ASSESSING MECHANICAL DAMAGE USING MULTIPLE DATA SETS IN INLINE INSPECTION

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Abstract

Mechanical damage by third party intervention continues to be a major factor in reportable incidents for hazardous liquid and gas pipelines. While several ongoing programs seek to limit third party damage incidents through public awareness, encroachment monitoring and one-call systems, others have focused efforts on the quantification of mechanical damage severity through modelling, the use of inline inspection (ILI) tools, and subsequent feature assessment at locations selected for excavation. Current generation ILI tools capable of acquiring multiple data sets in a single survey will provide an improved assessment of the severity of damaged zones using methods developed in earlier research programs as well as currently reported information. Magnetic flux leakage (MFL) type tools, using multiple field levels, varied field directions and high accuracy deformation sensors, enable accurate detection, sizing and classification, thus providing fundamental data for enhanced severity assessments. This paper will provide a review of multiple data set ILI results from several pipe joints with simulated mechanical damage locations created mimicking right-of-way encroachment events, in addition to field results from ILI surveys using multiple data set tools.

Introduction

Despite educational and monitoring efforts to reduce or eliminate mechanical damage to hazardous liquid and gas pipelines as a result of third party intervention, damage still occurs. As a result, quantifying the severity of this damage continues to be a priority for pipeline operators worldwide. The use of inline inspection (ILI) tools in conjunction with subsequent excavation and assessment remains the most reliable method for quantification of damage.

In the past, single technology ILI tools – for example, tools based solely on axial magnetic flux leakage (MFL) technology – were used to detect and quantify mechanical damage. However, studies have shown that, while single technology tools can collect useful data, there are also limitations to each type of technology. Therefore, multiple data set tools – tools incorporating multiple magnetic field levels, varied field directions, high accuracy deformation sensors and residual magnetism sensors – have been developed as a means to overcome these limitations and to provide more accurate and efficient detection, sizing and classification of third party induced defects.

Axial MFL

Axial MFL technology is the most commonly used method for inspecting pipelines for metal loss anomalies. Axial MFL is simpler and more robust than ultrasonic (UT) inline inspection. Further, the product in the line can be gas or liquid during the inspection. Axial MFL technology – and all MFL technology, for that matter – relies on the phenomenon of magnetic signal leakage which occurs at a metal loss defect in a pipe wall. In order to assure detection, the metal loss must be of sufficient volume and of a certain orientation relative to the induced magnetic flux within the pipe wall to create a flux disturbance that can then be detected by the inspection tool. As shown in Figure 1, axial MFL tools magnetize the pipe in the axial direction and are thus adept at detecting general metal loss and circumferential features.

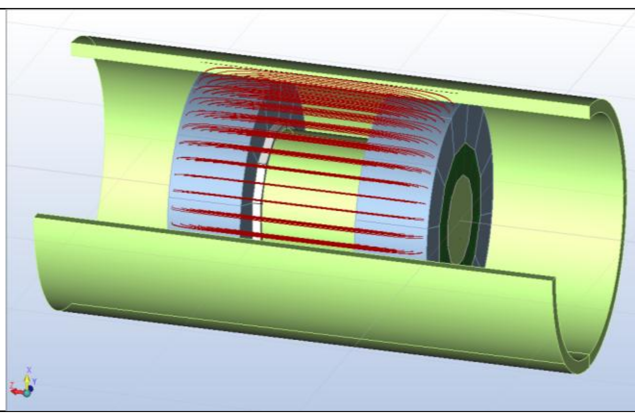

Figure 1: Axial MFL induces magnetism in the axial direction.

However, axial MFL tools do not reliably detect narrow defects with axial length (axial grooving and axial slotting), including those within the longitudinal weld seam. As shown in Figure 2, visualizing axial MFL technology can be equivalent to comparing observations of airflow streams. The blue airflow streams are partially disrupted as they flow around the object.

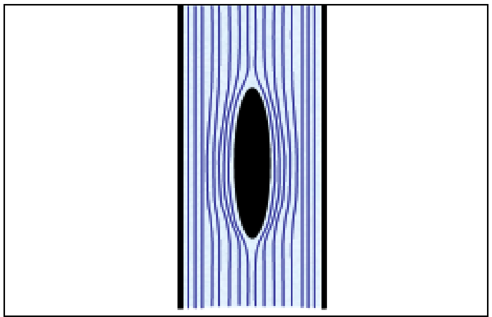

Figure 2: Visualization of axial MFL using airflow streams.

Circumferential MFL

In an attempt to detect axially oriented and axial seam features, inspection companies turned to MFL tools designed to magnetize in the circumferential (rather than axial) direction. Turning the axial magnetizer 90 degrees results in a tool that introduces a magnetic field in the circumferential (or transverse) direction. But increased detection of axial features comes at a price; as shown in Figure 3, circumferential MFL requires the use of two offset magnetizers to achieve full pipe wall coverage. And though circumferential MFL will detect crack-like features in the long seams, its use can also result in the improper classification of anomalies in the long-seam.

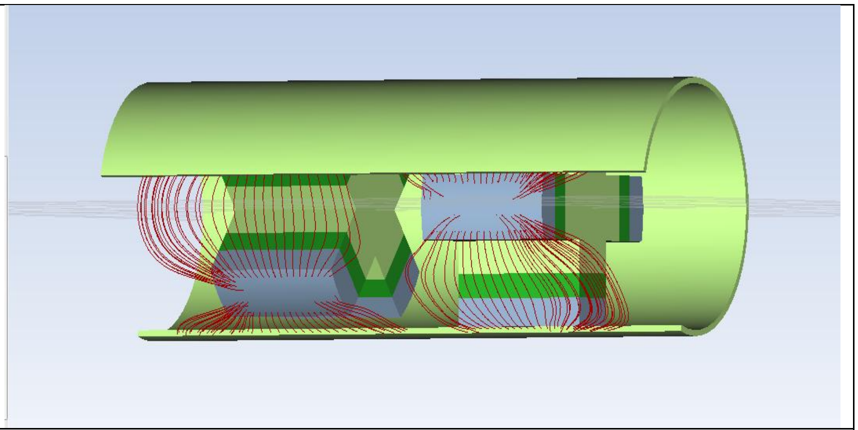

Figure 3: Circumferential MFL induces magnetism around the circumference but requires two magnetizers to achieve complete coverage.

In fact, running circumferential MFL alone may only show a defect in the seam. However, this defect may in fact have width indicative of a volumetric anomaly (having depth, length and width). As a result, circumferential MFL might report a crack-like seam defect when in actuality the defect may be a mill anomaly or an axially oriented shallow corrosion anomaly. In Figure 4, the airflow traveling circumferentially (transversely) is significantly disrupted.

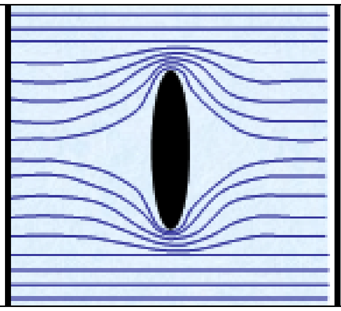

Figure 4: Visualization of circumferential MFL using airflow streams.

Oblique (Spiral) MFL

A third approach to seam assessment has been developed. This approach relies on an oblique (spiral) magnetic field. To investigate the theory of this concept, a relationship was established between the principal axis and the angle of incidence (spiral angle). A series of experiments were performed on flat plates with machined defects. As the plate was rotated in the field, the amplitude of flux leakage was measured in each of three coordinates. The spiral magnetizer was modeled in accordance to the flat plates. Various angles of spiral were then analyzed. It was determined that the optimum angle was 45 degrees, which achieves the same full-wall coverage as circumferential MFL but does so using just one compact magnetizer rather than the two that are traditionally required by circumferential MFL. As shown in Figure 5, this allows the magnetizer to be of a minimum length, contain the sensors within the optimum location and house this module without any sensor dead zone.

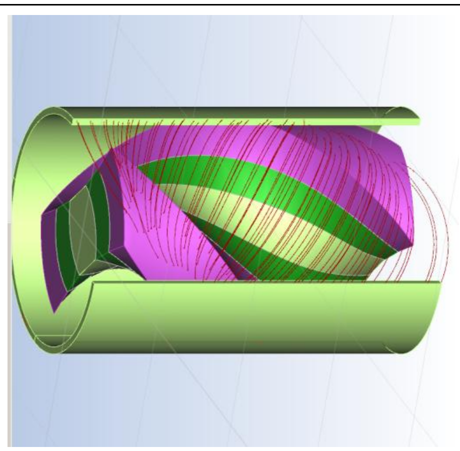

Figure 5: Oblique (spiral) MFL achieves complete coverage with just one magnetizer.

This research evolved into the technology now known as SpirALL™ MFL (SMFL) technology developed by T.D. Williamson.[1,2] This tool magnetizes in a helical, nearly 45-degree direction, in order to detect axial features while still keeping tool length at a minimum. As shown in Figure 6, the object significantly displaces the helical airflow stream and illustrates the concept of oblique inspection technology.

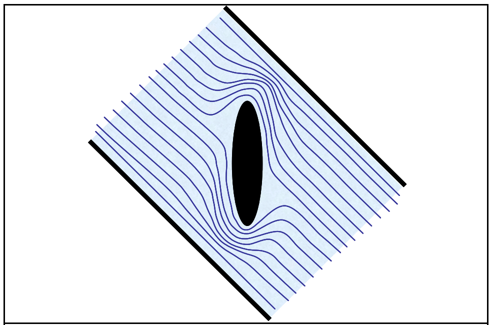

Figure 6: Visualization of oblique MFL using airflow streams.

Axial MFL and Oblique MFL in Combination

Because oblique MFL is more compact in design than other longitudinal assessment technologies, the oblique tool can be paired with axial technologies to overcome the limitations of either the axial and circumferential approach alone. Looking at a single pipeline through a variety of technologies does two things. First, it improves probability of detection, providing more opportunities for a defect or anomaly to be detected. Second, when an anomaly has been found, use of multiple technologies assists accurate identification. Obtaining multiple views of an anomaly from a single inspection run provides analysts with more data, information that can be correlated more completely than ever before. The end result for the pipeline operator: superior reporting, resulting in enhanced characterization and elimination of unnecessary excavations.

For example, combining axial MFL and oblique MFL allows for traditional internal and external metal loss assessment. Combining analysis of axial and oblique signatures simultaneously also eliminates guesswork in calling seam-weld anomalies, and it assists the quantification of other longitudinal defects in the pipe body. This improves the quality of data obtained from the inspection and reduces the time and money spent by the pipeline operator making unnecessary digs.

Field results from a series of 16-inch inspection tool runs indicated that SpirALL™ MFL technology successfully identifies narrow axial defects that normally would not be reported by axial MFL alone. In most cases, the anomalies found that are not detected by axial MFL are identified as planar, or crack-like in nature. Figure 7 shows examples of two such external anomalies, along with the corresponding SpirALL™ MFL and axial MFL technology screenshots. Due to their geometry, these anomalies are not detected by axial MFL.

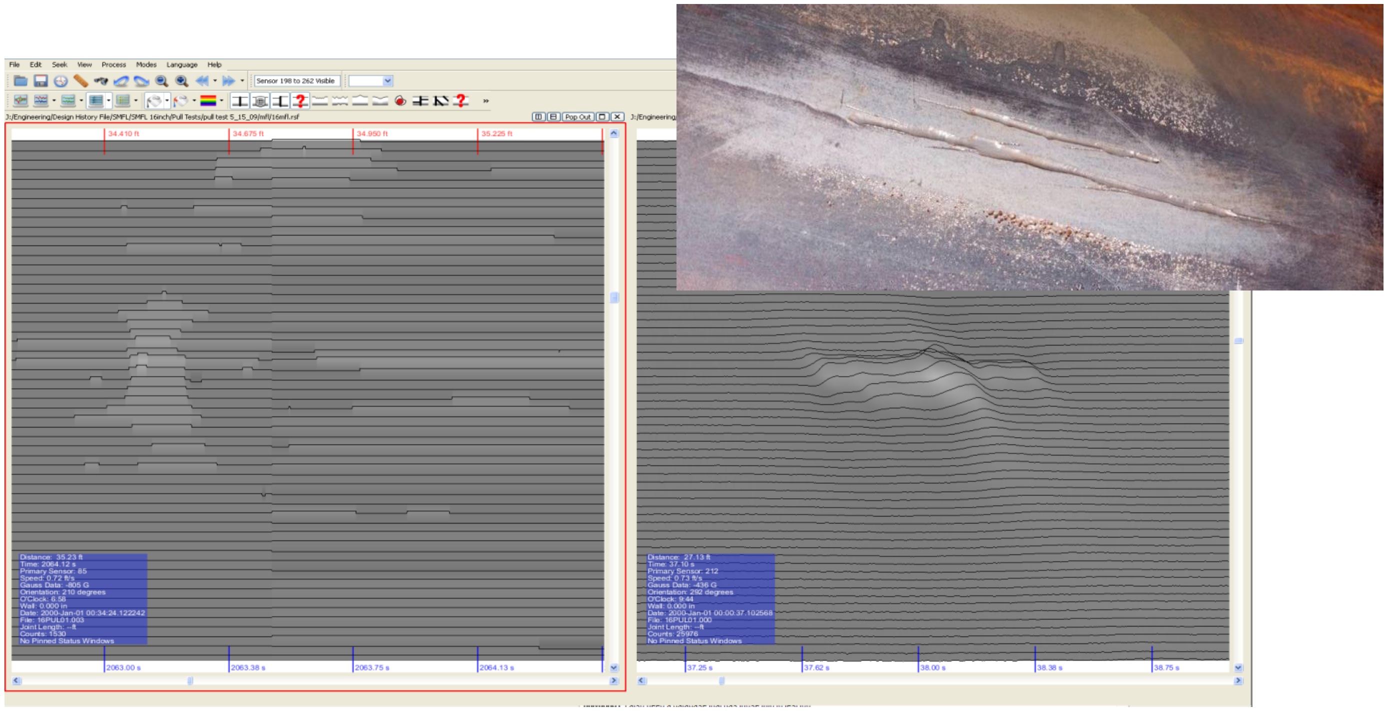

Figure 7: Very narrow defects.

Figure 8 shows axial MFL data on the left and SpirALL™ MFL technology data on the right. A previous circumferential MFL inspection had identified an anomaly within the long-seam as a crack-like feature. However, the anomaly is very evident in the axial MFL data (at left), which means it is volumetric rather than crack-like. By combining axial MFL with SpirALL™ MFL in the same run, it becomes possible to identify the anomaly as a metal loss feature that happens to be in the seam weld instead of a crack-like feature in the seam. In this case, 14 other similarly-characterized anomalies were excavated based on the circumferential MFL inspection. Use of axial MFL in conjunction with SpirALL™ MFL would have correctly eliminated all 15 from the dig list. Analysis of axial MFL and SpirALL™ MFL technology signatures simultaneously eliminates guesswork in calling seam-weld anomalies, so the pipeline operator spends less time and money making unnecessary digs.

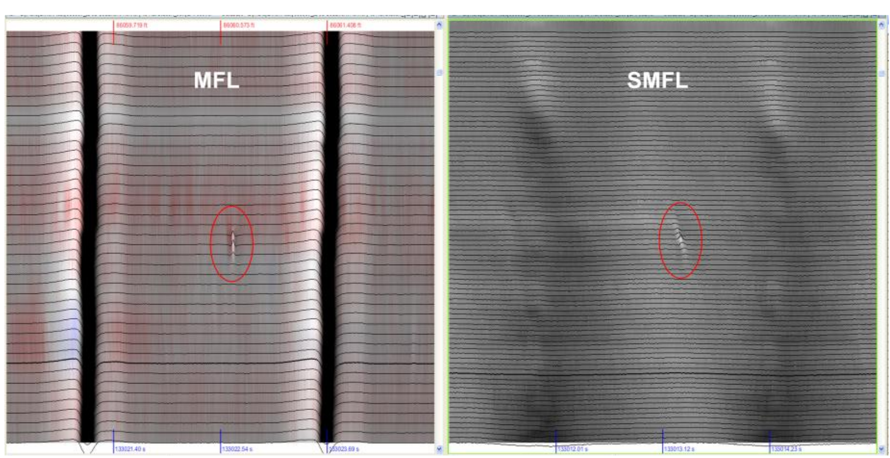

Figure 8: Comparison of axial MFL and SpirALL™ MFL (SMFL) technologies.

Multiple Data Set Technology

An ongoing effort to improve accuracy in pipeline integrity readings calls for the ability of inspection tools to yield multiple data sets. From the initial idea stage of the oblique MFL (SpirALL™ MFL) concept, the plan was always to incorporate multiple data-sensing technologies on a single tool to provide a comprehensive view of a pipeline. In addition to axial MFL and SpirALL™ MFL, a multiple data set platform can include:

- Mapping
- High-resolution deformation (DEF) for bore measurement and strain calculations
- Inside diameter/outside diameter (ID/OD) sensors incorporated on deformation arms for verification of internal/external metal loss classification and details on internal surface conditions; that is, discrimination of debris fields from dents or other bore reductions
- Residual or low-field sensors capable of detecting hard spots[3], the “halo-effect” due to dent re-rounding, and other differences in pipe characteristics (such as xGrade differences, etc.)

Inspection using varying magnetic fields and other sources, including deformation, improves detection and anomaly identification. Multiple views of the same anomaly in different data sets, from the same inspection, provide an increasingly clear picture, resulting in superior analysis and anomaly characterization.

Figure 9 shows the basic layout of a large diameter inspection tool with SpirALL™ MFL technology. In this case, a 24-inch tool is shown, which includes (front to rear, left to right) the drive section with high resolution deformation and odometers, SpirALL™ MFL technology section, axial MFL section, and low field section.

Figure 9: TDW 24-inch DEF + SpirALL™ MFL technology + MFL + LFM tool.

The anomaly shown in Figure 10 demonstrates the benefit of multiple data set technology. Availability of only the deformation (DEF) and MFL data would simply identify a dent at this location. DEF data reveals a dent at approximately seven o’clock and is confirmed in the MFL data including ID/OD overlay. The red hue indicates sensor lift-off at the indication, and with DEF plus MFL data, confirms the dent. The residual data indicates additional strain induced by the dent outside of the specific dent area, where the apparent strain that extends around the circumference beyond the dent area itself appears. The dent is located at the green oval, indicating that additional strain is present with the red background surrounding the dent. Note that the strain extends around the circumference.

However, what was not clear in the previous four data sets (DEF, MFL, ID/OD and residual) becomes very apparent upon review of SMFL data. There is a signature indicating the dent, though closer analysis reveals a gauss change. This gauss change confirms metal loss at the dent, metal loss which went undetected by MFL due to the geometry of the indication. This dent has associated metal loss (possibly from a gouge) that will rate a higher excavation priority from pipeline operators.

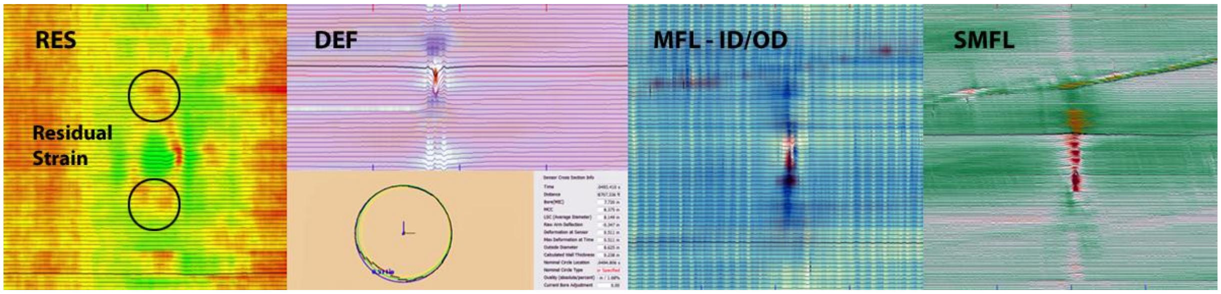

Figure 10: Using multiple data-sensing technologies to detect an anomaly.

Prioritizing Dents

As previously noted, the oblique field approach requires just one magnetizer to accomplish wall saturation and sensor placement. This leaves room on multiple data set tools for the addition of other technologies, such as low field or residual magnetics sensors. These additional sensors can be combined with high resolution deformation data and dent strain calculations to populate the Battelle dent prioritization model. This model takes into account not only immediate threat issues as stated in 49 CFR Part 192, but also includes dent re-rounding and pressure cycling. The model distinguishes and prioritizes the threat level of all mechanical damage items in the pipeline.[4]

As shown in Figure 11, the Battelle model attempts to qualify the severity of dents into the following categories:

- high priority
- moderate-high priority
- moderate priority
- moderate-low priority
- low priority

The model categorizes threats based on features of the mechanical damage, such as:

- dent depth
- movement or removal of metal
- steel micro-structure damage
- residual stresses and strains
- wall thinning
- cracking in areas pushed out by internal pressure

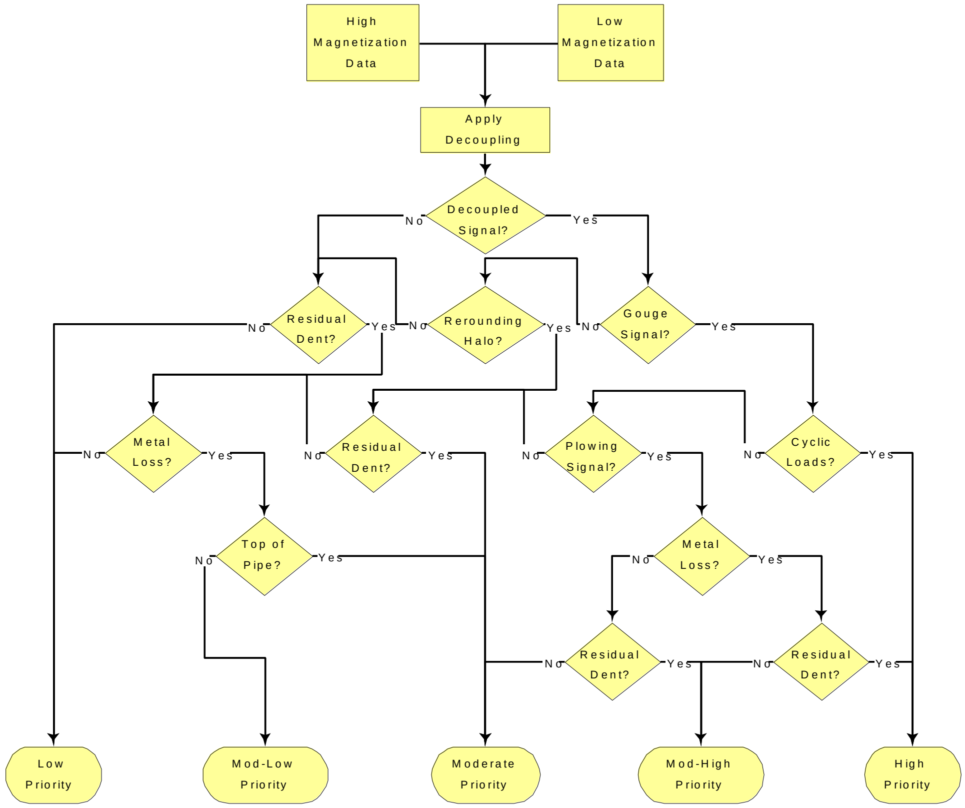

Figure 11: Simplified Battelle Dent Prioritization Model (for entire model see PRCI L52084).

Traditional MFL inspection tools detect metal-loss corrosion by using high magnetic fields to decrease noise. At high fields, dents with wall thinning and/or removed metal provide metal-loss corrosion like signals, and thus high-field MFL tools provide little information about micro-structure changes created as a result of mechanical damage. At much lower magnetization levels, structure changes (such as cold working, residual stresses and plastic deformation) are more pronounced. The big challenge in analyzing low-field magnetic flux density of micro-structure changes is that the measurements are less than ten gauss, which is an order of magnitude less than high-field. These problems are overcome with very low noise electronics.

Input for the prioritization model from low-field MFL includes dent re-rounding or pressure cycling. Figure 12 shows how the low-field data can be used to determine these inputs.

When the pipeline steel experiences a large loading the material flexes, and, if the load is great enough, the material will begin to yield plastically, changing the microstructure enough that the remnant ferro-magnetism will be altered. As a result, if the pipeline is dented enough to cause yield, then a low-field MFL will be able to qualify changes.

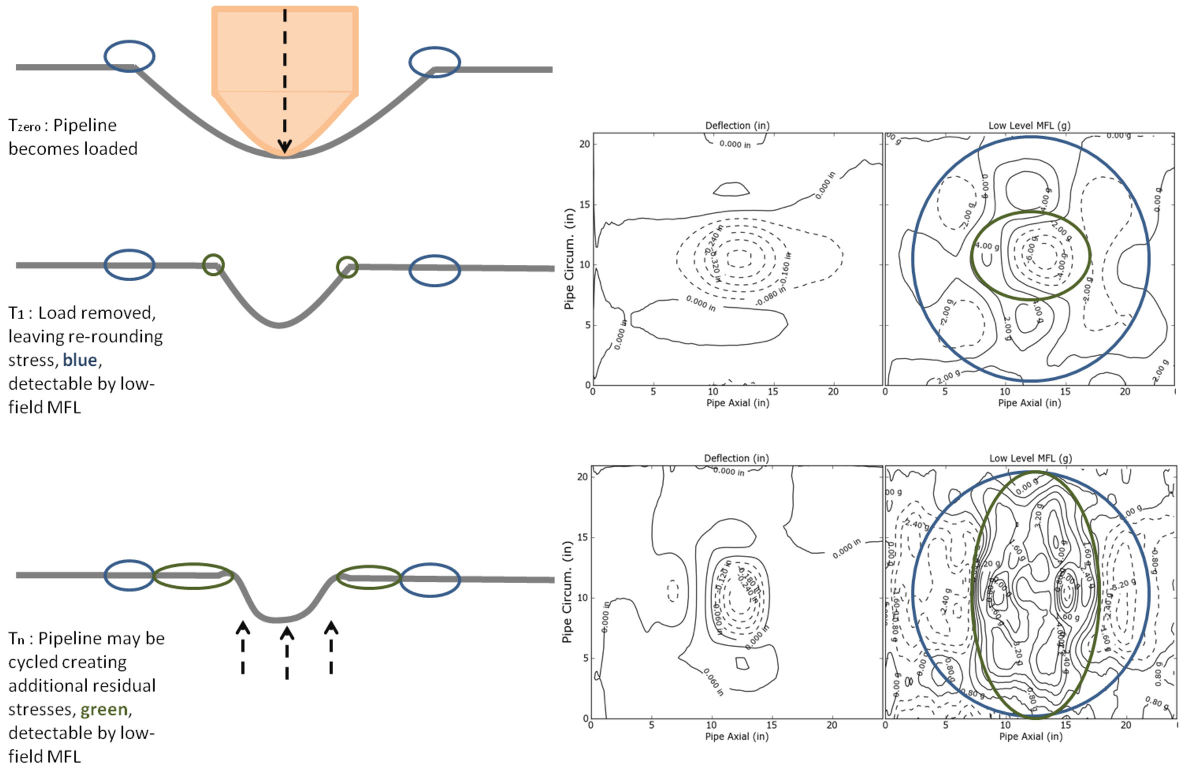

Figure 12: At left, theoretical concept shows sideview over time. At right, sample data view shows the deflection and low-field MFL signal for T_1 and Tn.

The Battelle model considers a re-rounded dent as being of higher severity than one without re-rounding because some of the metal has been altered as a result of loading. To determine if the dent is re-rounded, the area of the metallurgical change is much larger in diameter than the area of the physical dent. If the load is removed and the steel is allowed to spring back, then the extent of the low-field MFL will be greater than that of the deformation shown at T_1 in Figure 12. On the other hand, if the low-field signal near the dent does not show change from the nominal background, the assumption is that the micro-structure has not been significantly altered and thus has a lower severity (this happens with most rock dents).

Figure 13 is a screen capture from TDW PigTrap™ software displaying the characteristic shape of dent re-rounding. The classification of this feature was indentified due to the stress captured by low-field MFL.

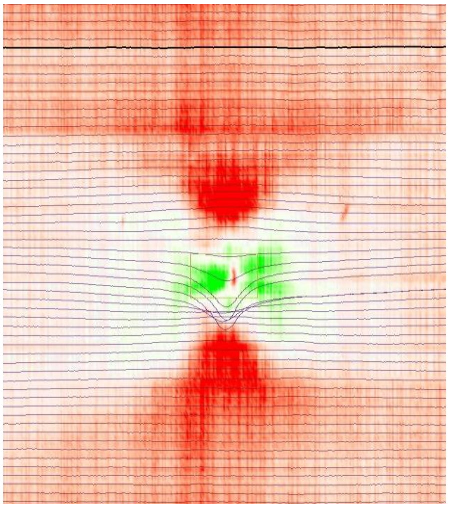

Figure 13: Re-rounded dent.

Because dent cycling can lead to fatigue, the Battelle model considers cycling as more severe than re-rounding. It is quite easy to identify cycling in the low-field data (see Tn of Figure 12). Over cycles of pressure, the edges of the dent flex, creating larger and larger gradients in the remnant magnetization.

Figure 14 is another screen capture of a dent showing the characteristic circular stress gradients indicative of pressure cycling. The classification of this feature was identified as cycled due to the “halo” effect seen around the dent. The halo is a collection of low field/residual magnetism coupled around the higher stress area surrounding the dent body.

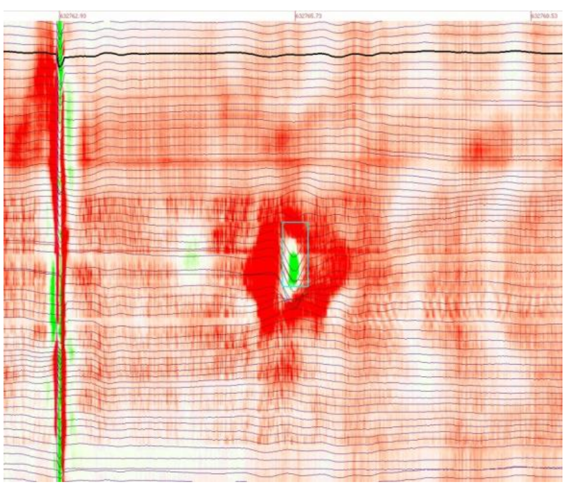

Figure 14: Pressure-cycled dent.

The Pipeline Research Council International (PRCI) report produced using the Battelle model utilized a decoupled low-field signal to determine the presence of gouging. The TDW multi-data set tool also uses the SMFL or oblique magnetization signals to help determine gouging, as it can be an easier way to interpret a data set, as seen in Figure 15. In this example, there is a manufactured dent with long gouge. Characterizing gouging using oblique data set is simpler as the long narrow features are clearly connected. Note that the tail indicated by the arrow in the Oblique data represents the gouge, and this gouge is not visible in the Axial or High Level MFL data.

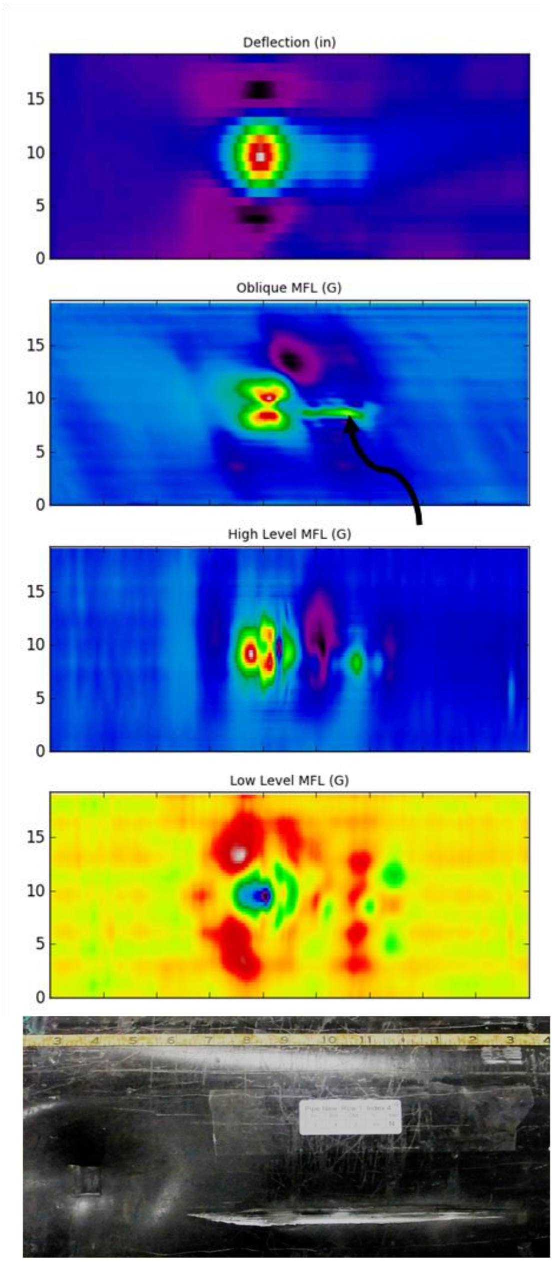

Figure 15: Identifying gouging via multiple data set technology.

TDW makes two additions to the Battelle model. First is addition of dent strain analysis[5] using the methods described in ASME B31.8, with additional corrections suggested by Gao et al.[6] and Lukasiewicz et al.[7] If the strain is greater than 6%, the severity of the dent is increased.

Second, if the dent is coincident with a girth or seam weld, then the severity is increased because any compression or tension placed on the weld has a higher likelihood of leading to cracking.

A TDW-produced report contains a final ranking of each dent to help prioritize the threats within a given pipeline, facilitating immediate as well as long-term maintenance.

Case Study

In October 2011, TDW employed multiple data-sensing technologies to inspect a 16-inch pipeline for a liquids operator in the Midwestern United States. The line was built in the 1950s and contains mostly 0.250” wall thickness. As a result of repeated pipeline failures, the operator was looking for extremely small dents with very small metal loss and cold working. The inspection tool used for this project included high-field MFL, SMFL, deformation and low-field MFL.

Figure 16 shows an example of a dent indentified during inline inspection and verified during subsequent non-destructive evaluation (NDE) in April 2012. This dent was about 0.95% deep and thus smaller than anyone would normally ever dig. The TDW inline inspection tool could see corrosion in the high-field MFL, corrosion and gouging in the SMFL, very small dent depth in deformation, and severe work hardening in the low-field MFL around the rim of the dent, as well as stress at the gouge. As noted below, this stress in the gouge was later found to be cracking.

TDW reported that this set of corrosion and gouging was associated with a very small dent in a work hardened area. Corrosion and gouging in relation to work hardened areas near dents are extremely severe because they are crack initiation points. Once initiated, a crack may at any moment rip open, causing the pipeline to leak oil.

From a corrosion/metal loss perspective, the worst scenario is to be near a dent, such as this one, that has been continuously cycled over a period of years. Corrosion and gouging itself can be serious, but it is also important to note that these are locations for cracking genesis if they are in a stressed location as a result of differences in metal hardness.

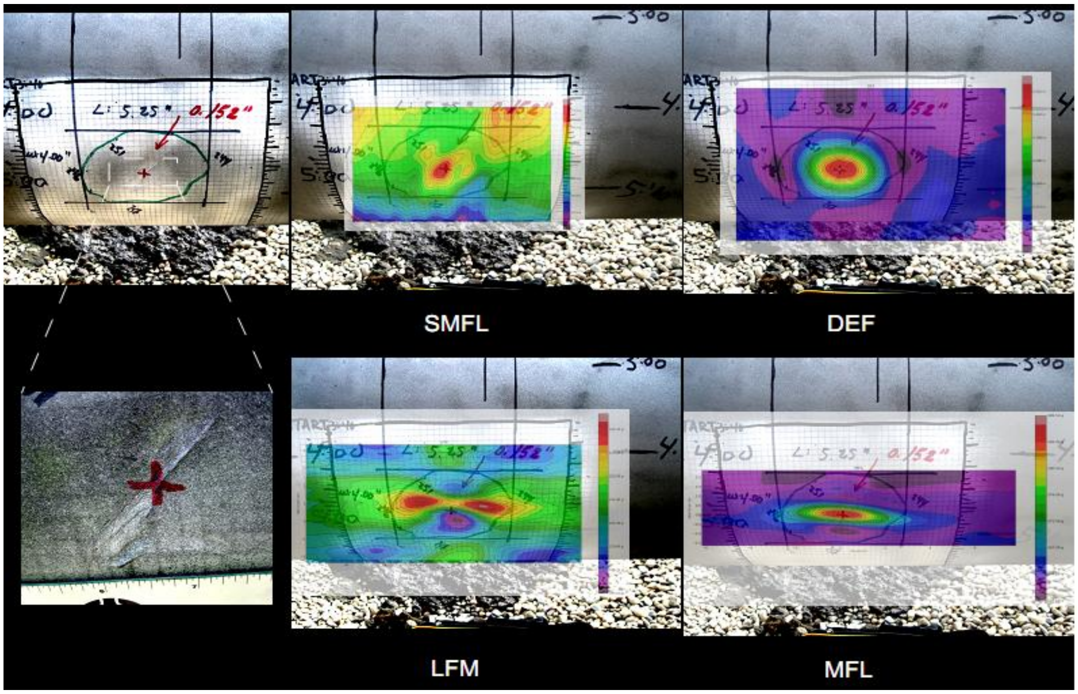

Figure 16: Inline inspection data overlaid onto actual field location.

Summary and Conclusions

Both axial MFL and circumferential MFL have inherent limitations. These limitations can be overcome through use of an oblique (spiral) magnetizer combined with axial MFL. SpirALL™ MFL technology will better detect axial features missed by axial MFL, and the fact that it is designed to run in combination with axial MFL will more effectively detect and characterize metal loss features in a pipeline including those within the long seam. To date, more than 5,000 miles (8,050 km) of pipeline have been successfully inspected using SpirALL™ MFL technology.

Capturing multiple data sets in a single inspection provides clarity of anomalies, which ultimately translates into greater accuracy of results delivered to the pipeline operator. Compared to circumferential MFL, SpirALL™ MFL technology has shown that it can eliminate unnecessary seam anomaly excavations and offer improved identification of other longitudinally oriented anomalies.

A key advantage afforded by oblique field technology is the ability to add other technologies, such as residual or low-field magnetics. The TDW Dent Prioritization Model combines all data sets with dent strain calculations into a comprehensive ranking system that can help operators prioritize dent excavations.

Acknowledgement

This paper is especially indebted to the work of Chris Goller, Senior Systems Engineer, T.D. Williamson, Inc.

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Notes