RECENT DEVELOPMENTS IN NDT SIMULATION

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Abstract

Since the beginning of the nineties, the CEA (the French Atomic Energy Commisssion), has been being developing ultrasonic modeling tools dedicated to NDT simulation and, over the years, integrated in the CIVA software platform. The models allow to compute ultrasonic beams generated by transducers in the inspected components, to conceive phased arrays transducers and to predict echoes arising from defects and boundaries. In the aim of fulfilling requirements of an intensive use, a twofold strategy has been put forward: i) the choice of semi-analytical approximated methods, and ii) the development of models integrated into modules usable by operators who are not simulation specialists. Over the years this approach is enriched by adaptations and improvements of the existing models or by new models, in order to extend the field of applicability of the simulation. In this communication, after having briefly described the main features of *CIVA* modeling approach we present several recent developments and examples of applications.

Introduction

Simulation plays an increasing role in the field of NDT and over the years its applications and objectives have become increasingly diverse. The first objective has been to improve the understanding of phenomena and to provide tools helping for analysis and interpretation of inspection results (see for example [1]). This objective is obviously still relevant, especially with the development of inversion algorithms allowing automatic diagnosis which are now possible with the progress of computation capabilities and numerical performances of the models [2], but, since several years simulation tools have also been used in very different purposes. Thus, a very important application of simulations, especially in the context of nuclear industry, is performance demonstrations and qualifications of methods. Simulations are then applied in order to evaluate the capabilities of a given method and to identify its limitations [3,4]. Another important application of simulation is the design and optimizations of inspections methods. It is particularly true for phased-arrays methods. In that case, the simulation tools can provide efficient delays laws to be applied to the array, even in complex configurations (see for example [5,6]). At last, simulation allows "virtual testing", which can be applied to take into account the controllability of components at the early stages of their conception. It appears nowadays, as an important challenge, especially in the aeronautic industry [6].

To fulfill the requirements related to these diverse applications, CEA launched in the early 90's the development of a NDT expertise software platform named CIVA [7]. The idea was to gather within the same software, imaging, processing and simulation tools in order to be able to directly and easily compare experimental and computed data. The project have gained in importance over the years. *CIVA* now includes CAD connexion allowing to perform simulation on CAD designed components and is not limited to ultrasonic testing since Eddy current models are already integrated in *CIVA* while Xray models integration are in progress. Moreover *CIVA* is become an integration platform allowing the integration of models and processing tools developed by various university laboratories.

UT simulation in *CIVA*

Semi-analytical and numerical approaches

In CEA the choice has been made for developing simulation codes based on semi-analytical methods involving physical approximations which have to be judiciously selected according to the application being considered. Indeed in NDT applications, propagation distances of ultrasounds are very large compared to wavelength, making numerical resolution of the wave-propagation equation on the basis of a spatial meshing of the volume involved very costly. The semi-analytical approach currently represents a solution optimizing at the same time needs of quantitative reliability, requirements for ease of interpretation of the results, versatility of simulated situations and numerical performance. While advances in computing have resulted in a huge, sustained growth in the computational power of microcomputers and work stations, the use of codes is itself changing concurrently and is becoming increasingly intensive in the context of multi-parameter simulation campaigns. This is the case, for instance, of demonstration of performance or in the context of inversion strategies.

Semi-analytical and fully numerical approaches are complementary. Firstly, the latter can be used to evaluate the validity of the approximations used in the former [8]. Also, in some complex situations, the semi-analytical methods cannot be applied and fully numerical methods are required. In some cases, hybrid models taking advantage simultaneously of both semi-analytical and numerical approaches can represent a solution. In the aim of predicting the response of complex defects such an hybrid model is being developed in the *CIVA* plat-form [9]. We present below this application.

Software integration

Different modules have been implemented in *CIVA*. These modules have different tasks: computation of the field transmitted in the component by a given transducer, prediction of echoes arising from defects, computation of delay laws for phased arrays applications, evaluation of coverage rates and so on. These modules share the same graphic user's interface system, and an important effort have been done on the development of user's friendly GUI's allowing an UT operator non familiar with numerical modeling to use the software.

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 [10]. Since several years *CIVA* has been connected to a CAD library. This connection makes possible ultrasonic simulations on non canonical geometries : Elbows, nozzles, 2D or 3D CAD file in a standard format (STEP, IGES).

The models: Radiation and propagation

A detailed description of the model used in *CIVA* to model radiation and propagation of ultrasounds can be found in this volume [11]. The model is based on the integral Rayleigh integral formulation of the radiated wave. The transducer is therefore considered as a distribution of particle velocity source over the emitting surface. The transmitted field results from the summation of the contributions of all these sources, each of them being computed by applying the so called pencil method. This method consists in describing the evolution of a pencil of rays emitted by the source and centered on the geometrical path. To deal with refraction or reflection, the pencil method applies the geometrical elastic approximation which is nothing but an asymptotic solution of the exact solution around the path of stationary phase. The pencil method allows to deal with anisotropic and heterogeneous materials, by considering the evolution of a pencil through homogeneous areas and refractions on interfaces planar or non planar. This model implemented in CIVA allows to deal with a wide range of transducers: wedge coupled or immersed, focused or not, standard or phased array.

The models: Formation of echoes

We now briefly describe the models used in *CIVA* to predict the echoes structure received by the probe. More detailed descriptions can be found elsewhere (see for example [12]). At one given probe position, the signals arising from a defect (or a boundary) may result from different ultrasonic paths leading for example to corner echoes, tip diffraction echoes, etc… The starting point of the model is to consider that the echo-structure is the sum of the contributions corresponding to these different paths, each of these contributions being computed independently. The prediction of the contribution of one path 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 (defects or boundaries) within this area ,and finally iii) the propagation to the receiver and reception.

The point i) has been discussed above. The computed incident field on the scatterer can be directly used as an input of the interaction model. However, depending on the situation different levels of approximations can be added to the description of this field, the most usual being to neglect the variations of the waveform itself in the beam. This approximation is usually quite sufficient to obtain accurate results and is numerically more efficient.

To deal with the point ii) the model applies the different classical approximations. 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. In order to predict the response of solid inclusions, a slightly modified form of the low-frequency Born approximation has been proposed and implemented [13].

Finally, the signal received by the probe (point iii) is obtained by applying a reciprocity relationship between transmission and reception and by summing the contributions of the different possible ultrasonic paths. The different ultrasonic paths linking the transmitter the defect and the receiver are taken into account so that mechanisms like corner effect, mode conversions or tip diffractions are well predicted.

Recent developments and application

Performance demonstration

We present here a first application of simulation achieved in the context of performance demonstration. The purpose here is the qualification of a UT method for the inspection of the upper shell of the steam generator of French PWR. The study [4] has been performed in collaboration with Electricité de France. The configuration is schematized on Figure 1. The component is inspected with a T45° wedge coupled transducer and the defects to be detected are breaking cracks. In parallel of a set of experiments which permitted to validate the simulation results, the simulation has been applied in order to evaluate the influence of different parameters on the detection capability of the method. Amongst these parameters, let us consider the size, the tilt and skew angle of the

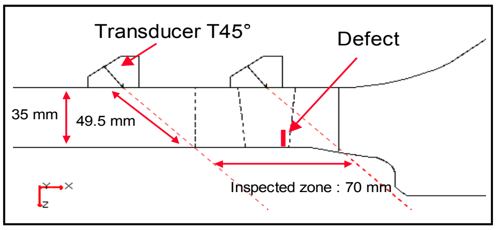

Figure 1: Demonstration performance of the inspection of the upper shell of steam generator of PWR. Zoom on the inspected area

defect. The tilt and skew angles define the orientation of the defect respectively in the plane of incidence and in the plane perpendicular to the plane of incidence. As illustrated on Figure 2, the conclusion is that the effect of the tilt orientation is small on the amplitude of the echo whereas the amplitude drastically decreases with even small skew angle. Moreover, the simulation has shown that the method is able to detect defect smaller than one millimetre and that no amplitude variations is observed for defects larger than 6mm.

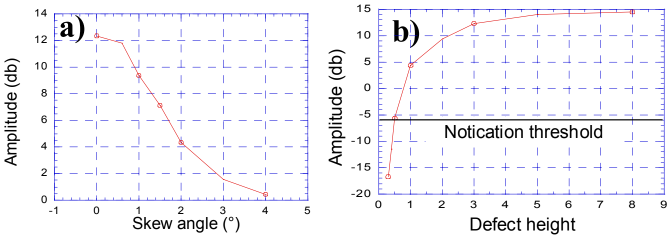

Figure 2: Demonstration performance of the inspection of the upper shell of steam generator of PWR. Influence of a) the skew angle, and b) the defect size.

Simulation on multi-layered composites

As mentioned above, over the years the modeling approach in *CIVA* has been being enriched with new development in order to deal with new applications. The second example shown here concerns the inspection of carbon-epoxy multi-layer structures. This work has been done in collaboration with EADS and partially in the framework of a BRITE project [14]. The aim is to predict the controllability of thick carbon-epoxy components whose geometry is not planar and which contain non parallel plies (see Figure 3). The approach we adopted has been to apply an homogeneization method leading to replace a succession of parallel layers by one homogeneous and anisotropic medium. The computation of the field transmitted by such a structure can therefore be achieved by using the model described above. The non planar geometry of the component can be taken into account and non parallel plies within the component are described by introducing a few number of homogeneous areas.

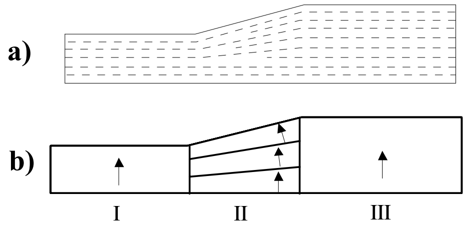

Figure 3: Homogenization of a multi-layered composites. Schematized view of a) the component (dotted lines indicating the orientation of plies) and b) the homogenized description.

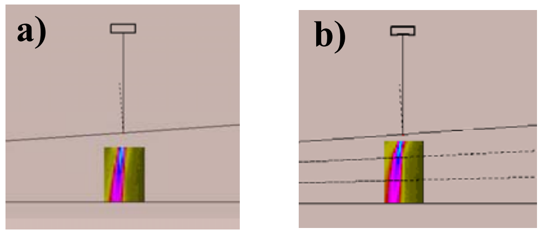

Figure 4: Simulation of the inspection of the component of Figure 2a). Computed beams a) without taking into account the varying orientation of plies; b) taking it into account.

By applying this approach it has been possible to evaluate the deviation of the beam transmitted by a focused immersed transducer at normal incidence and to show that the deviation induced by the surface misalignment is partially compensated by the effect of the varying orientation of plies as illustrated by Figure 4. This conclusion is in agreement with experimental observations.

Hybrid model

The last example presented here concerns the development of a semi-analytical/ FEM hybrid model within the *CIVA* platform. This work [10] is performed in collaboration with Electricité de France. Approximate theories such as Kirchhoff or GTD may fail at predicting responses from defects of complex geometry where scattering involves complicated processes. The goal of this hybrid model is to predict the response of complex defects when simplified theories are failing and also to determine when they are failing.

The idea is to apply in the surrounding of the defect a finite element scheme (Athena 3D developed by EdF/INRIA) which does not rely on physical approximation while the pencil method is applied to deal with the propagation between the probe and the defect. The interest of this approach is obviously to combine the advantages of the two methods while minimizing their inconveniences: Thanks to the finite elements an accurate description of the intricate phenomena in the surrounding of the defect is reached and thanks to the pencil method the computation time is optimized.

In this aim a coupling formula have been proposed, based on an integral formulation extending Auld's reciprocity principle to the transient case. The

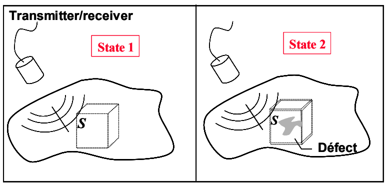

Figure 5: Illustration of the hybrid scheme in the pulse echo mode case: The coupling formula links two states. State 1: No defect, Semi-analytic computation of the propagation from the transducer to *S*; State 2: With defect, semi-analytic computation from transducer to *S* and FEM within *S*coupling formula links two states, one without defect (state 1 of Figure 5) a second one without defect (state 2 of Figure 5). The finite elements computation in this second state is performed within a parallelepipedic box as small as possible surrounding the defect. The incident field on the surface box, provided by the semi-analytical approach, is an input of the computation.

First results are presented on Figures 6 and 7. On Figure 6 is shown the response from a vertical crack in a steel part inspected by a T45° 2MHz transducer. On the computed signal, four main echoes can be identified. Echoes 1 and 2 are the near and far tip diffraction echoes. Echoes 3 and 4 are due to Rayleigh surface waves propagation along the crack and diffracted at tips. The response of a similar (same locations of the two tips) but irregular crack is shown on Figure 7 and compared to the response of the planar one. Near tip diffraction echoes are very similar in the two configurations, whereas far tip diffraction echoe mixing with surface wave echo in the irregular case seems of higher amplitude. Moreover, an echo appears between the two diffraction echoes coming from a bump in the crack shape.

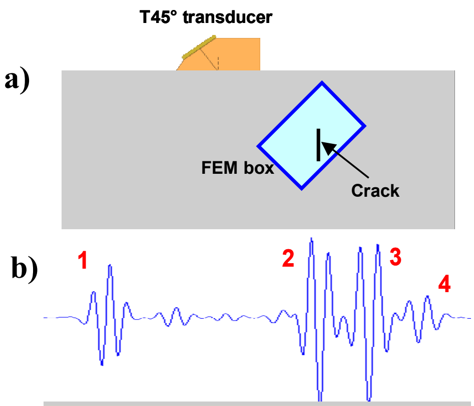

Figure 6: The hybrid model: Computation of the response of a planar crack. a) simulated configuration; b) computed Ascan

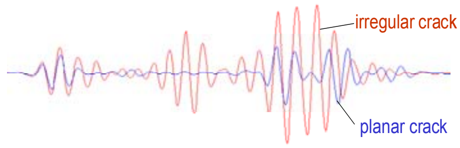

Figure 7: The hybrid model: Comparison between the computed Ascan issued from the irregular and planar cracks

Conclusion

We have discussed the main features of the NDT simulation approach adopted by the CEA in developing the *CIVA* software platform. Over the years the models implemented in *CIVA* are enriched by new developments in order to extend the applicability of the simulation codes to new applications. Several examples of such recent developments and applications have been presented.

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