Three-Dimensional FEM Of Magnetic Flux Leakage Technique In Plates With Defect And Without Defect

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Abstract

Magnetic flux leakage (MFL) testing is a prospective method for quantifying defects [1]. The normal components of MFL are usually used as a key vector to get defect information in MFL testing. The depth of defect is often accepted for justifying the dangerousness of defects [2]. So it is vital to get the depth information from the normal component of MFL in quantification testing. There are many factors such as defects depths, widths, lengths and shapes affecting the normal component of MFL. Many researches have focused on the influences of defects depths, widths and opening directions. However, there is little comment about defect length which is also an important parameter affecting MFL. In this paper, the MFL characteristics of defects, which have the same depth, same width, and different lengths, were studied. These works were helpful for MFL quantification testing. The magnetic flux leakage (MFL) method is currently the most commonly used pipeline inspection technique. Magnetic flux leakage (MFL) technique is widely used for non-destructive detection and evaluation of surface and sub-surface defects in ferromagnetic objects such as long oil and gas pipelines, storage tank floors and wire ropes [1]. The relation between defect parameters and MFL signals are analyzed. The tangential and normal components of leakage fields have been predicted to study the influence of defect location and depth on the detect ability of sub-surface defects by the MFL technique. The aim of the simulation is to find out how different flaw geometries and orientations influence the measured signal. To find flaws near the surface, a magnetic flux leakage (MFL) inspection system can be applied. In this paper, 3D FEM is used to analyze the MFL signals, a generalized potential formulation to the magneto static field MFL problem is discussed, typical 3D defects is accurately modeled and detailed comparison is done for model with defect and without defect. Finally, we want to infer the flaw geometry from the signals.

Keywords: Magnetic Flux Leakage, Magnetic flux density, 3D finite element modeling, Simulation analysis, Magnetic flux leakage signals.

1. Introduction

Magnetic flux leakage (MFL) technique is one of the basic methods of non-destructive testing (NDT) used for the in-line inspection (ILI) of pipelines and other objects made from materials with high magnetic permeability [1–3]. The MFL method uses the fact that near a defect in an externally magnetised material the field is forced out of the metal (“leaking”), which can be detected by field sensors. This “leak-field” provides information about the location and size, in some cases also the shape, of the defect. In this technique, the test object is magnetized to near saturation flux density. The presence of a defect in the test object acts as localized magnetic dipole with effective magnetic moment opposite to the applied magnetic field. This results in a proportion of the magnetic field leak out of the object surface. This leakage flux is detected by magnetic sensors and used to estimate the shape and size of the defect [2].
One advantage of MFL technique is its ability to model the leakage field from defect. The modeling enables the study of field/defect interactions and helps in better understanding and effective utilization of the MFL technique.

MFL modeling using FE method was first carried out by Lord and Huang [3]. This paper presents the three-dimensional FE modeling of leakage magnetic fields from surface and sub-surface defects of different dimensions in 12 mm thick carbon steel plate. The details of 3D model and results of FE study of the effects of depth location and depth on the detectability of sub-surface defects in the MFL technique are discussed in the paper.

1.1. Principle of MFL Detection

MFL test device obtains the magnitude of the defects by measuring the magnetic flux density leaked from the surface of the ferromagnetic material. If the components to be measured are not defective then all magnetic flux will pass through the components, as seen from Fig. 1(a). The presence of a defect in a magnetized ferromagnetic material results in a redistribution of magnetic field in the vicinity of the flaw, causing some of the magnetic field to "leak" out into the surrounding medium as shown in Fig. 1(b). This leakage field can be detected, using Hall element sensors to measure the axial or radial components of the magnetic flux density B.

![Diagram of MFL Detection](image)

Typical axial components of MFL signals obtained for the geometry. These signals are a measure of the fields which leak out from under the defect and this makes the magnetic flux pass through the detected components, making a detour from the defects. The width of the signal is proportional to the defect length (axial dimension) and the amplitude of the signal is proportional to both the defect length and depth. The last step in an MFL inspection is analysis.

Analysis is the process of estimating the geometry or severity of a defect (or imperfection) from the measured flux leakage field. The techniques and success of analyzing MFL data depend on the capabilities and limitations of the MFL tool, which are established by design and operational tradeoffs.

Magnetic flux leakage technique is generally considered to be the most cost-effective method for corrosion monitoring. MFL signals due to any irregularities are detected and stored within the tool.

Treating the MFL problem as magneto static, the following equations have been used with usual notations:

\[ B = \mu_0 H \]

\[ H = \mu_0 H + \mu_0 M \]
The field equations are supplemented by the constitutive relation that describes the behavior of electromagnetic materials. In permanent magnet region,

\[ \{B\} = \{\mu\} \{H\} + \mu_0 \{M\} \]

In other region

\[ \{B\} = \{\mu\}\{H\} \]

Figure 1.2. 3D Finite element modeling

Figure 1.3. Plotting of axial and radial component

2. Magnetization analysis of the pipeline

The magnetic flux leakage (MFL) type non-destructive testing (NDT) system is widely used to detect metal losses of the underground pipe in gas (PIG) pipelines[2-4]. In the system, a magnetization level is designed to be high enough to saturate the pipeline in order to leak the stray field in the metal loss region. The defect signals are measured during the sensor modules are running inside the underground pipeline. In the system, the sensor modules are consisted of permanent magnet, magnetic yoke and Hall sensors to detect the metal loss corrosion defect and any other damages of the oil-gas pipeline. The object pipeline is magnetically saturated by a
magnetic system with permanent magnet and yokes as in Fig. 1. Hall sensors detect the stray leakage fields in the metal loss region.

A sensor placed inside the pipe near the area of reduced wall thickness senses increased flux density due to the MFL. The measured flux leakage is dependent on the material characteristics of the pipe, wall thickness, stresses in pipelines, and dimensions of the flaw. Apart from the reduction of wall thickness, a crack in the pipe wall can also cause flux leakage.

MFL modeling is based on two methods:

**Finite element (FE) method**

In FE method, the leakage field is obtained by solving the relevant Maxwell’s equations with appropriate boundary conditions. The FE method is capable of modeling of nonlinear problems and irregular geometries which are difficult to be modeled analytically.

![Figure 3. Surface plot of axial magnetic flux density with defect 3.25x20 mm](image)

![Figure 4. Surface plot of axial magnetic flux density without defect](image)

2. Use of COMSOL Multiphysics

For our simulations we used COMSOL Multiphysics 3.5a with MATLAB R2007b. The situation is modeled using the “Electric and Induction currents” application mode contained in the AC/DC module. We used a time harmonic analysis and solved for both the electric and
magnetic potential. As the yoke moves rather slow over the steel object’s surface, the influence of this movement to the induced magnetic field is negligible. Hence, we set \( v=0 \) in the model.

3. 3D simulation

Three-dimensional finite element (FE) modeling of magnetic flux leakage (MFL) technique has been performed using COMSOL 4.2 for prediction of leakage fields from surface and sub-surface defects in 12.5 mm thick carbon steel plate. We start with the simpler and less memory and time consuming simulations in 2D. These simulations were performed on a cross section of the inspection system, such that the current through the coils is perpendicular to the geometry plane.

3.1 Geometry

With the 2D simulation taking place in the x-z-plane, we use the following axis convention:

- x-axis: the horizontal direction (this is the direction in which the yoke moves)
- y-axis: the height direction
- z-axis: perpendicular to 2D simulation

The 2D cross section shape (x-y-plane) of the yoke has been approximated by Beziér-curves. Concerning the coils, we waive to model single excitation windings. Instead, we define an external current on the cross section area. The steel object is a rectangular of 10 mm height and 115 mm width. The whole inspection scene is enclosed in a rectangular air region.

The MFL method relies on calibration runs for correct interpretation of the leakage signals in terms of defect location, size, and depth. The experimental results indicated that some pipeline defects can be found by former sensors and back sensors and its inner-outer position, other defects still can’t be found. The MFL signals obtained depend not only on the detector and the defect but also on running conditions, such as the tester’s velocity and stress, life-off and so on. Unlike analytical model finite elements simulation allows to consider actual defect shape features and also imperfections of magnetizing and measuring system. Still due to great amount of estimated parameters numerical diagnostic model built in such a way loses compactness property. To achieve proper parameterization accuracy several dozens of thousand models shall be calculated. The MFL inspection assembly is commonly referred to as pig”. In the MFL inspection tool, permanent or electromagnets are used to magnetize the pipe-wall in an axial direction and an array of Hall-effect sensors is usually installed around the circumference of the pig to sense the leakage flux caused by anomalies in the pipe-wall.

4. Conclusions

Three-dimensional FE modeling has been performed to study the effects of defect location and depth on the detectability of sub-surface defects in the MFL technique. The aim of our simulation is to find out how different flaw geometries and orientations influence the measured signal. However, the focus of this work is the technical realization of the simulation - especially the handling of the very thin magnetic layer in 3D. We limit our work mainly to block-shaped flaws (notches) which we varied in width, depth and orientation.
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REFERENCES