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# EVALUATION OF RAY-BASED METHODS FOR THE SIMULATION OF UT WELDS INSPECTION

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**ABSTRACT.** The reliability of ray-based approaches for the simulation of inspection of austenitic or bimetallic welds is assessed. A first modeling approach consists in describing the weld as a set of several anisotropic homogeneous domains with a given grain orientation. In this case, the rays travel in straight lines inside each domain. A second modeling approach uses dynamic ray tracing, considering a smooth description of the crystallographic orientation. Simulation results using both approaches are presented, discussed and compared to finite elements results.

**Keywords:** Weld Inspection, Dynamic Ray Tracing, Anisotropy.

**PACS:** 81.70.Ex

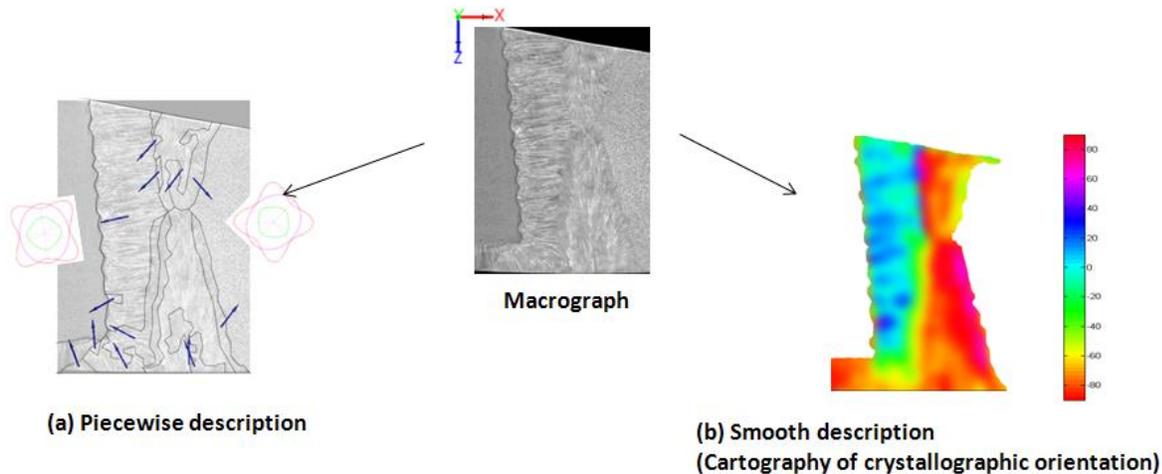
## INTRODUCTION

Ultrasonic techniques are used in various industrial sectors (nuclear, petrochemical, etc...) for the inspection of bimetallic or austenitic welds. The simulation of ultrasonic inspection of welds is a major challenge because of their anisotropic and heterogeneous nature. Because of the polycrystalline structure of the weld, the detection and characterization of defects may be complicated as the beam shows disturbances. Indeed, the effects of skewing of the beam can be observed on experimental structural echoes. Various models have been proposed in the literature to simulate the propagation of ultrasonic waves in welds. Alternatively to finite element method [1], semi-analytical propagation models based on ray theory have been implemented in the CIVA software [2, 3]. In this case, the weld is described as a set of several anisotropic homogeneous domains with a given crystallographic orientation in each domain. The rays propagate in straight line within those domains. At each interface, the reflection and refraction coefficients are calculated. If the domains have dimensions smaller than the wavelength, the results are valid provided there are small variations of impedance between two adjacent domains [4]. If this condition is not fulfilled, a continuously varying description of the grain orientation in the weld is to be preferred. In this case, dynamic ray tracing method (DRT) allows dealing with the propagation in anisotropic and inhomogeneous media [5]. In this paper, we discuss the applicability of both ray based models using either a piecewise description of the weld or a smooth description.

## CONTEXT: UT SIMULATION OF WELD INSPECTIONS

As far as simulation of UT weld inspection is concerned, two possible approaches may be investigated. Numerical methods such as finite elements (FE) or finite differences (FD) consist in giving locally an approximate solution of the equation of motion. If complex phenomena such as caustics or surface wave are implicitly taken into account in the simulation, computation time and memory requirements may be prohibitive, especially for 3D computations. On the other hand, ray-based approaches give a high frequency approximation of the exact solution of the wave equation at a moderate computation cost. One of the advantages of ray based methods is the possibility to interpret results in terms of ray trajectories, which can be very useful. A ray based approach is implemented in CIVA. The wave-field emitted by a transducer is approximated by using the Rayleigh surface integral. The surface of the transducer is discretized and each contribution is approached asymptotically using ray computation. The impulse response is subsequently obtained by summing the contributions from each elementary source.

The input data for any simulation code must feature the weld geometry, the elastic properties of the welding material, attenuation values and the crystallographic orientation at any position inside the weld. By applying image processing techniques on a macrograph of the weld, either a 'piecewise description' or a continuously varying description of the weld can be obtained [6]. In the case of a piecewise description of the weld, that is to say the weld is described as a set of homogeneous domains as on Fig 1.a, a 'straight ray tracing' model has to be used. In the case of a smooth description, the weld is described with a continuously varying crystallographic orientation and a dynamic ray tracing model has to be used. In both cases, the propagation model consists in solving the basic system of equations of ray theory for an anisotropic medium.



**FIGURE 1.** Macrograph of a bimetallic weld. Thanks to image processing techniques, either a) a piecewise description of the crystallographic orientation or b) a smooth description can be obtained.

The eikonal equation relates the travel time  $T$  of the wave front associated to a ray to the local wave speed  $c(\mathbf{x})$ .

$$(\nabla T)^2 = \frac{1}{c(\mathbf{x})^2} \quad (1)$$

Solving this equation allows the ray paths and travel time of the wavefront associated to the ray to be computed.

A second equation, called the transport equation allows the ray amplitude to be computed. The transport equation expresses the conservation of energy inside a ray tube.

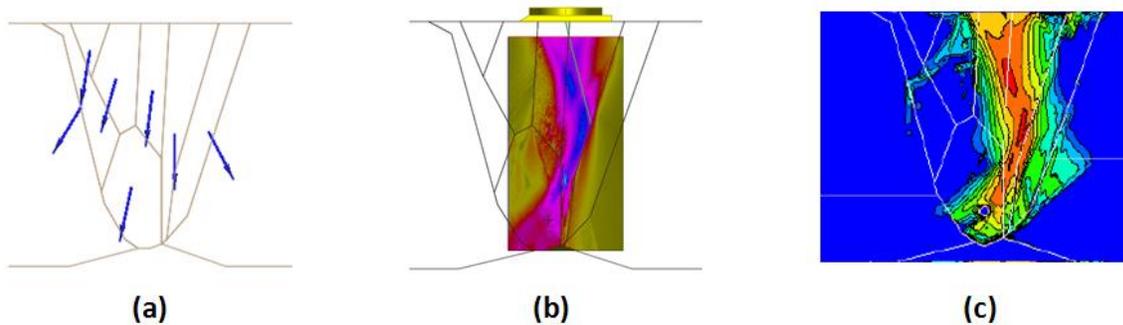
$$A(\mathbf{x})\nabla^2 T(\mathbf{x}) + 2\nabla A(\mathbf{x}) \cdot \nabla T(\mathbf{x}) = 0 \quad (2)$$

## RAY METHOD APPLIED ON PIECEWISE DESCRIPTIONS OF WELDS

### Straight Ray Tracing Model

For a piecewise description of the weld, the rays travel in straight lines inside each homogeneous domain. At each interface, a computation of the reflection and refraction coefficient is performed and the propagation within the next domains is pursued. The computation of the ray amplitude is performed through matrix products expressing the evolution of a paraxial ray describing a ray tube or pencil [7]. The results are valid if the domains have dimensions larger than the wavelength and present small variations of impedance between two adjacent areas.

Results of this straight ray tracing model, already implemented in CIVA, has been compared to results obtained with ATHENA, an elastodynamic finite element code developed by Electricité de France (EDF) [8]. A weld has been described as a set of homogeneous orthotropic domains. Each domain shows a given grain orientation represented by an arrow on Fig. 2. One can notice that the variations of impedance between neighboring domains are not important so that the validity domain of the straight ray tracing model is respected. A very good agreement can be observed on 2D computation results on Fig. 2. In particular, the beam deviation inside the weld is predicted by both CIVA and ATHENA codes.



**FIGURE 2.** (a) Piecewise description of a weld as a set of homogeneous domains with different crystallographic orientations represented by arrows. (b) Maximum particle velocity field for L0 inspection at 2.25 MHz obtained with a straight ray tracing model (CIVA) and (c) finite element model (ATHENA).

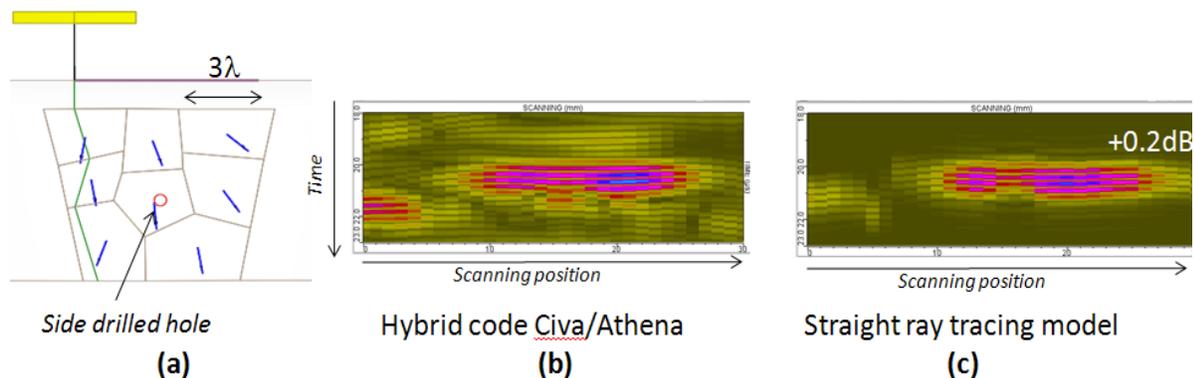
## Limits Of Validity

The ray theory being based on a high frequency approximation, its applicability is limited by several qualitative conditions [4]. One of them specifies that the characteristic lengths of the model should be larger than the wavelength. As far as the simulation of ultrasonic propagation in welds is concerned, this means that the presence of small domains with significant impedance contrast should be problematic.

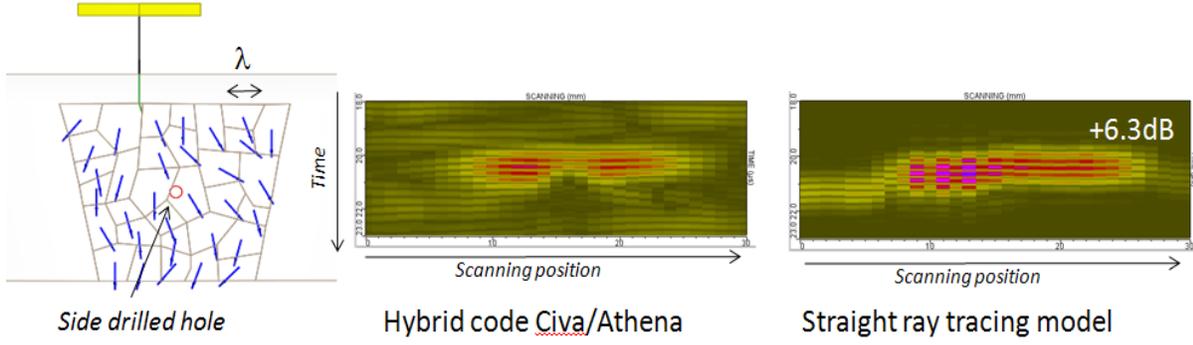
To verify this assumption, a numerical experiment has been performed in which two fictitious weld descriptions are considered. The two descriptions show approximately the same impedance contrast between two neighboring transversely isotropic domains but the characteristic length of a domain is about three wavelengths for the first description (Fig. 3) whereas it is about a wavelength for the second description (Fig. 4). Thus, if the first description respects the ray theory validity condition, the second description is supposed to possibly give inaccurate results.

Simulation results obtained with the straight ray tracing model, corresponding to the response of a side drilled hole located inside the weld have been compared with finite element results. Finite element results are obtained with a hybrid code developed by CEA and EDF that we use as a validation tool. This code uses a finite element box surrounding the weld that takes as input data the incoming ultrasonic field on the box boundaries. This incoming wave field emitted by a transducer is computed with CIVA and coupled with a finite element computation carried out by ATHENA inside the box containing the weld [9].

As the condition that the characteristic dimension of the domains should be larger than the wavelength is not fulfilled in the second description considered, we expect the first description to give more reliable results than the second one. This is confirmed on the Bscans corresponding to the responses of the side drilled hole positioned inside the weld (Fig. 3 and Fig. 4). For the first description, there is a very good agreement between results obtained with the hybrid finite element code and the straight ray tracing model. On the other hand, significant discrepancies between both models are observed for the second description. This confirms that one must pay attention to the smoothness of the description before performing a ray based simulation.



**FIGURE 3.** (a) Fictitious weld description respecting the ray theory validity conditions. The weld is described as a set of homogeneous domains with different crystallographic orientation represented by arrows (b) Simulated Bscan (L0 wave inspection, 2.25 MHz) obtained with hybrid code CIVA/ATHENA (c) Simulated Bscan obtained with a straight ray tracing model.



**FIGURE 4.** (a) Fictitious weld description that does not respect the ray theory validity conditions. The weld is described as a set of homogeneous domains with different crystallographic orientation represented by arrows (b) Simulated Bscan (L0 wave inspection, 2.25 MHz) obtained with hybrid code CIVA/ATHENA (c) Simulated Bscan obtained with a straight ray tracing model.

## RAY METHOD APPLIED ON SMOOTH DESCRIPTIONS OF WELDS

### Dynamic Ray Tracing Model

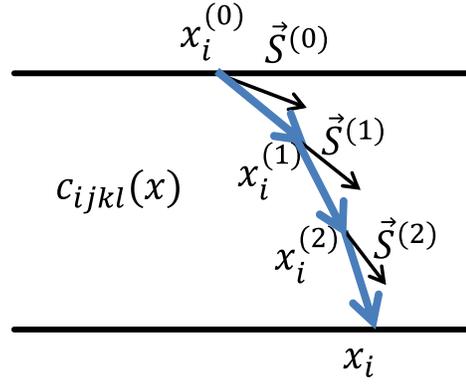
In the case of a smooth cartography of crystallographic orientation (Fig. 1b), the solution of the eikonal equation (1) is not as simple as in the case of the piecewise weld descriptions previously mentioned. Indeed, the ray trajectories are not straight lines any more. A differential system can be derived from the eikonal equation [5]:

$$\begin{aligned} \frac{dx_i}{dT} &= \frac{c_{ijkl}}{\rho} S_i P_j P_k = V_e^i \\ \frac{dS_i}{dT} &= -\frac{1}{2\rho} \frac{\partial c_{jklm}}{\partial x_i} S_k S_n P_j P_l \end{aligned} \quad (3)$$

$T$  is the travel time,  $c_{ijkl}$  are the elastic constants at the position  $x_i$ ,  $\rho$  the density,  $S_i$  are the components of the slowness vector,  $P_i$  the components of the polarization vector and  $V_e$  stands for the energy velocity. These two equations are coupled. The first one expresses the variation of the current ray position relatively to the travel time. It explicitly depends on the slowness. The second equation expresses the variation of the current slowness on the travel time which also depends on the current position  $x_i$ .

This system of ordinary differential equations can be solved for compressional or transverse waves to obtain the ray trajectories and slowness along the ray. Knowing the initial conditions, the system (3) can be solved by standard numerical techniques such as Euler's method or Runge-Kutta's method [10].

To solve the system, we need to know the elastic constants values and the value of their derivatives at any position inside the weld. The latter may be obtained either numerically if the weld is described as a cartography of crystallographic orientations as featured on Fig 1.b or analytically if the orientations are given by a law as proposed for example by Ogilvy [11].



**FIGURE 5.** Iterative computation of a ray trajectory obtained by solving equation (3).

The ray trajectory is computed iteratively as shown on Fig. 5. At each time step, position and slowness are updated. Subsequently, the computation of ray amplitude is performed as a first approximation by considering the medium to be locally homogeneous between each time-step. This approximation is valid only for slowly varying anisotropy and requires the use of a small time step when solving the differential system of equations. A more rigorous approach would consist in solving a differential system for paraxial quantities from the transport equation [5]. This would allow the use of high order numerical techniques to solve equation (3) that would involve a larger timestep.

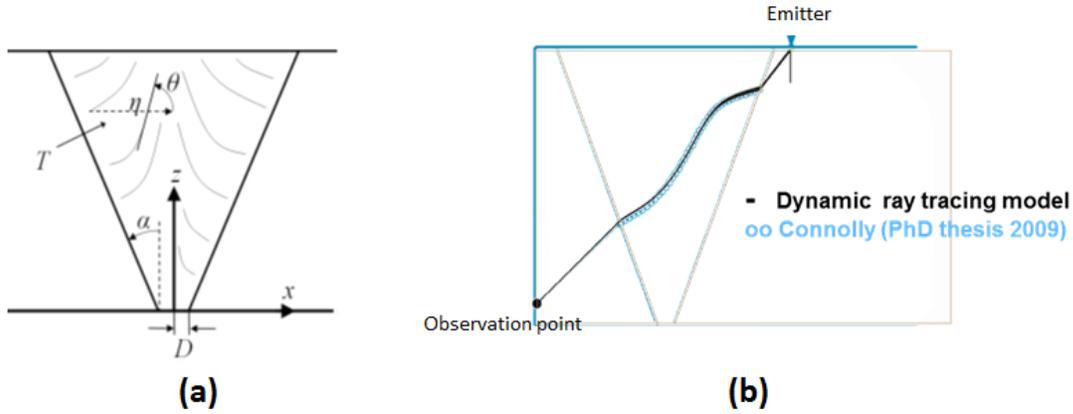
### **First results**

To validate our approach, we use the simplified model proposed by Ogilvy that assumes an analytical law to describe the variation of the crystallographic orientation along the weld. The V-shaped austenitic region modeled as transversely isotropic medium is surrounded on either side by ferritic steel modeled as a isotropic medium. The grain orientation inside the weld is represented on Fig. 6.

$$\theta = \begin{cases} -\operatorname{atan}\left(\frac{T(D+z \tan \alpha)}{x^\eta}\right) & \text{for } x \geq 0 \\ \operatorname{atan}\left(\frac{T(D+z \tan \alpha)}{x^\eta}\right) & \text{for } x < 0 \end{cases} \quad (4)$$

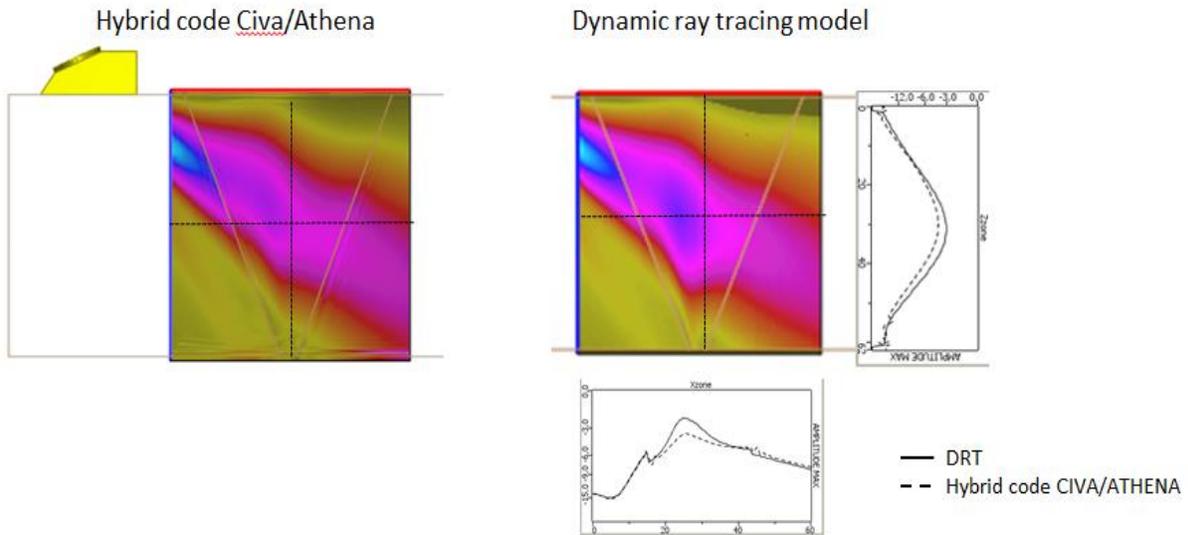
$T$  is proportional to the tangent of the grain axis at the sloping edge.  $\alpha$  and  $D$  are geometrical parameters shown on Fig. 6 and  $\eta$  is a parameter driving the variation of orientation in the  $x$  direction. The material is considered to be a transversely isotropic steel.

Our dynamic ray tracing model has been compared with results from Connolly's PhD thesis [12] taking  $\eta=1$ ,  $T=1$ ,  $\alpha = 21.80^\circ$  and  $D=2\text{mm}$ . Contrary to dynamic ray tracing model, Connolly's ray tracing model uses virtual boundary parallel to lines of constant crystallographic orientation. One can notice on Fig. 6 a very good agreement between both models for a ray trajectory crossing the weld.



**FIGURE 6.** (a) Typical weld description proposed by Ogilvy [11]. Crystallographic orientations inside the weld are determined by equation (4). (b) Comparison of present dynamic ray tracing model with Connolly’s ray tracing model.

Finally, a comparison between the wave field obtained using the dynamic ray tracing model and finite element results is shown on Fig. 7 on the same weld description. For the finite elements results, as in the previous section, the incoming wave field emitted by a transducer is computed with CIVA and coupled with a finite element computation performed with ATHENA inside the box containing the weld. There is a good agreement between both models even if slight discrepancies have to be investigated.



**FIGURE 7.** Comparison of maximum particle velocity field (L60 inspection, 2.25 MHz) obtained with finite elements (hybrid code CIVA/ATHENA) and the dynamic ray tracing model.

## CONCLUSION

Two ray based approaches have been assessed for the simulation of ultrasonic inspections of austenitic or bimetallic welds, depending either the weld is considered as a set of homogeneous domains of different crystallographic orientations or as an inhomogeneous medium with a continuously varying orientation. The first one involving a straight ray tracing model is presently implemented in the CIVA commercial package. Its validity domain has been underlined by comparison with a 2D Finite Element code. A special attention must be given to avoid the presence of small domains compared to the wavelength with significant impedance contrast between neighboring domains. Alternatively, the second approach based on dynamic ray tracing has been implemented in the case of a smooth weld description. In this case, ray trajectories are computed by solving a system of differential equations and the ray amplitudes are computed by considering the medium as locally homogeneous. Comparisons of 2D ray trajectories with literature and comparisons of wave field with finite elements have proven the relevance of the approach. Current work is in progress in order to connect the dynamic ray tracing model on smooth cartographies of crystallographic orientations obtained from image processing techniques applied on macrographs.

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