Validation of simulation tools for ultrasonic inspection of austenitic welds in the framework of the MOSAICS project

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Outline

- Context
- The MOSAICS project
- The CIVA dynamic ray tracing model: “CIVA weld”
- The 3D ATHENA code
- Ultrasonic inspection: comparison between experimental and modelling results
- Modelling influential parameters
- Conclusion
Context

Use of robust NDT numerical models:
- Understanding of complex physical phenomena
- Parametric studies in order to determine the performances and limitations of a NDT process (impact of influential parameters, qualification of UT processes)

Limitations for the UT inspection of austenitic welds in piping of primary circuit of EDF PWR plants and DCNS structures:
- Anisotropic, heterogeneous and coarse grain structures highly disturbing UT propagation
- Beam deviation, division and attenuation

![Image of weld inspection outside and inside the weld]
The MOSAICS project

- Duration: 10/2011 – 01/2015
- Supported by French National Research Agency
- 6 partners: EDF – DCNS – CEA – EXTENDE – Aix-Marseille University – INSA de Lyon

Objective: development and validation of numerical codes to predict the ultrasonic propagation in austenitic welds for a reliable NDT diagnosis

→ Development and validation of modelling tools used for ultrasonic testing of austenitic welds in 3D configurations
  - Finite element code ATHENA 3D
  - CIVA semi-analytical models: continuously varying model
The CIVA dynamic ray tracing model

- Method of paraxial rays in an anisotropic and gently inhomogeneous medium

- Weld described as a grain orientation mapping
  - Obtained with the Orientation J plug-in of the Image J software (EPFL)
  - Determines the orientation of every pixel of an image
  - Orientation imaging displayed on $[-90^\circ, 90^\circ]$ interval

- Smoothing filter (Gaussian function) characterized by its standard deviation $\sigma$ associated with the wavelength $\lambda$

- Spatial decimation can be performed to reduce the loading time of the mapping

Before smoothing and decimation

After smoothing and decimation
The ATHENA code

- FE code based on solving elastodynamic equation in the calculation zone expressed in terms of stress and velocities of displacements

- Modelling of the entire ultrasonic testing chain: specimen, probe, and defect

- Discretization:
  - Calculation domain: Cartesian regular 3D mesh
  - Defects: fictitious domains method (separate mesh)

- Grain orientation mapping:
  - Grid made of 2mm side squares
  - Measurements of columnar grain orientations by macrograph image processing (Hough transform)

- Attenuation problem reflecting the phenomenon of grain boundary scattering implemented in 2D and development for the 3D version; in progress

Objective of the study

- Validation of CIVA dynamic ray tracing model and of the ATHENA 3D code
  - Analysis of the amplitude before and after weld crossing for different calibration defects:
    - Side Drilled Holes (SDH)
    - Backwall breaking notches

- 2 application cases:
  - EDF application: anisotropic V-shape weld with orthotropic symmetry
  - DCNS application: primary safety valve nozzle (not presented today)
EDF application case: V-shaped weld

- Austenitic stainless steel grade 316 L weld realized with SMAW in vertically upward position
- Anisotropic material with orthotropic symmetry:

\[ \rho = 7.85 \times 10^3 \text{ kg/m}^3 \text{ et } C_{ij} = \begin{pmatrix} 247 & 110 & 148 & 0 & 0 & 0 \\ 110 & 247 & 148 & 0 & 0 & 0 \\ 148 & 148 & 218 & 0 & 0 & 0 \\ 0 & 0 & 0 & 105 & 0 & 0 \\ 0 & 0 & 0 & 0 & 105 & 0 \\ 0 & 0 & 0 & 0 & 0 & 80 \end{pmatrix} \]

- V bevel of 37 mm thickness
- Average grain tilt estimated to 18° along the welding direction (WD axis)
SDH validation results

Experiment | CIVA CV (with attenuation) | ATHENA 3D
--- | --- | ---
| 0 dB | 0 dB | -9.9 dB
| -12.7 dB | -12.3 dB | |

σ = 4 mm  
Decimation = 3 mm

Values chosen in order to minimize the discrepancy between experimental and modelling results in d1 and d2 directions for SDH defects.

<table>
<thead>
<tr>
<th></th>
<th>Experiment (dB)</th>
<th>Civa (dB)</th>
<th>ATHENA 3D (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direction d1</td>
<td>-12.7 ± 0.6</td>
<td>-12.3</td>
<td>-9.9</td>
</tr>
<tr>
<td>Direction d2</td>
<td>-9.3 ± 0.7</td>
<td>-8.1</td>
<td>-3.8</td>
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</tbody>
</table>
Validation results on notches

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<tr>
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<th>CIVA CV (with attenuation)</th>
<th>ATHENA 3D</th>
</tr>
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<tbody>
<tr>
<td>Direction d1</td>
<td>-12.7 ± 0.6</td>
<td>-10.5</td>
</tr>
<tr>
<td>Direction d2</td>
<td>-10.6 ± 0.9</td>
<td>-7.8</td>
</tr>
</tbody>
</table>

- CIVA: simulated results in good agreement with experimental ones
- ATHENA:
  - Prediction of scattering at each domain interface but underestimation of attenuation and overestimation of noise
  - New calculations with 3D attenuation model using INSA characterization work to be performed
  - Specific study to be carried out on the reproduction of coarse grain noise

\[ \sigma = 4 \text{ mm} \]

Décimation = 3 mm
CIVA influential parameters

- In CIVA_CV : 2 variables to specify before calculation
  - The size of the Gaussian window used as smoothing filter (\(\sigma\))
  - The decimation parameter

- **Empirical values definition**

- The SDH echoes amplitude converges when \(\sigma\) value increases
- Amplitude not equal the one measured experimentally

- The curve evolution changes according to the direction studied
- High sensitivity of the results with the 2 parameters
ATHENA3D influential parameters

influence of the weld grid description

- Key parameter for the UT modelling with ATHENA
- Comparison of 3 grid descriptions

<table>
<thead>
<tr>
<th></th>
<th>Experiment</th>
<th>Description 1 (2 mm grid)</th>
<th>Description 2 (1 mm grid)</th>
<th>Description 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defect echo amplitude (dB)</td>
<td>-12.5</td>
<td>-11.0</td>
<td>-7.0</td>
<td>-3.5</td>
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<tr>
<td>Structural Noise amplitude (dB)</td>
<td>-23.0</td>
<td>-11.0</td>
<td>-12.0</td>
<td>-18.0</td>
</tr>
<tr>
<td>SNR (dB)</td>
<td>11.5</td>
<td>0.0</td>
<td>5.0</td>
<td>14.5</td>
</tr>
</tbody>
</table>

Significant influence of the weld description on the FE modelling results in terms of echo amplitudes and noise level.
ATHENA3D influential parameters

**influence of $C_{ij}$ elastic constants**

- $C_{ij}$ coefficients describe the anisotropy degree of the weld
- Difficult to measure accurately
- Comparison of 2 sets of anisotropic constants with 2mm-square grid

<table>
<thead>
<tr>
<th></th>
<th>$C_{11}$</th>
<th>$C_{22}$</th>
<th>$C_{33}$</th>
<th>$C_{23}$</th>
<th>$C_{13}$</th>
<th>$C_{12}$</th>
<th>$C_{44}$</th>
<th>$C_{55}$</th>
<th>$C_{66}$</th>
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</thead>
<tbody>
<tr>
<td><strong>Set 1</strong></td>
<td>247</td>
<td>247</td>
<td>218</td>
<td>148</td>
<td>148</td>
<td>110</td>
<td>110</td>
<td>110</td>
<td>80</td>
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<tr>
<td><strong>Set 2</strong></td>
<td>250</td>
<td>255</td>
<td>230</td>
<td>137</td>
<td>127</td>
<td>112</td>
<td>102</td>
<td>123</td>
<td>60</td>
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</tbody>
</table>

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<th></th>
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<th>Set 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude (dB)</td>
<td>-11.0</td>
<td>-8.5</td>
</tr>
<tr>
<td>SNR (dB)</td>
<td>0.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Little changes on the $C_{ij}$ coefficients have an impact on the amplitude and SNR.

The second set of $C_{ij}$ describe a less anisotropic tensor.
Conclusion and outlook

MOSAICS progress:

- Development of simulation codes adapted to 3D configurations (any kind of anisotropy, probe, flaw)
- CIVA_CV: No more limitations associated to highly heterogeneous structures
- ATHENA3D: allows to deal with configurations impossible in the 2D version
- Experiment validation
  - Different configurations of weld and defects have been evaluated with L waves only
  - Disturbances (attenuation, deviation) and influence of the structure dissymmetry predictions

Outlook:

- Other kind of welds and propagation modes
- 3D attenuation model (complex elasticity constants)
- Study on the influence of the material input data (scale of weld description, elastic constant values,...)
Thank you for your attention!