Numerical Modeling and Experimental Study of MFL Technique for Detection of Sub-surface Pittings in Pipelines

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Abstract
Magnetic flux leakage (MFL) technique is currently the most commonly used method for corrosion monitoring in oil and gas pipelines. The present work employs 3D finite element modeling (FEM) to investigate the performance of MFL technique in detecting sub-surface pittings in pipelines. In order to simulate sub-surface pitting corrosion of oil and gas pipelines, rectangular pittings with different depths are modeled on a 10mm-thick steel plate. Then, the axial and radial components of MFL signals are obtained to investigate the influence of defect depth on detectability of sub-surface pittings by the MFL technique. Also, the influence of lift-off distance on MFL signals has been analyzed for enhancing the reliability of detection of defects. The results indicate that the designed magnetizer assembly renders detectability of pitting defects located at 9mm below surface in a 10mm-thick steel plate, which can meet the industry demand for in-service inspection. The MFL signals have also been obtained experimentally using an experimental set-up at the laboratory facilities on a steel plate containing sub-surface pittings. A good agreement between FEM and experimental results confirms that 3D FEM is an effective analysis method for MFL technique in the pipeline inspection.

Keywords: Pipeline, Corrosion, Magnetic flux leakage.

1- Introduction
Pipelines are a major means for transporting the gas and oil products over long distances. The pipelines exist in a corrosive environment. In such conditions, corrosion and erosion cause the thickness of the steel pipelines to decrease and fail and can even lead to leakage and rupture which cause fires, explosions and pollution of the environment. Therefore, periodic corrosion monitoring of the pipelines is one of the most important tasks for pipelines. In particular, the detection and characterization of sub-surface defects has always been of great industrial interest. Over the years, several non-destructive testing (NDT) methods have been investigated for corrosion monitoring of pipelines. Pipelines are often made of ferromagnetic materials with good permeability, so that the use of magnetic flux leakage (MFL) method is quite suitable for inspecting the corrosions of the pipelines and locating defects. MFL is one type of electromagnetic methods which is widely used for non-destructive inspection of steel pipelines. The basic principle of this method is that a powerful permanent magnet such as neodymium magnets is used to magnetize to saturation the steel under inspection. At areas where there is corrosion or metal loss, magnetic flux leaks from the steel and this flux is detected by a set of magnetic sensors. Then, the sensors’ signals will be processed to identify damaged areas and to estimate width, length and depth of metal loss [1-7].

Finite element method (FEM) is a convenient tool to model process of corrosion detection by means of MFL method. Two-dimensional (2D) simulation has been used to study the MFL signals from different defect sizes, materials, magnetizing levels and so on and it has also shown to be an effective technique. However, in 2D simulations, defects are considered as 2D geometry instead of really 3D geometry. Also, the 2D simulation falls short of estimating accurately the required magnetic saturation level in the test piece. Some of the research works on MFL technique using FEM have been conducted worldwide [8-11].

In this study, COMSOL-based 3D FEM model is used to simulate MFL signals from sub-surface pitting corrosions of different depths in the 10 mm-thick ferromagnetic plate. Also, the influence of lift-off distance on the MFL signals is studied. The designed magnetizer assembly renders detectability of pitting defects located at 9mm below surface in a 10mm-thick steel plate, which can meet the industry demand for in-service inspection. Then, the designed magnetizer assembly and test piece are manufactured. Finally, MFL tests are carried out and the numerical simulation results are validated with the experimental results.

2- Finite element modeling (FEM)
Maxwell’s equations are used to model the MFL technique with the magneto static assumption. These equations are presented below [12-13].

\[ \nabla \times \mathbf{H} = 0 \]  
\[ \nabla \cdot \mathbf{B} = 0 \]

Where \( \mathbf{H} \) [A/m] is the intensity of the magnetic field, \( \mathbf{B} \) [T] is the magnetic flux density. In addition, the following equations have to be used.
Where $\mu_0$ is the permeability of free space ($4\pi\times10^{-7}$ Tm/A) and M is the magnetization of the ferromagnet and permanent magnet. Vector potential $A$ can be defined according to the below equation.

$$B = \nabla \times A$$ (4)

Then, the system equations follow as:

$$\nabla \times \left( \frac{1}{\mu_0} \nabla \times A - M \right) = 0$$ (5)

$$\nabla \times \left( \frac{1}{\mu_0} \nabla \times A \right) = 0$$ (6)

The equation (5) is applied to ferromagnetic materials and permanent magnet. The equation (6) is applied to free space. Boundary conditions i.e. the value of $A$ (vector potential) is considered zero at infinity and continuous at interfaces. The equations (5) and (6) are solved subject to defined boundary conditions to obtain the magnetic flux density detected by magnetic sensors.

3D FEM is a powerful tool for the analysis of the magnetizer assembly used in the MFL technique. It allows solving the non-linear equations governing the physical behavior of the system, and allows estimating the value of the magnetic field components at every point in the system. In this paper, COMSOL software was used to set up the 3D MFL model in the magneto static mode.

3D view of the MFL system together with the magnetizer arrangement is shown in Figure 1. The specimen length was 400mm, width was 140mm, and thickness was 10mm. The magnetizer assembly had two magnets, two couplings and one yoke. Yoke was meant to complete the magnetic circuit. Two neodymium magnets of thickness 40mm were used to magnetize the specimen to saturation. In this study, Magnetization of the permanent magnets was considered equal to 10e6 A/m.

![Figure 1. 3D model of MFL system](image)

The material of the specimen, couplings and yoke was steel X52. Figure 2 shows the B-H curve of X52 material. According to Figure 2, the strength of the magnetic field required to magnetically saturate the specimen is about 2Tesla.

![Figure 2. BH curve of X52 material](image)

Figure 3 schematically shows the specimen containing sub-surface pitting and lift-off distance. The rectangular sub-surface pitting was assumed to be present at the center of the specimen. The width and length of the pitting were both
These dimensions were kept constant, while the depth of the pitting was varied from 10% (1mm) to 90% (9mm) of the thickness of the specimen.

Figure 3. Schematic illustration of sub-surface pitting and lift-off distance

Figure 4 shows the 3D model discretized by tetrahedral elements. The elements near defects were refined to obtain precise results.

Figure 4. Finite element mesh

After defining geometry, materials, boundary conditions and mesh, the solution by the finite element method can be calculated. Figure 5 shows the saturation levels inside the specimen obtained from 3D model and how the field lines travel through each element of the magnetizer assembly. As shown in Figure 5, the flux lines originate at the north pole of the right magnet, pass through a ferromagnetic coupling, enter the plate wall, pass through the other ferromagnetic coupling, and then enter the south pole of the left magnet. Inside the ferromagnetic yoke, the flux lines flow from the left to the right, thus completing the magnetic circuit. The appropriate magnetization level of the specimen is an important parameter of MFL technique for pipeline inspection.

Figure 5. Magnetic flux behavior in the magnetizer assembly

COMSOL allows visualizing of the amplitude of the magnetic flux components onto the scanning area as a C-scan image. Figure 6 shows the C-scan image of the axial and radial MFL components for the sub-surface pitting with a depth of 1mm. Similarly, Figure 7 shows the C-scan image of the axial and radial MFL components for the sub-surface pitting with a depth of 9mm. The solid squares in the C-scans represent the real position of the pitting. The lift-off was considered 2mm. The intensities of both components of the leakage fields for the pitting are found to increase with the increase in the pitting depth. Also, the length and width of the pitting can be easily predicted from the span of MFL signals (both radial and axial).
The axial and radial MFL B-scans for a range of pitting depths from 1mm to 9mm are shown in Figures 8(a) and (b), respectively. It can be seen that the intensity of MFL signals decreases with the decreasing depths of the sub-surface pitting. However, sub-surface pittings with different depths can be discriminated easily.

Pitting depth is the most important parameter for the pipeline integrity. As shown from the Figure 8, the designed magnetizer assembly renders detectability of pitting located at 9mm below surface in a 10mm-thick steel plate, which can meet the industry demand for in-service inspection. The peak-to-peak value of radial flux resulting from the sub-surface pitting corrosion of 10%t (1mm) depth is about 100gauss, which can easily be detected by magnetic sensors.

Signal amplitudes for sub-surface pittings of different depths have been determined and are plotted in Figures 9(a) and (b) for both axial and radial MFL components. It can be seen that the relation between MFL amplitudes and pitting depths is somewhat linear.
Figures 10(a) and (b) show the relation between MFL amplitudes and pitting depths at different lift-off distances for both axial and radial MFL components. It can be seen that the MFL amplitudes decrease with the increase in lift-off distance. However, the effect of lift-off distance on the radial MFL amplitudes is more pronounced than axial MFL amplitudes.

3- Experimental tests
Following the FEM, an experimental MFL system was established as shown in Figure 11(a). The measurement system consisted of a magnetizer assembly, a three-axis scanner, a data acquisition system and other associated units. The axial component of the MFL signals was measured with an mg-3002 gauss meter from Lutron. The distance between the specimen surface and the sensor was kept constant (2mm), as the sensor was moving by means of a scanner. The measurements were made on a ferromagnetic steel plate with a thickness of 10mm. The photo of the steel plate is shown in Figure 11(b). Rectangular pitting defects with different depths were machined at one side of the specimen. Figure 11(c) shows the details of the machined pittings. During the MFL measurements, the sensor was placed on the defect-free side of the specimen to detect the sub-surface pittings. The step resolution of the scanner was set to 4mm in axial direction and 5mm in circumferential direction. At every x-y position in the scanning area, the MFL signals were precisely measured and recorded on a computer for the further processing.
Figure 12 shows the result of the experimental test as a C-scan image. The positions of the pittings are given by the black squares. Figure 12 shows that magnetic flux spreads in the circumferential direction beyond the defects and overestimate the corrosion areas. This effect often called blooming effect.

Figure 13 shows the MFL B-scans of the experiment and FEM in the vicinity of the sub-surface pittings with depths of 4mm and 6mm. The FEM signal patterns are very similar to the experimental signals. The mean error is 9%. The reason for this relative error is mainly due to the small inaccuracies in the magnetic properties of the material used in the FEM with respect to the magnetic properties of the real material used in the experiment.

4- Conclusions
This paper has investigated the performance of MFL technique for the detection of localized sub-surface pittings in ferromagnetic pipelines. The study was carried out through extensive finite element analysis in 3D using COMSOL software. In order to simulate sub-surface pitting corrosion of oil and gas pipelines, rectangular pittings with different depths were modeled on a 10mm-thick steel plate. Then, the axial and radial components of MFL signals were obtained to investigate the influence of defect depth on detectability of sub-surface pittings by the MFL technique. Also, the influence of lift-off distance on MFL signals was analyzed for enhancing the reliability of detection of defects. The results indicated that the designed magnetizer assembly renders detectability of pittings located at 9mm below surface in a 10mm-thick steel plate, which can meet the industry demand for in-service inspection. Finally, an experimental set-up was established for evaluating the FEM results, which were in good agreement with experimental measurements.

References


