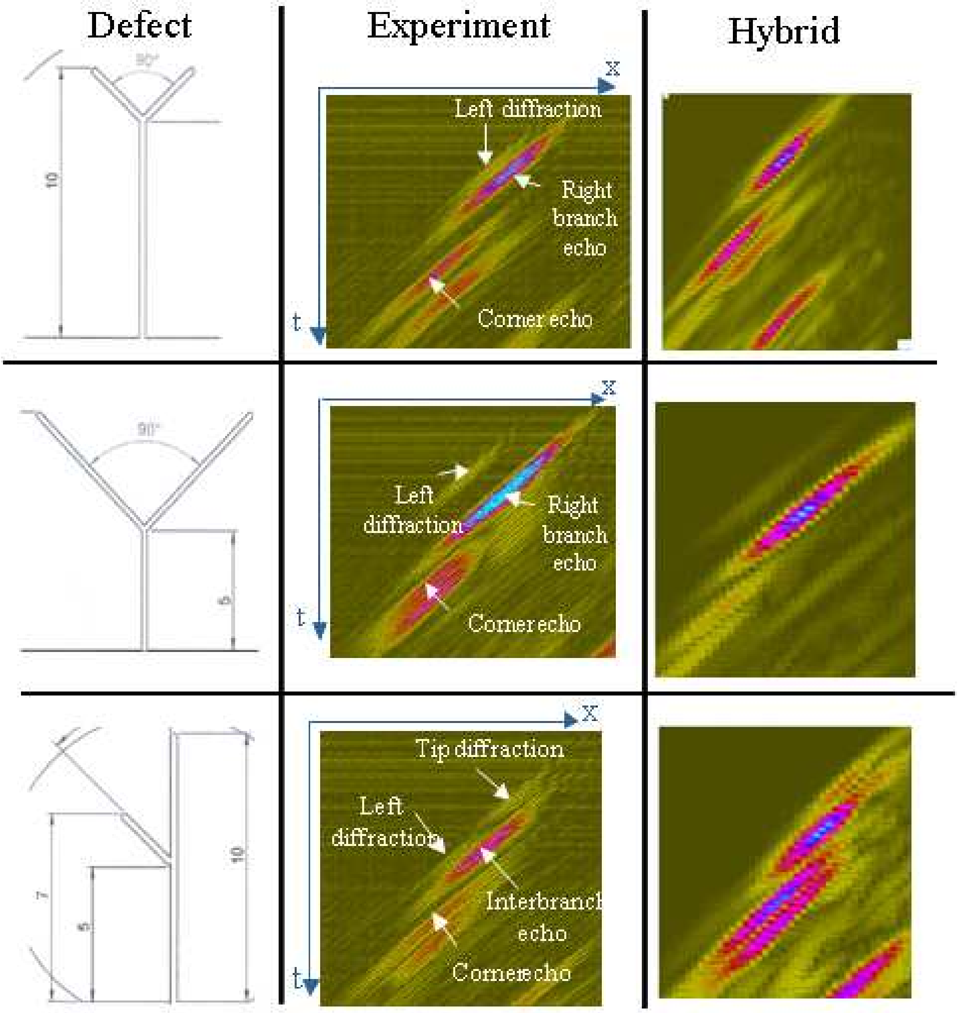

Figure 5: Experimental [6] and simulated cross-section views of the 5 and 20 facets flaws

CONCLUSION

The MOHYCAN project aims to improve an original approach coupling the finite element code ATHENA and the semi-analytical model used in CIVA to predict the radiated US-field. This hybrid approach tends to combine the advantages of both semi-analytical and numerical methods computing most of the propagation with a ray-based method while wave/defect interaction is computed with FEM in a restricted area around the defect. A first major improvement concerns the modification of the coupling conditions allowing to reduce the size of the FE box to the flaw dimension itself. The reduced size of the mesh leads to decrease not only the memory but also the iteration number used for wave/defect interaction.
In order to handle 3D configurations, developments have been carried out to build a parallel code allowing running the FEM calculations over different hardware configurations (standard PC or clusters) in order to take advantage of their resources. In the second part of this paper, several examples of application of the 2D simulation tool have been presented, mostly dealing

with complex flaw shapes (array of defects, irregular – rough – defects, branched defects), which illustrate complex interactions arising for such configurations. Experimental validations were also carried out for those cases.
Complex 3D configuration cases shall soon be carried out with the coupling method and compared to experimental data, which will fully demonstrate the ability of the coupling method to solve realistic 3D industrial problems.

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