SIMULATION OF ULTRASONIC INSPECTION OF DISSIMILAR METAL WELDS USING RAY-BASED APPROACHES

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ABSTRACT
Dissimilar metal welds (DMWs) of the primary loop of French nuclear power plants exhibit complex anisotropic and inhomogeneous material properties. Ultrasonic inspections of such materials are limited due to beam attenuation, skewing and splitting. Accurate numerical simulation tools are useful to optimize Ultrasonic Non Destructive Testing, and develop new signal processing and data reconstruction techniques dedicated to inspection of DMWs. In the past years, several approaches were addressed, either relying on numerical algorithms (finite elements, finite difference-time difference) or semi-analytical techniques (ray-based approaches). This paper presents two ray-based approaches applied to the simulation of DMW inspection. Firstly, the weld material properties are described as a set of anisotropic homogeneous domains. Rays travel in straight lines between two interfaces and reflection coefficients are taken into account as the ray moves from one domain to the next. In the second approach, which is an improved version of the first approach, a smooth description of the grains orientation is considered. Such descriptions may come from a functional form which links the grains orientation to a set of parameters that must be fixed for the considered weld. Alternatively, grains orientation is obtained through an image processing technique applied to metallographic pictures of the weld. Ray propagation is then computed using a dynamic ray tracing algorithm. Here, both approaches are applied to DMWs similar to those found in French nuclear power plants. Simulation results are discussed and compared to finite elements and experimental results.

INTRODUCTION
In the nuclear industry, Ultrasonic Non Destructive Testing (NDT) techniques are used to control welded joints of the primary circuit of Pressurized Water Reactor (PWR). Those techniques allow the detection, the localization and the characterization of defects located inside or in the vicinity of bimetallic welds. However, the interpretation of on-site inspections of dissimilar welds is particularly difficult due to their internal structures. Indeed, the anisotropic and inhomogeneous polycrystalline structure of the weld implies some disturbances of the beam, such as splitting and skewing [1]. Then, the simulation of ultrasonic inspection can be a powerful tool to understand these phenomena.

Various models have been developed to simulate the ultrasonic propagation such as finite element models [2][3] or ray-tracing models [4]. In the CIVA software [5], a semi-analytical propagation model, based on Dynamic Ray Tracing model (DRT), which evaluate the ray trajectories and the travel-time and compute the amplitude of a ray tube during the propagation, has been implemented. This model has been applied on a weld described as a set of several homogeneous domains with a constant crystallographic orientation [6]. In this paper, we present a generalization of this model that takes into account a continuously varying description of the grain orientation in the weld. The validation of this model is performed with comparisons with finite element model and with experiments.

PRESENTATION OF THE MODELS
A bimetallic weld located in the primary circuit of nuclear power plants is composed of Inconel or stainless steel and joined ferritic steel and stainless steel. Its metallurgical structure (which depends on many parameters such as the grade of steel, the diameter of the electrode, the velocity and the process of the welding) is inhomogeneous and strongly anisotropic (cf. Figure 1a).
To simulate this kind of welds in the CIVA platform, the current model is based on the DRT model applied to homogeneous media. This model consists in the resolution of two systems of differential equations: the first, named axial ray system, enables the evaluation of the ray trajectory and the associated time of flight and the second, the paraxial ray system, enables the estimation of the amplitude associated to an elementary tube of rays. In the current model, the weld needs to be described as a set of several homogeneous domains with a given crystallographic orientation (cf. Figure 1b). The ray propagates then along a constant direction of energy and the transmitted and refracted coefficients are evaluated at each interface (Figure 2a). For that, the geometry of the weld, the elasticity constants, the attenuation of the welding materials and the crystallographic orientation of the grain are required.

This model gives satisfying results while the domains have greater dimensions than the wavelength. Nevertheless if the contrast of impedance between two neighboring media is big, the limits of the model are reached. Furthermore, the division of the weld in homogeneous domains is not always easy and can imply numerical artifacts or unrealistic mode conversions. Thus the DRT model must evolve to be applied on continuous descriptions of the crystallographic orientation in order to limit these problems. In this extension of the model, the position and the energy velocity are evaluated at each step of time. Consequently, the ray does not propagate in straight line anymore but in curved line (Figure 2b). Description such as slowly continuously varying cartography of the orientation can be obtained either with an analytical law [4] or thanks to an image processing technique as illustrated in Figure 1c) [7].

**NUMERICAL VALIDATION**

**Comparison with piecewise description**

The first validation of the improved model consists in comparison with the current model. For that, two piecewise descriptions, a description in 7 homogeneous domains and a description in 23 homogeneous domains, are used.
The improved DRT model has been applied on a V-shaped weld on which the crystallographic orientation is described by a closed-form expression proposed by Ogilvy [4]:

\[
\theta = f(x) = \begin{cases} 
\tan^{-1}\left(\frac{T(D + z \cdot \tan \alpha)}{x^\eta}\right) & \text{for } x > 0 \\
\frac{\pi}{2} & \text{for } x = 0 \\
-\tan^{-1}\left(\frac{T(D + z \cdot \tan \alpha)}{(-x)^\eta}\right) & \text{for } x < 0
\end{cases}
\]

Parameters \(D\) and \(\alpha\) describe the geometry of the weld when \(T\) and \(\eta\) express the evolution of the orientation of the grains. In this example, the following values have been chosen: \(D = 2\) mm, \(\alpha = 21.8^\circ\), \(T = 1\) and \(\eta = 1\). The different descriptions are given in Figure 3.

First, the ray trajectories have been compared in order to validate the resolution of the axial ray system.

Figure 4 represents the ray trajectories evaluated for the different descriptions. The trajectories of a ray evaluated with the dynamic ray tracing model are identical to those obtained by the piecewise description. However more is the number of domains, more the ray trajectories converges. Indeed in the description in 7 domains, the trajectories are more rectilinear and a little difference between the impacts of the rays can be observed.

Figure 3: Different descriptions for the validation: from left to right, smooth description, 7 domains description and 23 domains description.

Figure 4: Comparison of ray trajectories between smooth description and piecewise description: on the top, description in 7 domains and on the bottom, description in 23 domains.
The axial ray system has been validated through the comparison of the ray trajectories. The next step consists in the evaluation of the ray amplitudes. To this aim, we have compared the ultrasonic wave field computed with the smooth and the piecewise descriptions. The comparison of the maximum particle velocity is given in Figure 5 for the different descriptions. A good agreement is obtained between smooth descriptions and the description in 23 domains. On the other hand, with the description in 7 domains, the interfaces of each domain are more visible on the beam. Furthermore, the comparison of echodynamics, which are the maximum of the particular velocity modulus on a line, shows that results for 7 domains are not as good as for 23 domains. Indeed, discrepancies of 1.5 dB are observed and the echodynamics are disturbed.

**Comparison with Finite Element model**

Now that the convergence between the piecewise and the smooth descriptions has been validated on a simple description of weld, the aim is to apply the DRT model to a more realistic description of the crystallographic orientation. The smooth description of realistic dissimilar metal weld presented in Figure 1c) is thus studied. This description is obtained by an image processing of the macrographs, the steps of this process being presented in [7]. The maximum particle velocity evaluated with the DRT model is then compared with those obtained with the hybrid code CIVA-ATHENA. In this code, a computation area is defined. Out of this area, a semi-analytical model is used for the computation of incident beam whereas in this area finite element (FE) model is used [8]. The simulation has been done in 2D with an immersion probe with a 12.7 mm diameter emitting longitudinal waves at 60° at 2 MHz. Results are shown in Figure 6:
The comparison of the longitudinal wave field evaluated with both models presents a very good agreement. Nevertheless, some differences are observed since the simulation with the DRT model has been made only for the direct longitudinal wave while the hybrid code takes into account all the physical phenomenon such as the shear waves, the reflections and the mode conversions. The beam of greater intensity on the echodynamics evaluated with the hybrid model corresponds to the shear wave. Furthermore, on the ultrasonic wave field evaluated with the DRT model, the beam seems to split in three beams: the main beam similar to those obtained by the hybrid model, one caused by the junction of weld and cladding interfaces and another one caused by the modification of the bevel slope. The latter are numerical artifacts caused by non smooth interfaces which are not well taken into account in the ray theory. Non smooth interfaces are interfaces for which the normal at the interface is non continuous.

EXPERIMENTAL VALIDATION

Comparison with transmitted beam measurement
Since it is not possible to perform 3D computation with the hybrid code CIVA/ATHENA, experimental validations have been performed on a mock-up of the weld used for the numerical validations in order to validate the 3D model. The acquisition has been realized with a L60° wedge probe with 12.7 mm diameter at 2 MHz fixed on the weld. The receiver is a 0.2 mm needle hydrophone which can be moved to do a 2D scanning in order to measure the transmitted beam. The experimental setup is shown in Figure 7.

![Experimental setup of transmitted beam measurement.](image)

This configuration has been reproduced in simulation in order to compare experimental and simulated beam of the ultrasonic longitudinal wave. Results are shown in Figure 8 and Figure 9 for the transmitter above the weld and above the cladding respectively. On the left of these figures, are presented the maximal amplitude of the transmitted beam for each position of the receiver. On the right, are given the echodynamics which corresponds to the amplitude on the red lines on the transmitted beam: the curves on the top corresponding to the vertical ones and on the bottom to the horizontal ones. The amplitudes have been normalized and only the dimensions are compared.
Figure 8: Comparison of the experimental and 3D computed transmitted wave field of the longitudinal wave with the probe above the weld.

Figure 9: Comparison of the experimental and 3D computed transmitted wave field of the longitudinal wave with the probe above the cladding.

The experimental and simulated results present a good agreement as shown in the representation of the wave field and on the superposition of the echodynamics. Furthermore, the dimensions of the longitudinal focal spot at -6 dB are well evaluated with the DRT model. However, some numerical problems are shown in the simulated wave field. In Figure 8, the important contributions on the left of the picture are numerical artifacts due to the interface. Indeed, they come from the discontinuity of the normal at the interface between the weld and the buttering. Furthermore, the echodynamics in Figure 9 are disturbed which corresponds to a chaotic behavior of the rays [9], resulting in an inaccurate wave field computation. In order to overcome this problem, a work can be made to smooth the description thanks to the minimization of the Sobolev norm of the slowness [10] or on the model by solving the problem of caustics with the Maslov method [11].
CONCLUSION

This paper has presented the improvements made in CIVA platform to simulate the ultrasonic propagation in anisotropic and inhomogeneous media, such as welds. A dynamic ray tracing model, usually applied in geophysics, has been developed. First, this model has been validated for a V-butt weld whose crystallographic orientation has been described by a closed-form expression. The ray trajectories and the longitudinal ultrasonic beam have been successfully compared to a piecewise description. Then the model has been applied on a smooth cartography of the crystallographic orientation and compared with results obtained with a hybrid code. The 2D simulations of the ultrasonic longitudinal wave field realized with both models have shown very good agreement. Lastly, 3D simulations have been successfully compared to experimental results.

In comparison with the current model in CIVA, the DRT model enables to obtain better results with a more realistic description. Nevertheless, some additional improvements are expected. First, the shear waves have to be taken into account to fully validate the DRT model. Secondly, numerical problems such as the chaotic behavior of the rays must be solved. In order to improve the computation time and the numerical precision, the order of the underlying iterative numerical scheme is planned to be increased by using the common fourth-order Runge-Kutta method. Then, the model will be applied to other mocks-up of bimetallic and austenitic welds described with a continuously varying crystallographic orientation.

REFERENCES