COMPARISON OF TWO EDDY CURRENT SIMULATION METHODS IN STEEL PIPES

B. Bisiaux¹, L Maurice²

¹ VALLOUREC RESEARCH AULNOYE, Scientific Director
60 route de Leval – 59620 AULNOYE AYMERIES, France, bernard.bisiaux@vallourec.fr
² Studies engineer, EDF – Generation Nuclear Engineering Division, CEIDRE, NDT service
2 rue Ampère - 93206 Saint-Denis Cedex, France, lea.maurice@edf.fr

ABSTRACT

In the framework of the COFREND working group on "Eddy Current Modelling", a benchmark has been proposed by the Vallourec research center. This case corresponds to the modelling of the industrial online testing of seamless steel pipes using the eddy current method with encircling coils. In this framework, the Vallourec research center (VRA Vallourec Research Aulnoye) has studied two solutions based on two different methods: the first is based on semi-analytical methods using CIVA software developed by the CEA, while the second is based on the finite element method using the COMSOL Multiphysics program. The results obtained from these two approaches are very similar and are consistent with the experimental data. It proves that both simulation methods are valid and are complementary to each other.

Key words: COFREND, Eddy Current, CIVA, COMSOL, simulation

1. Introduction

Use of non-destructive examination (NDE) modelling and simulation software and more particularly software for modelling Eddy Current testing has become increasingly widespread in recent years and more and more common in various industrial applications. The main advantages of the digital modelling of these tests are that it offers:
- improved understanding of the physical phenomenon in operation and their effects on the inspection results;
- an aid to the design of new probes or inspection benches;
- an aid to the qualification of non-destructive examination techniques so as to cover most of the influence factors (dimensions and materials of the parts, probe guiding errors, etc.) while reducing the necessary number of tests [1];
- support for the interpretation of the signals produced during inspections of complex configurations. Simulation is also being increasingly integrated into flaw reconstruction models [2], [3].

Before deciding to use simulation software, non-destructive testing (NDT) engineers must however check the ability of the software to provide results that correspond to the experimental results of these inspections in the specific configurations of their applications.
Benchmarking the various candidate simulation programs appears to be the best way to do this, on a test case representative of the NDE application under consideration. The results of the modelling are then compared to the reference results, generally obtained from experimental measurements or an already approved simulation software program.

It is in this perspective that the COFREND working group on "Eddy Current Modelling" founded in 2003 has for some years now been working on the definition of test cases inspired by industrial issues. Its aim is to define test cases that can be understood by as many people as possible so as to favour discussion and comparison of the solutions offered by the candidate codes. The Vallourec group, firmly convinced that simulation is an important input to the NDT of pipes, as performed on all the pipes it produces, has played an active role in this working group via its research centre, and has proposed test case no. 6 which involves the simulation of an on-line industrial Eddy Current inspection of steel pipes using the encircling coil method. After briefly presenting the COFREND working group, this paper will describe test case no. 6. We will present the first solution using CIVA software which uses a semi-analytical method and whose special module for the modelling of Eddy Current inspection of pipes was mainly developed as part of a PhD project in cooperation between Vallourec, the C.E.A. and the Signals and Systems Laboratory (L2S) of Supélec [4]. Finally, we will present the results of the first simulations made for this test case at the Vallourec research centre using a new candidate software program, COMSOL Multiphysics, which uses the finite element method.

2. Presentation of the “Eddy Current Modelling” working group

The COFREND working group on "Eddy Current Modelling" [8] aims to promote simulation software as an aid to industrial NDE using the Eddy Current method [5]. Its work is twofold:
- It organizes technical events and publishes documents on the theme of the modelling of non-destructive examination by Eddy Currents (available on the group website).
- It defines reference test cases that are representative of the problems encountered in industrial NDT (in the "Benchmarks" section of its website), with every data published.

This working group is composed of representatives of the main industries that use NDE in France: nuclear (AREVA, EDF), aeronautics (Dassault, EADS, SNECMA), metallurgy (Vallourec), government institutions (IRSN), NDE equipment and service providers (Alphatest, Zetec), representatives of industrial and academic research centres (CEA, Supelec/CNRS) and software developers (CEDRAT, EXTENDE). The group is also open to exchanges with similar programs conducted in other countries. The resolution of the proposed test cases is open to all candidate codes. At present, 6 test cases have been defined or are in the process of being defined.

3. Description of test case No. 6 proposed by VALLOUREC

The issue concerned by test case No. 6 is the on-line industrial Eddy Current inspection of seamless steel pipes using external encircling probes. The test case more specifically concerns the inspection of a pipe containing several artificial flaws such as holes or grooves (Fig. 1), whose dimensions are given in Table 1 together with their electromagnetic characteristics. The inspection is performed with the pipe moving in a linear fashion through the probe and the pipe speed at an industrial testing rate can be up to 2 m/s.

The encircling coil is a differential probe with separate functions. It is composed of one transmitting coil and two receiving coils. Their dimensions are given in Table 2. No core is used. The transmitter coil generates a magnetic field inside the pipe which in turn generates eddy currents at the surface of the pipe. For this, the transmitter coil is powered by a sinusoidal current, whose intensity could not be checked on the experimental equipment used as a reference for comparing the simulation results. The exciting current is conventionally set at 1 Amp in the

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simulations. The differences in this setting between the simulations and the experiment will be compensated by the calibration.

Table 1: Configuration of the pipe and the flaws in test case No. 6

<table>
<thead>
<tr>
<th>Pipe dimensions:</th>
<th>Outside diameter: 32 mm - Wall thickness: 8 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe material:</td>
<td>Stainless steel grade TP304L – main components: iron (~73%), chromium (~18%) and nickel (~9%). Conductivity: $\sigma = 1.43 \times 10^6$ S.m$^{-1}$ Magnetic permeability: $\mu_r = 4\pi \times 10^{-7}$ H.m$^{-1}$</td>
</tr>
<tr>
<td>Flaw 1:</td>
<td>Through hole (depth: 8 mm) - Diameter: 3.5 mm</td>
</tr>
<tr>
<td>Flaw 2:</td>
<td>Flat-bottomed hole, depth: 2 mm - Diameter: 3.5 mm</td>
</tr>
<tr>
<td>Flaw 3:</td>
<td>Flat-bottomed hole, depth: 3 mm - Diameter: 3.5 mm</td>
</tr>
<tr>
<td>Flaw 4:</td>
<td>Flat-bottomed hole, depth: 5 mm - Diameter: 3.5 mm</td>
</tr>
<tr>
<td>Flaw 5:</td>
<td>Circular external groove: (around entire circumference 360°) - Depth: 0.5 mm - Width: 1 mm</td>
</tr>
</tbody>
</table>

Fig. 1: Diagram of test case No. 6

Table 2: Dimensions of inspection equipment

<table>
<thead>
<tr>
<th>Transmitter coil</th>
<th>Receiver coils</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inside diameter: 47 mm</td>
<td>Inside diameter: 41 mm</td>
</tr>
<tr>
<td>Wall thickness: 2.4 mm</td>
<td>Wall thickness: 1 mm</td>
</tr>
<tr>
<td>Width: 30 mm</td>
<td>Width: 2 mm</td>
</tr>
<tr>
<td>Number of turns: 200</td>
<td>Number of turns: 200</td>
</tr>
<tr>
<td>Space between coils: 2mm (2-2-2 configuration).</td>
<td></td>
</tr>
</tbody>
</table>

Use of two receiver coils allows the inspection to be performed in differential mode, which reduces the measurement noise when inspecting pipes at high speed by compensating for the variations in air gap and in the metallurgical structure of the pipes. The complex impedance at the terminals of the receiver coils is measured and the resulting inspection signal in differential
mode corresponds to the difference in impedance at the coil terminals. This difference is made electronically on the inspection equipment using a Wheatstone bridge.

![Diagram of offset case](image)

**Fig. 2: Diagram of offset case**

The test case considers two pipe positions inside the coils. Firstly, the classic configuration or "centred case" where the pipe is correctly centred inside the coils corresponds to the optimum inspection conditions. Secondly, the "offset case" configuration where the centre of the pipe is offset by 2 mm from the centre of the coils ($\delta = 2\text{mm}$ in Fig. 2). These conditions correspond to the maximum shift of the pipe as it is guided through the inspection equipment. The ability to perform simulations of this type of offset and to estimate its influence on the variation in the flaw responses is a major industrial issue when estimating the repeatability of these inspections by modelling. The considered frequencies in this work were 3, 50, and 100 kHz.

The results of the modelling will be compared to the reference results from an experimental installation in the proposed configuration. The amplitude settings of the phase under consideration will correspond to calibration on flaw no. 3.

4. **Solutions for test case No. 6: Simulations in CIVA and experimental data**

The first candidate simulation code tested for this case was naturally the CIVA simulation software developed by CEA. This software is dedicated to the modelling of several NDE methods: ultrasonic testing, eddy current testing and radiographic testing. The simulation codes are based on semi-analytical methods, which ensure rapid calculations. In the case of eddy current modelling, the code is based on the use of integral formulation of the Maxwell equations. Furthermore, the modelling in CIVA of eddy current inspections of pipes was developed essentially as part of the PhD thesis of Christophe REBOUD, conducted in cooperation with VALLOUREC, the C.E.A. and the Signals and Systems Laboratory (L2S) of Supélec. This thesis allowed us to integrate new modelling codes into CIVA in order to take into account complex axisymmetrical configurations such as simulating an inspection where the pipe is offset in relation to the encircling coils [4], [6]. As part of this thesis, experimental validations on one of the eddy current inspection benches at the VALLOUREC research centre (Fig. 3) were carried out, including the configurations used in case no. 6.

The validations of the CIVA software and the experimental results only concerned hole type flaws which are the most significant from an industrial point of view. The results in the complex impedance plan (Lissajous curves) for experimental acquisitions and simulations at frequency 3 kHz are presented in Fig. 4 for the centred case and in Fig. 5 for the offset case. Table 3
compares differences in magnitude ($\Delta A$) in dB and the phase deviations ($\Delta \phi$) in degrees obtained from the various flaws in both cases and at the 3 tested frequencies.

Fig. 3: Eddy current inspection bench at the Vallourec research centre

The close correspondence between the experimental results and the results of the simulations with CIVA (error under 1.5 dB in amplitude and 6° in phase, which is the repeatability criteria for experimental measurements) allowed the CIVA software to be qualified as a reliable simulation code for modelling eddy current inspection of pipes.

Fig. 4: CIVA results and experimental measurements at frequency 3 kHz - centred case.

5. First simulations in COMSOL Multiphysics and comparison with CIVA

In addition to the CIVA simulation software, the Vallourec research centre is currently seeking to develop new eddy current inspection modelling software using the finite element (FE) method. Indeed, we considered that the two approaches could prove to be complementary. For example, when it is impossible to validate simulations by means of experimental measurements (design of a new type of probe or feasibility study for the inspection of new products), a comparison of the results obtained using the two simulation methods could allow the risks of incorrectly interpreting the simulation results to be minimized. In addition, while the FE method
takes longer in terms of setting and calculation time than the semi-analytical method, it offers greater flexibility on the configurations to be modelled and the approximations to be used.

![Fig. 5: CIVA results and experimental measurements at frequency 3 kHz - offset case.](image)

Table 3: Comparison between CIVA simulations and experimental measurements - test case no.6

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Flaw No.</th>
<th>f = 3 kHz</th>
<th>f = 50 kHz</th>
<th>f = 100 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ΔA (dB)</td>
<td>Δφ (°)</td>
<td>ΔA (dB)</td>
</tr>
<tr>
<td>Centred case</td>
<td>1</td>
<td>0.39</td>
<td>-6</td>
<td>-0.67</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-0.44</td>
<td>-1</td>
<td>-0.76</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.23</td>
<td>-4</td>
<td>0</td>
</tr>
<tr>
<td>Offset case</td>
<td>1</td>
<td>1.18</td>
<td>-4</td>
<td>-0.34</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-0.8</td>
<td>-1</td>
<td>-0.26</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.72</td>
<td>-2</td>
<td>-0.12</td>
</tr>
</tbody>
</table>

Work is therefore in progress with the Digital Simulations department of the Vallourec research centre directed by Emmanuel Desdoit to develop the FE method of modelling eddy current inspections. The software selected is COMSOL Multiphysics, which is already used by the Vallourec research centre for mechanical, thermal and electromagnetic simulations of Vallourec's products and processes. This software also includes some electromagnetic modules adapted to the modelling of eddy current inspections [7].

The first developed models were made in 2D and therefore only allow axisymmetrical configurations to be simulated. To validate these first simulations, it was therefore decided to model the part of test case no. 6 that meets these test constraints: inspection of flaw no. 5 (external circular groove over 360°, 0.5 mm deep and 1 mm wide) in the centred case. Fig. 6 illustrates the results of the calculation of eddy current flux density in the pipe around this flaw by means of 2D COMSOL modelling Multiphysics.

![Experience](image)

![CIVA simulations](image)

Results obtained in COMSOL Multiphysics
were compared with those obtained in CIVA. As we did not have any experimental results for this case, we considered the results obtained in CIVA as the reference results on the grounds that CIVA has proven reliability for the simulation of eddy current inspections.

![Eddy current flux density in the pipe obtained in COMSOL Multiphysics.](image)

**Fig. 6:** Eddy current flux density in the pipe obtained in COMSOL Multiphysics.

The results obtained using both simulation methods are shown in Fig. 7 in the complex impedance plane. These results show that there is a very high correlation between the two methods. Owing to these encouraging results, the Vallourec research centre is continuing its development work in order to model the inspections in 3D using COMSOL Multiphysics, which will allow all possible industrial configurations to be simulated; this modelling will then be tested on the other aspects of test case no. 6 (hole type flaws in offset cases).

### 6. Conclusion

The modelling of NDE is increasingly used in industry at various stages from design to the qualification of an inspection technique. Industrial users of this type of modelling are faced with a major problem when it comes to selecting and validating the simulation software used for this. For this reason, the COFREND working group on “Eddy Current Modelling” proposes different reference test cases representative of the problems encountered in industry.

Vallourec in cooperation with the CEA has proposed test case no. 6 as described in this document. This case concerns the industrial on-line eddy current inspection of steel pipes using encircling coils. A first solution to the case proposed was offered using the CIVA simulation software and compared to the experimental reference results. This allowed us to demonstrate that CIVA, based on semi-analytical methods, provides reliable models of eddy current inspections of pipes. Complementary to this method, work is in progress at the Vallourec research centre to develop FE modelling of eddy current inspections of pipes using COMSOL Multiphysics software. An initial 2D model was developed to model axisymmetrical configurations, and tested on test case no. 6. The obtained results were compared to those obtained in CIVA. We observed a strong correlation between the results of the two models.

Owing to these encouraging results, the Vallourec research centre is continuing its development work to create 3D models in COMSOL Multiphysics, and thus obtain finite element models of the various eddy current inspection configurations for the non-destructive examination of pipes.
Fig. 7: Comparison between the simulated results in CIVA and COMSOL Multiphysics obtained on the external circular groove in the centred case

7. References


