LOW FREQUENCY EDDY CURRENTS WITH MAGNETIC SATURATION FOR IN-LINE DETECTION AND SIZING OF STRESS CORROSION CRACKS

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INTRODUCTION

Under previous programs for the Pipeline Research Committee, Battelle has developed and field tested a low frequency eddy current instrument for characterizing stress corrosion cracks in pipelines. While a significant improvement over conventional magnetic particle inspections, the eddy current method as it was developed in these programs is limited to use for inspections of pipelines from the outside surface. This paper examines the possibility of using this low frequency eddy current equipment to detect and size stress corrosion cracks from the interior of the pipeline by magnetically saturating the pipeline to reduce its permeability and thereby increase penetration of the eddy currents into the pipe.

Simply lowering the frequency to obtain a suitable skin depth for large pipe permeabilities is not sufficient. If the frequency is simply decreased in high permeability materials, the magnetic flux tends to spread laterally out from the test coil, making it more sensitive to disturbances outside the general area of interest. Also, all measurements are ultimately limited by the signal-to-noise ratio of the measured signal. Excluding electronic noise from the equipment, noise in eddy current testing is inversely proportional to test frequency. The higher the test frequency, the higher the signal-to-noise ratio, and so, the more likely a defect will be detectable. Therefore, the pipeline permeability has to be reduced so frequency can be high enough to detect these stress corrosion cracks. The pipeline permeability can be reduced by magnetically saturating the pipe wall.

This study was divided into two parts, an analytical study to determine how well eddy currents could be used to detect cracks as a function of the pipeline's permeability and an experimental study to verify the analytical study and to determine by how much pipeline permeability can be reduced.

ANALYTICAL MODELING

Analytical (finite element) models of eddy current systems were used to design the eddy current probes, including the shape of the cores, to obtain the optimum penetration into the pipe wall and to select the best test frequencies for different pipe materials and defect depths. This knowledge allowed us to design an eddy current probe with the maximum defect sensitivity (probe response to a defect) for a given situation. The "signal" levels caused by variations in pipeline permeability, pipeline conductivity, probe core permeability and geometry, coil frequency, and probe lift-off can be calculated less expensively and more quickly than these same parameters can be measured in the laboratory.

Because three-dimensional eddy current software is very expensive, requires very long solution times, and in certain instances, can give somewhat unreliable solutions, two-dimensional finite element models were used in conjunction with the Burrow's model[1] to calculate the defect sensitivity of the various three-dimensional cases. Two-dimensional models can calculate three-dimensional fields exactly if the system is axisymmetric or if the field distributions are more-or-less independent of length. This calculation, of course, cannot be done if a crack (which is neither axisymmetric nor of infinite width) is to be modeled. However, the Burrow's model uses the electromagnetic fields calculated in a permeable and conducting media, such as a pipeline, in the absence of any defects and computes the defect sensitivity of an eddy current system for a small flaw in this media (pipeline). A full crack can be modeled by breaking it up into small Burrow flaws, and the total defect sensitivity for the 3-D system can be obtain by summing the effects of all these small flaws.

Burrows Model

The Burrow's model calculates the magnetic and eddy current dipoles that would be caused by a small flaw in the pipe. It then uses these dipoles to predict the defect sensitivity of a coil system due to this flaw. In essence, the Burrow's model gives a second order approximation to the defect sensitivity by replacing the flaw with the equivalent eddy current and magnetic dipoles. The Burrow's model assumes the defect is small compared with the dimensions of the system, and that the flaw is sufficiently far away from other discontinuities in permeability and conductivity such as the edge of the pipe or another flaw. Similar methods have been used with success in other applications[2].

The Burrow's impedance change induced in an eddy current coil by a flaw's equivalent dipoles is

$$\Delta \mathbb{I} = -\frac{3}{2} V \frac{(\sigma E \alpha E + i \omega \mu H \beta H)}{I^2} \tag{1}$$

where V is the volume of the flaw, E and H are the fields in the pipe in the absence of any defect, I is the coil's amp-turns, ω is the angular frequency of the fields, μ is the pipeline permeability, σ is the pipeline conductivity, and α and β are factors that depend on flaw geometry.

The electric field, E, and magnetic field, H, are calculated using the 2-D finite element models. The pipeline conductivity, σ, and permeability, μ, of the pipeline is assumed to be known in advanced. The geometric factors, α and β, represent the shape and orientation of the flaw. A flat disc shape having a radius much larger than its width oriented with its face perpendicular to the induced eddy currents and parallel to the magnetic field is used. This shape and orientation is very similar to that of the flat crack. For the thin disc, α and β have the values

$$\alpha=\frac{4}{3\pi}\frac{b}{a} \qquad \beta=\frac{4}{3} \tag{2}$$

where b is the disc radius, and a is the disc width. Each part of the crack in the defect area was assumed to be a small Burrow's flaw where the above conditions hold true. The total defect sensitivity was then taken to be the sum of all the small flaws in the defect region.

$$\Delta I_{Total}=\sum\nolimits_{elements}\Delta I \tag{3}$$

Although this method is by no means mathematically rigorous, it is acceptable for a first order calculation. As an estimate on this method's accuracy, several 3-D defects were modeled and compared with Equation 3. All were in close agreement. Figure 1 shows a typical result. Thus, we believe that the Burrow's model in conjunction with the 2-D finite element calculations is an appropriate method for evaluating the effects of cracks on the responses of an eddy current probe.

Analytical Results

Three coil geometries were modeled; the cup core, cylindrical core, and U-core coils. Defect sensitivity was calculated using the three core geometries for a variety of cases. For the most part, we concentrated on defect sensitivity for lower pipeline permeabilities and smaller defects (less than 50 percent deep), since these cases were our intended target. Also, we concentrated more on the cup core and probe core coil geometries since early on the defect sensitivity of the U-core was found to be very poor. The following is a summary of the analytical results:

- There is an optimum skin depth for which defect sensitivity is greatest. The optimum skin depth was found to be independent of pipeline conductivity, coil frequency, and lift-off, and roughly independent of

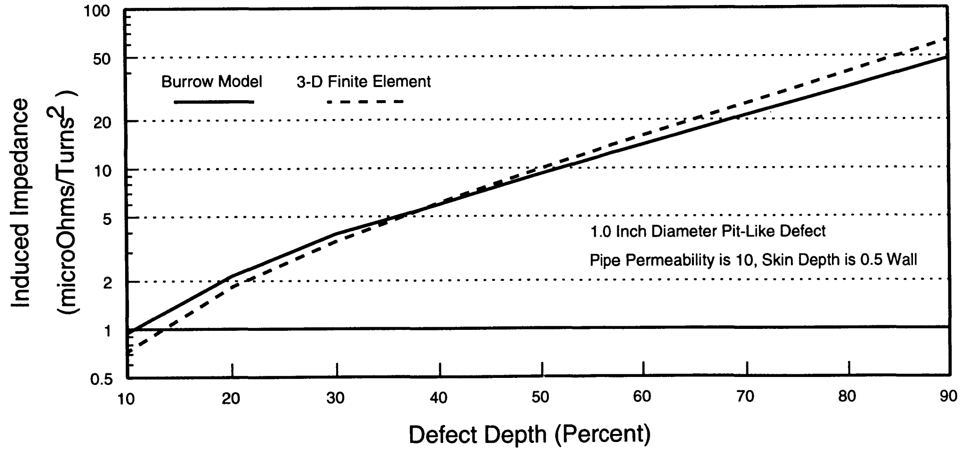

Figure 1. A comparison of a three-dimensional finite element model with the Burrow's and two-dimensional finite element method.

pipeline permeability and coil geometry. Interestingly, the optimum skin depth for all the probe types considered was around 50 percent of the pipe wall thickness, increasing slightly for shallower defects.

- As defect depth increases, defect sensitivity increases approximately exponentially for all permeabilities. See Figure 2 below.

- Reducing permeability and increasing the frequency to maintain the optimum skin depth will increase the defect sensitivity. See Figure 2 below.

- Lower pipe conductivities increase defect sensitivities. Since the optimum skin depth is independent of conductivity, the frequency is increased for a lower conductivity.

- Defect sensitivity decreased as the permeability of the probe's core decreased. Stray field leakage from the pipeline may saturate the ferrite cores reducing defect sensitivity. Because of their geometries, the cup core and U-core are most affected. However, as long as the core permeability remains much larger than the pipeline permeability, the loss in defect sensitivity is minimal.

- Probe lift-off from the pipe surface is a very serious problem. As lift-off increases, the defect sensitivity greatly decreases. This problem lessens as pipeline permeability is reduced. Even so, at a pipeline permeability below 10, a 0.020 inch lift-off (which in practice is very small) reduces the defect sensitivity roughly by a factor of 2.0 and a lift-off of 0.050 inch by a factor of 3.5.

- For larger defects (>50 percent deep) impedance variations from lift-off will mask defect signals. The relative phase angle between defect signals and lift-off cannot be used to eliminate lift-off effects.

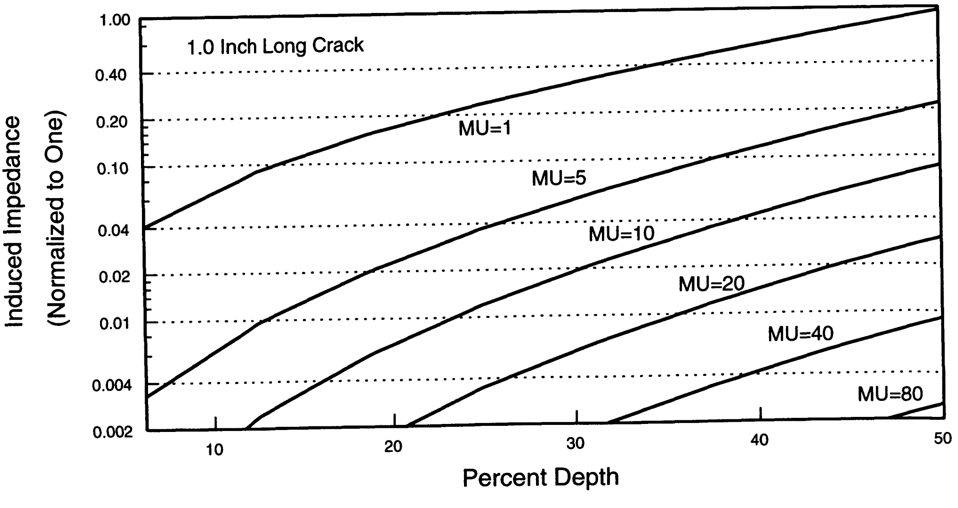

Figure 2. The calculated defect sensitivity (normalized) as a function of defect depth and pipeline permeability. The skin depth for all cases is 50 percent of the wall.

Ignoring lift-off, the cup core coil has the best defect sensitivity followed by the cylindrical core coil. However, when lift-off is considered, the cylindrical core coil has the best defect sensitivity. Although the U-core has the worst sensitivity, it does have the ability to determine the orientation of the crack.

Figures 2 and 3 show examples of the typical calculated results. Figure 2 (last page) shows the calculated defect sensitivity as a function of defect depth and pipe permeability. The defect is 1 inch long, probe type is the cup core coil, and for all cases, the skin depth was kept constant at 50 percent of wall thickness. Figure 3 (below) shows the calculated defect sensitivity as a function of defect depth at various probe lift-offs. The probe type is the cup core probe, the skin depth is constant at 50 percent of wall thickness, and the pipeline's relative permeability is 5.

Based on the above results and previous experience, we estimated that if pipeline permeability can be reduced to about 10, shallow defects as small as 30 percent deep should be detectable.

EXPERIMENTAL WORK

In our experimental study, we magnetized the pipe to different levels using an electromagnet and measured defect sensitivity using the probe types analyzed above. The pipe sample was 24 inches long, 16 inches wide, and 0.265 inch thick. There were 16 defects cut into the pipe sample using electro discharge machining (EDM). The defects were 9 mils wide with lengths of 1 and 2 inches and depths ranging from 10 to 100 percent deep.

The first goal was to determine the level to which the pipeline permeability could be reduced. In realistic situations, the only way to magnetize a pipeline is in a direction parallel to the surface of the pipe, either along the pipe axis or the pipe circumference. However, the magnetic field from the probe is generated so that it is perpendicular to the pipe surface. Therefore, the permeability one must reference is the transverse permeability not the longitudinal permeability[3]. In the course of this

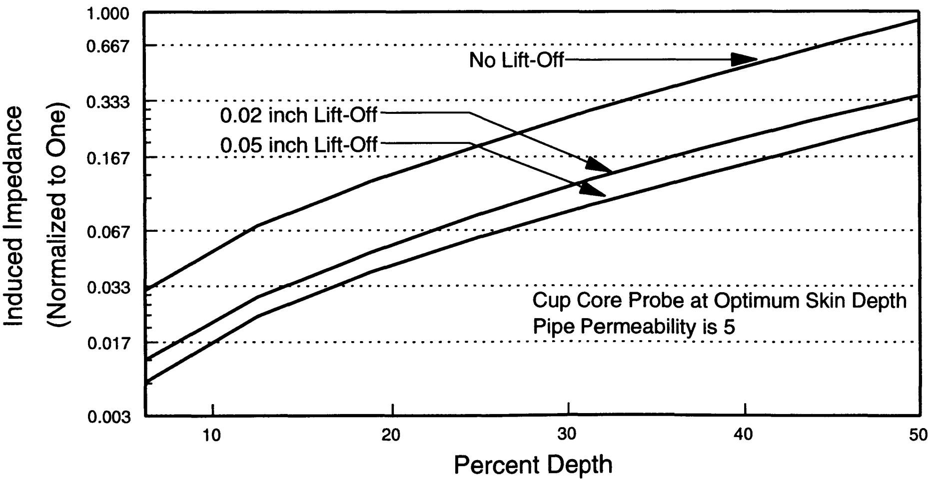

Figure 3. Analytical calculations showing the effect of lift-off.

work, a nondestructive method of measuring the transverse permeability was found and used[4]. With our experimental setup, field levels greater than 2000 Oersteds were produced (unpractical for realistic field situations). Although the longitudinal permeability was reduced to about 10, the transverse permeability was reduced only to a value of 33. We concluded that currently the pipeline permeability could not be reduced further. Similar problems in reducing permeability to increase defect sensitivity have been reported by others[5].

With this limitation on the permeability reduction, experimental work was done using the probe types previously analyzed. In general, the analytical results were verified. Specifically,

- There is an optimum skin depth, which was experimentally found to be about 50 percent of wall thickness and independent of defect depth, probe type, permeability, and lift-off.
- Defect sensitivity did increase with decreasing pipeline permeability. Reducing the permeability from 120 (unmagnetized) to 33 increased the defect sensitivity by about a factor of 100 for the cup core coil with no lift-off. This factor is slightly smaller with lift-off.
- Defect sensitivity increased roughly exponentially with defect depth.
- With lift-off less than 0.015-inch, the cup core coil showed the highest defect sensitivity, followed by the cylindrical core. For a lift-off greater than 0.015-inch, the cylindrical core probe had the better defect sensitivity. The U-core coil has the expected direction determining capabilities, but performed very poorly relative to the other two probes.
- At very high magnetization levels (>2000 Oersteds), the cup core and U-core probe's core began to saturate, and their defect sensitivity began to lessen.
- At a pipeline permeability of 33, the smallest discernable defect was 30 percent deep for the cup core coil with no lift-off. At a lift-off greater than 0.20 inch, the smallest discernable defect was 50 percent deep.
- Unfortunately, signals from material variations in the pipe sample (noise) were of the same magnitude and phase as the shallower cracks. Therefore, even though 30 percent deep cracks were discernable in a laboratory environment, detecting defects smaller than 50 percent is unpractical.
- Even allowing for phase differences, lift-off variations greater than 0.015-inch (noise), which are small for most realistic situations, can mask signals from larger (50-70 percent deep) defects.

Figures 4 and 5 show examples of the experimental data. Figure 4 shows the measured defect sensitivity as a function of defect depth and pipe permeability. The markers are the measured data points. The defect is 2 inches long, the probe type is the cup core coil with no lift-off, and for all cases, the skin depth was kept constant at 50 percent of wall thickness. Note that at a permeability of 120, no defects below 60

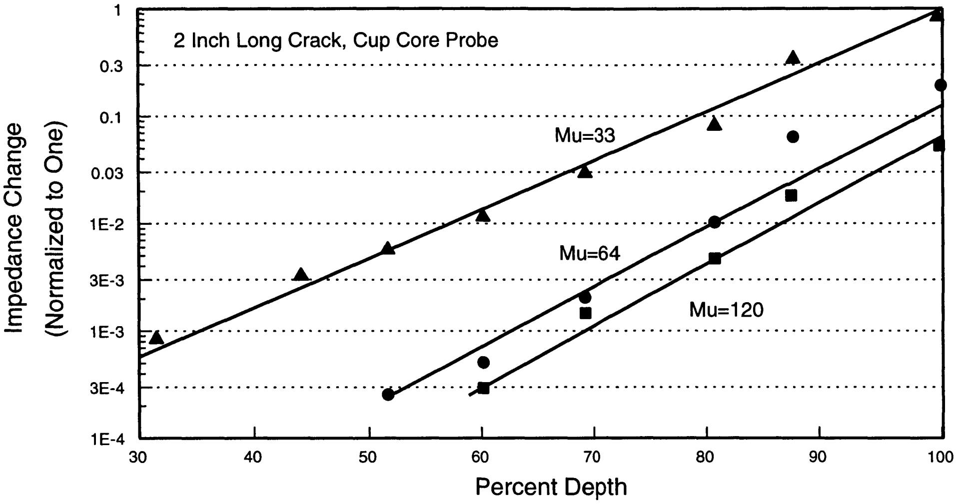

Figure 4. Experimental defect sensitivity as a function of defect depth for various permeabilities. In all cases, skin depth is 50 percent of wall thickness.

percent deep could be detected, but at a permeability of 33, defects as small as 30 percent deep could be detected. Figure 5 shows the measured defect sensitivity as a function of defect depth for the cup core and cylindrical core probes at a permeability of 33 with no lift-off. The horizontal lines show the change in probe impedance caused by a 0.015-inch lift-off. If this change is used as an estimate of the noise for the defect signal, then the signal-to-noise ratio for these probes would make detecting defects below 80 percent deep impossible. In fact, probe lift-off and variations within the pipe material produce signals that will mask defect signals and make their detection impossible in realistic situations.

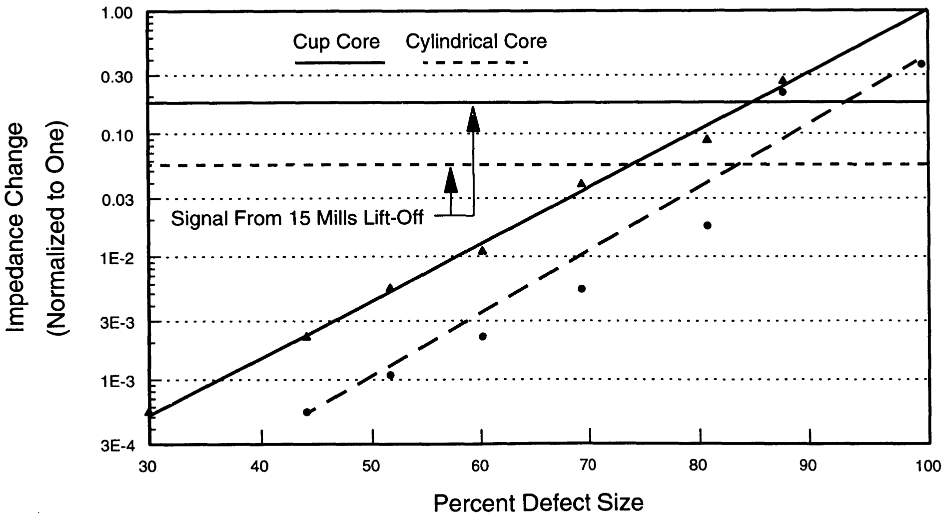

Figure 5. Experimental defect sensitivity for the cup core and cylindrical core probe types. The horizontal lines reflect signal change from lift-off.

SUMMARY

The Burrow's method with the two-dimensional finite element models worked well for modeling the response of eddy current probes to stress corrosion cracks. The predictions of general coil characteristics and the response to defects were found to be accurate experimentally.

Analytical analysis showed that if pipeline permeability could be reduced to about 10, then cracks as shallow as 30 percent deep could be detected. However, experimental work showed that the pipeline's transverse permeability could be reduced only to about 33. Even so, under carefully controlled conditions, cracks as small as 30 percent deep were discernable. Unfortunately, signal changes, i.e. noise, due to material variations and lift-off will make detecting cracks less than 80 percent deep unlikely in practice.

Therefore, unless a method can be found to further reduce the pipeline's permeability, using low frequency eddy currents with magnetic saturation of the pipe wall as an in-line inspection method will not work.

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