Abstract:

The use of in-line inspection tools is today a standard procedure regarding the maintenance of high pressure pipelines. Inspection tools utilizing ultrasound technology have been successfully used for close to 20 years now and have proven themselves regarding their reliability, measurement accuracy and robustness of the data collected.

Over the years, the capabilities of this class of tools have been extended and today a large variety of special tool configurations are available to address the multitude of inspection requirements the pipeline industry has.

This paper will provide an overview of some of these special configurations of high resolution ultrasonic tools that have been developed based on customer needs. Examples will be shown from a variety of case studies, describing the added value that the use of these tools provide.

The effect of increased resolution and measurement accuracy will be discussed and its impact on integrity assessment.

The examples covered include combination tools for metal loss and crack inspection, multi-technology tools for the inspection of gas pipelines, special configurations for the use in a high wax content environment, and finally the inspection for pitting and small localized corrosion features.

1 Introduction

With a worldwide aging pipeline infrastructure and increasing economical and regulatory constraints for pipeline operators, pipeline integrity issues are an area of increasing relevance. In many countries of the world pipeline regulations not only demand inspections or monitoring of structural integrity at certain intervals, but a continuous process of verification of pipeline integrity and fitness-for-purpose. In-line inspections complemented by other inspection techniques applied externally are today the method of choice for these inspection requirements. Many regulations recommend or even demand the use of intelligent pigs [1, 2]. The use of these tools provides an effective and efficient way to inspect large length of pipelines within reasonably short time spans.

The purpose of an in-line inspection is the detection, sizing and location of flaws and defects within the pipe wall. In other words, the determination of geometric dimensions, which in turn are used as input for the codes applied for integrity assessment.
There is a huge choice of inline inspection (ILI) tools on the market today. Useful information can be found in the literature [3, 4] and is regularly published in the industry journals.

The following three diagrams provide a short overview regarding the in-line inspection technologies currently commercially available and the inspection missions that can be covered.

The most widely performed inspections relate to geometry inspection, metal loss and lately also crack inspections.

A trend in the industry, mainly driven by developments in electronics and increase in the number of individual channels that these units can record is the combination of technologies. Two terms widely used today are "Combo-Tools" and "Multi-Technology Tools":

The information provided by ILI tools basically consists of geometric data regarding a flaw or anomaly found, namely:

- length (how long is a flaw from beginning to end, extent in the direction of the pipe?)
- depth (how deep is a flaw, deepest point?)
- width (how wide is a flaw, circumferential extent?)
• circumferential position (orientation, o’clock position of a flaw?)
• longitudinal position (where along the line is the flaw?)
• pipeline route (where is the pipeline and was there any change in position?)

This data is then used to analyze the integrity of a line. Integrity assessment and fitness-for-purpose investigations in turn play an important role in defining and optimizing maintenance and possible rehabilitation procedures. Two extremely important issues within this context are the defect specifications (probability of detection, probability of identification) achieved and the question of measurement accuracy (confidence level).

2 Technologies Applied for Metal Loss and Corrosion Inspection

This paper will not address geometric inspection and mapping, but will focus mainly on metal loss and corrosion inspection, the most widely performed inspection type. The well proven technologies applied for metal loss and corrosion inspections today are magnetic flux leakage (MFL) and ultrasound (UT). Both technologies are based on different physical principles, both with their individual characteristics. This paper will not add to the published comparisons of magnetic flux leakage versus ultrasound technologies, but will address different configurations of ultrasound tools available today.

Some publications refer to three non-destructive testing technologies being applied for metal loss and crack inspection, namely magnetic flux leakage, ultrasound and EMAT (where EMAT actually stands for electro-magnetic transducers). This is not quite right, because EMAT is really just another means of inducing ultrasound, basically an alternative to using the well known piezo-electric transducers.

Figure 1: Ultrasound principle for wall thickness measurement

Figure 1 depicts the ultrasound principle most widely used for metal loss inspection and quantitative wall thickness measurement. A sufficient number of ultrasound
probes must be used to ensure full circumferential coverage of the pipe. Here, one piezo-electric transducer is sketched at two locations. The transducer sends out a short pulse of ultrasonic energy which is initially reflected from the internal surface of the pipe wall. The ultrasonic signal is not an individual arrow, but a wave front of acoustic energy. Part of this signal will be reflected; the remainder will enter the wall and be reflected from the outer surface of the pipe, the back wall. The electronics of the tool will precisely measure the time of flight. As the speed of sound of the medium in the pipe and also the pipe wall are known and constant, the time of flight will provide quantitative values for the stand-off distance between sensor and internal wall, as well as the wall thickness. Any changes in stand-off and wall thickness readings will clearly identify internal metal loss; any changes in wall thickness only will identify external metal loss. In addition, ultrasound can detect and size mid wall features such as laminations and inclusions.

The drawback is that piezo-electric transducers require a liquid medium. This liquid is present in oil or products lines, but not in gas pipelines for instance. The liquid is needed to ensure that a sufficiently strong ultrasonic signal enters the wall. In a gas environment too much energy is lost and a meaningful measurement cannot be achieved.

However, this predicament can be overcome by using a methodology to induce the ultrasonic signal directly in the wall to be inspected, EMAT. Figure 2 shows the simplified principle.

![Figure 2: EMAT-working principle](image)

Another flaw type which can significantly affect the integrity of a line is a crack or material separation. Due to the loading conditions present in pipelines - from a stress analysis perspective they are actually pressure vessels with a cylindrical geometry - they are in most cases orientated in a longitudinal direction - along the axis of the pipe - and grow in a radial direction, parallel to the ultrasonic beam depicted in figure 1. As they are parallel, they would not cause a reflection and therefore would be "invisible". For this reason it is necessary to search for cracks with an ultrasonic beam travelling under an angle, as shown in figure 3. A crack will now reflect the signal and can be detected reliably.
Figure 3: Ultrasound principle for crack inspection

3 Typical Thresholds

Table 1 shows typical thresholds regarding the depth sizing of metal loss for different in-line inspection tools. This means any feature or flaw in the pipe wall must have a minimum depth in order to be picked up by the inspection tool utilized. Typical values regarding the minimum defect diameters a feature must have in order to be detected and sized by a magnetic flux leakage tool are between 1 and 3 x t (MFL-tools usually relate defect specifications to the wall thickness (t) of the line being inspected). For a 10 mm wall thickness this would mean 30 mm. A typical industry specification for high resolution ultrasound tools is a minimum depth of 0.5 mm, with a minimum surface diameter of 20 mm. Detection only can usually be achieved for smaller surface diameters. Some magnetic flux leakage tools state 1 x t, and ultrasonic tools 10 mm.

<table>
<thead>
<tr>
<th>Tool Type</th>
<th>MFL high resolution</th>
<th>MFL extra high resolution</th>
<th>UT high resolution</th>
<th>UT pitting configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General Metal Loss</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum depth of feature to ensure detection</td>
<td>&gt; 10 % t</td>
<td>&gt; 5 % t usually valid for internal metal loss.</td>
<td>0.5 mm</td>
<td>0.5 mm</td>
</tr>
<tr>
<td><strong>Pitting Corrosion</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum depth of feature to ensure detection</td>
<td>&gt; 20 % t</td>
<td>&gt; 10 % t usually valid for internal metal loss.</td>
<td>1.5 mm for minimum feature diameter of 10 mm</td>
<td>1.5 mm for minimum feature diameter of 5 mm</td>
</tr>
</tbody>
</table>

where t = wall thickness.

Table 1: Typical minimum defect specification for different tool types
Only recently have ultrasonic tools entered the market which offer full depth sizing capabilities starting from a depth of 0.4 mm with a surface diameter of 10 mm, and detection without depth sizing starting from a surface diameter of 5 mm.

4 The Three Dimensions of Resolution

The term resolution is most widely used in relation to depth measurement in the context of metal loss surveys, i.e. relating to the question of how precisely a given tool can resolve the depth of a flaw. Another critical issue is the ability of a tool to reliably detect the actual deepest point of a metal loss feature. However, it has to be noted that resolution is an issue of all three dimensions, e.g. depth, axial size (length of feature along the pipe) and width (circumferential extent of feature).

➤ Axial Resolution and Circumferential Resolution

Measurements taken by an in-line inspection tool basically supply a grid of measurement points taken. The actual area that a sensor covers will ensure that there is overlap from sensor to sensor, thus ensuring full coverage of the pipe wall. A standard value in the industry regarding axial resolution is approximately 3 mm, i.e. taking a reading every 3 mm along the axial direction of the pipe. For an average speed of 1 m/s during the inspection this value relates to a pulse repetition frequency of 300 Hz. The term “pulse repetition frequency” relates to the number of times the ultrasound transducer switches from emitting to receiving a signal per second. The number of samples taken can be raised, for example by increasing the pulse repetition frequency, whilst retaining the same inspection speed (e.g. 600 Hz at a speed of 1 m/s would result in an axial sampling of 1.67 mm or 3.3 mm at 2 m/s). Latest generation ultrasonic tools are available which can offer a 0.75 mm sampling (i.e. one measurement taken every 0.75 mm). Advanced electronics also allow for survey speeds to be increased to approximately 2.5 m/s.

Most ultrasonic tools on the market relate to the resolution 3 mm in the axial direction and approximately 8 mm in the circumferential direction. This configuration is often referred to as “high resolution”, making use of the same term also used for magnetic flux leakage tools.

➤ Depth Resolution vs. Accuracy

The depth resolution of an inspection tool indicates which precision the depth measurement can achieve. It is not to be mistaken with the depth sizing accuracy, which is a value defined by the operator of the tool and which is usually stated in the defect specification sheet. An important aspect in depth sizing accuracy is to consider whether a measurement technique provides quantitative depth measurement characteristics or qualitative ones. Ultrasound is an example of a quantitative wall thickness measurement technique. Wall thickness, and in the case of metal loss, remaining wall thickness, can be measured directly in mm. The accuracy is determined by the hardware capabilities of the tool, e.g. sensor design, electronics. Resolution relates to the quality of the measurement. The better the resolution an inspection tool can achieve the greater its ability to precisely measure the depth contour of a given flaw or defect.

The issue of resolution and its effect on integrity assessment is discussed in more detail in [5].
Regarding the depth sizing accuracy of ultrasound tools, it is also important to understand that an average value of wall thickness is determined regarding the time of flight (i.e. time taken until an emitted ultrasonic signal returns to the transducer) for all reflections received for a given sensor covering a specific area. A transducer with an emitting diameter of 10 mm will cover a greater area than, say, a 6 mm sensor. The true actual area covered will further depend on whether the transducers used are focused or not, see figure 4.

The geometries and specifications of the ultrasonic transducers used in the industry determine the minimum defect specifications attainable. Typical industry values for the detection of metal loss features start from a feature diameter of 10 mm and depth sizing capabilities starting from feature diameters of 20 mm. These values were the reason why ultrasonic tools were considered less suitable for pitting inspection compared to magnetic flux leakage tools for a long time.

Today, modern configurations of ultrasonic in-line inspection tools are available which can achieve detection thresholds for metal loss starting from a surface diameter of 5 mm, with full depth sizing capabilities starting from 10 mm surface diameter. The advantage over magnetic flux leakage is that these new configurations of tools provide quantitative sizing for the depth of pitting corrosion and the remaining wall.

These configurations make use of a closer sensor spacing in the circumferential direction of the pipe and higher pulse repetition frequencies enhancing the axial resolution, resulting in a more highly resolving grid.

Due to the optimized sensor carrier design used for pitting inspection, the circumferential spacing of the sensors was decreased to 3.7 mm for the tool considered here. The axial sampling can be increased from 3 mm to 1.5 mm (i.e. one reading taken every 1.5 mm along the pipe axis) or even to 0.75 mm.
Figure 5 shows as an example the various UT sensor plate layouts for standard high resolution, enhanced resolution and pitting resolution.

![Sensor Plate Layout](image)

In general it can be said that the more readings a tool can take for a given area inspected, the better. If only a relatively small number of readings (i.e. samples) can be taken for a given area, the effect of any spurious signal will be much larger than if a higher number of readings can be obtained. Increasing the resolution will of course result in a higher total number of sensors used and therefore number of electronic channels the in-line inspection tool needs to provide, in order to secure full circumferential coverage of the pipe surface. The great advantage is that such a "pitting"-resolution tool provides reliable detection and sizing of local metal loss, such as pitting corrosion, with the precision and confidence level of an ultrasound tool.

Table 2 provides a rough guide regarding the capabilities of different tool types available regarding the detection and sizing of localized metal loss and pitting corrosion.

According to the POF Standard [6], the geometrical parameters of anomalies are length "L", width "W", depth "d" and reference wall thickness "t". The parameter A is used for the geometrical classification of the anomalies detected by a tool. This parameter is needed for pipes with t<10 mm. The geometrical parameter A is linked to the NDE methods in the following manner:

- If $t < 10 \text{ mm}$ then $A = 10 \text{ mm}$
- If $t \geq 10 \text{ mm}$ then $A = t$
<table>
<thead>
<tr>
<th></th>
<th>High Resolution MFL</th>
<th>MFL &amp; UT combination tools</th>
<th>High Resolution UT</th>
<th>Pitting Configuration UT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feature surface dimension: 10 mm by 10 mm; wall thickness (t): 10 mm</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>detection only</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>depth sizing</td>
<td>x</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>quantitative wall thickness measurement</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

| Feature surface dimension: 10 mm by 10 mm, wall thickness (t): 20 mm | X                           | X                           | X            | X                       |
| detection only           | X                           | X                           | X            | X                       |
| depth sizing             | x                           | X                           | X            | X                       |
| quantitative wall thickness measurement | x                           | x                           | x            | x                       |

* definition according to POF.

Table 2: Detection and sizing capabilities regarding localized metal loss (pitting) for different in-line inspection tool types.

Pitting is defined in said document as a feature having a surface area of less than $2A \times 2A$. A feature as small as $0.5A \times 0.5A$ is termed "pin hole" type feature. Applying these defect specifications means that the new generation of ultrasound tools with pitting configuration can offer detection and sizing capabilities for pitting and pin hole type features.

6. Special Configurations

6.1 Combining Metal Loss and Crack Inspection

In the past, metal loss and crack inspections had to be performed completely separate of each other. Mainly due to developments in electronics and the ability to incorporate more and more recording channels, it is now possible to combine both these inspection tasks. The major advantages are that both inspections missions can be carried out in a single tool run, with considerable savings regarding all operational

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1 Typical minimum defect specification reported in industry for magnetic flux tools is $t \times t$, detection only; depth sizing starting from $2t \times 2t$.
2 combines high resolution MFL and UT.
3 Typical minimum defect specification reported in industry for ultrasonic high resolution is $20 \text{mm} \times 20 \text{mm}$ for depth sizing and $10 \times 10 \text{mm}$ for detection only.
4 Typical minimum defect specification reported in industry for ultrasonic pitting corrosion tools is $10 \text{mm} \times 10 \text{mm}$ for depth sizing and $5 \text{mm} \times 5 \text{mm}$ for detection only.
aspects of an in-line inspection, e.g. only one cleaning program instead of two, one run of the inspection tool, metal loss and crack data can be correlated with high precision.

Figure 6a shows one of the sensor plates used by such a tool combining transducers arranged at right angles at the wall to be inspected as well transducers fixed at an angle to the wall, resulting in the ultrasonic signal travelling under a $45^0$ within the pipe wall.

Figure 6b shows the launch of a 40" tool combining metal loss and crack inspection. Further information can be found in [7,8].

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6.2 Multi-Technology Tool for the Quantitative Wall Thickness Measurement in Gas Pipelines

Gas pipelines are traditionally inspected with MFL tools. The major advantages of ultrasonic tools, namely the ability to perform precise quantitative wall thickness inspections, recording the true river bottom profile - contour of an anomaly - being able to detect and size mid-wall anomalies in addition to internal and external ones and the ability to detect hydrogen induced cracking could only be made use of, if the tool is run in a suitable liquid batch. For operational reasons, as well as cost reasons, this is often not feasible.

The need for a liquid batch can however be overcome by using an alternative method to induce the ultrasonic signal into the pipe wall. As shown earlier in this paper, this can be achieved by utilizing electro-magnetic acoustic transducers (EMAT). Figure 7 shows a multi-technology tool utilizing EMAT as well as magnetic flux leakage and eddy current technologies to provide the precision and accuracy of ultrasound for gas pipelines.

The reason for utilizing additional non destructive technologies is a limitation of EMAT based on its working principle. As the ultrasound wave is generated at the surface of the pipe wall to be inspected, the distance between the transducer and the internal surface cannot be measured. This implies that internal corrosion cannot be sized. This is overcome by using eddy current technology which is very sensitive for detecting and sizing internal flaws, or rather near bound flaws.
6.3 Special Tool Configuration for Liquid Lines with High Wax Content

Offshore crude oil lines often have high contents of wax being present, deposited on the pipe wall or transported with the flow. The presence of this wax can seriously affect the performance of a chosen in-line inspection tool and lead to a dramatic deterioration of the quality of the inspection data, thus endangering the purpose of the inspection and leading to waste of time and money. Significant amounts of wax or paraffin deposits can still be in a line, even after lengthy and careful cleaning. Issues such as the pour point can lead to wax falling out of the oil, immediately after a cleaning run, making it next to impossible to achieve a completely clean wall prior to launching an intelligent inspection tool.

Based on the analysis of available data regarding previous tool performance, operational parameters and procedures, a tool modification program was initiated by a large offshore operator to design a special ultrasonic tool configuration, optimized for the inspection in a heavy wax environment.

Figure 7: Launch of multi-technology tool in a 42” gas pipeline

Figure 8: Wax built up on sensor carrier
The major issues which had to be addressed from the tool design side were the sensor carrier and the odometer wheels. Fig. 8 shows a sensor carrier being clogged up by wax. Here the ultrasonic signal would disperse resulting in echo loss. Fig. 9 shows the modified sensor carrier after the run in a heavy wax line. As can be seen the modifications led to the tool coming out in a much “cleaner” state, ensuring that the sensors were able to pick up good quality signals.

Figure 9: Modified sensor carrier; clean after run in high wax content line

The odometer information is of critical importance in order to locate and length size any anomaly found. In a heavy wax environment the odometer can slip, leading to erroneous information. Again after special modifications to the wheel, slippage could be reduced to a tolerable amount. Further information can be found in [9].

6.4 Detection and Sizing of Localized Corrosion and Pitting

6.4.1 Local Corrosion: Detecting and Identifying The Deepest Point

Figure 10a shows a screenshot of a localized corrosion feature (surface diameter less than 20 mm) detected with a specially configured ultrasonic tool using a 5.5 mm circumferential sensor spacing. The metal loss was clearly detected and sized. The B-Scan of the ultrasonic data shows a corrosion feature with a maximum depth of 9 mm. Figure 10b shows the same feature detected and sized with a tool using a standard industry configuration. The depth sizing delivered a value of 4.6 mm. Both configurations have performed to within their specifications, but show the effect of sensor spacing with regard to the detection and sizing of small area metal loss. Even smaller features will be detected and sized reliably with a tool using a pitting configuration and a 3.7 mm circumferential spacing.
Figure 10a,b: Improved depth sizing capability for localized metal loss and pitting corrosion with a surface area of less than 20 mm by 20 mm

This screenshot nicely shows the importance of resolution with the regard to the sizing of localized metal loss, such as pitting corrosion.

6.4.2 Localized Corrosion in Girth Weld

Figures 11a shows the screenshot of the data obtained for a 12” product pipeline with a wall thickness range from approximately 6 to 8 mm. The inspection identified a localized metal loss feature within the girth weld zone. The detection and sizing of this type of flaw requires a pitting resolution or at least an enhanced resolution above the normal industry standard. For this inspection the axial resolution of the tool was set to 1.5 mm (i.e. 1 reading taken by each sensor every 1.5 mm in the axial direction) and approximately 4 mm for the circumferential resolution. Figure 11b shows a photograph of the feature, after the feature had been verified and the pipe had been excavated. The dimensions of the feature found were 15 x 56 mm.
Figure 11a: Screenshot of inspection data for localized metal loss feature in girth weld

Figure 11b: Localized metal loss feature in girth weld

7 Conclusions

In-line inspection tools provide important data regarding the flaws and anomalies detected in a pipeline wall. This data, comprising of geometric information regarding the length, width, depth and location of flaws and anomalies are critical input for integrity assessment and subsequent effective planning of repair and rehabilitation measures. Modern integrity assessment codes benefit from higher levels of inspection data quality, especially with regard to accuracy and resolution. Ultrasonic in-line inspection
tools provide these accuracies and confidence levels as well as quantitative measurement capabilities, allowing for a less conservative assessment. Latest generation ultrasonic tools with special pitting configurations widen the scope of inspection of ultrasonic tools and provide detection and accurate sizing capabilities for these small metal loss and corrosion features and are ideally suited for the future requirements regarding integrity assessment, fitness-for-purpose and corrosion growth studies.

A large variety of special tool configurations is available, each specifically optimized to meet the inspection requirements of the pipeline industry.

8 References