Review of Sensor Technologies for In-line Inspection of Natural Gas Pipelines

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Introduction

This paper reviews existing sensor technologies for in-line inspection of pipelines (ILI). This information is in support of the development and application of new sensors compatible with a robotic vehicle for ILI that can maneuver within the pipe, enhancing sensor performance and inspection capabilities.

When examining the condition of a pipeline, In-Line Inspection (ILI) utilizing various Non-Destructive Testing (NDT) methods is an essential tool and a significant factor in establishing a quality management program that ensures safe, cost effective operation of the pipeline.

No NDT technology or technique is universally applicable. Therefore, pipeline operators and inspection service companies jointly choose the appropriate technology for each particular situation. The level of defect specification needed is matched to the performance of the tool.

Existing In-line Inspection Tools

Magnetic Flux Leakage

Magnetic flux leakage (MFL) is the most commonly used ILI technology. Some applicable literature is available, varying from a very informative Battelle site, to a few vendors' sites on the Web, listed here for the interested reader:

http://www.battelle.org:8765/query.html?col=internet&qt=mfl
http://www.bjservices.com/
http://www.piigroup.com/in-line_inspection/tools/magnescan.html
http://www.magpiesystems.com/
http://pipe-line.com/plg-main.html
http://www.3p-services.com/eindex.htm

The list is certainly not exhaustive and does not reflect Sandia National Laboratories' bias by inclusion or omission.

MFL inspection tools locate pipeline defects by applying a saturating magnetic field, supplied by huge magnets, into the pipe material and then sensing a local change in this applied field.

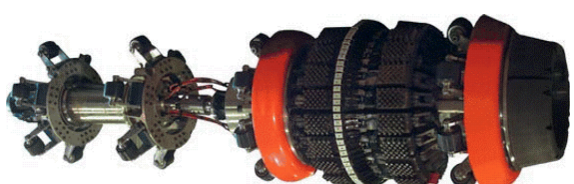

Figure 3: A typical MFL pig.[1]

Some Advantages to MFL

- Most common test means true comparison on data obtained
- Varying levels of sensitivity can be chosen according to testing needs
    - Standard, or Low-Resolution tools
    - High Resolution (High-Res) tools
    - Extra High-Resolution (XHR) tools.
    - The XHR "newest generation" systems have a very high number of sensors

[1] Source: http://www.bjservices.com/

Types of Flaws Detected

The MFL Response to pipeline anomalies depends primarily on:

- Magnetic properties of pipeline steel. Missing material, whether iron that has actually been removed or corrosion that turns steel into non-ferromagnetic iron oxide is detected because it reduces the local ability of the pipe to carry magnetic flux
- Anomaly geometry. Mechanical damage can be detected because the magnetic properties of steel are changed locally due to plastic deformation

Sensor and Data Recorder Comparisons

There are varying technology levels within the standard and High-Res groups. The most recent High-Res tools utilize "Hall effect" sensors. Hall sensors give direct measurement of flux leakage. Earlier versions used induction-coil sensors. Coil sensors provide inferred or indirect measurements of flux leakage.

High-Res and XHR tools record in a digital, solid-state format while Standard or Low-Res tools may record in an analog, magnetic tape format. Solid-state recording has the advantage of easily storing the large data volumes generated. Solid-state is also more forgiving to the shock and vibration effects encountered when running in an internal pipeline environment than magnetic tape recording.

Detection Capabilities

The major difference between the Low and High-Res tools is the resolution and accuracy of the data recorded. Standard tools have larger and fewer sensor pads, which reduce anomaly definition, especially when there are many small anomalies in close proximity.

High-Res tools utilize a larger number of smaller sensors, and provide better anomaly sizing. Yet there are still fine features that only the XHR tools can define. The desired anomaly accuracy will affect tool choice.

<u>Low-Res or Standard tools:</u>

- Sensor spacing; not standardized but fewer large sensors with greater spacing than High-Res
- Sizing; Anomaly grading to a minimum 20% wall loss, with 15 – 20% accuracy[2]

<u>High-Res tools:</u>

- Sensor spacing; 0.50" to 0.75" (10-17mm)
- Sizing; Anomaly grading to within 10% of wall loss, with 10 – 15% accuracy

<u>Extra High-Resolution (XHR) tools:</u>

- Sensor spacing; 0.15" to 0.30" (4-8mm)
- ID/OD discrimination
- Sizing; accuracy levels for low-level corrosion detection of <10% Wall Thickness and sizing accuracy of ~5-10% Wall Thickness
- Long inspection ranges

Disadvantages With MFL Include:

- The need for large quantities of data that is typically interpreted by humans
- Product flow restriction
- Permanent magnetization of pipe

Industry is divided on which MFL tool to use for an inspection. For example, arguments for Low-Res include:

- They are sufficient for inspections
- They have lower inspection costs
- Faster and cheaper vs. more detailed High-Res. data are a good trade off

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[2] "Smart Pigging: Lessons Learned, Terry R. Shamblin

These factors are significant enough to typically limit inspection to older pipelines in high consequence areas.

Eddy current

Eddy current Testing (ET) is an electromagnetic NDT technique that can only be used on conductive materials. Its applications range from crack detection, to the rapid sorting of small components for flaws, size variations, or material variation. ET is commonly used in the aerospace, automotive, marine, and manufacturing industries. http://www.smarteddy.com/smart.html

When an energized coil is brought near the surface of a conductive component, electromagnetic eddy currents are induced in the specimen. These eddy currents set up magnetic fields within the specimen that tend to oppose the original magnetic field. The impedance of the coil is affected by the presence of the induced eddy currents in the specimen.

When the eddy currents in the specimen are distorted by the presence of flaws or material variations, the impedance in the coil is also altered. This change is measured and displayed in a manner that indicates the type of flaw or material condition (Figure 4).

The interested reader is referred to the very complete bibliography: http://phy-server.phy.queensu.ca/wwwhome/atherton/papers/rfec_papers.htm

Some Advantages to ET

- Non-contact test
- No residual effects
- MFL induced currents can be detected by ET sensors

A thorough explanation of advanced ET method and its advantages over conventional eddy current methods, including its ability to look at the entire wall thickness are available at: http://phy-server.phy.queensu.ca/wwwhome/atherton/rfliintr.html

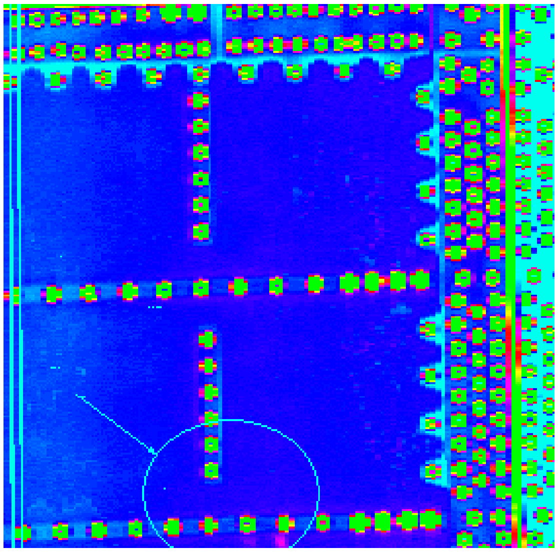

Figure 4: Eddy Current Inspection Results of a DC-9, Sandia National Laboratories

Types of Flaws Detected

- Cracks
- Laminar defects
- Assess wall thickness

Emerging Applications

- Eddy current NDT technology, relative to gas pipelines, is typically an external inspection technique, but some specialized techniques hold promise for internal inspection
- An effort is underway to look at using ET within pipes: http://phy-server.phy.queensu.ca/wwwhome/atherton/remote_field.html
- An effort, in Russia, focuses on stress corrosion crack detection using eddy current methods: http://www.ndt.net/article/wcndt00/papers/idn453/idn453.htm

Disadvantages With ET

- Slow response limits ILI applications at current pigs speeds
- Maintaining appropriate lift off distance (sensitive to coupling variations)

Ultrasonic Testing (UT)

Ultrasonic inspection uses sound waves of short wavelength and high frequency to detect flaws or measure material thickness. Ultrasonic tools give excellent results and anomaly accuracy. However, they are primarily used by companies with product lines that are inspecting for stress corrosion cracking and other forms of corrosion.

Some Advantages to UT

- Direct and linear wall thickness measurement method, and reliable defect depth sizing and good repeatability
- No upper limit to pipe-wall thickness, relative to inspection
- Sensitive to a larger number of features than MFL

Types of Flaws Detected

- Internal/External metal loss
- Longitudinal channeling
- Blisters/Inclusions
- Deformations
- Flanges
- Laminations (sloping & hydrogen induced)
- Cracking
- Weld characteristics
- Wall thickness variations
- Usable on bends, tees, and valves

Detection Capabilities

- Basic accuracy of depth measurements: ± 0.5 mm (0.02 in.)
- For flat surfaces and wall thickness: ± 0.2 mm (0.008 in.)
- Longitudinal Resolution: 3 mm (0.12 in.)
- Circumferential Resolution: 8 mm (0.3 in.)
- Minimum detectable corrosion depth: 0.2 mm (0.008 in.)

Disadvantages With UT

- Difficulty in coupling to the pipe wall with a fast moving pig
- Flow restriction while pigging

Clearly, the difficulty in coupling to the pipe limits the quality of the data as well as the size of defect that can be spotted. Various coupling schemes, such as liquid filled wheels containing the UT transducer, have been used in gas lines, with varying results. This technology is used in ILI by a few vendors, primarily using tethered tools, which limits inspections to ten miles or less. The following websites contain further information:
http://www.gasandoil.com/goc/company/cnn65104.htm
http://www.hitechtech.com/pipeline.htm
http://www.gri.org/pub/abstracts/gri97_0073.html
http://www.ndt.net/article/pacndt98/4/4.htm

Electromagnetic Acoustic Transducer (EMAT)

Application of EMATs for use in ILI is still in the developmental phase. The EMAT consists of a coil in a magnetic field at the internal surface of the pipe wall. Alternating current placed through the coil induces a current in the pipe wall, causing Lorentz forces (force acting on moving charges in magnetic fields), which in turn generate ultrasound. The type and the configuration of the transducer used define the types and modes of generated ultrasound and the characteristics of its propagation through the pipe wall.

Some Advantages to EMAT

- Dry coupling, readily applicable in gas pipelines
- Improved capability of horizontally polarized shear waves for inspection on areas such as welds
- Improved scanning process reliability, due to the absence of couplant, reducing the risk of overlooking defects where coupling has been lost

Types of Flaws Detected

- Internal/External metal loss
- Longitudinal channeling
- Blisters/Inclusions
- Deformations
- Laminations (sloping & hydrogen induced)
- Cracking
- Weld characterists
- Wall thickness variations
- Applicable to flanges, valves, bends, and tees

Disadvantages with EMAT

- EMAT needs to be located ~1mm from the test object
- Relatively low transmitted ultrasonic energy. Because of this, the dynamic range is determined (in many cases) by electronic noise
- High frequencies cannot be applied

In pipeline inspection application, EMATS may have some distinct advantages over UT, which requires liquid coupling. The interested reader is directed to a few websites detailing discussing applications in detail:
http://www.gri.org/pub/contents/sep/19980921/111711/emattool_net_version.html
http://www.gri.org/pub/abstracts/gri98_0041.html

Acoustic Emission (AE)

This technique involves permanently attaching one or more ultrasonic transducers to the object and analyzing the sounds generated or induced into the system using computer-based instruments. This method of inspection is not associated with pigging, but rather is an effort to monitor pipeline conditions without the use of a pig.

Some Advantages to AE

- Whole structure can be monitored from a few locations
- Structure can be tested in use (without taking it out of service or interrupting product flow)
- Continuous monitoring with alarms is possible
- Can potentially discriminate between internal, mid-wall, and external defects
- Microscopic changes can be detected if sufficient energy is released
- Source location is also possible using multiple sensors

Types of Flaws Detected

The noises monitored may arise from;

- Friction (including bearing wear)
- Crack growth
- Turbulence (including leakage)
- Material changes such as corrosion[3]

Disadvantages with AE

- Limited resolution
- Potentially very large infrastructure needed
- Can only detect active changes, variations, or damage
- Not a mature technology for pipeline inspection and lacks wide scale use

[3] http://www.piigroup.com/in-line_inspection/tools/ultrascanwm.html

Existing In-line Measurement Tools

Geometry Tools

Sometimes referred to as caliper pigs, geometry tools utilize either mechanical or electromagnetic methods to measure the bore of the pipe.

Applications Include

- Dent detection caused during backfill (new pipelines)
- Out-of-round/bend inspection
- Monitoring the bore of pipelines to detect mechanical or third party damage
- Pipeline restriction inspection prior to running larger, more sophisticated tools

The most primitive style simply deflects material on the pig to establish the maximum safe size for the pigs following. More advanced styles use mechanical detectors that log the location of the geometry. Again, a few sample websites include:
http://www.tdwilliamson.com/pigdw/geometry.html
http://www.bright.net/~pasngas/eduro.htm

Odometer Wheels

For ILI to be of use to a pipeline owner, the information on defects must be accurately correlated with the location, otherwise large sections of pipe would have to be excavated. Typical basic location is established by using a simple odometer wheel rolling along the pipe wall. Accuracy of this method depends on the cleanliness and condition of the pipe interior since slippage can cause inaccuracy.

Mapping/GPS Tools

These tools are based on newer technology than and are much more accurate than odometer wheels. These systems are, of course, more complicated, power dependent, and more expensive to run than simple odometer wheels.

The operation of mapping tools is based on inertial navigation using built-in gyroscopes and accelerometers. Data acquired are X, Y, Z angular change and X, Y, Z velocity changes.

Applications and Advantages Over Odometer Wheels Include

- Verification of existing and creation of new pipeline log books
- Determination of any changes in pipeline geometry
- Bend measurement
- Direct feed into geographic information system (GIS)-based data management and display systems
- Establishes absolute coordinates
- Superimposing inspection results with other geographical data and aerial data possible
- Enables combining data with results of other pipeline data into single database

Running mapping tools before or after an in-line inspection run allows for subsequent correlation that can lead to locating the ILI data with sub-meter accuracy.

Video

Video imaging of the interior of natural gas pipelines is currently performed by at least one company. The images are certainly valuable for gross diagnostic of the pipe’s condition, but unfortunately, provide little detail about the true condition of the pipeline. A sample of this existing technology is shown in Figure 3.

Some Advantages of Video

- Provide intuitive view
- Area sensor rather than single point
- Relatively fast

Figure 3: Video from a new smart pig[4]

Types of Flaws Detected

- Cracks
- Pits
- Dents
- Corrosion

Some Disadvantages of Video

- Detailed inspection of particular flaws is not practical
- Same data taken for "good" pipe as well as defect areas creates large amounts of data to be evaluated
- High pig speeds make high resolution pictures problematic
- Dependent on lighting, which requires cumbersome power supply
- Images without NDT data support are subject to misinterpretation
- Surface inspection only

Use of video and other imaging devices is currently limited, primarily because current pigs cannot stop and often the camera is beyond the defect before a more detailed image can be taken.

[4] *Source: http://www.neo.no/pRes.sreleases.html*

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