THE EFFECTS OF FLUX LEAKAGE MAGNETIZER VELOCITY ON VOLUMETRIC DEFECT SIGNALS

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INTRODUCTION

The inspection requirements of the hundreds of thousands of miles of pipeline worldwide necessitates the use of high inspection velocities. Unfortunately, high inspection velocities can compromise the ability to detect and characterize defects[1,2]. These velocity effects need to be quantified in order to have a complete understanding of MFL inspection capabilities. This paper presents an explanation and a summary of these effects based on two and three dimensional finite element analysis and experimental results. Selected finite element and experimental results are also shown. The specific problem addressed is large diameter (>12 inches), ferromagnetic steel pipe material and inspection velocities up to 10 miles per hour. The defects are volumetric metal loss generally caused by corrosion.

In electromagnetics, Lorentz' Law states that a charge moving perpendicular to a static magnetic field will experience a force perpendicular to both the velocity and field. This law also applies to conducting material moving relative to a perpendicular static magnetic field[3]. For this case, the Lorentz force induces a current density within the conducting material. The current density, J, the conductor's velocity relative to the field, v_c, and the magnetic field, B, are related by Equation 1

$$\vec{J}=\sigma\vec{v}_c\times\vec{B} \tag{1}$$

where σ is the conductivity of the material. Note that v_c is the velocity of the conducting material relative to the field, not the velocity of the field.

An MFL in-line inspection tool moving down a pipeline produces just such a case. Flux near defects and the magnetizer's pole pieces is perpendicular to and moving relative to the pipeline which is a conducting material. Therefore, near these regions, current is induced. These velocity induced currents will alter the existing flux in the pipe and so the leakage field. Because the leakage field is affected, detection and characterization of defects will be affected.

The effects of magnetizer velocity can be decoupled into two separate effects:

a defect-velocity effect and a magnetizer tool-velocity effect. Both have separate causes and distinct effects. The defect-velocity effect is a local effect due only to the flux leakage around the defect. The magnetizer-velocity effect is caused by the flux near the magnetizer's pole only.

DEFECT-VELOCITY INTERACTION

Velocity Induced Currents

Near a volumetric metal loss defect in a pipe wall, flux will "leak out". When this magnetic flux leakage occurs, the field gains a component perpendicular to the relative velocity of the pipe wall and a current is induced. These velocity induced currents flow near the defect and are responsible for changes in the MFL signals. Thus, it is important to understand how they are induced and their effect on these signals.

These currents are created two ways. The primary portion of the current is induced by the Lorentz force, J=σvxB (v=- magnetizer velocity). In the pipeline, the velocity is axial, and so, this term yields both circumferential and radial current flow.

An axial current flow is also induced. This current flow is caused by an electrostatic potential, V, created by a divergence in the Lorentz current density near the defect corners. This result can be seen as follows. Using the definition of the magnetic vector potential and Ampere's law, the magnetic vector potential, A, can be defined in terms of J as

$$\vec{A}=\mu\int_{\tau}\frac{\vec{J}(\vec{r}')}{|\vec{r}'|}d\vec{r}' \tag{2}$$

where the low frequency Lorentz gauge,

$$\nabla\cdot\vec{A}=-\mu\sigma V \tag{3}$$

has been used. Taking the divergence of both sides of Equation 2 and equating it to Equation 3 yields,

$$V=-\frac{1}{\sigma}\int_{\tau}\frac{\nabla\cdot\vec{J}}{|\vec{r}|}d\vec{r} \tag{4}$$

The current divergence acts as a pseudo-charge density thereby creating an electrostatic potential. This potential will also induce current.

The electrostatic potential created here causes current to flow axially, circumferential current to flow in the opposite direction of the Lorentz circumferential current, and causes radial current to flow in the same direction as the Lorentz radial current. This current density is generally an order of magnitude less than the Lorentz force current density.

Since the magnetic flux leakage and current divergences are a local effect about the defect, so too is the induced current flow. Figure 1 shows the general direction of the current flow around the defect. In general, the circumferential current flow is the largest. The radial current flow is about a fourth and the axial current flow is about a tenth of the circumferential current density. Also, the circumferential current density has the greatest effect on the MFL signals. These velocity induced currents have been experimentally measured on the pipe wall surfaces.

General Effects on Characterization

Figure 2 shows the general effects of the defect-velocity interaction on the MFL signals. This figure shows a surface map of the axial (top), radial (middle) and circumferential (bottom) MFL signals 0.1 inch above the inside pipe wall for a 3-D finite element model. The defect is a 2 inch axially long, 3 inch cicumferentially wide, 50 percent deep square defect. The effect of the magnetizer has been eliminated by

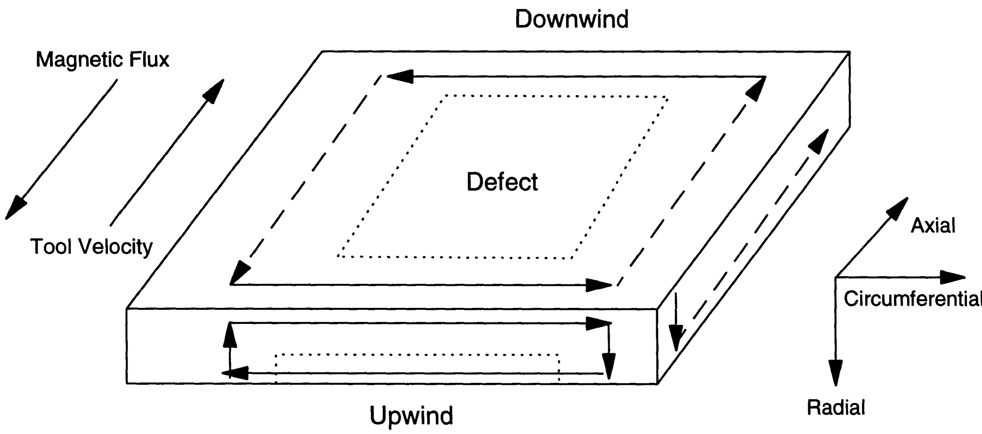

Figure 1. The general direction of the induced current caused by the defect-velocity interaction.

applying a uniform field along the axis of the pipe. This condition is the same as having an infinite pole spacing. For comparison, both a slow (static) and typical (7mph) magnetizer velocity are shown. The static case is on the left. The axial direction is upward, radial direction is into the paper, and the circumferential direction is sideways. The magnetizer is moving upward. For future reference, the bottom of the page is upwind and the top is downwind.

The defect-velocity interaction usually tends to decrease the MFL downwind

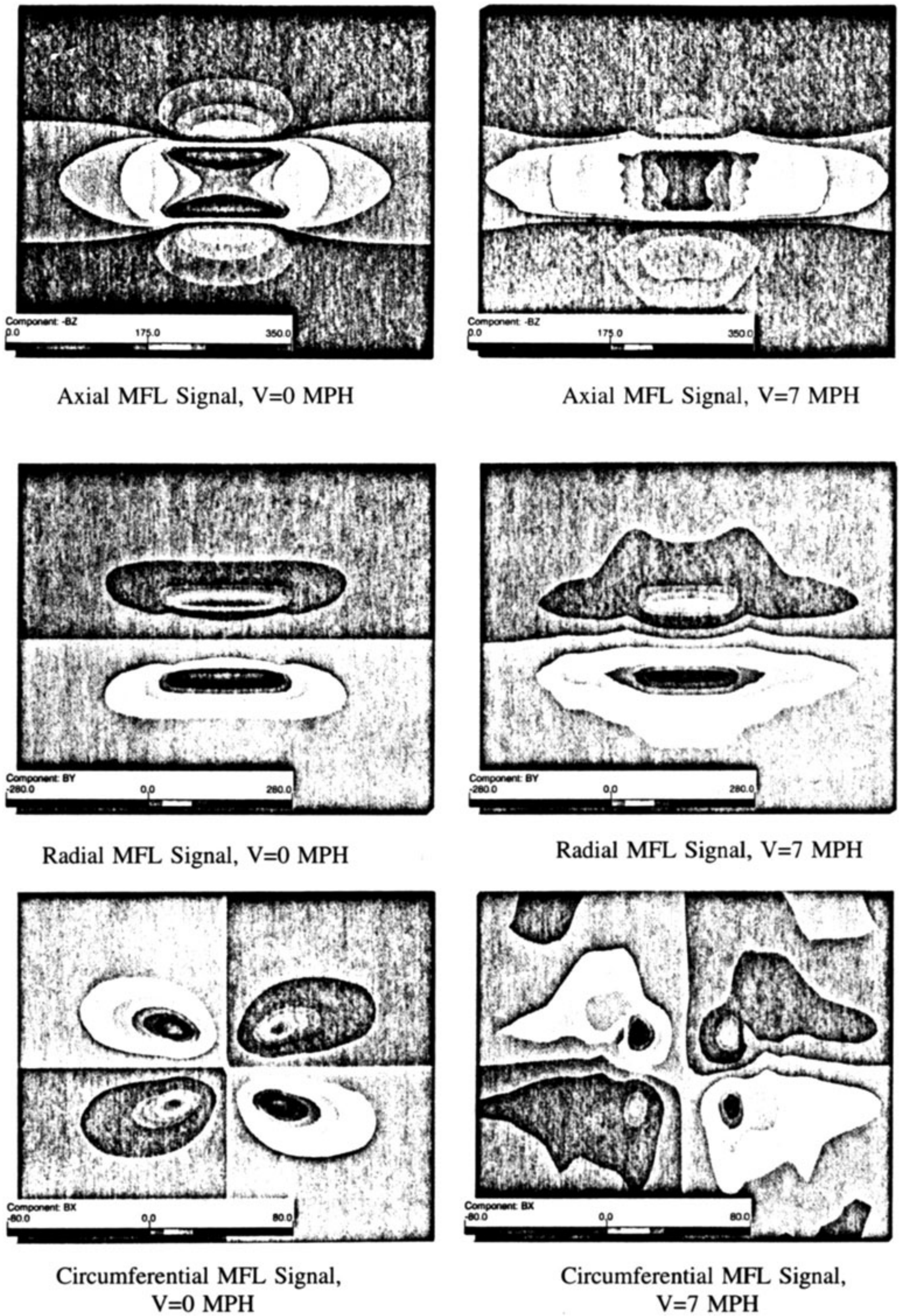

Figure 2. The general effects of the defect-velocity interaction on MFL signals.

signal's amplitude. It also tends to drag the MFL signal upwind and smear the signal circumferentially, i.e., the drag effect[2]. In general, characterization of defects are affected as follows:

Axial Length: In general, length measurements are not affected. The maximum slope-slope axial length measurements and the radial and circumferential peak-peak length measurements do not significantly change.

Circumferential Width: In general, width measurements are only slightly affected. The maximum slope-slope axial and radial width measurements (line taken circumferentially) make defects appear slightly wider. The circumferential peak-peak width measurements are not affected.

Radial Depth: In general, depth measurements are greatly affected. The peak and peak-peak amplitudes used to characterize depth decrease making defects appear shallower. This measurement is perhaps the most affected.

Radial Cross Section: In general, these measurements are slightly affected due to the drag effect. The drag effect distorts the signal by inducing an asymmetry and also by changing the slope of the MFL signals. In general, both these factors make the radial cross section appear more asymmetric and the top and bottom angle less steep.

Surface Shape: In general, this measurement is only slightly affect. Axial and radial measurements make defect's surface shape appear slightly rounder and the circumferential peak location measurements at the defects edges are not affected.

Influencing Parameters

The defect-velocity effect is a function of magnetizer speed, defect geometry, and magnetization level. There is little effect due to pipe wall thickness or pipeline diameter. Analytical analysis was done using two and three dimensional finite element modeling and experimental confirmation of these results was done using the linear test rig and pull rig of the Gas Research Institute Pipeline Simulation Facility[4]. The following is a summary of these factors.

Magnetizer speed: As expected, the defect-velocity effect depends on the magnetizer speed. The faster the magnetizer velocity, the larger the induced current, and so the greater the effect on MFL signals. As magnetizer velocity increases, all of the defect-velocity effects increase. In general, velocity effects are minimal for magnetizer speeds less than 4 miles per hour.

Magnetization Level: In general, lower magnetization levels show larger effects. At low magnetization levels (below the knee of the BH curve), the MFL signal amplitudes are significantly reduced. At high magnetization levels (saturation), the MFL signals are only slightly affected.

Defect Geometry: The defect-velocity interaction is strongly dependent on defect geometry. Not all defects are equally affected by the defect-velocity interaction. In fact, some defects show no effect. Defects which are small, spherical, and pit-like are virtually unaffected.

The following summarizes those defects most affected.

- Defect lengths between 2 and 3 inches
- Wider defects
- Deeper defect depths at lower magnetization levels (below the knee of the BH curve) Shallower defect depths at higher magnetization levels (at or above the curve's knee)
- Radial cross sections which are sharper edged and more square
- Surface shapes which are sharper edged and more square

The defect-velocity interaction also depends on whether or not the defect is located inside or outside the pipeline. If the defect happens to be inside the pipeline, opposite effects can occur[2].

Figure 3 shows experimental results from the linear test rig. This figure shows the defect-velocity effect on the axial MFL signals as a function of defect geometry. For comparison, magnetizer speeds of 2.0 and 8.0 miles per hour are shown. To eliminate the effect of the magnetizer, the pole spacing was made large enough (14 inches) so as to not interfere.

MAGNETIZER-VELOCITY INTERACTION

The magnetizer-velocity interaction induces currents underneath the magnetizer's pole pieces[2]. In accordance with Lenz' Law, these currents create a flux which oppose the flux in the pipe. The flux underneath the poles are perpendicular to the velocity and so induce a current. These currents then tend to lower the magnetization level in the pipe.

The general effect of the magnetizer-velocity interaction is to reduce the flux

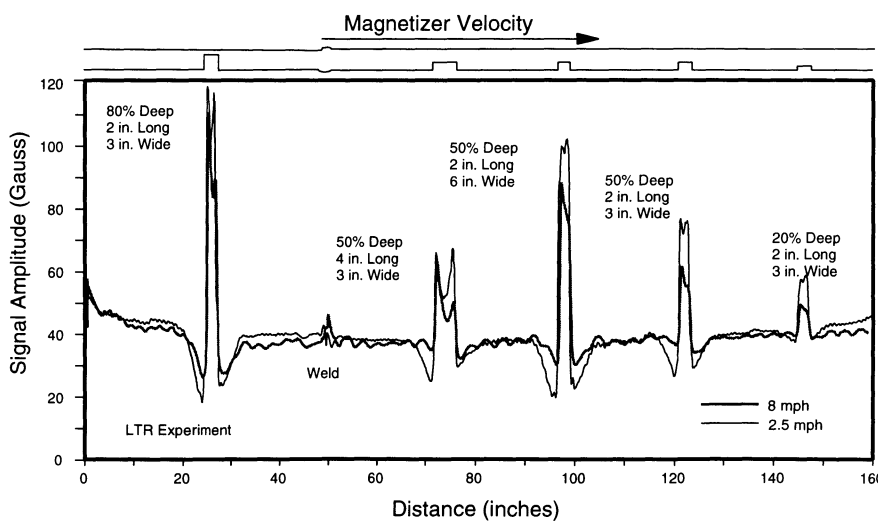

Figure 3. Selected experimental results showing the defect-velocity interaction as a function of defect geometry.

level in the pipe wall. The factors influencing the severity of this effect are pole spacing, magnetizer strength, and sensor position.

Pole Spacing: In general, shorter pole spacings show a greater velocity affect. For the linear test rig's magnetizer assembly, a pole spacing of about 10 inches (inside to inside) or greater shows very little magnetizer-velocity effect. Also, the test bed vehicle which has a pole spacing of about 14 inches shows very little magnetizer-velocity effect.

Magnetizer Strength: In general, the larger the magnetization level in the pipe wall, the less the velocity effect. Ironically, one way to increase the magnetization level in the pipe wall is to decrease the pole spacing. However, as explained above, decreasing the pole spacing also increases the magnetizer-velocity effect. This leads one to believe that there is an optimum pole spacing available which would maximize MFL signal and minimize the velocity effect.

Sensor Position: Because the induced currents are dragged beneath the poles, sensor location very important. Sensors placed upwind are less effected by the dragged current and so notice less of a velocity effect.

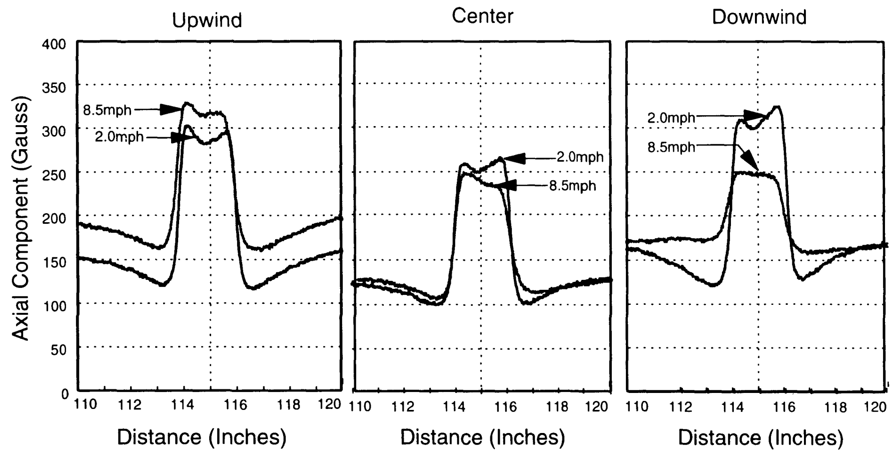

Figure 4. The magnetizer velocity effect as a function of sensor position.

Figure 4 shows experimental results for the magnetizer-velocity interaction as a function of sensor position. The defect is a 2 by 3 inch by 50 percent deep square defect. The pole spacing is 10 inches. Note, that the upwind signal although slightly shifted higher is least affected by velocity.

SUMMARY

The effect of magnetizer velocity is important because it impacts the basic relationships used to estimate defect dimensions from the MFL signal. The effects of magnetizer velocity can be decoupled into two separate effects, a defect-velocity effect and a magnetizer tool-velocity effect, each with separate origins and distinct results.

The defect-velocity interaction tends to decrease signal amplitude and cause asymmetries in the MFL signal. Not all defects are equally affected. In general, the defects which are between 2-3 inches long, wider, shallower and squarer are most affected. Smaller, spherical, pit-like defects are not affected.

The magnetizer-velocity effect tends to reduce the field level in the pipe wall. Here, larger pole spacings, higher magnetization levels and an upwind sensor position will reduce this effect

Understanding the effect of magnetizer velocity on signals from volumetric defects will help in the development of compensation functions to correct signals for inspection variables and constraints. Compensation functions take information on inspection variables such as velocity for recorded signals and output the corrected baseline signals that would have been detected if the signals were not changed by the operation variables. These corrected signals will then be used to estimate defect geometry.

ACKNOWLEDGEMENTS

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