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Electromagnetic methods for detecting corrosion in underground pipelines: magnetic flux leakage (MFL)

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Abstract: This chapter discusses electromagnetic in-line inspection tools as they relate to pipeline integrity. It covers magnetic flux leakage (MFL), the most commonly used inspection technology for pipelines. MFL has been successfully used for nearly 50 years to detect, identify, and size metal loss due to corrosion.

Key words: in-line inspection, magnetic flux leakage, pipeline integrity, smart pig.

7.1 Introduction

An in-line inspection tool is a self-contained device that moves through a pipeline with the product or fluid in the pipe. Pipeline operators use in-line inspections along with other activities to evaluate and monitor the integrity of hundreds of thousands of miles of lines. Combinations of these activities constitute the overall integrity management program of the pipeline operator. This chapter discusses electromagnetic in-line inspection systems as they relate to pipeline integrity. It summarizes the capabilities of various tools, and discusses how the tools are best used.

MFL is the most common electromagnetic inspection technology for metal loss and has been used for 50 years in pipeline systems around the world. It has successfully found defects that could have led to failures. Understanding its capabilities and weaknesses is critical in using the results of an inspection. Other electromagnetic technologies include those based on eddy currents and electromagnetically induced ultrasonics. Each of these technologies is newer and less widely used than MFL. These technologies are generally being developed to detect and size cracks rather than metal-loss anomalies.

7.2 Background and definitions

This chapter is based, in large part, on Bubenik *et al*. (2000). In-line inspection tools are also referred to as smart pigs. These tools inspect the full thickness of the pipe wall and are designed to look for conditions such as metal-loss corrosion, cracks, and other anomalies.

An in-line inspection involves collecting data continuously along a pipeline and interpreting the data. The data are analyzed using software and manual techniques. The inspection and data analysis are referred to as an inspection system in this chapter.

Data analysis has three primary steps: detection, identification, and sizing. Detection involves recognizing a measurable signal that is above a threshold value and differentiating it from other signals. Signals can be from any number of conditions, such as natural pipeline variations in wall thickness or metallurgy.

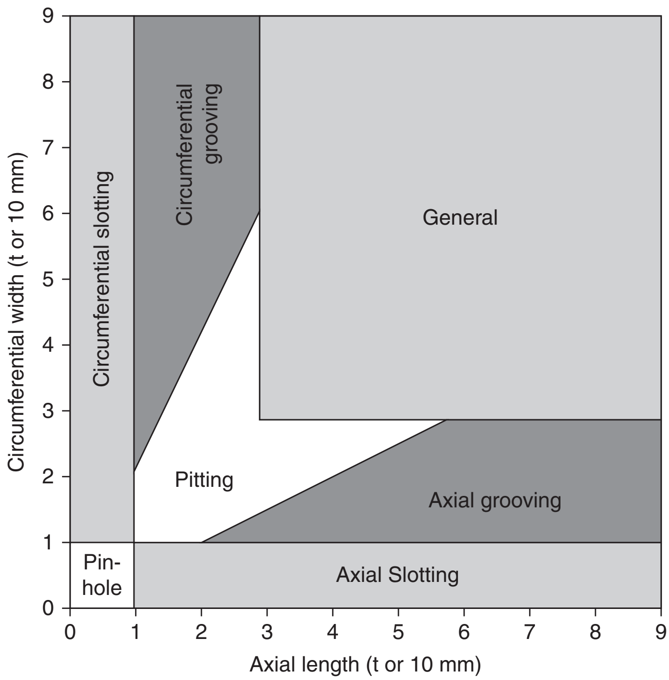
Determining the source of the signal is called identification. During the identification phase, the source is determined to be, for example, a pipeline component or potential metal-loss anomaly. Next, for suspected defects, the anomaly is sized. Sizing involves estimating the dimensions of an anomaly from the measured signals. For metal loss, inspection vendors usually estimate the length, depth, and width.

Sizing is used to determine the severity of an anomaly from the inspection signal. If the anomaly fails one or more acceptance criteria, it is referred to as a defect. If it does not fail, it is considered an imperfection.

7.3 Typical inspection system capabilities

Electromagnetic in-line inspection tools are typically designed to detect and size one type of anomaly, most commonly metal-loss corrosion. The reliability with which the tool finds such anomalies is a function of the depth, length, and width of the metal loss. Detection is best for large metal-loss anomalies with relatively sharp edges. Most inspection vendors claim depth detection thresholds of 5–15% of the wall thickness and threshold lengths of several times the wall thickness. Detection reliabilities (i.e., probabilities of detection) are usually quoted at the detection threshold. A common probability of detection is 90% or 95% for anomalies whose depth is greater than 10% of the wall thickness.

The probability of correct identification varies with the size and shape of the anomaly. For example, a common probability of correct identification is 95–98% for metal-loss corrosion greater than the detection thresholds. The corresponding probability for other types of metal loss, such as gouging, is less.



7.1 ILI sizing chart.

Like detection and identification, sizing accuracies with electromagnetic tools are a function of the size and shape of an anomaly. Figure 7.1 shows sizing categories as a function of anomaly length and width. Most inspection systems are capable of accurate sizing in some, but not all, categories shown, but few systems are capable of accurately sizing in the pin-hole category.

Inspection capabilities are not necessarily constant during a smart pig run. Many operational conditions affect and often decrease accuracy and reliability. For example, high velocities reduce detection reliability. The detection reliability and sizing accuracy can therefore vary during an inspection. Consequently, it is important to control those operational conditions to increase detection reliability and sizing accuracy during an inspection.

Regardless of the controls used during a smart pig inspection, no inspection is perfect. Smart pigging cannot detect every condition that could threaten the integrity of a pipeline, just as no medical diagnosis can detect all illness in humans. Smart pigging, like hydrotesting and all other pipeline maintenance tools, has limitations. Understanding these limitations allows smart pigging to be used to its greatest advantage in combination with other activities.

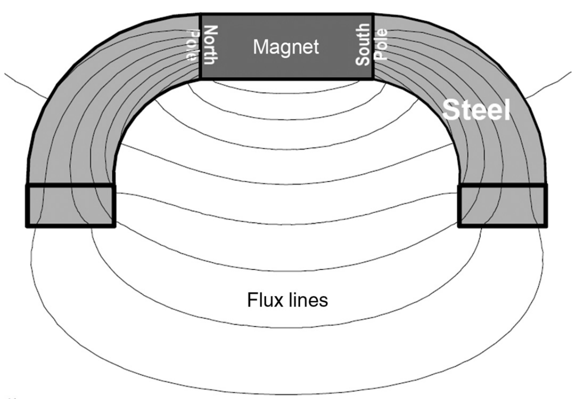
7.4 Magnetic flux leakage (MFL) pigs

MFL pigs were first introduced in the mid 1960s. Since then, in-line inspection capabilities have evolved, and they continue to evolve today. MFL is the oldest and most commonly used inspection method for pipelines. It can reliably detect metal loss due to corrosion and, often, gouging. In addition, while not designed for this purpose, MFL systems can sometimes find metallurgical and other geometric anomalies, such as dents.

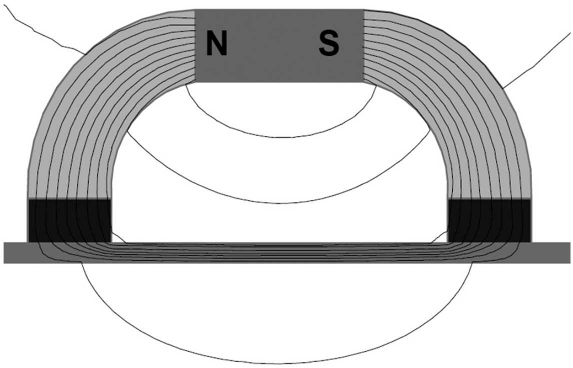
7.4.1 Principles and technologies

MFL starts with a magnet. A magnet has two ends, called north and south poles. The poles exert forces on iron and steel. This force of attraction is caused by the magnetic field. Figure 7.2 illustrates the flux lines around a magnet and its poles as calculated using finite-element analyses. The magnet is the dark gray bar near the top of the figure. Flux lines represent the strength and direction of the magnetic field, where dense lines imply a strong magnetic field. The curved sections attached to the poles are magnetic material (steel or iron), which is used to channel magnetic flux in a particular direction.

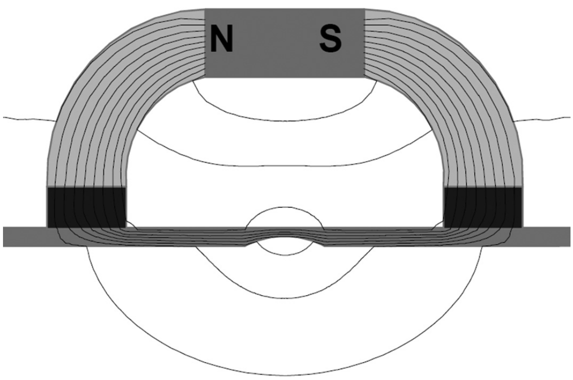
When a magnet is placed next to a pipe wall, most of the flux lines pass through the pipe wall, as shown in Fig. 7.3. The pipe wall is a preferred path for the flux because it is easier to magnetize. While most of the flux lines concentrate in the pipe wall, a few pass through the surrounding media. Figure 7.4 shows that flux leakage occurs at a metal-loss anomaly,



7.2 Flux lines around a magnet.



7.3 Flux lines at the pipe wall.



7.4 Flux lines at an anomaly.

where there is a local decrease in the thickness of the pipe. At the anomaly, the flux that had been carried by the lost metal must go somewhere. Some are carried by the thinner section, and some 'leaks' from both surfaces of the pipe.

A sensor positioned on the inside (magnet side) of the pipe is typically used to measure the magnetic field adjacent to the pipe wall. At a metal-loss anomaly, the sensor records a higher flux density or magnetic field, which indicates the presence of an anomaly. In this manner, an MFL pig detects an anomaly that causes flux to leak. The measured leakage field depends on the depth, length, width, and shape of the anomaly, as well as the magnetic properties of the nearby material. To characterize the anomaly, the measured leakage field must be analyzed.

Groups of sensors are contained in sensor heads that are mounted between the magnets. These heads are spring mounted and move along the inner pipe wall. Maintaining close contact with the pipe wall is important because the distance between a sensor and the pipe wall affects the measured signal.

To summarize, MFL tools apply the principles of flux leakage inside the rugged environment of a pressurized and flowing pipeline. A magnetizing system applies a magnetic field as the tool moves through the line. Anomalies distort this applied field, producing flux leakage. The amount of flux leakage depends on the size and shape of the anomaly, as well as the magnetic properties of the nearby pipe steel. Sensors measure flux leakage, and a recording system stores the measurements inside the inspection tool. The measurements are analyzed after the inspection is completed to identify anomalies, determine their origin, and estimate the anomaly geometry and severity.

7.4.2 Magnetization direction

Magnetization direction plays an important role in establishing the capabilities of an MFL inspection system. Most MFL tools magnetize in the axial direction and create flux lines that run parallel to the pipe axis. All MFL systems are more sensitive to anomalies that cut across flux lines than those that are parallel to the flux. Therefore, tools that use axial magnetization are more sensitive to anomalies that are circumferentially wide because they cut across flux lines. They are less sensitive to anomalies that are circumferentially narrow.

Some MFL tools are designed to magnetize in the circumferential direction. These tools are most sensitive to axially long anomalies and, as expected, least sensitive to axially short anomalies. Other tools magnetize in a spiral pattern. These implementations are more sensitive to any anomaly that is not aligned with the corresponding flux lines.

Engineering mechanics shows that axially long anomalies are generally more severe than axially short anomalies. Circumferential width plays a lesser role. Why do all MFL tools not magnetize in the circumferential or spiral direction? The answer lies in the complexity of the resulting MFL tools and signals, and how parameters such as tool speed affect signal strength and shape.

7.4.3 Velocity and other effects

A moving magnetic field (an MFL in-line inspection tool) in a conductor (the pipe) will induce electrical currents in the conductor. These currents, in turn, affect the applied and leakage fields. As a result, MFL inspection is velocity dependent. The electrical currents induced by the movement of an MFL tool depend on the direction of motion relative to the flux direction. When the motion and flux direction are the same, there is a small effect. When the directions are perpendicular, the effect is much greater. As a result, circumferentially applied fields (and circumferential MFL tools) are more sensitive to velocity than axially applied fields (and axial MFL tools). Spirally applied fields are somewhat sensitive to velocity.

Mechanical stress and strain affect the magnetic properties of the pipe steel. A change in magnetic properties, in turn, affects the applied field strength and uniformity. As a result, stress makes analysis of inspection data more difficult. Stress effects are most pronounced at lower magnetic field strengths. So, most inspection companies design their systems with very strong magnets.

7.4.4 Assessing MFL results

The relationships between MFL signals and anomaly geometry and severity are complex. It is important to understand three key concepts. First, there is not a one-to-one relationship between the MFL signal components and anomaly dimensions, such as depth, length, and width. For example, deep anomalies create strong signals in most MFL tools except when the anomaly is long and narrow. For long narrow anomalies, the signals become increasingly smaller as the anomaly width decreases. For axial cracks, the signal essentially disappears!

The second key concept is that the tool design and inspection conditions affect the measured signals. Designers of any piece of equipment make compromises to make the equipment easier to use or cheaper to build. Inspection vendors are no exception. Tradeoffs are frequently made to improve the capabilities in one area at the expense of those in another.

Third, inspection conditions affect the signals. Previously mentioned examples include tool velocity (which can vary significantly during the inspection of a natural gas pipeline) and separation between the sensor and the pipe wall. Other examples include remnant magnetization (magnetization left from previous inspections), changes in wall thickness and pipe grade, and the presence of nearby metallic objects. These examples are not all-inclusive.

7.5 Summary of MFL strengths and weaknesses

Table 7.1 shows some of the advantages and disadvantages of three key variables that affect MFL tool design. Magnetization direction is a dominant parameter, with tradeoffs being between sensitivity to long narrow anomalies, velocity effects, and tool complexity. Magnet pole spacing is also important. Tight spacing provides the ability to traverse tight bends, but with less accurate detection and sizing of some anomalies. Magnet strength affects detection and sizing accuracy. Stronger magnets are often used, which makes signal interpretation easier for metal-loss anomalies, but with reduced sensitivity to some anomaly types.

Table 7.1 Some advantages and disadvantages of commonly seen MFL tool configurations

Factor	Advantages	Disadvantages
Axial magnetic fields	Less sensitive to velocity than with circumferential or spiral magnetic fields	Less sensitive to long narrow anomalies than circumferential or spiral magnetic fields
Circumferential magnetic fields	More sensitive to long narrow anomalies than with axial or spiral magnetic fields	Compared to axial magnetic fields: • More sensitive to velocity • Less sizing accuracy for most anomalies • Requires second magnetizer
Spiral magnetic field	Sensitive to both long narrow anomalies and short wide anomalies	More complex signal to evaluate than with axial or circumferential magnetic fields – less accurate detection and sizing of some anomalies Less sensitive to anomalies in the direction of the spiral magnetic field Requires second magnetizer
Magnet poles that are close together	Ability to pass through tight bends	More sensitive to velocity than with poles that are widely spaced
Magnet poles that are far apart	Less sensitive to velocity than poles that are closely spaced	Cannot pass through tight bends
Stronger magnets	Easier to analyze leakage fields	Less sensitivity to mechanical damage
Weaker magnets	More sensitivity to metallurgical anomalies and mechanical damage	More difficult to analyze signals than with strong magnets

As a consequence of these and other tradeoffs, each smart pig has unique strengths and weaknesses, making one type of pig more appropriate for certain types of anomalies or conditions. Some improvements expand the range of anomaly types detected by the pig, while others address entirely different problems. Selecting the 'right' pig for each job is important.

7.5.1 Estimated MFL pig capabilities

Knowing that each pig has strengths and weaknesses is important, but quantifying pig capabilities is more important. Because every pipeline is unique, the capabilities vary and it is difficult to obtain objective measures of pig performance under all conditions. Inspection vendors general provide performance specifications, which give estimated capabilities under typical pipeline operating conditions.

Table 7.2 shows a typical set of sizing accuracies for MFL tools that magnetizes in the axial, circumferential, and spiral direction. The anomaly

Table 7.2 Typical MFL performance specifications

	General	Pitting	Axial grooving	Circumferential grooving
Axial MFL				
Depth at probability of detection (POD) = 90%	**0.10 t**	0.12 t	0.20 t	0.12 t
Depth sizing accuracy at 80% confidence	**±0.10 t**	±0.15 t	±0.20 t	±0.15 t
Length sizing accuracy at 80% confidence	**±15 mm**	±12 mm	±15 mm	±12 mm
Width sizing accuracy at 80% confidence	±20 mm	**±12 mm**	**±12 mm**	±20 mm
Circumferential MFL				
Depth at POD = 90%	0.15 t	0.15 t	**0.10 t**	0.15 t
Depth sizing accuracy at 80% confidence	±0.15 t	±0.19 t	**±0.15 t**	±0.20 t
Length sizing accuracy at 80% confidence	**±15 mm**	±12 mm	**±15 mm**	±15 mm
Width sizing accuracy at 80% confidence	**±15 mm**	±15 mm	±15 mm	**±8 mm**
Spiral MFL				
Depth at POD = 90%	**0.10 t**	**0.10 t**	0.15 t	**0.10 t**
Depth sizing accuracy at 80% confidence	**±0.10 t**	**±0.10 t**	**±0.15 t**	**±0.10 t**
Length sizing accuracy at 80% confidence	±20 mm	**±10 mm**	±20 mm	**±10 mm**
Width sizing accuracy at 80% confidence	±20 mm	±20 mm	±20 mm	±20 mm

descriptions at the top of each column refer to the categories defined earlier in Fig. 7.1. Note that the capabilities shown are typical – prospective buyers of MFL inspection services should always check the actual performance specification of a given tool.

The inspection system that performs best in each category is highlighted in Table 7.2. As expected, the axial and spiral inspection systems are less sensitive to axial grooving and more sensitive to circumferential grooving than a tool that magnetizes in the circumferential direction. The circumferential tool is also somewhat less sensitive to general and pitting metal loss.

7.6 Conclusion and future trends

In-line inspection technologies are evolving, not static. This evolution is leading to smart pigs with expanded and improved capabilities. As these capabilities enter the marketplace, additional and more powerful inspection systems will be available for monitoring pipeline integrity.

MFL inspection systems are the oldest type of smart pig used by the pipeline industry. Axial MFL tools have the longest history and are best understood. Consequently, future improvements for this type of system are expected to be modest. Circumferential and spiral tools are newer and have more room for improvement.

There are also ongoing developments on the use of multiple technologies on a single in-line inspection tool. These developments include combinations of technologies to either expand the range of anomaly types covered by the system (e. g., denting and metal loss) or to improve the detection and sizing of one or more anomaly types (e.g., metal-loss corrosion). The use of caliper and MFL inspection technologies is an example of the first, while using MFL and ultrasonic wall measurement technologies is an example of the latter.

For all tools, ongoing developments will lead to improvements in capabilities, but like all other technological developments, they will require time before they are widely available. Development time is needed for the basic analysis methodologies, tool design concepts, and testing under normal pipeline operating conditions. This latter step is crucial and time consuming; it can easily take years to accomplish. This step is essential, though, in providing inspection equipment that is rugged, reliable, and accurate.

In-line inspection is a powerful tool that can and should be part of the integrity management programs of pipeline operators. Smart pigs are not a panacea, though, and they are not the 'right' tool for every application. Consequently, each case should be considered separately, weighing the strengths and weaknesses of different pigs against the expected conditions on a pipeline. The analyses must then match the reported anomaly population, and appropriate decision models must be used to ensure that the most important risks to pipeline integrity have been addressed.

7.7 Sources of further information and advice

- **American Gas Association (AGA)** – The AGA represents and advocates the interest of more than 200 local energy companies that deliver clean natural gas throughout the United States.
- **Gas Research Institute (GRI) –** This organization ceased operations in 2006 and its assets (physical and human) were transferred to the not-for-profit R&D organization Gas Technology Institute (GTI).
- **GTI** – The GTI, formed in April 2000 by the combination of the GRI and the Institute of Gas Technology (IGT), is a leading research, development and training organization serving the global natural gas industry and energy markets.
- **Interstate Natural Gas Association of America (INGAA)** – INGAA is a trade organization comprising 25 members, advocating regulatory and legislative positions of importance to the natural gas pipeline industry in North America and providing a key link between natural gas producers and consumers.
- **NYSEARCH –** NYSEARCH is a voluntary R&D sub-organization of the Northeast Gas Association currently serving 19 member companies from North America (although membership is not limited to any geographic region). NYSEARCH works collaboratively with Pipeline and Hazardous Materials Safety Administration (PHMSA) and other R&D organizations. A large part of its focus is product development and technology transfer.
- **Operations Technology Development (OTD) –** OTD is a not-for-profit corporation led by its 23 members, who serve over 26 million natural gas customers in the United States and Canada and pool their collaborative funding and resources to address current and future industry needs.
- **Pigging Products & Services Association –** Further information on the current capabilities of MFL and other in-line inspection systems can be found at the website of the Pigging Products & Services Association, http://www.ppsa-online.com/.
- **PHMSA –** PHMSA establishes national policy, sets and enforces standards, educates, and conducts research with the aim to protect people and the environment from the risks of hazardous materials transportation.
- **Pipeline Research Council International (PRCI) –** PRCI is a not-for-profit membership organization that implements R&D for the energy pipeline transmission industry, including 38 of the world's leading pipeline operating companies.

7.8 References

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