THE EFFECTS OF MAGNETIZER VELOCITY ON MAGNETIC FLUX LEAKAGE SIGNALS

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INTRODUCTION

In many magnetic flux leakage applications, the nondestructive inspection constraints suggest the use of high inspection velocities. However, high inspection velocities can compromise the ability to detect and characterize defects. In general, velocity effects can be detected at speeds exceeding a few miles per hour [1]. These effects need to be quantified in order to have a complete understanding of the capability of the inspection system. This paper presents the application and results of axisymmetric finite element modeling for the examination of the effects of the magnetizer speed on flux leakage signals. The specific problem addressed is large diameter pipeline steels, and a velocity range of from 0 to 15 miles per hour. The modeling examines the interaction of the magnetizer, pipe material and metal loss defects. Experimental confirmation of selected results is also provided.

Lenz’s Law states that a changing magnetic field induces a current that opposes the changing field that produced it. An MFL in-line inspection tool traveling down a pipeline creates a changing magnetic field. So, the moving tool generates eddy currents in the pipe that oppose and reduce the strength of the applied magnetic field. This reduction of the applied magnetic field decreases flux leakage levels. Because the flux leakage levels are reduced, detection and characterization of defects are affected.

A theoretical explanation of velocity effects involves the velocity vector, \( V \), and magnetic flux density vector, \( B \) [2]. The current density, \( J_v \), in a pipe generated by a magnetizing assembly moving down at a velocity, \( V \), can be found by

\[
J_v = \sigma V \times B
\]

where \( \sigma \) is the conductivity of the pipe steel and \( \times \) is the cross product operator. The cross product operator indicates that when \( V \) and \( B \) are in the same direction, there is no current due to velocity; when \( V \) and \( B \) are perpendicular to each other the maximum current is induced. Where uniform magnetic fields exist in the pipe, \( B \) and \( V \) are in
the same direction and no currents are induced. However, near defects and pole pieces the magnetic field vector is no longer in the same direction as the velocity vector and currents will be induced. These currents will affect the magnetic flux density in the pipe, which in turn affects flux leakage around defects. Because the flux leakage is affected, detection and characterization are also affected.

APPLICATION OF VELOCITY FINITE-ELEMENT ANALYSIS

The effects of a magnet/sensor moving through a pipe at various speeds is being examined using finite-element methods. Figure 1 shows the geometry of the magnetizing assembly. The tool’s poles are 6.0 inches apart, 3.0 inches in the direction of movement and 4.0 inches perpendicular to the direction of movement. The tool magnets are 1.0 inch tall and have a coercivity of 8.0 koersted. The tool brushes are 1.0 inch thick. (These values are typical of MFL pipeline inspection systems.) The tool geometry and material properties have a significant impact on the magnitude of the velocity effects. The coupling of the magnetic field through the brushes into the pipe is a very critical variable. Currently, the nonlinear permeability of the brushes is modeled using a modified version of the pipe’s B-H curve by assuming the brushes saturate four times faster than the pipe and have a quarter of the pipe permeability. This assumption is based on an area reduction of the magnetic material. In addition, all parametric studies assumed a pipe diameter of 24 inches, a wall thickness of 0.300 inches, and a pipe grade of X52.

To obtain accurate results, the finite element size $\delta$ should be on the order of

$$\delta = \frac{2}{\mu \sigma V}$$

where $\mu$ is the permeability and $\sigma$ is the conductivity in the region of interest and $V$ is the desired velocity [3]. This value is roughly 1 mm (0.040 inches) for a tool speed of 10 miles per hour. Because higher tool speeds require smaller elements, the number of elements in a model is proportional to the tool speed.

![Diagram](image-url)  
**Fig. 1.** Magnetizing assembly configuration for velocity finite element modeling.
Defect Modeling with Magnetizing Assembly

Modeling of defects is a computationally intensive task. For eddy current calculations, models with defects require up to 10,000 elements and require up to 4 hours of solution time. Furthermore, sensor position is an issue. To obtain accurate results, the defect must be moved relative to the pole pieces. The procedure is as follows:

1. Starting with the leading edge of the defect one half inch ahead of the sensor location (usually midway between the pole pieces), the geometry is divided into finite elements and solved.
2. The defect is moved along the pipe in quarter-inch increments. Each geometry is divided into finite elements and solved.
3. Step 2 is repeated until the trailing edge of the defect is a half-inch beyond the sensor location.

The sensor reading must be extracted in the same location relative to the magnetizing assembly. With each defect increment requiring 4 hours of computer time, problems can require over 100 hours to obtain a solution.

Defect Modeling Without a Magnetizing Assembly

In the modeling of flux leakage from metal loss defects under typical inspection velocities, the geometry of both the defect and the magnetizing assembly play a significant role. To develop a fundamental understanding of MFL technology and to determine which variable is more significant, isolation of variables is useful. The focus has been on the defect-field interaction at various velocities. The effect of the tool has been eliminated by applying a uniform magnetic field along the axis of the pipe. This is the same as having an infinite pole spacing on the tool. By eliminating the effects of the tool and considering the pipe and defect only, many computational complexities are eliminated. The applied field is produced by boundary conditions, which makes the computations very efficient, and since the pole spacing is infinite, the need to step the defect between the pole pieces is unnecessary. This reduces solution times to a few hours.

VELOCITY FINITE-ELEMENT MODELING RESULTS

Velocity affects both the applied flux density and the leakage field. Velocity affects the applied density by inducing eddy currents near the pole pieces. Velocity affects the leakage fields by inducing eddy currents near defects. A more detailed explanation of these effects is contain in the following two sections.

Field Strength

Velocity reduces the applied field strength by inducing eddy currents that oppose magnetization near the pole pieces. These effects can be significant if they reduce a high or medium applied field strength to a low field strength. The effects of a magnetizing assembly moving at various speeds along a pipe with no defects were examined using finite-element methods.
Fig. 2. The induced eddy currents at different depths in the pipe wall for a MFL magnetizer moving at a speed of 10 miles per hour.

Figure 2 shows calculated eddy currents at different locations through the pipe wall at 10 miles per hour. The peaks occur directly under the pole pieces. This result is as expected because the eddy currents are proportional to the component of the magnetic field that is perpendicular to the velocity and the majority of the perpendicular field is located at the poles. There is an asymmetry in the eddy current density, with the leading density being greater. Also, the eddy current density and asymmetry decrease nonlinearly through the wall thickness.

Figure 3 shows calculated effects of velocity on the applied field levels in a pipe wall with no defects for a slow (static solution) velocity and a speed of 10 miles per

Fig. 3. The reduction in field levels in the pipe wall for a magnetizer at a slow (static solution) velocity and a speed of 10 miles per hour.
hour. For the static case, the tangential (axial) component of the magnetic field in the pipe is fairly uniform between the pole pieces. For the 10 mph case, the tangential component of the magnetic field drops 10 percent and the symmetry is lost. So, the applied field is reduced and disturbed, which affects detection and characterization.

**Leakage Fields**

Velocity affects flux leakage fields by inducing additional eddy currents near the defects. Figure 4 shows finite-element results for a defect being inspected at velocities of 0 and 10 miles per hour. The defect is a 2-inch long, 50-percent deep, circumferential groove in a 0.300-inch thick pipe. Note that Figure 4 represents the leakage field near the defect, not the overall applied field as shown earlier in Figure 3. Velocity reduces the flux leakage field significantly. These results were confirmed using the linear test rig of the Gas Research Institute Pipeline Simulation Facilities [4]. The defect is a 2.0-inch long, 50-percent deep, 6-inch circumferential wide corrosion defect in a 0.375-inch thick pipe. Figure 5 shows the tangential field components for the linear test rig experiment at 2.5 and 8.0 miles per hour. The results are qualitatively similar to those shown in Figure 4. Figures 4 and 5 illustrate three effects of velocity on flux leakage signals:

1. The amplitude of the flux leakage field decreases as velocity increases. This reduction affects defect detection and characterization accuracy.
2. The symmetry of the flux leakage field is lost. A loss in symmetry affects the ability to infer defect length, which is usually based on the length of the measured leakage field. Previously, length characterization was considered to be relatively simple and accurate.
3. The signal shifts towards the trailing pole piece. Therefore, axially staggering sensors to gain 100 percent circumferential coverage may lead to signal amplitude discrepancies, which may affect characterization.

![Fig 4. A velocity modeling result for a metal loss defect at velocities of 0 and 10 miles per hour.](image-url)
Fig 5. Linear test rig experimental results for a metal loss defect at velocities of 2.5 and 8 miles per hour.

The effects of velocity on measured flux leakage signals are a function of defect depth, length, width, shape and interior or exterior pipe surface. A number of other parameters also influence velocity effects, including the geometry of the magnetizing assembly, magnetization level, and the pipe being inspected. The finite-element modeling program followed a systematic approach of parametrically varying one variable at a time.

The effects of individual parameters were determined by comparing leakage signals to those of a reference defect. The reference defect was a 50-percent deep, 2-inch long, circumferential groove with a square cross section. In all velocity results, the reference for all axial distance measurements is the defect center and the upstream direction is to the left. Six velocities ranging from 0 to 15 mph were examined, though only the 0 and 10 mph are shown.

Selected results from the finite-element modeling are shown in Figure 6. Each of these figures shows the tangential (axial) component of the magnetic field as a function of sensor position and velocity. The top four signals show the effect of defect geometry only, with pole spacing infinite. The effect of velocity on signal amplitude is a function of defect depth. As compared to the 50 percent deep 2-inch long reference defect, the velocity effects for the 80 percent defect are less pronounced than the 50 percent defect. However, for a 20 percent through-wall 2-inch long defect, the effect of velocity is more pronounced. As for defect length, the signals from the 2.0-inch long defect are reduced more than those from the 4.0-inch long defect. Whether the defect is on the inner or outer diameter is an important variable, with the fifth signal showing an increase of the leading portion of the signal as compared with a decrease for the outside diameter defects. Magnetization level is also an important variable. The sixth signal shows that velocity effects are more pronounced when magnetization levels are well below saturation. The geometry of the magnetizer is also critical. For example, signal 7 shows that reducing the pole spacing to 6 inches both reduces the peak signal level of both peaks as well as increases the base signal levels.
Fig 6. Selected velocity modeling results.
Finally, the sensor position with respect to the magnetizes poles (for a 6 inch pole spacing) can also affect the measured signal as shown by signal 8.

SUMMARY

Finite-element modeling techniques can include the effect of velocity. The modeling examines the interaction of the magnetizer, pipe material, and metal loss defects. The modeling that is being performed has been divided into two parts. First, the interaction of a moving uniform field on various defects geometries can be examined, thus eliminating the effect of the magnetizing assembly. Then the magnetizing assembly can be added, providing results on the defect-velocity-magnetizer interaction.

Velocity effects are important because they impact the basic relationships used to estimate the dimensions of a defects from the leakage field. In general, MFL technology is a mature technology for the detection of critical metal loss defects. Characterization of defect geometry is more difficult because of the many parameters that effect the leakage signal, and future research is required to achieve improved characterization accuracy. The capability of modeling the effects of parameter variations will help in the development of improved characterization functions.

ACKNOWLEDGEMENTS

The research for this paper was funded by the Gas Research Institute using the NDE Laboratory of the GRI Pipeline Research Facility. This program is under the direction of Gregory Ridderbusch and Thomas Steinbauer of GRI.

REFERENCES


