Development of an EMAT-based Crack Inspection Tool for Small Diameter and Difficult-to-Inspect Pipelines

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Abstract

Small-diameter pipeline crack in-line inspection (ILI) has typically been an underserved industry segment, primarily due to the difficulties associated with the physical limitations of packaging sensors, electronics and power sources within a small housing which is then able to successfully navigate challenging pipeline configurations. New ILI technologies are often therefore introduced for larger diameter tools and then miniaturized as far as possible. This paper presents the development, testing and implementation of an Electro-Magnetic Acoustic Transducer (EMAT) inspection vehicle specifically designed to detect and characterize longitudinal cracks in small diameter and difficult to inspect gas pipelines.

The paper will present the initial tool development and subsequent implementation on to a free-swimming bi-directional inspection vehicle. Since then, the tool has successfully and safely completed its initial inspections which provided critical information in the tool's performance and further design improvements. Secondly the paper will present, via case studies, the tool's performance in detecting and identifying axially orientated cracking anomalies through both full-scale testing and field validations. The case studies include comparisons with additional inspection data streams, providing an integrated approach to the identification of complex morphologies or interacting anomalies.

Nomenclature

API:	American Petroleum Industry
CW:	Clockwise
CCW:	Counter Clockwise
dB:	Decibels (20 x log)
DEF:	Deformation
EDM:	Electric Discharge Machining
EMAT:	Electromagnetic Acoustic Transducer
FBE:	Fusion Bonded Epoxy
GTI:	Gas Technology Institute
ID/OD:	Inside/Outside Diameter
ILI:	In Line Inspection
IMU:	Inertial Measurement Unit
INGAA:	Interstate Natural Gas Association of America
MAOP:	Maximum Allowable Operating Pressure
MFL-A:	Magnetic Flux Leakage - Axial
NDE:	Non-destructive Evaluation
NN-pH	Near Neutral pH
OTD:	Operations Technology Development
PAUT:	Phased Array Ultrasound
PHMSA:	Pipeline Hazardous Material Safety Admin.
POI:	Probability of Identification
SCC:	Stress Corrosion Cracking
STFT:	Short Time Fourier Transform
UT:	Ultrasonic

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Introduction

The goals of the original PHMSA/GTI/OTD funded program focused on difficult-to-inspect 8” distribution lines and specifically to provide an ILI alternative to hydrotesting for lines that did not have post-construction pressure test records. Bondurant, et al (1,2) provides an overview of the original goals, motivation, and results of the original program.

The PHMSA/GTI/OTD program focused on demonstration of the basic technical approach and resulted in an 8” tool that had a good collapse factor, low drag for low flow applications and would negotiate 1.5 D bends. This tool uses guided acoustic waves that are launched circumferentially for crack detection and measurement. In addition, the transducer measurement and processing approach solved the acoustic congestion problem that exists when using guided waves in small diameter pipes. The acoustic congestion problem may be defined as the multiple, interfering, chaotic signatures caused by the wrapping of guided waves around the circumference of the pipe when waves are transmitted and/or received by an arbitrary transceiver. The patented approach comprises launching interrogation waves in one direction around the pipe and then using a special receiver that can decompose the waves into components that correspond to the clockwise or anticlockwise direction of the wave propagation (3). This allows decomposition of the data into two sets of data: forward reference, and backward flaw signatures simplifying detection and characterization of the flaws.

An illustration of the signal congestion effect and subsequent mitigation through the principles described above can be seen in Figure 1. The image on the left shows a conventional approach and the multiple signal responses correlating to flaw responses associated with the clockwise (CW) and counter clockwise (CCW) guided waves alongside the actual responses from the CW and CCW signals. The image on the right shows the flaw response caused by the unidirectional guided wave and the resulting simpler signal composition as explained subsequently.

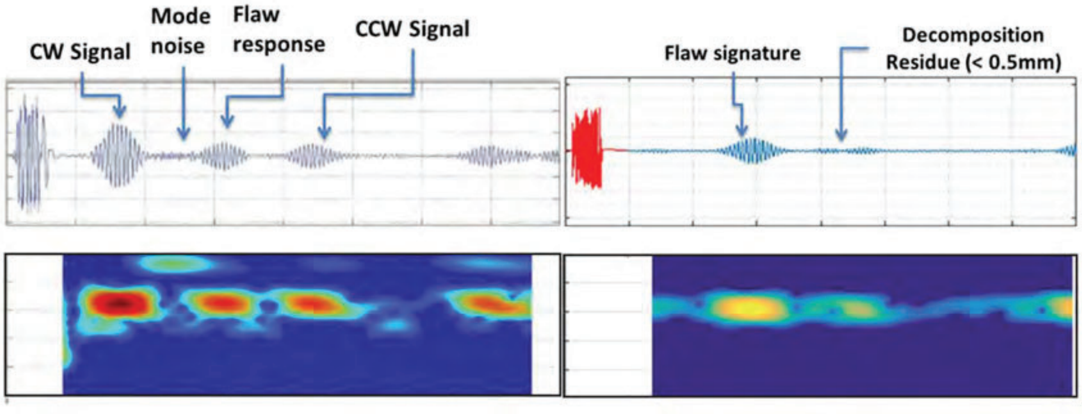

Figure 1: Illustrative example of signal congestion and its amelioration.

Figure 1 shows the numerous acoustic signatures that a traditional EMAT transceiver operating in a small diameter pipeline will acquire and one that an analyst will have to parse through before recognizing an anomaly. The analyst will require a thorough understanding of the physics such as knowledge of the velocity of wave which can vary, the size of the pipe and whether multiple modes (typical of guided waves) are present in the signature. Additionally, parsing large datasets in this manner is cumbersome. The images on the right show the decomposed output from this small

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diameter tool that uses a unidirectional transmitter as well as a receiver that can perform directional decomposition described earlier. Clearly, this output contains only the flaw signature with negligible noise from residues resulting from finite (real world) capture and processing capability. The work of an analyst or even that of an automated process (software) is much simpler and faster in this scenario. With further processing it is also possible to handle anomaly obscuring effects of pipe seam welds purely because of the simplicity of the output shown above.

This illustrative example shows the simplification potential of the patented approach which will be even more pronounced when the complexity of the environment increases, e.g., multiple flaws and their orientation with respect to the transmitters and receivers, and further so for smaller diameter pipes where the circumferential distance between events decreases. The approach also supports a longer guided wave path length (i.e., each module can independently interrogate the full circumference of the pipe) which has additional benefits related to coverage redundancy and the ability to quantify (and subsequently normalise) any localized effects which may affect the tools performance, i.e., material variations or attenuation effects.

Tool challenges for Small Pipes

The initial tool development resulted in a tool that could be used with a wireline system consistent with the goals put forth at the time. Therefore, it did not operate under pressure or move at the necessary velocities for a useable free-swimming ILI tool. Our subsequent goal for this phase of the program was to develop a free-swimming tool that would operate under pressure but maintain the unpiggable-pipeline targeted features. This imposes additional constraints on the already challenging problem of inspecting small diameter pipelines.

Eight-inch diameter tools that are required to traverse 1.5 D bends result in small spaces for transducers, transducer suspension, pressure housing, connectors, magnetics, and electronics. The small packaging also demands attention to power consumption and heat dissipation. The electronics used in the current tool had to go on a power diet which resulted significantly smaller power consumption and commensurate reduction in heat and increase in tool run time. Besides these improvements, another useful feature is the ability to maintain a short overall tool string length. The minimal configuration in the wireline tool was a single measurement module and a battery/encoder module. The sensor modules contained the EMAT transducers as well as all the associated excitation, digitization, and storage electronics.

Our design goal for this phase was to maintain this two-module capability, but to design the architecture so that multiple sensor modules and battery modules can be added to the tool string as was necessary for a specific inspection. The ability to integrate the transducers with the associated electronics within the same module help with tool modularity and minimizes the overall length of the tool. This also minimized the cabling between modules improving reliability. The nominal deployed tool contains two sensor modules, and rotationally clocked with respect to each other and with the interrogation wave propagating in opposite directions. This provides detection redundancy and addresses flaws which maybe more visible in one direction as opposed to the other. The sensor module clocking also provides detection redundancy such that if a transducer pad in one module is temporarily lifted off the surface due to a dent or seam, the other module will not pass over the same surface feature to assure the flaw is not missed.

It should also be noted that the tool stores the ultrasonic data without any modification. This provides information to an advanced analyst during the post inspection data analysis phase to help

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discriminate between injurious and non-injurious flaws as well as to determine if the data is invalid for analysis.

Testing and Qualification

API 1163 describes the requirements to qualify an ILI System and categorizes into the following methodologies:

a) Verified Historical Data;
b) Full-Scale Tests from real to artificial anomalies; and/or
c) Small-scale tests, modelling, and/or analyses

Each of these methodologies have distinct advantages and disadvantages and can provide unique insights into various aspects of an ILI system which ultimately all contribute to the end goal, i.e., a validated performance specification.

Initial testing focused on small-scale and lab-based modelling to determine a preliminary design specification and was previously presented by Kannajosyula et al (4). Figure 2 show the signal responses from a portion of the small-scale testing and includes notched samples in a seam welded pipe spool. As can be seen, 7 of 8 notches are visible in the data with the smallest notch (10%wt or 0.85mm) below the detection threshold and aligns with the preliminary design requirements to provide minimum detection capability of 2mm depth with the intention of extending this down to 1mm in future generations.

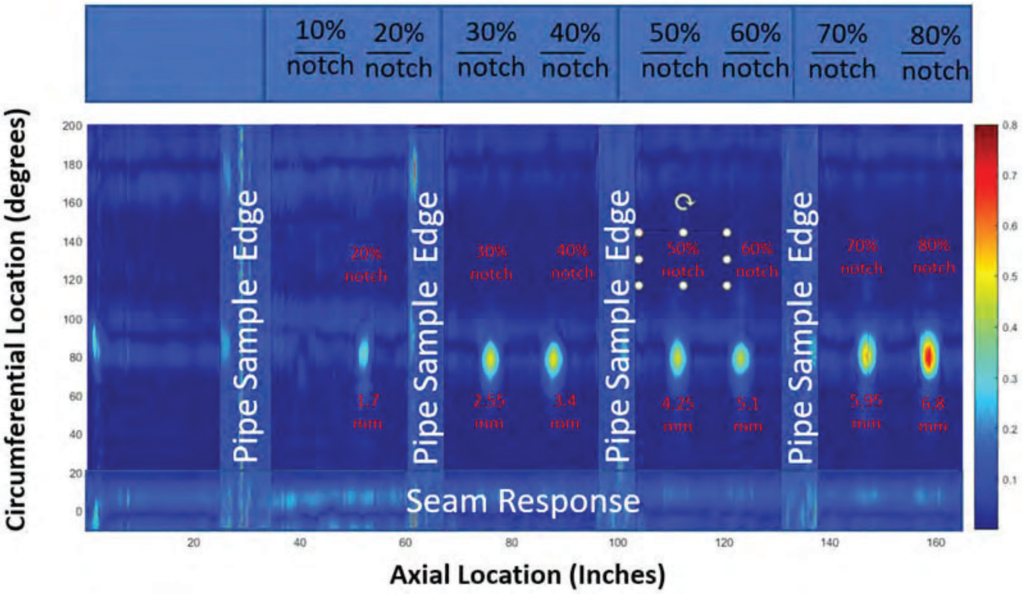

Figure 2: Notched seamed pipe testing results

As previously mentioned, the small diameter, pipeline crack ILI inspection has typically been an underserved industry segment and there was a keen interest from pipeline operators to provide test environments to support the tool development and validation. From the authors' experience there are tangible differences between test and operational environments and ultimately the inspection results, so it was an excellent opportunity to put the tool "through its paces" and gain additional insights prior to moving to full scale testing. To date there have been over 200 miles of inspection in diameters between NPS 8-12 with eight (8) pipeline operators. For some operators there was limited experience with an EMAT (or any other type of cracking) inspection which provided an opportunity to review existing validation or NDE procedures prior to the in-field validation program. Phlipot et al (6), noted that existing ILI procedures and knowledge can be leveraged and, although the framework is essentially the same, there are unique considerations for EMAT ILI to be taken into account.

Verified historical data is an excellent way to qualify an ILI system however there can be challenges as certain elements are not within the control of the tester. The distribution of flaw sizes may not be statistically representative, e.g., the majority of the flaws encountered through excavations are likely smaller in depth which will inherently have a smaller measurement error when compared to a population subset of larger flaws. Also, it is unlikely to be able to cover a full range of essential variables[1], hence the qualification program is complemented utilising all three methodologies. Details of verified historical data is provided in subsequent chapters and the case study.

Based on all the collected learnings and iterative improvements from the operational runs, the tool is currently undergoing full-scale testing which includes test spools with manufactured anomalies with statistically informed dimensions along with additional test spools containing real and simulated anomalies. This data will provide statistical validation of the performance specification and augment with the other qualification data sets.

Case Study – SCC and Seam Weld Cracking

A subject pipeline, identified as susceptible to Seam Weld Cracking and Near-Neutral pH SCC, was selected for a pilot inspection, with the pipeline details provided in Table 1. The pilot inspection was conducted utilising a two-sensor module configuration with each module transmitting in alternative i.e., CW and CCW directions.

Table 1: Case Study 1 Pipeline Details

Nominal Pipe OD	12-Inch
Pipeline Length	19 miles
Wall Thickness	0.250, 0.281, 0.312, 0.375, 0.5”
Steel Grade	X42, X46, X52, X60
Seam Type	ERW, Seamless
Coating Type(s)	Dearborn Wax
Product During Inspection	Gas
Flow Velocity	3 mph / 1.36 m/s

Results

In total six (6) crack-like linear indications were reported to the operator of which three (3) were excavated during the dig program which are summarized in Table 2.

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[1] The common set of characteristics or analysis steps for a family (series) of ILI tools that may be covered within one performance specification.

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Table 2: Summary of Excavation Findings

Feature Number	Feature	Reported Depth (%)	Reported Length (in)	As-found Information
EMAT-02	Linear Colony	20	4.5	NN-ph SCC near LSW
EMAT-07	Linear Colony	40	4.5	SCC from hook crack
EMAT-08	Linear Anomaly	53	3.5	NN-ph SCC near LSW

All of the excavated were found to be Near-neutral SCC near the weld seam. Some of the excavated areas were found to have coincident weld anomalies or selective seam weld corrosion at the same location. Figures 3, 4 show the metallurgical reports and subsequent cracking features which were removed from service.

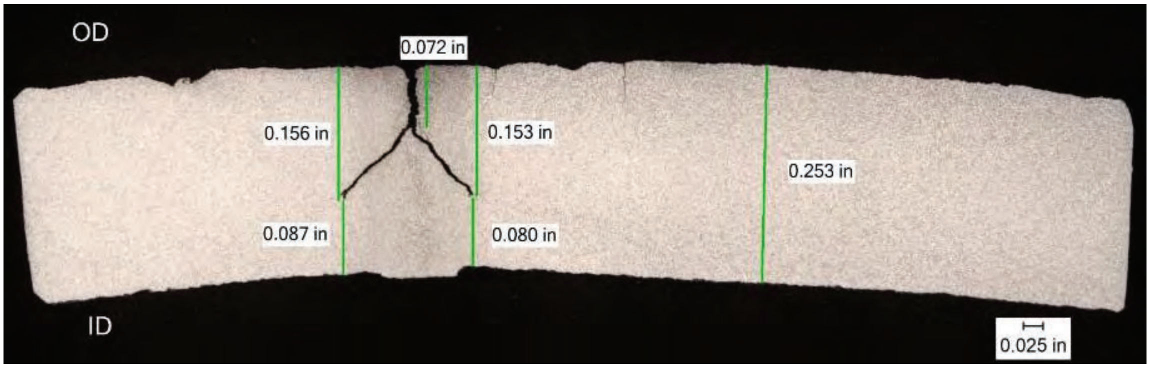

Figure 3: EMAT-08 SCC Colony - 1

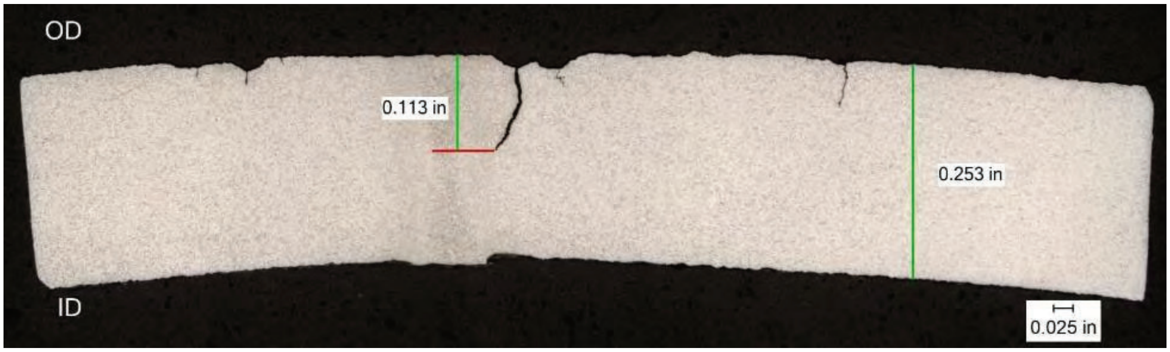

Figure 4: EMAT-08 SCC Colony - 2

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Lessons Learned

In this particular inspection a number of lessons learned were identified and shared with the operator and applied to future inspections. In this case study pipeline although two modules were utilised there were areas only one module was able to capture data valid for analysis. The 2nd module provides redundancy however even with a single module the tool was able to detect and identify pipeline cracking. As previously mentioned, the design basis required flexible sensor module configurations for different pipeline specifics. Longer pipelines or high attenuating environments may require additional modules whereas there are instances where the inspection objectives can be met with a single module although two modules would be a standard configuration.

As described later within this paper, to support the Probability of Identification (POI) an additional inspection (MFL-A) is utilised to provide an additional data stream and a different lens to the data analyst. In this case study pipeline the MFL-A vehicle was ran after the EMAT and was unable to pass an unknown geometry configuration and did not collect data for the full pipeline. The EMAT tool had successfully passed, confirming its collapsibility and capabilities to navigate difficult to inspect pipelines.

Case Study – Dent with Cracking

A subject pipeline was selected for a pilot inspection, with the pipeline details provided in Table 3. The pilot inspection was conducted utilising a two-sensor module configuration with each module transmitting in alternative i.e., CW and CCW directions.

Table 3: Case Study 2 Pipeline Details

Nominal Pipe OD	8-Inch
Pipeline Length	15.2 miles
Wall Thickness	0.188, 0.250, 0322, 0.375, 0.5”
Steel Grade	B, X42, X52, X52
Seam Type	ERW
Coating Type(s)	Tape
Product During Inspection	Gas
Flow Velocity	2.6 mph / 1.17 m/s

Caliper/IMU and MFL inspections performed prior to the EMAT identified a 2.84% dent which was excavated, and a small colony of cracks was identified away from the centre of the dent, as predicted by dent restraint calculations as shown in Figure 5.

The spool was removed for further testing and arranged in a pull setup to validate the EMAT tool’s ability to identify the crack. The tests were conducted at multiple tool orientations to determine any effects if the Transmitter or Receiver pads were interacting with the dent and could experience sensor lift off.

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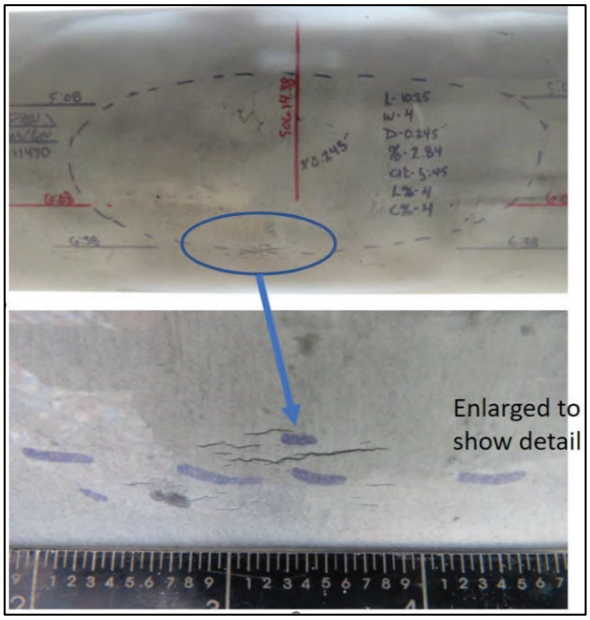

Figure 5: Dent with Associated Cracking

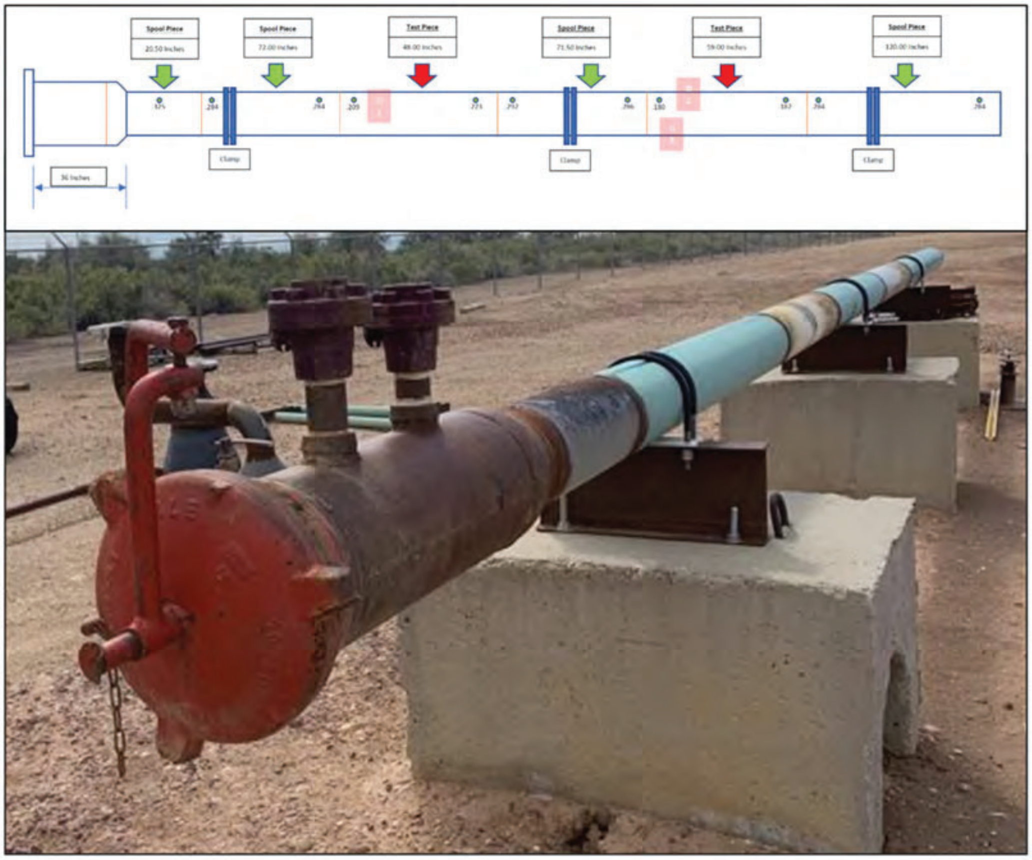

Figure 6: Test Setup and Schematic

Figures 7 and 8 show the results of the pull test and signal capture at the dent location. Figure 7 represents a situation where the dent is not interacting with either of the sensor pads and a linear indication is clearly visible in the captured data. Figure 8 shows the signal data when a sensor pad is directly over the sensor pad and the indication is still visible although the data is disturbed by the associated lift-off related to the dent profile and would be a challenge to analyse in isolation.

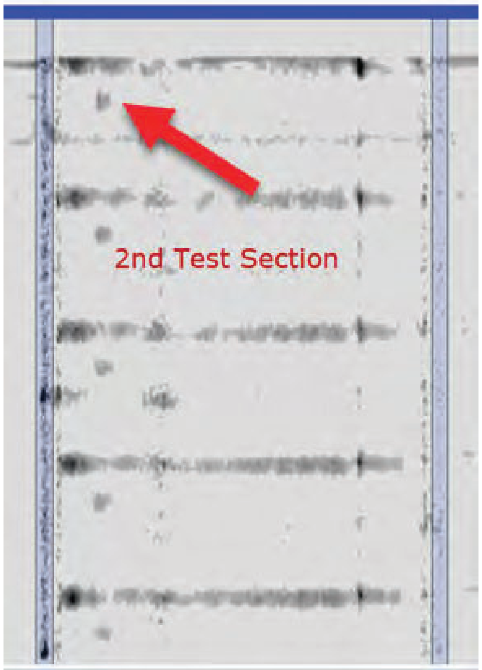

Figure 7: Tx/Rx Not Interacting with Dent

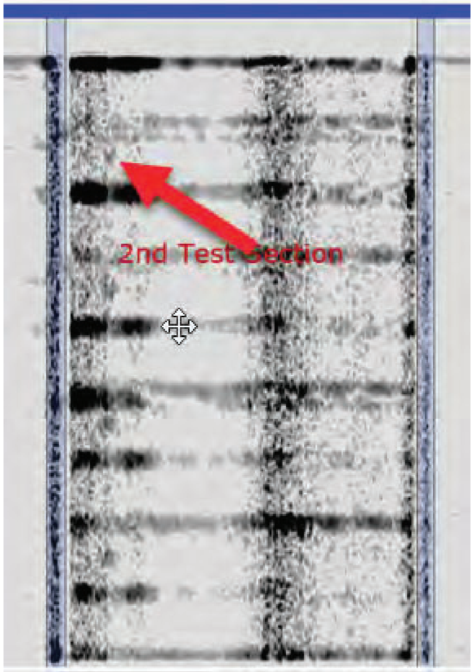

Figure 8: Clocked Tx/Rx Interacting with Dent

Following the confirmation of the ability of EMAT to detect cracks in dents, the EMAT inspection data was reviewed to screen all the locations identified by the calliper inspection as containing dents for potential cracking anomalies. None of the dents were found to have reportable anomalies and a subset of these dents, Table 4, were excavated and NDE performed. None of the excavated dents were found to contain cracking above the detection specification of the EMAT tool.

Table 4: Dents excavated and evaluated

Wheel Count	ILI Results	Field Results
3736.89	1.25% dent	1.99% dent
6708.18	1.83 % dent	1.10% dent
27898.42	1.02% dent	0.25% dent
44003.36	1.16% dent	0.58% dent / 6% ML / 0.5" LA colony
47032.18	1.19% dent	0.76% dent
68654.89	1.38% dent w/ ML	1.94% dent / 0.1" LA

Lessons Learned

In this Case Study pipeline two modules were utilised, with one of the modules purposefully oriented to interact with the dent geometry to cause a degradation of signal quality from that module. While the crack colony was still detectable with that module, the signal quality was greatly reduced. With the long interrogation path, the other module successfully identified the crack colony without any degradation. Although the remaining dents in the pipeline did not contain cracking above the EMAT tool's minimum detectable defect dimensions further testing is planned to quantify these promising results.

Integrated Results

A perceived challenge on the EMAT technology is the ability to ability to classify[2] indications (signals) recorded during the inspection. Recent INGAA guidance (7) identified that "*co-located features with defects make discrimination more difficult, and therefore, EMAT ILI results are often paired with metal loss inspection technologies to further increase the identification and reporting of crack anomalies such as SCC*". Furthermore, additional data streams can also be incorporated in the analyst evaluation process to determine confidence in the indication being crack-like.

The design of the EMAT system is optimized to reduce the number of data indications produced by metal loss, and to allow for those that are produced to be identified using the full A-scan waveform. The full-scale testing includes general metal loss, general metal loss with notches, and isolated notches. The redundancy of having multiple modules included in the tool observing anomalies from different directions (CW and CCW) allows for improved classification and sizing when multiple coincident features are present, such as a cracks within general corrosion.

All inspections with the EMAT system have been performed and assessed in combination with other technologies; EMAT + DEF + MFL-A. These additional datasets have been used to develop stand-alone EMAT interpretation methodologies as well as to produce API 1176 (8) reporting via combined datasets. Additional data streams such as coating, manufacturer and previous NDE results can also be integrated to refine the classification process. Examples of features on multiple technologies are shown in the figures below.

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[2] To identify the cause of an inspection indication (e.g., anomaly, nonrelevant indication, feature component, or type of imperfection/defect).

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Figures 9 and 10 show an example where strong reflections are observed in the EMAT signal data which correspond to identifiable signatures in the same location in the MFL-A and Caliper data. As previously noted the ability to access the signal data is of particular importance in the analysis process.

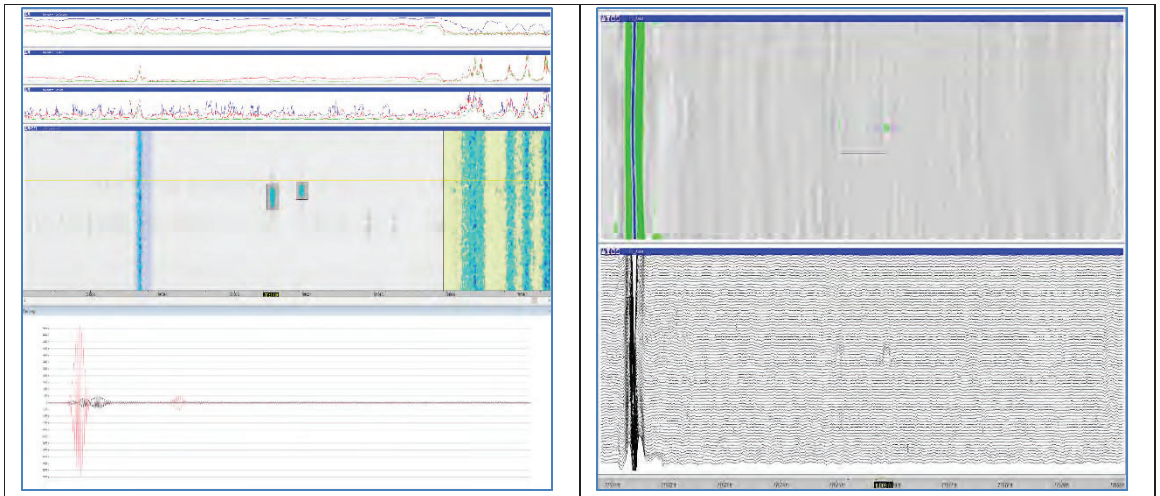

Figure 9: CAD weld signatures on EMAT and MFL

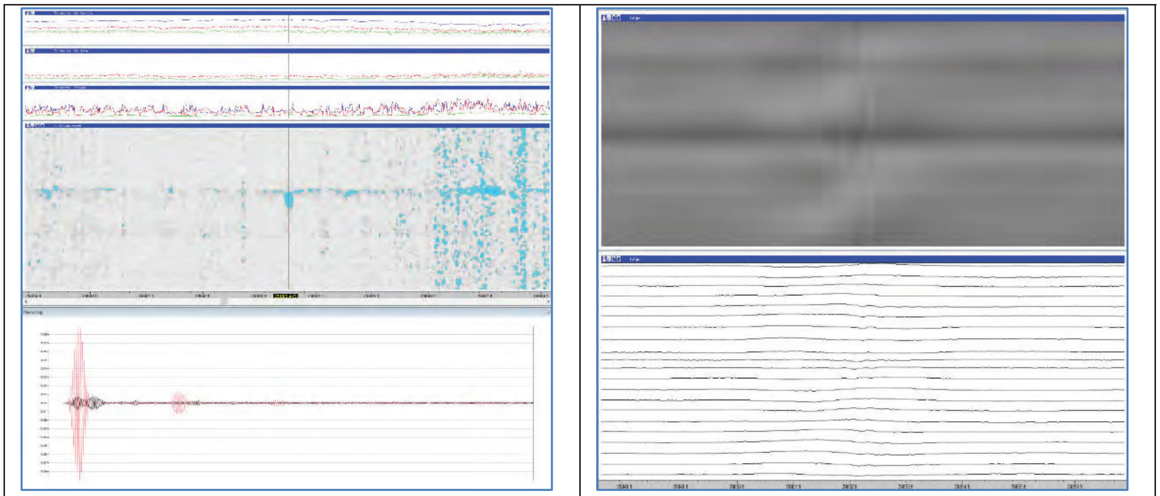

Figure 10: Wrinkle signature on EMAT and Caliper

Figure 11 details an example of a crack-like indication in the EMAT signal data which correlates to very low-level corrosion signatures in the MFL-A data. This could represent a condition in which SCC, especially near-neutral-pH SCC, has been observed (9). This can be further augmented with additional data streams such as coating type and Cathodic Potential evaluation criteria.

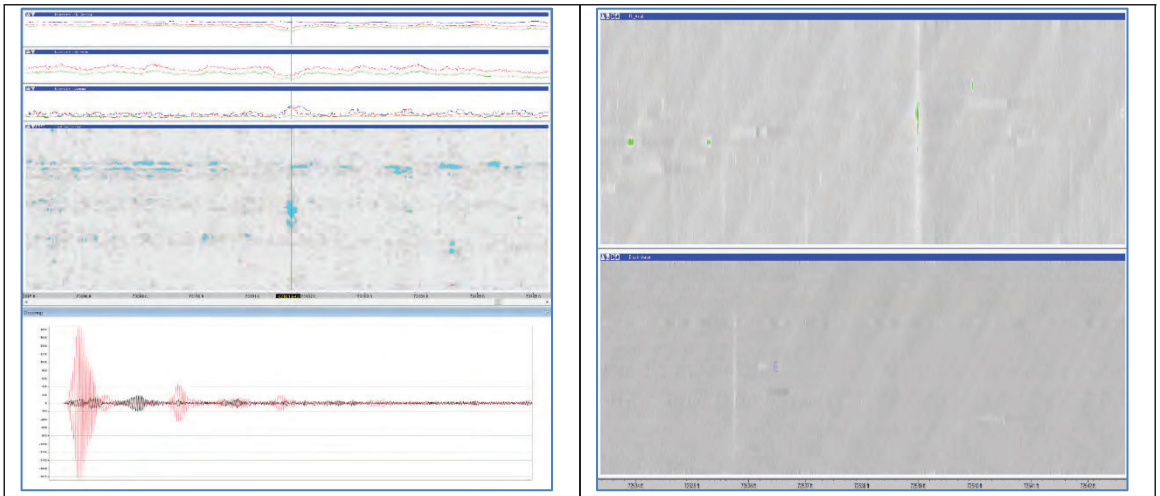

Figure 11: Crack (SCC) Signature on EMAT and MFL

Conclusions

The paper presented details of development and testing of an EMAT tool for inspecting small diameter pipes for crack inspection. Difficulties and challenges encountered during the initial development, such as signal congestion in guided waves, were discussed. An effective solution was developed for addressing these difficulties.

The performance specification of the EMAT sensor is developed through both small and large-scale testing, incrementally challenging the technology with smaller flaws and complex geometries. In parallel, the testing program was supported with pilot operational runs which provided further insights into the challenges and differences between testing and operational environments. A case study was provided which detailed one of the early inspections and subsequent lessons learned. The experience gained from each inspection enabled iterative design modifications and subsequent performance improvements were realized. At the time of writing, the EMAT technology has collected over 200 miles of pipeline data through 8 inspections and successfully identified both axially aligned SCC and Seam Weld Flaws which were subsequently excavated, confirmed, and removed from service.

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