3D FINITE ELEMENT METHODS FOR MODELING MFL INSPECTION OF PIPELINES

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INTRODUCTION

It is estimated that there are about one million kilometers of gas and liquid transmission pipelines operating across the globe today. Pipelines, owing to their strategic role of transporting gas and liquid fuels, are of immense capital value. Potential degradation and failure of pipelines is a sensitive issue both with the public and legislative bodies, since the consequences of failure could include injuries and death. In addition, pipeline failures have severe financial consequences. More than half the pipelines in use today are 30 or more years old and invariably have experienced some deterioration. Preventive maintenance using nondestructive evaluation (NDE) techniques plays an important role in ensuring safe pipeline operation [1].

Magnetic flux leakage (MFL) inspection, over the years, has proven to be the most effective NDE technique in achieving the required performance for metal-loss inspection in a pipeline environment [2]. The MFL method is a magnetostatic method, commonly using permanent magnets to set up the required electromagnetic field. The magnetizer used in the MFL inspection of gas pipelines is shown in Figure 1. The inspection tool magnetizes the ferromagnetic pipewall in between the two brushes. The presence of a defect in the pipewall results in a redistribution of magnetic field in the vicinity of the flaw, causing some of the magnetic field to leak out. The leakage field is detected using Hall element sensors to measure the axial or radial components of the magnetic flux density $\overline{B}$. This constitutes the active leakage field measurement, which is well documented in literature [3].

Several numerical methods are available for simulating magnetostatic phenomena, both in terms of the choice of the variable and also the solution method.

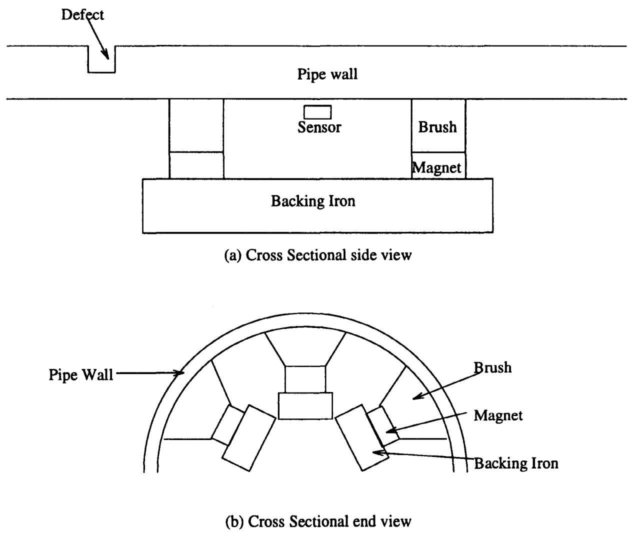

Figure 1. Typical MFL inspection vehicle.

However, each method has its own limitations when applied to the specific situation of modeling MFL inspection of pipelines. This paper studies the finite element modeling (FEM) techniques available for the 3D modeling of MFL inspection of pipelines. Two cases are considered: (a) Inspections in which the magnetizer moves at velocities of less than 5 ms^{-1}, where velocity effects are negligible. For this situation the magnetic scalar potential (ψ) formulation (MSP formulation) is used in conjunction with the classical node-based finite element technique. (b) For magnetizer velocities above 5 ms^{-1}, velocity effects are significant and the model has to incorporate these effects. The magnetic vector potential ($\overline{A}$) formulation (MVP formulation), using edge-based finite element methods, is used in these situations. This paper presents the governing equations and the method of solution for each case. Results are presented validating the codes for the static case. Results demonstrating the effects of velocity on the field contours are also included.

FINITE ELEMENT METHODS

Choice of Variables

Finite element modeling of magnetostatic fields, in terms of field quantities $(\overline{E}, \overline{H}, \overline{B}, \overline{D} or \overline{J})$, would be ideal since they are the quantities of interest. However, they are all discontinuous over boundaries and material interfaces: $D_{1t} \neq D_{2t}$, $E_{1n} \neq E_{2n}$ when $\epsilon_1 \neq \epsilon_2$; $B_{1t} \neq B_{2t}$, $H_{1n} \neq H_{2n}$ when $\mu_1 \neq \mu_2$; $J_{1t} \neq J_{2t}$ when $\sigma_1 \neq \sigma_2$. These discontinuities are difficult to model in a finite element simulation. Hence auxiliary variables such as the magnetic scalar potential (ψ) and the magnetic vector potential ($\overline{A}$) have been traditionally used in solving magnetostatic problems using finite element techniques.

For magnetostatics, $\nabla \times \overline{H} = 0$. Hence we can define the magnetic scalar potential ψ as: $\overline{H} = -\nabla\psi$. Also, considering that $\nabla.\overline{B} = 0$, the governing equation in the case of MSP formulation is written as the Poisson's equation:

$$\nabla.\mu\nabla\psi = -\rho_m \tag{1}$$

where $\rho_m = -\nabla.\overline{B}_{rem}$ is referred to as the "magnetic charge density" ($\overline{B}_{rem}$ is the remanent magnetization of the material).

The alternative approach is to use the magnetic vector potential ($\overline{A}$). Since $\nabla.\overline{B} = 0$, we can define $\overline{A}$ such that $\nabla \times \overline{A} = \overline{B}$. Considering $\nabla \times \overline{H} = \overline{J}_s$, we can arrive at the elliptic partial differential equation:

$$\nabla \times \frac{1}{\mu} \nabla \times \overline{A} = \overline{J}_s \tag{2}$$

where $\overline{J}_s$ is the source current density used to simulate the permanent magnet as an equivalent electromagnet.

In situations where motionally induced currents are significant, $\nabla \times \overline{H} = \overline{J}$ (where $\overline{J}$ is the sum of the source current density and the motionally induced current density). In this case, as per the definitions above, the MSP formulation cannot be used. However, the MVP formulation can be used and the governing equation is:

$$\nabla \times \frac{1}{\mu} \nabla \times \overline{A} = \overline{J}_s - \sigma \frac{\partial \overline{A}}{\partial t} + \sigma \overline{V} \times \nabla \times \overline{A} \tag{3}$$

The discretization of the governing equation, for the finite element solution, involves the selection of optimal element shapes and interpolating functions which is discussed in the following paragraphs.

Choice of Elements

Classical FEM methods use nodal elements, where the unknown variable is calculated at the nodes. The shape functions used in this case are scalars and hence these elements are ideally suited for calculating scalar quantities. The finite element approximation using nodal elements is expressed as:

$$\psi = \sum_k \psi_k N_k \tag{4}$$

where the subscript k stands for the node number and N_k is the scalar shape function corresponding to that node.

Nodal elements are also employed to compute vectors by considering the vector as a triplet of scalars, and the approximation is:

$$\overline{A} = \sum_k \overline{A}_k N_k \tag{5}$$

This method of computing vector quantities, using scalar elements, has proven to be extremely useful in 2D modeling. However, in 3D modeling, this method encounters several problems including: (a) difficulty in ensuring the divergence condition, (b) difficulty of imposing material interface conditions, and (c) field singularities at conductor corners.

Recently, edge elements, where the shape functions are vectors, have been shown to be better suited for modeling vector fields in three dimensions. The edge-based FEM method has been shown to be free of all the previously mentioned

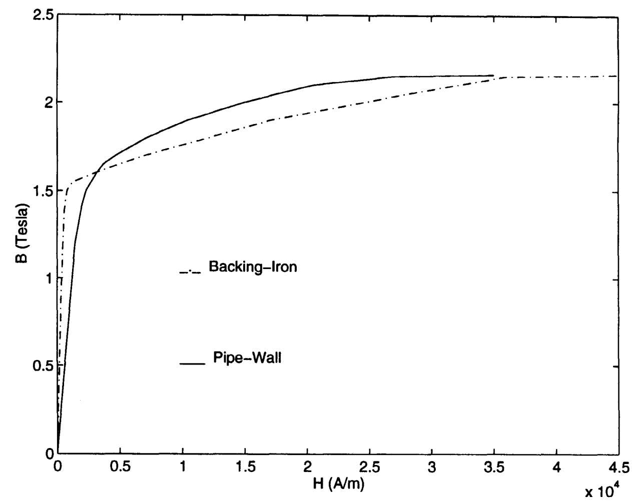

Figure 2. BH curves used in the FEM code.

shortcomings associated with nodal elements [4]. The finite element approximation using edge elements is:

$$\overline{A} = \sum_m A_m \overline{N}_m \tag{6}$$

Here, the subscript m is the edge number and $\overline{N}_m$ is the vector shape function corresponding to that edge.

As described earlier, this work reports : (a) results from the MSP formulation corresponding to Equation 1, solved using the nodal elements corresponding to Equation 4, and (b) results from the MVP formulation corresponding to Equations 2 and 3 using edge elements corresponding to Equation 6.

RESULTS

Numerical methods must be validated before accepting the results generated. The methods can be validated either by comparing with experiments, or by comparing with a different approach which could be either analytical or numerical. The MSP formulation using nodal elements has been validated by comparing with experimental results. Experimental results include measured values of the static axial ($\overline{B}_z$), and radial ($\overline{B}_r$) components of flux density, for an axial scan line directly above the pipewall, in the vicinity of the magnetizer. The geometries considered are: (a) the magnetizer placed in the pipe, and (b) the magnetizer placed in air (the scan line being at a liftoff equal to the pipewall thickness).

In modeling the geometry shown in Figure 1 several variables have to be accurately specified including: (a) the dimensions of the different parts, (b) the coercivity of the permanent magnet, and (c) the nonlinear BH curves for the ferromagnetic parts. Whereas the dimensions of the geometry can be accurately controlled by the manufacturer, it is more difficult to control, exactly, the nonlinear behavior of the ferromagnetic parts or the coercivity of the magnet.

Since the permanent magnet is the source of the magnetic field for the MFL

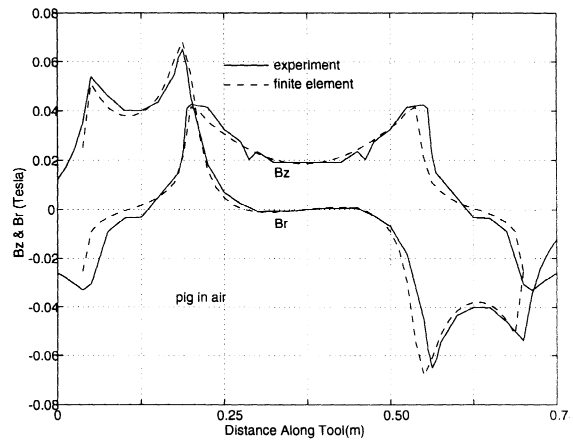

Figure 3. Comparison of experimental and FEM results with the magnetizer placed in air.

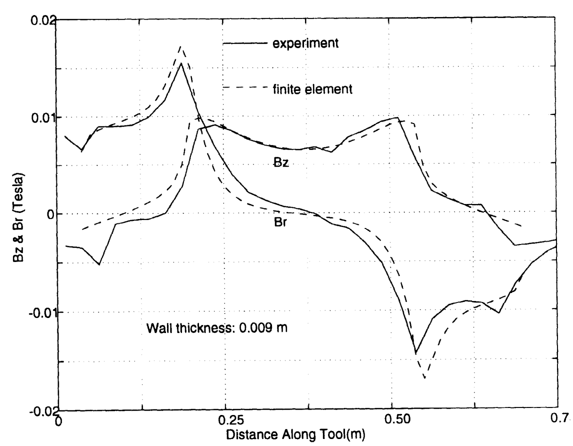

Figure 4. Comparisons of experimental and FEM results with the magnetizer place in a pipe.

inspection, the ability to predict quantitatively accurate results depends largely on the accuracy of the coercivity of the magnet used in the model. Since, using the manufacturer specified coercivity did not result in the desired accuracy from the FEM codes, experiments were conducted at the Battelle Memorial Research Center, in Columbus, Ohio, to estimate the coercivity. While the manufacturer specified coercivity is 135 A/m, experiments estimate the coercivity at 95 A/m. By varying the coercivity (in the FEM code) in this range, it is found that a coercivity of 120 A/m provides the best match between FEM predictions and experimental results.

The pipewall in gas pipelines is specified to be grade X52. The backing-iron of the magnetizer is made of mild steel (0.18 % C). BH curves used for the pipewall and the backing-iron are shown in Figure 2. These curves are obtained after modifying the manufacturer specified curves, such that an optimal match between FEM predictions and experimental results is achieved. Typical results showing excellent comparison between the FEM solutions and the experimental scans are presented in Figures 3 and 4.

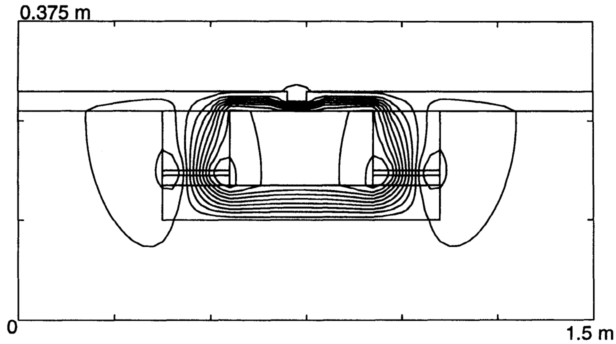

Figure 5. Geometry and field lines corresponding to the MVP formulation (static case).

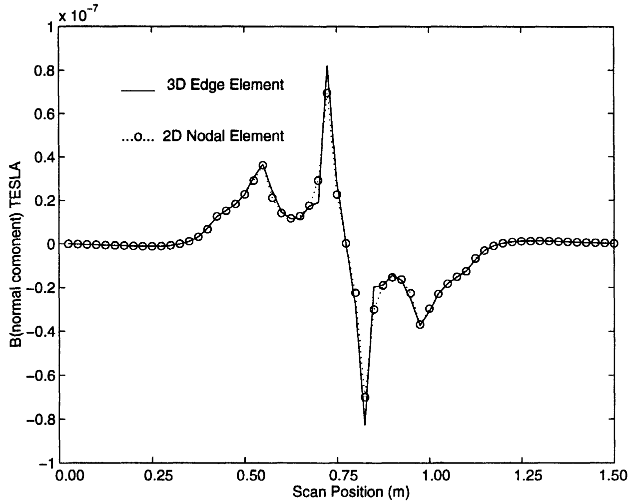

Figure 6. Validation of the MVP formulation (static case).

The MVP formulation using edge elements is in the preliminary stages of its development. The formulation has been validated for the static case by comparing results from the 3D edge element code with the results from a 2D nodal element code with a 2D geometry. The geometry and the flux lines are shown in Figure 5. The validation is shown in Figure 6 for a scan line, immediately above the pipewall.

Also, the 3D edge element code has been used to model velocity effects with the 2D geometry. The results are shown in Figure 7. The results predict the theoretically expected dragging of the flux lines as the magnetizer moves (from top to bottom).

FUTURE WORK

Future work planned includes a quantitative validation of the velocity effect predictions for a full 3D geometry. The 3D edge element code incorporating velocity effects will then be exercised to gain a better understanding of the MFL magnetizer used in the inspection of pipelines.

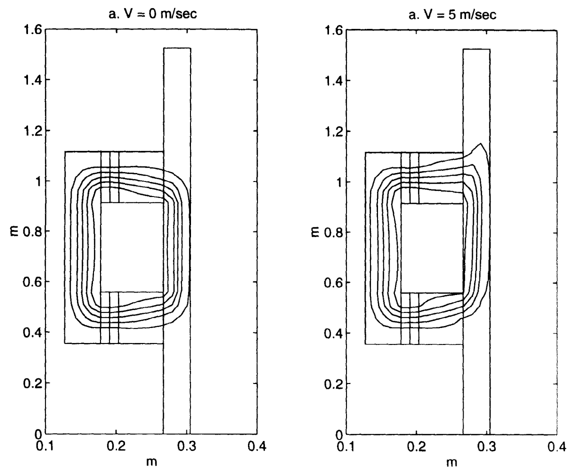

Figure 7. The effect of velocity on the flux lines.

ACKNOWLEDGMENTS

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REFERENCES

1. J.F. Kiefner, R.W. Wright, and R.J. Eiber, "Final report on the NDT needs for pipeline integrity assurance," *American Gas Association*, 1986.
2. R.W.E. Shannon and L. Jackson, "Flux leakage testing applied to operational pipelines," *Materials Evaluation*, vol. 46, pp. 1516-1524, 1988.
3. W. Lord, J.M. Bridges and R. Palanisamy, "Residual and active leakage fields around defects in ferromagnetic materials," *Materials Evaluation*, pp. 47-54, July 1978.
4. J. Jin, "The Finite Element Method in Electromagnetics" *John Wiley and Sons*, 1993.