Modelling of magnetic flux leakage testing through surface integral formulation

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Abstract
Magnetic flux leakage is a well-known non-destructive testing for ferromagnetic pipes during production in Vallourec. A testing bench is composed of an inductive circuit to create very high magnetic field within the piece under test and one or several sensors on the outer side of the pipe to detect flux leakages due to flaws. As opposed to other non-destructive techniques (like UT, ECT, RT, etc.), there is no available dedicated modelling tool on the market for this technology permitting to ease the development of new devices or optimize the testing. Vallourec Research Center France (VRCF) and CEA LIST are collaborating to develop this kind of tool. Concerning modelling, this problem is difficult to solve due to high differences between flaw and magnetic circuit in terms of size and magnetic nonlinearity of ferromagnetic pipes. This article presents results in the magneto-static case with linear behavior based on surface integral framework by CEA LIST. The goal is to validate the proposed tool on a set of reference notches through the comparison of modelling results and experimental data. Benefits of the proposed solution and perspectives of this tool are discussed.

Keywords: magnetic flux leakage, steel pipe, numerical modelling.

1. Introduction

NDT (nondestructive testing) equipments are crucial in the quality loop control for pipe production. Amongst all the classical NDT techniques (ultrasonic testing - UT, eddy current testing - ECT, radiographic testing - RT), magnetic flux leakage testing (MFL) is well-known to be efficient in the detection of volume defects in ferromagnetic steel pipes. For detection of inner defects, this method is efficient up to 15 mm of wall thickness.

Magnetic flux leakage testing is based on the magnetization of a ferromagnetic steel pipe through magnetization coils. Since the pipe is ferromagnetic, the magnetic field is channelled in the wall thickness. In case of defect, the magnetic field leaks [1]. The magnetic field on the surface of the pipe is modified. This modification can be measured through inductive coils or Hall effect sensors. The principle is very close to magnetic particle inspection (MPI) which is used for manual detection of defect and where a magnetization yoke is put on the piece under test and the magnetic leakage is revealed through the clustering of magnetic particles around the defect which acts as a magnet.

VRCF works on the improvement of magnetic flux leakage inspection in Vallourec mills. To help such developments, a MFL lab bench with a Rotomat® Ro440 base supplied by Institut Dr Foerster has been invested as illustrated Figure 1.

The excitation magnetic field is performed through inductive coils with DC-current. The magnetization field is channelled to the pipe through magnetization shoes. Between the two shoes, the field is channelled by the wall thickness. In case of the defect, the field leaks. To catch the leakage, the magnetic field is measured on the surface of the pipe. In the case of a mill bench, the pole shoes and the sensor may rotate around the pipe and the pipe is flowing at the center of the rotation. This set allows testing the whole pipe. In the opposite, the VRCF lab bench maintains the pipe to make it rotate. The testing head (pole shoes and sensor) are moving along the pipe. These two ways are equivalent for the testing.
In addition of the interest of this bench for the improvement of knowledge and the development of innovative solutions, modelling allows the anticipation of some results and to choose the right direction for the development to avoid expensive and long trials campaigns. To our knowledge, in the market there is no dedicated modelling software to the magnetic flux leakage testing like CIVA for UT, ECT and RT. The only manner to model this problem is to resort to finite element modelling through commercial software able to handle electromagnetic equations. Finite element modelling is well-known to be efficient to deal with problems with complex geometries. Nevertheless, even with commercial software, the set-up of the models is not easy and necessary computation time and memory can be very high. To overcome these limitations, a model is proposed hereafter to simulate magnetic field for MFL testing.

A first model has been detailed in [2]. This model is limited to 2D geometries but it can handle nonlinear materials (with a magnetic permeability depending on the magnetic field – B-H curves). Nevertheless, the limitation to 2D geometries allows only simulation of infinite length defect and prevents from modelling realistic defects. The model detailed here allows simulation of 3D defects.

2. 3D models for magnetic flux leakage testing

2.1 Integral model

In first approximation, the magnetic field is assumed to be static. It means that the eddy current due to the rotation of the pipe are not taken into account. This assumption allows reducing the model to a Laplace problem. This problem is considered under the integral form of the one-layer scalar potential [3]. In this case, the surface density to determine on the surface of the magnetic objects is the normal component of the magnetization vector. The magnetic field is computed through the calculation of the radiation of the density solution at the observed points.

For this study, the pipe and the magnetization shoes (Figure 1.b) are finely meshed and the cylindrical circuit between the poles (Figure 1.a) (with the coils) is grossly meshed. The mesh and the surface density are illustrated at Figure 2. The same magnetic permeability has been used for all the pieces (relative magnetic permeability is 420). The main difficulty is to
represent a small reference notch (less than 1 mm in deep and width) in a huge system (the outer diameter of the cylinder is around 1.3 m and the pipe is 1 m long).

Moreover, the surface density around the defect is low regarding the density around the poles; it may lead to numerical noise in the defect area. This problem should be normally solved through the fine meshing around sharp edges of the geometry and around the defect. Furthermore, approximate functions resorted are 2nd or 4th order polynomials. Thanks this, the mesh can unleashed around the poles and the defect allowing a reasonable computation time and a good accuracy of the solution.

![Figure 2: normalized solution of the integral probe. From left to right: global overview, zoom on pole and pipe, zoom on the notch. Coils are illustrated in yellow and the meshing is in white](image)

To avoid a different meshing at different position of the notch around the pipe, it is preferred to put the notch at the top of the pipe and to observe the magnetic field around the notch.

### 2.2 Finite element model

Simulations of magnetic flux leakage testing have also been carried out with Finite Element Model (FEM) software package. One of the advantages of FEM software is the possibility to handle a wide range of physics and geometry.

In order to reduce the numerical noise and to obtain a sufficiently accurate results, the notch and pipe have been finely meshed (Figure 3). The schemes discretization in space is based on second-order elements.

![Figure 2: mesh discretization. From left to right: global overview, zoom on pole and pipe.](image)
Even though it was possible to take the pipe rotation into account, it was decided to model a stationary pipe for this study. As, in the integral model the notch was positioned at the top of the pipe.

### 3. Comparison with experimental data

#### 3.1 Test-case definition

In order to assess the efficiency of the models, a test case is defined with the next characteristics:

- **Pipe:**
  - Outer diameter: 114.3 mm;
  - Wall thickness: 7.37 mm.
- Rotation speed: 60 rounds/min;
- Linear speed of the pipe: 60 mm/min

All the pieces have a relative magnetic permeability of 420.

The rotation speed is low enough to respect the magneto-static assumptions and to limit the effects of the eddy currents in the pipe. In a first stage, modelling results and experimental data (from the VRCF bench) are compared on a reference notch:

- Length: 30 mm;
- Width: 0.5 mm;
- Depth: 5% of the wall thickness.

The magnetic field is measured at an altitude of 1 mm above the pipe outer surface.

Two directions of the magnetic field are measured: the radial one $B_r$ and the tangential one $B_\theta$ as illustrated Figure 3.

*Figure 3: conventions for the magnetic field.*
3.2 Mapping of the magnetic field for the reference notch

The mapping of the magnetic field acquired on the pipe is illustrated Figure 4 with the reference notch. The mapping is limited to the area around the notch.

![Figure 4: mapping of the magnetic field measured on the VRCF bench](image)

Mappings are the magnetic field measured around the pipe and around the pipe in the chosen area. For all the mappings, the x-axis represents the longitudinal position of the sensor along the length of the pipe and the y-axis the angular position around the circumference of the pipe.

To compare all the results together (experimental data and simulated data), all the data are normalized according to the maximum amplitude of the signal.

The mapping of the simulated magnetic field through the integral form for is illustrated on Figure 5 in the case of the reference notch.
The same mapping has been performed in the case of finite element modelling. Results are illustrated Figure 6.

Results appear close together showing efficient model. Nevertheless, it must be stated that simulated data and experimental data are a little bit different: in the case of simulated data, the mapping is the magnetic field picked-up on points whereas in the case of experimental data, the measurements cannot be point-wise. In the latter case, experimental data should be a summation of the magnetic field on the measurement area.
3.3 Comparisons experimental data / simulated data

In order to compare the models with the experimental data, the two components of the magnetic field are plotted together.

Figure 7, the normal field $B_r$ is plotted in the case of the reference notch. On the left, the maximum value for each spire is plotted. On the right, the maximum value for each line is plotted. Figure 8, the same plots are illustrated for the tangential field $B_\theta$.

**Figure 7: radial component of the magnetic field $B_r$**
(integral form “CEA” / finite elements “VRCF” model results and experimental data “exp”)

**Figure 8: circunferential component of the magnetic field $B_\theta$**
(integral form “CEA” / finite elements “VRCF” model results and experimental data “exp”)

It appears on these figures that the simulated field and the measured field have a good matching. The asymmetry of the components along the angular position $\theta$ (figures at the right) is present in experimental data and simulated data. Nevertheless, along the longitudinal $z$ position the step-like profiles in the simulated data (figures at the left) are not observed in the experimental data. This difference could be explained by the fact that the transfer function of the sensor is not taken into account for the moment in the models. The sensor may sum the magnetic field on its active area.

The same comparison is performed for another notch (20 mm length / 0.5 mm width and 10% WT depth). The maximum amplitude of the signal on the first notch is considered as a reference notch for normalization of the data. Results are illustrated Figure 9 and Figure 10.

Figure 9: radial component of the magnetic field $B_r$

Figure 10: circumferential component of the magnetic field $B_\theta$
Even with a different notch size, the results of the models match together. The two models give satisfactory results close to the experimental data, even if we observe some minor differences in maximal amplitude (less than 2 dB) between experimental data and models on the radial component.

In addition with the way to handle the sensor and the manufacturing tolerances of the notches used in experiments, the differences between experimental data and simulated data could be explained by:

- Magneto-static assumption: the eddy currents are not taken into account with these models. This can influence the results even if the experimental data are acquired with a low rotation speed;
- Nonlinear material: the B-H curve is not taken into account in this model. The magnetic permeability is the same in all the elements. This also could influence the results.

These points represent potential ways of evolution of the models which could be studied in the future to raise the models as close as possible to the experiments.

4. Conclusion

Through a partnership between Vallourec Research Center France and CEA LIST, two modelling methods of magnetic flux leakage inspection of ferromagnetic steel pipes has been developed using respectively integral forms and finite elements.

First results of the modelling show a good matching with experimental data. Even if additional comparisons must be performed with other notch sizes to assess the accuracy of the models, the developed modelling tools already appears as promising for supporting future developments of this Non-Destructive Testing technology.

This work has permitted also to underline some potential ways of evolution in order to get more realistic models. First, the transfer function of the sensors should be investigated and integrated into the models. Then, it appears also that two main physical phenomena can influence the experimental results in a significant way and could be also investigated. The first one is the influence of the rotation speed which should have an effect on the results due to creation of eddy currents in the material. The second one is the non-linearity of the magnetic permeability in the material in function of the local magnetic field value, which is not taken into account in the present models.

References

