Springer

Journal of Mechanical Science and Technology 23 (2009) 109~113

Journal of
Mechanical
Science and
Technology

www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-008-1005-5

Numerical simulation and experiments of magnetic flux leakage inspection in pipeline steel †

Xun-Bo Li[1,*], Xiang Li[1], Liang Chen[1], Pei-Fu Feng[1],
Hai-Dong Wang[1] and Zuo-Ying Huang[2]

[1]School of Mechatronics Engineering, University of Electronic Science and Technology of China, Chengdu, 610054, P.R. China
[2]Department of Instrument Science and Engineering, Shanghai Jiaotong University, Shanghai, 200240, P.R. China

(Manuscript Received June 19, 2008; Revised September 25, 2008; Accepted October 1, 2008)

Abstract

The magnetic flux leakage (MFL) method is currently the most commonly used pipeline inspection technique. In this paper, numerical simulation and experimental investigation on defect inspection in pipeline steel using MFL were carried out. In theoretical analysis, typical three-dimensional (3D) defects were accurately modeled and detailed MFL signals in the test surface were calculated by 3D finite element method (FEM). To confirm the 3D FEM results, different artificial defects were made and the MFL experiments were performed. The experimental study demonstrated that the results were agreement with the 3D FEM result. The results show that the 3D FEM is an effective analysis method for pipeline steel MFL inspection.

Keywords: Finite element method; Inspection; Magnetic flux leakage; Pipeline steel

1. Introduction

With the widespread application and fast development of oil pipeline networks, the pipeline inspection technology has been used more extensively. Over the years, many different non-destructive testing techniques have been investigated for evaluating the condition of pipelines. The magnetic flux leakage (MFL) technique is generally considered to be the most cost-effective method for corrosion monitoring. In this technique, the wall of the pipeline is magnetized axially to near saturation flux density. If, at some point, the wall thickness is reduced by a defect, a higher fraction of the magnetic flux will 'leak' from the wall into the air inside and outside the pipe. The magnetic leakage field measured nearby the pipe contains information about the pipe conditions. The inspection vehicle consists of a magnetizer, which is made of permanent magnet or coil, and circumferentially distributed sensor assembly which is a hall sensor or signal pick up coil [1-5].

Two-dimensional (2D) finite element method (FEM) has been used to investigate the MFL signals under different defect shapes, materials, magnetizing situation and so on, and it has also proven to be an effective method [6]. However, in 2D FEM, the defects are also treated as 2D profile instead of actually three-dimensional (3D) geometry, and the resulting MFL signal is single channel, whereas the actual signals are multi-channel. More recently, 3D FEM has been used to analyze the flaw MFL fields [7-9].

In this paper, 3D FEM is adopted to analyze the MFL method, accurate 3D defects are modeled and detailed MFL signals in the test surface are calculated by using this method. MFL experiments are conducted and the experimental results are compared with that of FEM.

† This paper was recommended for publication in revised form by Associate Editor Jooho Choi
*Corresponding author. Tel.: +86 28 83202576, Fax.: +86 28 83202576
E-mail address: zwest_213@163.com

2. 3D Finite element method of MFL model

Using the magnetic scalar potential method, the MFL problem can be treated as a magnetostatic problem which can be formulated by Maxwell's equations as follows:

$$\nabla \times \{H\} = \{J_s\} \quad (1)$$

$$\nabla \bullet \{B\} = 0 \quad (2)$$

where {H} is the magnetic field intensity vector, $\{J_s\}$ is the applied source current density vector and {B} is the magnetic flux density vector.

To describe the properties of the electromagnetic materials, the field equations are supplemented by the constitutive relationships.

$$\{B\} = [\mu]\{H\} + \mu_0\{M_0\} \quad (3)$$

in the permanent magnet region.

$$\{B\} = [\mu]\{H\} \quad (4)$$

in other regions.
where [μ] is the magnetic permeability matrix, and $\{M_0\}$ is the permanent intrinsic magnetization vector.

In the domain of a magnetostatic field problem, a solution is sought which satisfies the Maxwell Eqs. (1)-(2) and the constitutive relationships Eq. (3) in the following form:

$$\{H\} = \{H_g\} - \nabla\phi_g \quad (5)$$

$$\nabla \bullet [\mu]\nabla\phi_g - \nabla \bullet [\mu]\{H_g\} - \nabla \bullet \mu_0\{M_0\} = \{0\} \quad (6)$$

where $\{H_g\}$ is the preliminary magnetic field, and ϕ_g is the generalized potential.

Based on variation principles, the finite element matrix equations can be derived. Furthermore, these scalar potential element matrices can be written by using the following formulae:

$$\left[K^M\right] = \left[K^L\right] + \left[K^N\right] \quad (7)$$

$$\left[K^L\right] = \int_V \left(\nabla\{N\}^T\right)^T [\mu]\left(\nabla\{N\}^T\right) dV \quad (8)$$

$$\left[K^N\right] = \int_V \frac{\partial\mu_h}{\partial|H|}\left(\{H\}^T\nabla\{N\}^T\right)^T\left(\{H\}^T\nabla\{N\}^T\right)\frac{dV}{|H|} \quad (9)$$

where {N} is the element shape functions.

Load vectors are expressed as:

$$[J_i] = \int_V \left(\nabla\{N\}^T\right)^T [\mu]\left(|H_g| + |H_c|\right) dV \quad (10)$$

where $|H_c|$ is the coercive force vector.

Fig. 1 shows the geometry of the problem in a simplified 3D MFL model. The specimen length is 500mm, width is 120mm, and thickness is 12mm. The magnetic circuit consists of the yoke, permanent magnet, brush and the pipeline. Two permanent magnets, of thickness 20mm, are used for magnetic flux induction to magnetize the pipeline to saturation, and the material accumulates high magnetic energy, with high coercive force of 872000 A/m and stable magnetic property. The material of the pipeline is X52 and the yoke is mild steel. The flaw is located at the center of the specimen.

Fig. 2 shows the B-H curves. It is assumed that the material of the brush has the same B-H curve as that of the yoke material. The calculations are made with the ANSYS finite element software. The most fundamental element of 3D is a tetrahedron. Element PLANE53 is used to define the main model region.

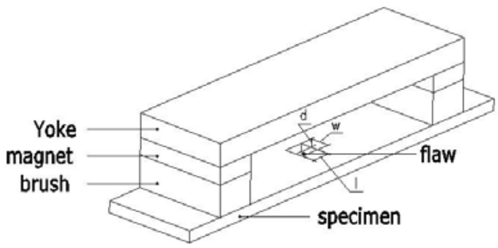


Fig. 1. Geometry of 3D MFL model.

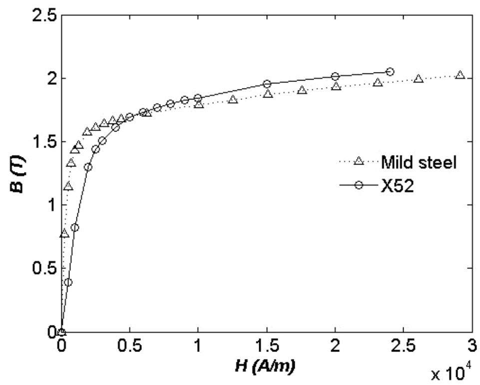
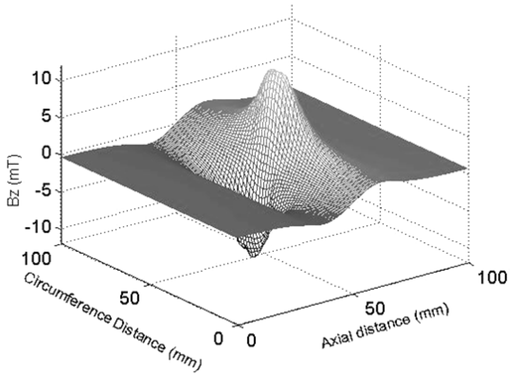


Fig. 2. B-H curve of the material.

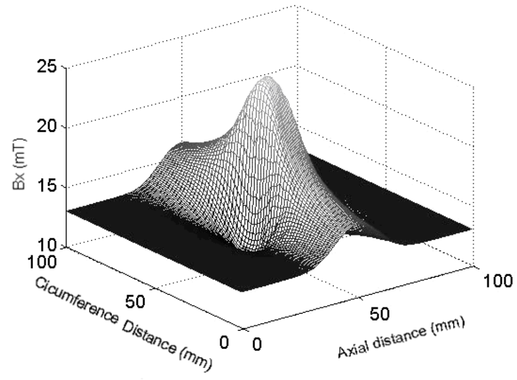
Fig. 3 shows a surface plot of the amplitude of the radial and axial component of magnetic flux density in the vicinity of a flaw which was 10mm×10mm×6mm and lift-off is 2mm.

3. Experiments and discussions

The photograph of the MFL measurements system is shown in Fig. 4. The apparatus contains a permanent magnet assembly, a DC motor control system, a data acquisition system (DAS) and other associated units. The permanent magnet assembly includes a magnetic circuit, a hall probe, and a signal pre-procession circuit. A DC motor, a speed-transformation and two relays constitute the DC motor control system which is used to control the movement of the permanent magnet assembly. The main unit of the DAS is a host PC, and a data acquisition instrument is used for data monitor and logging.



(a) Radial component



(b) Axial component

Fig. 3. Surface plot of the amplitude of the radial and axial component of magnetic flux density (10mm×10mm×6mm).

There are 16 Hall sensors of which lift-off is 2mm to measure the leakage flux, with the necessary amplification and filter to record the signal. The Hall sensor, UGN3503, is a hall-effect integrated sensor which includes a Hall sensing element, linear amplifier, and emitter-follower output stage and sensitivity is 13mV/mT. The interval of center of each sensor is 10mm.

In order to perform this experiment, different artificial defects are made on the specimen whose thickness is 12mm. Fig. 5 shows the plots of radial component and axial component of magnetic flux density of the defects which have a diameter of 12mm and their depths are 10% (1.2mm), 20% (2.5mm), 50% (6mm), 100% (12mm), respectively. The velocity of the permanent magnet assembly is 200mm/s with a sample frequency of 1000Hz.

To confirm the 3D FEM results, we compared it with the experimental results. Fig. 6 shows the MFL signal radial component plot of the experiment and FEM in the vicinity of a defect with a diameter of 12mm and depth of 6mm. The experiment, real line, MFL peak-peak value (MFLpp) is 66.6mT, and the FEM, dashed, MFLpp is 64.7mT. The relative error is 2.9%. The FEM signal patterns are very similar to the experimental measurement. This comparison and the other 11 comparisons which include different length, width and depth are shown in Table 1. It demonstrates that the 3D FEM simulation is believable.

4. Conclusions

This paper presents 3D FEM analysis and experiments of MFL inspection in pipeline steel. Accurate problem description and experimental results are provided. The magnetic flux density is calculated for flaws by using 3D FEM. Different artificial defects are made and the MFL experiments are performed. The experimental results demonstrate that the 3D FEM results were in agreement with the experiment

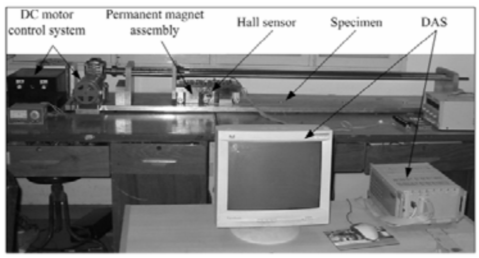
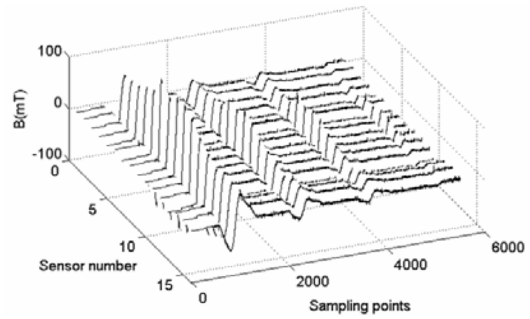


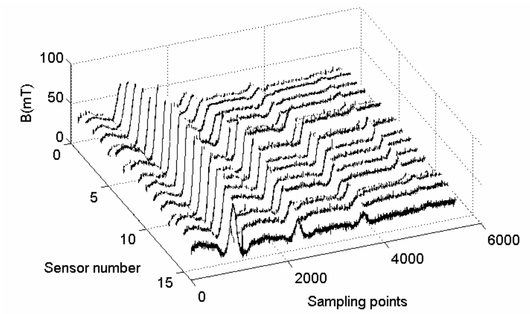
Fig. 4. Photograph of the MFL measurement system.

Table1. MFLpp comparison between experiments and FEM.

ID	Defect dimension (mm)	Defect depth (mm)	Experiment MFLpp (mT)	FEM MFLpp (mT)	Relative Error (%)
1	Φ12	1.2	13.5	12.3	8.9
2	Φ12	2.5	31.8	29.6	6.9
3	Φ12	6	66.6	64.7	2.9
4	Φ12	12	153.5	141.9	7.9
5	Φ16	2.5	46.7	42.5	9.0
6	Φ16	6	98.4	93.5	5.0
7	Φ16	9.6	132.6	128.8	2.9
8	12×2	6	16.4	14.4	12.2
9	12×6	6	46.5	43.2	7.1
10	12×12	6	82.3	75.9	7.7
11	6×12	6	75.3	71.5	5.1
12	2×12	6	70.2	67.2	4.3



(a) Radial component



(b) Axial component

Fig. 5. Plot of radial and axial component of magnetic flux density (12mm diameter and with different depths of 12mm, 6mm, 2.5mm, and 1.2mm).

results. The results show that the 3D FEM is an effective analysis method for MFL in pipeline steel inspection.

Acknowledgments

The authors thank the Institute of Automatic Detection, Shanghai Jiaotong University for providing the experiments. This work was supported by JIN CHUAN Advance Research Program of Science and Technology, and Science Foundation for Young Teachers of University of Electronic Science and Technology of China.

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Xun-Bo Li received his M.S. and Ph.D degree from University of Electronic Science and Technology of China in 1991 and 2001, respectively. Dr. Li is currently a Professor at the School of Mechatronics Engineering, University of Electronic Science and Technology of China in Chengdu, P.R. China. Dr. Li's research interests are in the area of Mechatronics, measurement and NDT.