

Technology Status Report
on

Implementing Current In-line Inspection Technologies on Crawler Systems

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Abstract

Inspection of pipelines is important to ensure safe and reliable delivery of fossil energy products. However, not all pipelines can be inspected with the current systems, which use tools commonly called pigs that move inside the pipeline propelled by the product flow at speeds. Inspection platforms that crawl slowly inside a pipeline are being developed to maneuver past the physical barriers that limit inspection. These crawlers can move down the pipeline independent of the product flow, and even stop for detailed defect assessment. The sensors on these crawlers must assess a wide range of pipeline conditions including corrosion (pitting, patches, and general), mechanical damage, coating adherence, cracking, and seam weld defects. The sensors also must be small in physical size, lightweight, and have low electrical power consumption as compared to the propulsion system. In-line inspection equipment is commonly used to examine a large portion of the long distance transmission pipeline system that transports natural gas from well gathering points to local distribution companies. However, there is only a limited amount of commercial available equipment for inspecting the shorter runs of pipe owned by distribution companies. This report provides a review of pipeline inspection sensors and their applicability for crawler systems.

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Executive Summary

Pipelines are an efficient and generally safe mode for distributing natural gas and other energy products directly to end users. The pipeline infrastructure is well designed, built, and maintained, as demonstrated by the low number of failures caused by natural degradation mechanisms. One would expect failures related to time-dependent degradation, such as leaks and ruptures caused by corrosion, to increase as pipelines age. However, each year the number of such incidents is nearly the same as incidents of third-party damage caused by excavation equipment, which are independent of the age of the pipe. Thus, the pipeline infrastructure, while aging, remains adequately functional, and its general replacement is both expensive and unwarranted. However, isolated incidents do occur, raising public concern. Detection of problems prior to incident occurring would keep the pipeline infrastructure operating in an inconspicuous manner that is preferred by both the public and the pipeline owners.

To detect problems prior to incidents, inspection equipment is required to interrogate the pipeline infrastructure for degradation mechanisms. In-line inspection equipment is commonly used to examine a large portion of the long distance transmission pipeline system that transports natural gas from well gathering points to local distribution companies. However, there is only a limited amount of commercial available equipment for inspecting the shorter runs of pipe owned by distribution companies. The primary reasons for this are:

- Lack of sensors that are physically small and reasonably low power to interrogate the full pipe wall
- Low pressure and flow rates necessitating the propulsion of the inspection vehicle by means other than the product flow
- Conditions that make inspection of these pipelines unique, thus eliminating the economies of scale.

This status report provides a review of pipeline inspection sensors and their applicability for crawler systems.

Inspection Technologies for Pipelines

In-line inspection of pipelines is commercially performed using magnetic and ultrasonic methods. Electromagnetic techniques such as the remote field technique and pulsed eddy currents have had limited use in pipeline inspection. The basic principles, attributes, and deficiencies of these inspection methods are summarized in the following sections.

Magnetic Flux Leakage

Magnetic flux leakage (MFL) was first commercially used to inspect pipeline in 1964. Today it is the most commonly used in-line inspection method [1,2] for pipelines. MFL technology can successfully overcome the physical and practical inspection challenges presented by transmission pipelines. The systems can be designed to remain functional in an abusive pipeline environment

for long distances and at product flow speeds. The permanent magnets used in this inspection technology need no energy source during an inspection, and the sensors and data recorders require reasonably low power to operate. The magnetic flux naturally enters the pipe and distributes evenly to produce a full volumetric inspection. Often various deficiencies of MFL systems are highlighted, but the attributes described above keep MFL at the forefront of pipeline inspection technologies. There are two widely used implementations of MFL that can be differentiated by the orientation of the magnetization in terms of axial or circumferential direction. These are discussed next.

Axial MFL

Axial MFL is the oldest and still the most common implementation of the MFL inspection method. The term axial, describing the orientation of the magnetizing field as illustrated in Figure 1, was added recently after other implementations, such as circumferential MFL, were developed. The phrase MFL tool when used alone almost always refers to the axial implementation.

Axial MFL tools are most sensitive to volumetric or metal-loss defects with a significant circumferential extent or width. They are much less sensitive to cracks and axially oriented metal loss. Most axial MFL tools magnetically saturate the pipe wall to reduce the effects of material variations and stress. As a result, the tools are less sensitive to defects in which the most significant characteristic is a change in material or magnetic properties (e.g., hard spots and microstructural damage near gouges). Nearly all axial MFL systems provide uniform magnetic fields at each sensor around the pipe. This approach, when combined with high magnetization strength, minimizes signal conditioning and compensation requirements in the analysis process.



Figure 1. An axial MFL magnetizer.

Some early axial MFL systems used electromagnets for magnetization, but most tools now use very strong permanent magnets. Nearly all current axial MFL systems have the capability to magnetically saturate the pipe at wall thicknesses on the order of 30 mm (1.2 inches) in pipe diameters greater than 24 inches – above this wall thickness, the inspection results are less accurate. For smaller diameters, the space available for the magnets is constrained; consequently, less magnetization force can be carried. As a result, the inspection results are more sensitive to wall thickness.

Most MFL systems use steel brushes to couple the magnetic energy into the pipe and provide flexibility at intrusions into the internal diameter, such as a weld drop-through. The brushes enable an MFL tool pass through a pipe that has a local deformation (e.g., dent) of up to 10 percent of the pipe diameter. General interior bore restrictions must be 5 percent or less for a MFL tool to pass. Reduced port valves and other restrictions are problematic for MFL tools. The magnetic holding forces and friction caused by the brushes can significantly increase propulsion requirements.

Many axial MFL inspection systems are advertised as high resolution. Early axial MFL systems stored data on modified 24-channel audio tape recording equipment. High resolution was initially defined as indicating the use of more sensors than on one of these early systems. A more scientific definition involves the circumferential extent of defects to be sized. Applying the

Nyquist sampling theorem to the flux leakage from small pit defects, the circumferential sensor spacing must be less than half the circumferential extent of the pit to be assessed. Wall thickness also affects minimum spacing. For example, pits less than two times the wall thickness are more difficult to size, regardless of the number of sensors used. For defects with a diameter less than a wall thickness, most of the flux spreads circumferentially around the defect rather than leaking from the pipe, making detection difficult.

For high-resolution axial MFL tools, there is a theoretical minimum sensor spacing for most applications that is on the order of the wall thickness. Since the tools must cover a range of wall thickness, a practical definition of sensor spacing for a high-resolution tool is between 6 and 12 mm (0.25 to 0.5 inch). Circumferential sensor spacings closer than 6 mm (0.25 inch) do not provide a significant advantage in metal-loss defect sizing, although they improve the ability to detect some pinhole defects and crack-like defects. The distance between measurements in the axial direction can be much less, and is governed by the minimum axial length that the tool must detect and size. Typical measurement spacings are between 2.5 to 5 mm (0.1 to 0.2 inches).

MFL sensors measure one component of the flux leakage field at a point, but flux leakage is a vector quantity with three directional components. Most axial MFL tools measure only the axial component (for circumferential MFL, the circumferential component is commonly measured). The other components (radial and circumferential for axial tools) can provide some additional information that can be useful for sizing. The information from each component is somewhat correlated, however. In experiments on patch corrosion defects at Battelle's Pipeline Simulation Facility, the information content in two sensor components was found to be about twenty percent larger than that in one component. Thus, a modest increase in sizing accuracy is possible with tools that measure more than one component of the flux leakage field.

The velocity of an axial MFL tool through a pipeline significantly affects defect signals at speeds over 2.5 m/s (5.6 mph) in 12-inch diameter pipe (inspection speed affects nearly all electromagnetic inspection methodologies). These effects are reported to be manageable for larger diameter tools at speeds up to 4 m/s (9 mph). Below these speeds, velocity effects are small, making sizing and detection easier. Some tools have a minimum acceptable speed on the order of 1.0 m/s (2.2 mph) in low pressure gas lines. This limitation is not due to velocity effects at these low speeds. Instead, below about 27.5 bar (400 psi), significant variations in velocity are common as the tool stops and starts during the run.

Axial MFL tools are best suited for volumetric metal-loss defects with a width greater than two wall thicknesses. Axial MFL tools can detect 95 percent of corrosion defects that are greater than 10 percent of the wall thickness. The sizing accuracy is generally specified as +/- 10 percent of the wall thickness with a confidence of 80 percent. Axially aligned defects and deeper defects are not sized as accurately because the flux spreads around the defect rather than leak. Axial MFL tools generally have the same performance capability for pipe diameters greater than about 300 mm (12 inches) and at speeds up to 4 m/s (9 mph). Axial MFL tools are available for smaller pipeline diameters, as small as 100 mm (4 inches), with reduced performance capabilities. Generally, these tools perform best at velocities below 2.5 m/s (5.6 mph).

Circumferential MFL

Circumferential MFL is a new twist on an old technology. Longitudinal defects, such as SCC, longitudinal corrosion, long seam defects, and axially oriented mechanical damage, are of significant concern to the pipeline industry. These defects tend to increase stress levels in the remaining pipe material. To improve detection and sizing of longitudinal defects, the orientation of the magnetic field was changed from the traditional axial direction to circumferential, as illustrated in Figure 2. As a result, circumferential MFL tools are most sensitive to defects with a significant axial length. They are somewhat sensitive to axially aligned cracks and not sensitive to circumferentially aligned cracks.

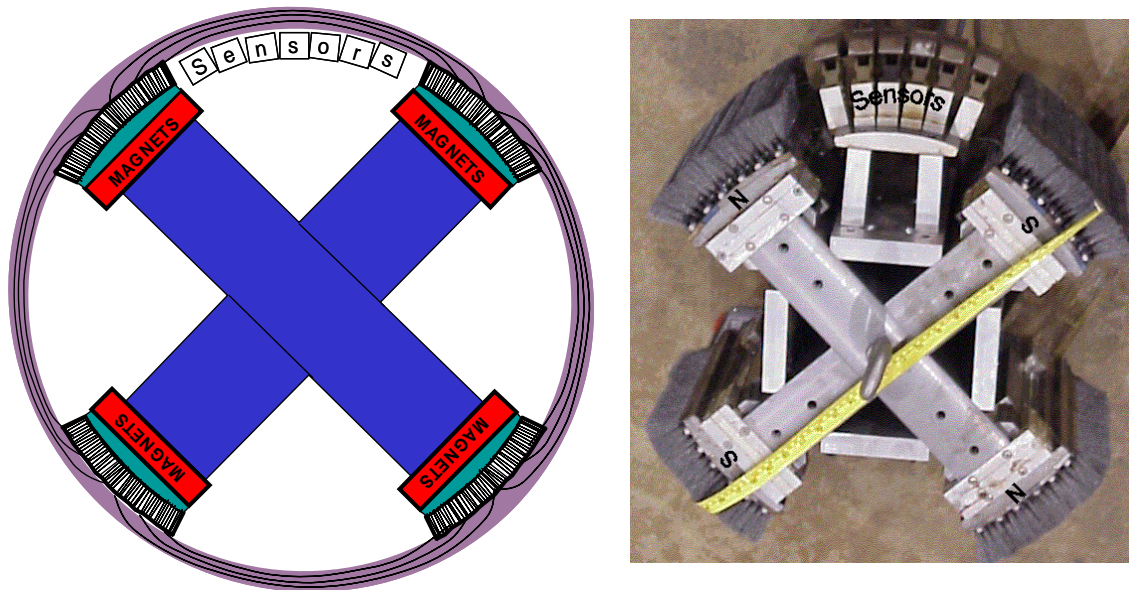


Figure 2. A circumferential MFL magnetizer.

Magnetization levels vary significantly with circumferential MFL tools because it is much more difficult to saturate the pipe material in the circumferential direction. The magnetic field strength is greatest near the magnetizer poles and smallest at the center. The lack of uniformity on the magnetic field makes defect sizing more difficult. A defect near one magnetic pole gives a signal that is different from the signal of the same defect when it is equidistant from the magnet poles. Consequently, compensation methods are used to adjust signal amplitudes and account for the varying magnetic field. This compensation adds a significant amount of complexity to defect detection and analysis procedures. For defects that span one or more poles, compensation methods may mask the defect signal, resulting in a false negative or undersizing of a potentially critical defect.

Velocity effects for circumferential MFL are detectable at much lower speeds and are more significant than for axial MFL. Velocity-induced signal changes can be detected at speeds of 1.0 m/s (2.2 mph). Above this velocity and for defects midway between the poles, the signal amplitude is reduced and compensation for velocity is possible. If the defect is closer to one pole,

However, the flux leakage is also distorted, making sizing much more difficult. As velocity increases, the magnetizing field also starts to concentrate at the inner surface of the pipe (i.e., it varies through the thickness as well as around the circumference). This effect also makes sizing and detection of outside-diameter defects more difficult.

More sensors are needed for circumferential MFL than axial MFL to achieve similar accuracies. For circumferential MFL, the flux spreads in the axial direction, which helps reduce axial sample interval but not sensor spacing requirements. Therefore, to accurately record the flux leakage, the sensor spacing interval around the pipe is half that of axial MFL, typically between 2.5 to 5 mm (0.1 to 0.2 inch). For example, an axial tool with 250 sensors would have the same flux recording fidelity as a circumferential tool with 500 sensors. The sampling requirement along the pipe (in the axial direction) is helped by flux spreading, but most implementations stay with the same data interval as axial MFL to simplify data display, analysis, and overlay.

As for axial MFL, the manner in which the depth of a defect affects circumferential MFL signals changes with increasing depth. These effects are more significant and begin at shallower depths with circumferential MFL than with axial MFL, strongly affecting sizing accuracy. As a result, circumferential MFL tools are not as accurate at sizing defects as axial MFL tools. The sizing accuracy is generally specified as +/- 15 percent of the wall thickness with a confidence of 80 percent.

Propelling MFL Tools

MFL tools are propelled by the product flow. Cups that seal against the pipe wall prevent product from flowing around a tool. As additional product is pumped into the pipe behind the tool, a differential pressure is established. When the differential pressure times the area of the tool is sufficient to overcome the weight and friction forces, the tool is propelled down the pipeline. Typically, it requires a differential pressure of about 15 to 25 pounds to overcome friction and initiate motion, and 5 to 15 pounds to maintain a consistent velocity. The average speed of the tool is defined by the flow rate. The uniformity in liquid pipelines is excellent since the product is essentially noncompressible; however, in gas pipelines the speed can vary significantly and is dependent on the on the pressure in the pipe. High pressures dampen the velocity excursions.

A 24-inch diameter MFL tool can weigh more than 2400 pounds, about the weight of a compact car. The weight of the MFL tool increases with pipe diameter, as shown in Figure 3. However, the driving force not including friction (the weight divided the cross sectional area), also shown in Figure 3, is between 4 and 7 pounds per square inch, nearly independent of pipe diameter. Friction at least doubles the driving force requirements. Because of these high formal requirements, differential pressure is clearly an efficient way to propel MFL tools in a pipeline.

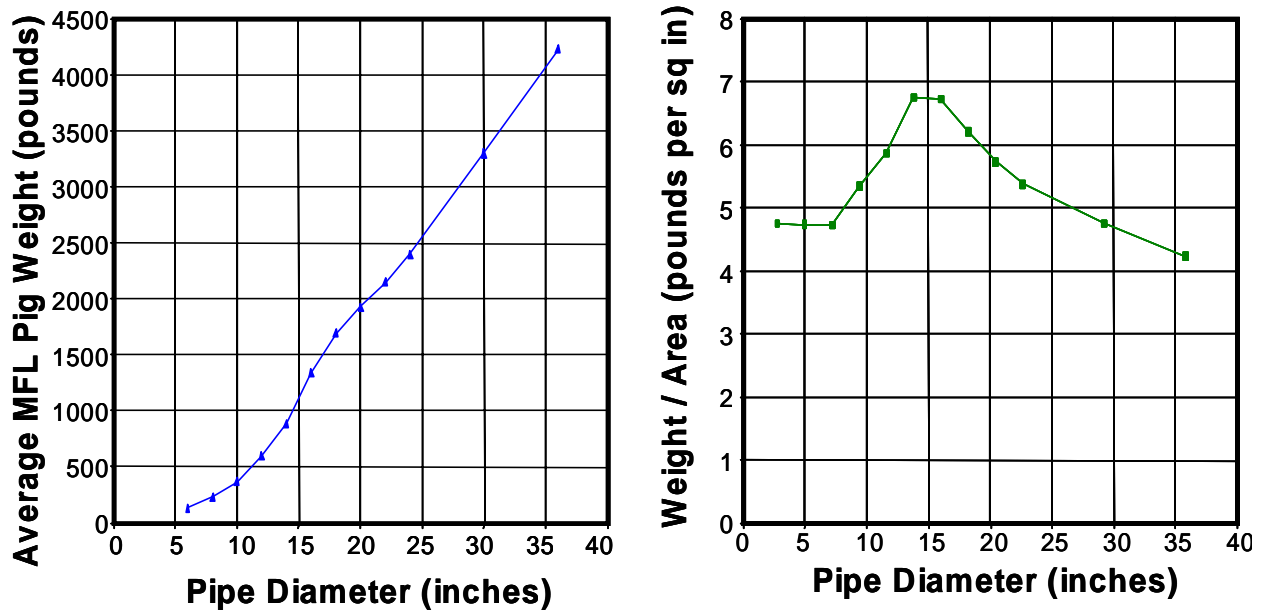


Figure 3. The weight and propelling force requirements for MFL tools.

Ultrasonic Inspection Technology

Ultrasonic testing (UT) can be used to measure the wall thickness of pipe to detect corrosion. In another implementation it can detect cracks [3]. The basics of each technology is discussed next.

Wall Thickness Measurement

High frequency sound waves have been employed to inspect pipelines from the inside since the mid 1980s [4,5]. The basic principle, illustrated in Figure 4, is similar to handheld ultrasonic equipment used to measure wall thickness and detect cracks. Pulses of ultrasonic energy between 1 and 10 MHz are launched from a piezoelectric transducer. These pulses are reflected by the inside and outside surface of the pipe. By measuring the time between the reflections and knowing the speed of sound in steel pipe (nearly constant for most pipes), it is possible to establish the thickness of the pipe.

The industry standard thickness measurement accuracy for handheld ultrasonic thickness gauges is nominally 0.001 inch (0.025 mm). These use high-frequency transducers with multiple elements and signal averaging to reduce noise. Because of the speed of the product flow, in-line inspection tools use a single signal to assess thickness. They also use lower frequency transducers (around 5 MHz) to overcome surface roughness challenges. The typical accuracy of an in-line inspection tool is 0.020 inch (0.5 mm).

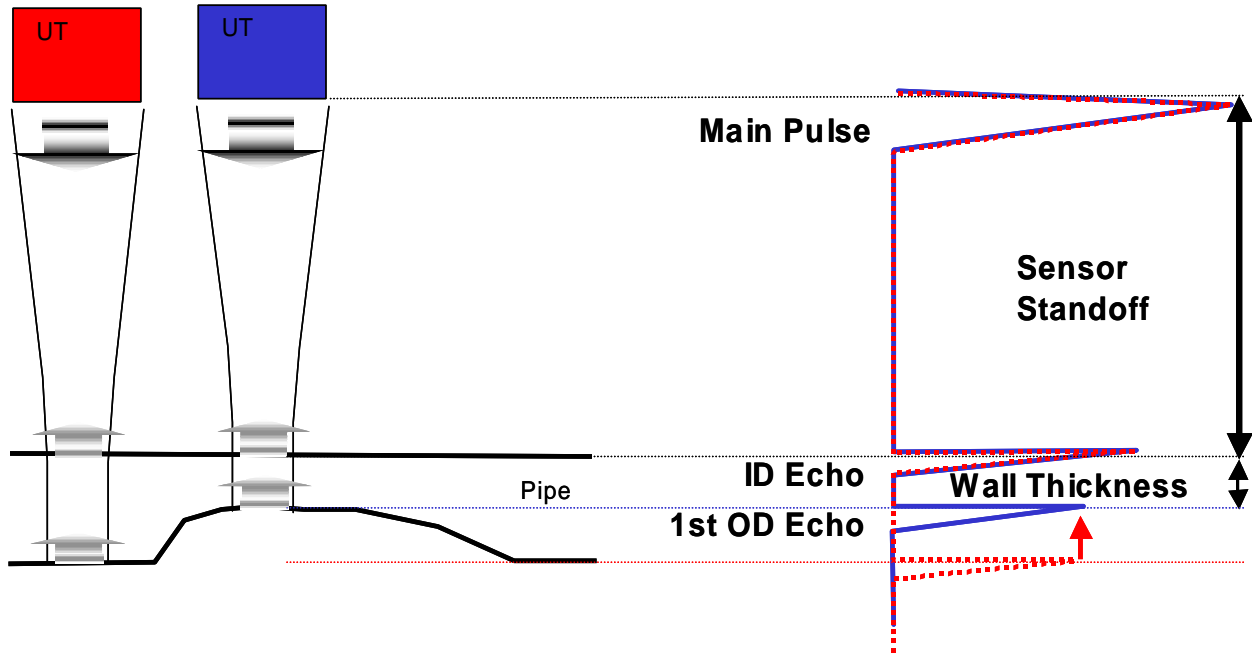


Figure 4. The pulse echo ultrasonic method for measuring wall thickness.

While the ultrasonic technique provides sufficient accuracy for assessment of defects, the practical use of this technology is limited. The ultrasonic method requires a liquid to couple the ultrasonic energy from the transducer to the pipe and back. While this is practical for oil and liquid products pipelines, application in gas lines is not as simple. Filling a gas pipeline is rarely practical. Also the ultrasonic tools employ a large number of sensors, on the order of 10 per diameter inch. Historically, data processing and storage time have limited the speed of the inspection to around 3.0 mph; however, recent developments in electronics have increased inspection speed capability.

While the wall thickness measurements are accurate in noise free pipe, distinguishing corrosion from other reflectors such as laminations and inclusions has caused some problems. Ultrasonic pigs can miss defects behind laminations and small sharp geometries. Also, the pipeline must be extremely clean without any debris or deposits. In general, if a signal can be recorded, an assessment of wall thickness can be made. Unlike MFL tools, depth accuracies are not a function of wall thickness; thus, errors are expressed in length units, not in percent. To summarize the differences in the two technologies, MFL tools reliably generate signals from metal loss defects but interpretation is often difficult; ultrasonic signals are simple to interpret but attaining a signal is difficult because of the many inspection variables.

Ultrasonic Crack Detection

Some attempts have been made to detect cracks using ultrasonic inspection techniques; these differ primarily in the way the ultrasonic energy enters the pipe. Liquid coupled methods, wheel

coupled methods, and electromagnetic acoustic transducers have proven capable of detecting longitudinal cracks, but they all have limitations.

GE-PII developed the first angle-beam ultrasonic tool in the 1970s, and the tool has seen some use in operating pipelines. The tool uses liquid-filled wheels, illustrated in Figure 5, to allow ultrasonic energy to be coupled into the pipe wall of gas-filled lines. The number of sensors is limited by the number of wheels, and sophisticated signal processing is needed to detect and characterize cracks. Generally, the tool has proven effective at detecting and sizing some cracks and crack colonies. Questions about its ability to discriminate between crack signals and non-crack signals remain. In addition, reliable estimates of probabilities of detection and sizing accuracies are not available.

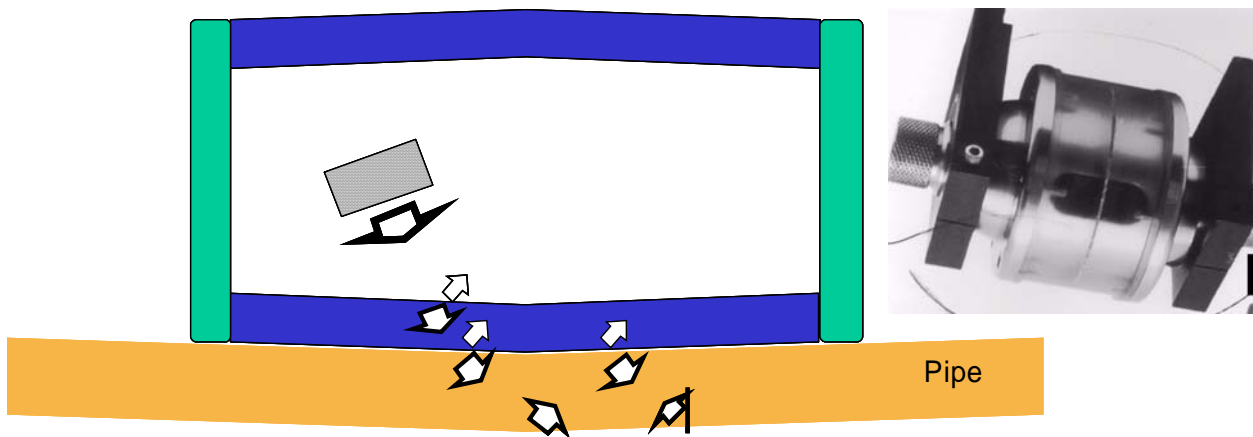


Figure 5. Wheel coupled ultrasonic inspection for cracks in pipelines.

Two pipeline inspection companies supply angle-beam ultrasonic tools. These tools, illustrated in Figure 6, operate only in liquid-filled lines. The liquid couples the ultrasonic energy into the pipe wall, negating the need for a wheel. The liquid coupled tool has many more sensors than the wheeled tool, and it is reported to have greater sizing and detection accuracies. Liquid coupled angle beam tools have the same difficulties encountered with wall thickness tools, including speed restrictions and problems distinguishing cracks from laminations and inclusions.

Several attempts have been made to develop a commercial electromagnetic acoustic transducer (EMAT) inspection system for cracks. EMAT is an ultrasonic inspection technique that operates at a lower frequency, typically 200 to 800 KHz, as compared to piezoelectric ultrasonic, which typically operates at a frequency of 1 to 20 MHz. The waves generated by EMATs are bounded by the inner and outer diameter of the pipe. Wave types include

- Raleigh wave — ultrasonic waves bounded by one surface – surface waves
- Lamb waves — ultrasonic waves in bounded medium such as plates
 - Symmetric — both surfaces move in together
 - Antisymmetric — both surfaces move in opposition
- Shear horizontal plate waves.

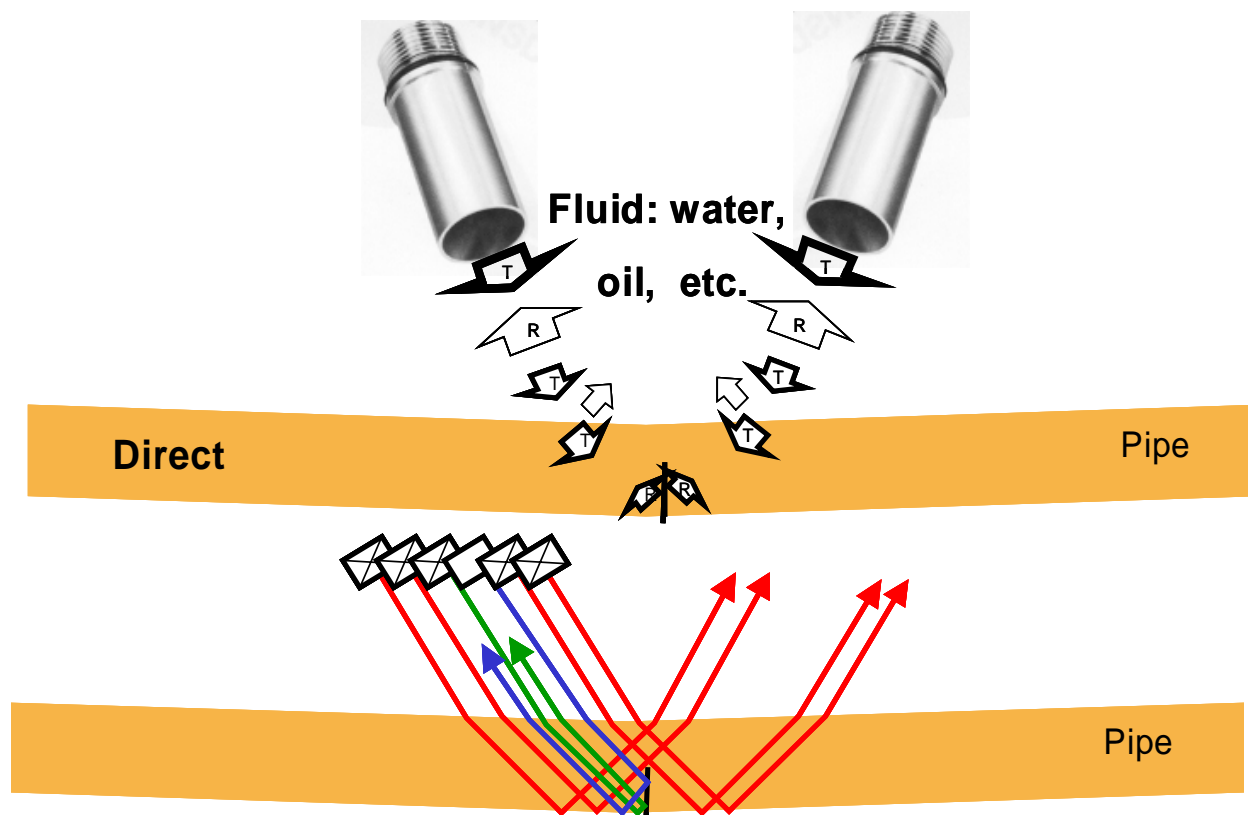


Figure 6. Liquid coupled angle beam inspection for the detection of cracks.

Generation of these waves, illustrated in Figure 7, requires a strong static magnetic field and coil that is pulsed to create localized eddy currents in the pipe that oscillate at the designed inspection frequency. The wavelength is defined by the spacing of the meandering coil. The wave mode is dependent on the wall thickness. A change in one variable can cause a different wave type to be launched, which can affect inspection results. The coils have to be near the pipe surface to generate sufficient energy for detection of pipeline defects such as cracks. For long-distance pipeline inspections, the thin polymer covering the coil is worn away by the rough internal surface of the pipe. The primary advantages of EMATS are

- No liquid coupling media required
- Bounded wave propagates in the pipe wall.

Disadvantages of EMATS include

- Implementation challenges
- Wall thickness dependency of sensors
- Many possible modes; different modes provide unique results
- Lower frequency signal than the other techniques can reduce resolution and restrict sizing capability.

Early efforts by the Pipeline Research Council International (PRCI) that were directed at pipeline inspection included work by C.W. Pope in Australia and T.D. Williamson in the United States in the 1980s and 1990s. These efforts were combined in the middle 1990s, and then transferred to Tuboscope in the late 1990s. This tool and other EMAT implementations are under development. Considering all the ultrasonic inspection methods, EMAT have the greatest potential for implementation on crawler systems.

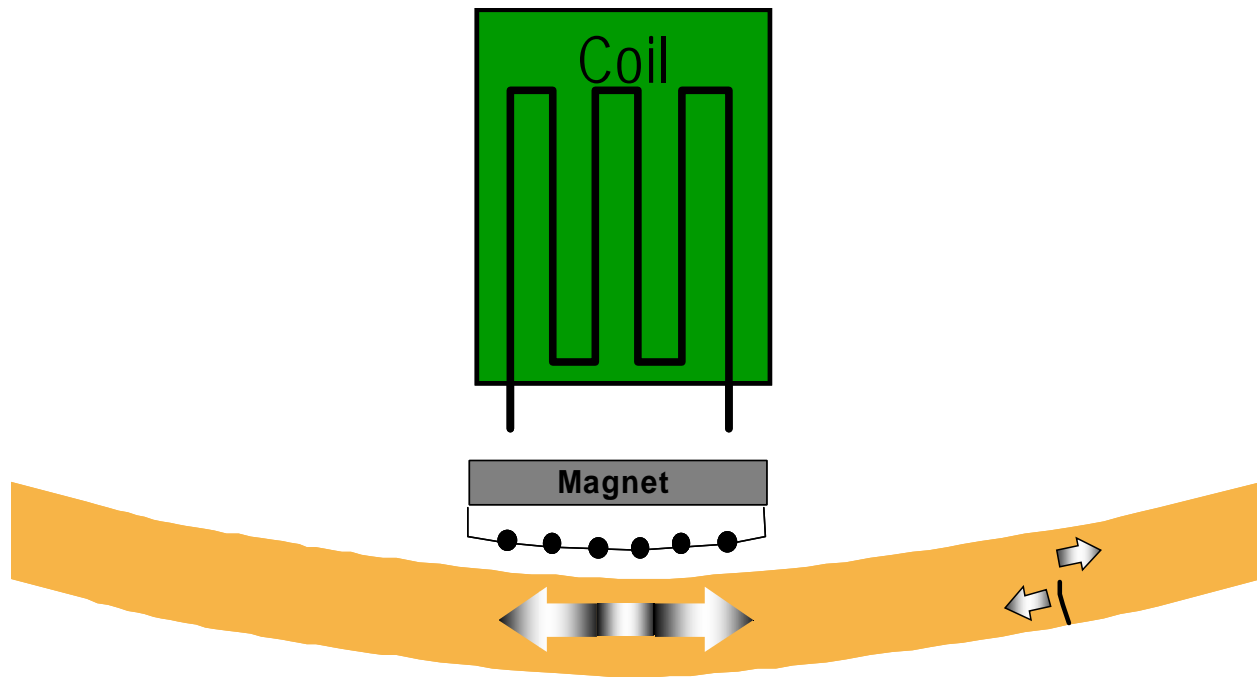


Figure 7. Electromagnetic acoustic transducer inspection for the inspection of pipes for cracks.

Remote Field Technique (RFT)

The remote field technique has been used successfully to detect a variety of defect and material conditions in both magnetic and nonmagnetic conductive tubes and pipes [6,7,8]. The remote field eddy current technique uses a sinusoidal current flowing in an exciter coil to induce currents in the pipe and a remote receiver coil over two pipe diameters away to detect defects such as metal loss and stress corrosion cracks. Since the remote field eddy current technique detects signals of known frequencies, sharp filters can be used to detect defect signals while eliminating other sources of electromagnetic noise. Along with detecting stress corrosion cracks, the potential exists for remote field eddy current techniques to detect cracks associated with mechanical damage and to provide additional information for characterizing the severity of the damaged region.

Constraints have been identified that limit the implementation of this inspection technique. Traditional remote field eddy current techniques use low-frequency exciters, which limits the maximum speed at which inspection equipment can travel. Typically, these speeds have been less than one mile per hour, severely limiting potential uses on in-line inspection equipment [7]. Detecting pipeline defects depends on the strength of the eddy currents, which depends on the excitation frequency and magnetic permeability of the pipe material. The magnetic permeability can be decreased by a strong static magnetic field, similar to the field applied by MFL magnetizers. With the permeability reduced, the signal levels at the sensor will be increased. Alternatively, excitation frequency can be increased for improved inspection speed while keeping signal level constant [9].

A schematic of the remote field eddy current technique is illustrated in Figure 8. An exciter, which is sized to nearly the same diameter as the inside diameter of the pipe, is driven with a low-frequency sinusoidal current. A small magnetic field sensor is positioned some distance away. One portion of the magnetic field generated by the exciter travels down the inside of the pipe, with the field directly coupled to the sensor. A second portion of the alternating magnetic field propagates through the material of the pipe, inducing eddy currents as it goes. Once the magnetic field penetrates the outside wall of the pipe, it spreads along the surface of the pipe and re-enters the pipe, again inducing eddy currents to flow in the pipe material. This second path is referred to as the remote path. The total magnetic field and eddy current flow at any point is the combination of directly coupled and remotely coupled fields.

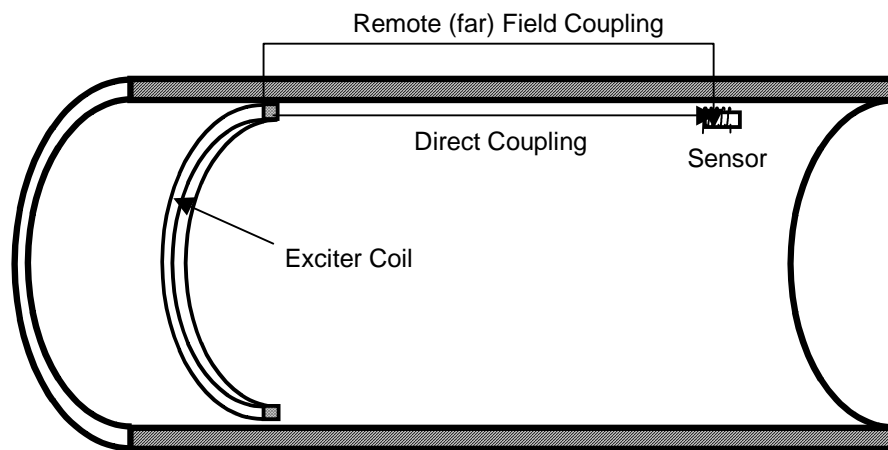


Figure 8. Remote field eddy current exciter and sensor configuration.

The key to remote field eddy current testing is to choose a sensor position where the remotely coupled field is large compared with a directly coupled field. This is possible since the directly coupled field decays at a faster rate, as shown in Figure 9. This semi-logarithmic plot shows that the decays of both the remote and direct field are exponential and the decay constant for the direct field is nearly four times as fast as the remote field. Also, the combined magnetic field is less than the direct field in the near field, and it is less than the remote field in the far field. This phenomenon is due to the fact that phase difference for the two paths is always greater than 90 degrees for distances greater than a coil diameter.

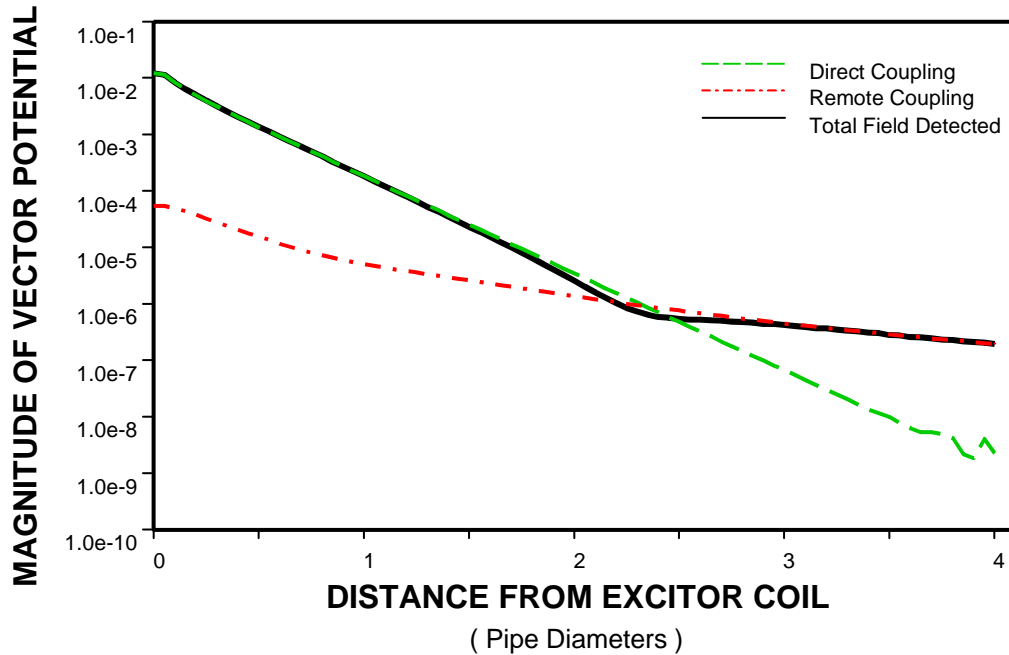


Figure 9. Calculated magnitude of the remote field eddy current effect.

Pulsed Eddy Current

Pulsed eddy current inspection has the potential to inspect conductive materials such as pipelines. However, like EMATs, successful implementations of this technology are limited.

Oak Ridge National Laboratory [10] has designed and developed a pulsed magnetic saturation method for the eddy current testing of steel steam generator tubes with wall thickness 0.2 inch. It was shown that the current pulse that passes through an electromagnet has sufficient amplitude to saturate the ferromagnetic tube. Defects near the external surfaces can be detected by analyzing the decay of the current pulse. The defects signals can be differentiated from the signal variations that naturally occur in steam generator tubes. Special consideration must be given to the amplitude and duration of the pulse to prevent overheating problems. Peak power levels of 500 kilowatts and duty cycles of 1 millisecond were used to attain results.

A commercial pulsed eddy current instrument is available for inspection of thermally insulated carbon steel components [11, 12]. The instrument measures the wall thickness without any requirement for contact with the steel component itself. The instrument compares the relative decay of eddy currents induced in the pipe to establish wall thickness in pipe up to 1 inch thick. The instrument can work up to 4 inches away from the pipe surface, but requires signal averaging that can take approximately 2 to 5 seconds. Typically used to detect corrosion under insulation and erosion, it can also be applied for measuring wall thickness through coating or scaling.

Summary

Although several nondestructive in-line inspection technologies are commercially available for assessment of pipeline defects, no current implementation of the technologies appears well suited for implementation on crawler systems. Table 1 list the most significant advantages and disadvantages of the technologies with regard to crawler implementation.

Table 1. Most significant advantages and disadvantages of pipeline inspection technologies as applied to crawler systems.

Technology	Advantage	Disadvantage
MFL	Proven, rugged technology can operate at reasonable product flow speeds.	Heavy with large drag forces. Limited wall thickness measurement accuracy.
Liquid Coupled UT	Most accurate technology for wall thickness.	Not practical in gas lines.
Wheel Coupled UT	Liquid couplings not required. Reasonable wall thickness measurements.	Large sensor heads.
EMATs	Electromagnetic coupling of ultrasonic signal. Sensitive to many defects and conditions.	Many implementations have failed to achieve commercial success. Unproven measurement accuracy.
Remote Field Technique	Can operate at large liftoffs. Reasonable wall thickness measurements. Sensitive to many pipeline defects.	Signal levels small. Significant excitation power needed.
Pulsed Eddy Current	Can operate at large liftoffs.	One commercial system. Significant excitation power needed. Limited wall thickness measurement accuracy.

Small, light, low power sensors systems are needed for the inspection of some pipeline systems. These will interface with crawlers systems currently being developed to enable the assessment of pipeline currently classified as unpiggable. New electromagnetic techniques are being developed under this program that incorporate moving permanent magnets, either rotating for the case of sinusoidal eddy currents or translational for pulsed eddy currents. Moving high-strength, permanent magnets reduces power consumption and improves energy coupling into the pipe wall. These sensors will enhance the capability of inspection platforms that crawl inside a pipeline circumventing the physical barriers that limit pipeline inspections.

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