Ultrasonic Phased Array Crack Detection Update

By A. Hugger, D. Allen, I. Lachtchouk, P. Senf (GE Oil & Gas, PII Pipeline Solutions) and S. Falter (GE Inspection Technology Systems)

1 Abstract
This paper provides the results of two dig verification programs carried out in 2008, based on the inspection reports of GE's inline inspection (ILI) tool using ultrasonic Phased Array sensors. The specialties in the related inspection programs were the large number of defects and their elaborate measurement in the field. Furthermore, in one of the inspections, a conventional ultrasonic crack detection tool was running simultaneously. This allowed a direct comparison between the Phased Array ILI tool and a crack detection ILI tool using single crystal oscillator (piezo) transducers.

2 Introduction
In 2005, GE delivered the first Phased Array ultrasonic inline inspection tool to the oil and gas pipeline inspection market. This introduction extended the list of firsts for new technology that this company has developed; a list including ultrasonic wall thickness measurement in 1985, ultrasonic crack detection in 1995 and crack detection in gas lines with EMAT in 2002. Since its introduction, the Phased Array tool inspected 4700 km of pipelines. A portion of this work has been conducted in crack detection mode only, another in a combined wall thickness measurement and crack detection (DUO) mode. This paper focuses on the crack inspection results.

The first project (case study 1) involves the inspection of 3 lines with a total length of 1086 km in the DUO mode. The key issue threatening the 26” lines in North America transporting diesel was Stress Corrosion Cracking (SCC). Following the inspection program and delivery of the final report, the pipeline operator selected and excavated a total of 76 SCC features. Since all defects were located on the pipeline’s external surface, the sizing of the defects in the report could be confirmed through an accurate method involving incrementally grinding out the defects. Accurate field verification is not always conducted, but was in this case, allowing for a valuable comparison of inspection data.

The second project of interest (case study 2) consists of an inspection of three pipeline sections with a total length of 941 km. Because the pipeline typically transported gas, the inspections were conducted in either a water or diesel batch so that the inspection tool had the necessary liquid couplant required by use of ultrasonic sensors. The Phased Array inspection tool was operated in crack detection mode for each of the three 34” pipeline sections. In the first of the three sections, a crack detection tool with conventional ultrasonic single crystal oscillator transducers was included in the same batch along with the Phased Array tool. This was the first time ever two crack detection tools have been operated in a pipeline at the same time. This approach provided two sets of measured data for the same pipeline section allowing a comparison of the Phased Array data to the more common single crystal oscillator transducer data. From the inspection of the first section, 64 crack-like defects to date have been selected and excavated. The defect size derived from the inspection data was also evaluated through a field measurement through a grinding method.
3  Ultrasound Crack Detection Refresher
Conventional ultrasound crack detection tools use angular oriented, single crystal oscillator transducers in a defined distance to the surface. A part of the ultrasonic pulse penetrates into the pipe wall with refracted angle, and skips between the internal and external surface (see left sensor in Fig. 1). If a longitudinal crack in the pipe wall with connection to the surface appears within the sound path (see right sensor in Fig. 1) a part of the pulse will be reflected by the crack and return on the same path back to the sensor. The reflected sound wave is detected by the sensor and converted into an electrical signal, which is further processed and stored in memory banks on the tool.

Fig 1: Principle of ultrasonic crack detection. Sound path of the ultrasonic pulse in the pipe wall (left). Sound path of an ultrasonic pulse with a crack reflecting the sound (right).

4  Phased Array Refresher
Instead of a single crystal oscillator ($\varnothing \approx 13$ mm) a Phased Array is composed of many narrow stripe-like elements. Several neighboring elements (width $\approx 0.4$ mm) are electronically grouped together to form a “virtual” sensor. By varying the timing sequence in which the various elements of the “virtual” sensor are excited (on the order of nanoseconds), the resulting ultrasonic pulse which is formed travels away from the sensor with an angle (see Fig. 2, left part) or with a specific beam shape (e.g. focused, see Fig. 2, right part). The sequence and the amount of the delay determine the direction and the angle of the ultrasonic pulse. By delaying the excitation of the elements in the center of the virtual sensor, the pulse can also be focused (e.g. for a wall thickness measurement).

Fig. 2: Steering of the ultrasonic pulse by delaying the excitation between neighboring elements

Because the grouping of elements is performed electronically, the specific elements which are grouped or how they are excited can be easily and quickly changed. Each element can also be grouped into more than one virtual sensor, providing for multiple
purposes of the same element in different virtual sensors. For example, one virtual sensor can first generate a sound wave in the clockwise direction, then in the counter clockwise direction, and finally perpendicular to the pipe wall. Since two neighboring virtual sensors have an overlap, the same elements will also contribute to each of these two virtual sensors.

*Fig 3: Same elements used for clockwise and counter clockwise shots (left). Reflection from a crack (right).*

5 GE’s Ultrasonic Phased Array Tool

*Fig. 4: Launching of GE’s Ultrasound Phased Array Tool “UltraScan DUO”*

Like other inline inspection tools, the Phased Array tool consists of battery bodies, electronic bodies and a sensor carrier. Pipeline medium acting against the polyurethane cups mounted on the tool provides the driving force for the tool in the pipeline (see Fig. 4).

The sensor carrier consists of three separate sensor rings, each oriented at a rotated angle from each other to provide complete 360 degree sensor coverage of the pipe
wall circumference. Each sensor contains an array of elements (see Fig. 5), and depending on the measurement mode selected, contains up to as many as 44 virtual (grouped) sensors.

*Fig. 5: Phased Array sensor carrier. Staggered arrangement of three rings (left). Rear view of the sensor carrier pulled into a pipe (right).*

6 Run Record
Since its launch in 2005, the tool has commercially inspected 4691 km of pipeline (status March 2009), predominately operating in crack detection mode only.

*Fig. 6: Run Record*

7 Client's Requirements
In order to manage their pipeline integrity as reliable and cost effective as possible, pipeline operators depend on the quality of the data provided by the ILI reports. The most crucial criteria for each reported defect are:
1. Complete detection of the defect according to tool specification
2. Correct classification of the defect regarding feature type
3. Correct declaration of the defect location
4. Accurate sizing of the defect within the tool specification
7.1 Defect Detection
The defect detection capability of an ILI tool is quantified by its POD (Probability of Detection). This value states a run-independent probability that the tool is capable of detecting a defect with a defined property (e.g. minimum defect size). The calculation of the POD involves a consideration of all existing defects in a pipeline, both those which may or may not have been detected. To completely evaluate the tool’s performance against its specified POD, it is necessary to identify any defects which may have not been detected by the tool. Since this is not possible in a real pipeline inspection because the entire length of the pipe would need to be uncovered and surveyed, the POD value is commonly calculated by using the results of pipe loop tests, which contain defects of various sizes, both above and below the tool’s specification.

During field verification activities, large sections of the pipe are uncovered on either side of the location containing the feature of interest. The fully exposed length of the pipe is surveyed by local NDE. Minor defects could possibly be located in addition to the reported features. This additional information is used in estimating the performance of the tool against its stated specification.

The POD value for the Phased Array UltraScan DUO tool was evaluated through extensive loop testing. The outcome demonstrates that, for example, a crack with a length of 25 mm and a depth of 1 mm can be reliably detected with a POD of 90% according to API 1163 methodology.

7.2 Defect Classification
If an ILI tool has difficulties in distinguishing between severe and non-severe defects (e.g. between cracks and mid-wall laminations), the value of an inspection can be significantly reduced. Additional field activity based on misclassifications leads to significant, but unnecessary costs. A reliable Integrity Management program is also constrained by wrong classified features.

The discrimination capability is quantified by the POI (Probability of Identification) value. In contrast to the POD value, the POI value can be evaluated based on field verifications. With a sufficient number of "digs", the POI can be calculated for a single inspection.

A POI value for the discrimination capability of cracks of the Phased Array UltraScan DUO tool was calculated based on conducted dig verifications. The outcome demonstrates that for each inspection run, a POI of 90% could be exceeded using the methods of API 1163.

7.3 Defect Location
Obviously, reporting the correct defect location is essential. Any deviation can lead to digging in the wrong place or misinterpreting field verification activities. Distance, pipe number, distance to the girth weld and circumferential position have to be provided for each defect. All tolerances are defined in the tool specification.
7.4 Sizing of Defects

The sizing accuracy of a tool has a significant impact on the Integrity Management plans for a specific pipeline. The advantages of higher accuracies are:

- Lower number of dig verifications required, since excavation of less severe defects can be postponed.
- Less conservatism in pressure calculation possible, which allows higher operation pressure, less repairs and longer inspection intervals.

The sizing accuracy is defined by a tolerance and an associated certainty. The length of a crack, for example, can be stated as ±10 mm with a 90% certainty. These values are determined from dig verification results as well as from loop test results; both having specific advantages. Dig verification results are based on real defects with all kinds of variations regarding shape and orientation. The sizes of the defects which are often machined into the test loop are known reliably, allowing for a better comparison to the tool's results by eliminating most of the error associated from field measurement techniques.

To avoid false conclusions from the verification results, the error from the field technique must be kept as low as possible. Experience has shown that the method of grinding the defects in incremental steps leads to a very reliable measurement. With this method, the wall thickness at the area of the defect is first measured with an accurate ultrasonic wall thickness measurement device. Then the wall is ground and the defect is measured in incremental steps of 10% wall thickness until the deepest portion of the defect is completely removed. By documenting the results of each step, a “profile” of the cracks can be generated.

*Fig. 7: Defects ground in 10% steps*

<table>
<thead>
<tr>
<th>Prior to grinding</th>
<th>After 10% grinding</th>
</tr>
</thead>
<tbody>
<tr>
<td>After 20% grinding</td>
<td>Removed after 30% grinding</td>
</tr>
</tbody>
</table>
8 Case Study 1
GE’s Phased Array tool inspected three 26” lines in North America with a total length of 1086 km in the DUO mode (simultaneous crack detection and wall thickness measurement). The inspected pipelines transport diesel, which was also used as coupling medium during the runs. The only relevant defect type detected was SCC.

8.1 Defect Classification
All 76 feature verifications confirmed the classification from the report. There were no false digs. This totally complies with the 90% POI statement of the tool specification.

8.2 Crack Sizing
For SCC, the maximum depth, the length of the crack field and the length of the largest interlinked crack are reported for each crack field. In order to obtain optimum defect sizing, the first dig results were used to finalize the sizing algorithms. As Fig. 8 & 9 show, 64 of 76 reported depths were within the ±1mm band indicated by the red lines and 41 of 53 verified lengths of interlinked cracks were within the ±40/-20 mm range indicated by the black dashed lines. This means, that the depths measurement of the inline inspection complies with the 90% certainty statement (with 95% confidence, according to API 1163) of the tool specification. The certainty of the length measurement seems to be near to 90% - for the clarification of this case, the interaction rules applied in field and with the ILI data need to be considered.

It must be noted that the current method for reporting the depth of features with the conventional ultrasonic crack tools is to state a depth band, usually expressed as a percentage of wall thickness (e.g. 0-12.5%, 12.5 – 25%, etc) with a tolerance added to that band. If the actual depth band plus tolerance range were plotted on the graph in Figure 8 for each corresponding feature, the area bounded by that tolerance would be much wider than the width of the red lines shown.

Fig. 8: Unity plot predicted depth vs. field depth

Fig. 9: Largest interlinked crack: deviation from field measurement
9 Case Study 2
GE’s Phased Array tool inspected three 36” lines also in North America with a total length of 941 km in the crack detection mode. The pipelines transport gas. For the inspections, water or diesel batches were used for the coupling. In one of the lines an additional GE UltraScan CD crack detection tool was run simultaneously.

9.1 Defect Classification
All 64 feature verifications confirmed the classification from the report. There were no false digs. This totally complies with the 90% POI statement of the tool specification.

9.2 Crack Sizing
For SCC, the maximum depth, the length of the crack field and the length of the largest interlinked crack are reported for each crack field. In order to obtain optimum defect sizing, the first dig results were used to finalize the sizing algorithms.

As Fig. 10 & 11 show, 53 of 64 reported depths were within the ±1mm band indicated by the red dashed lines and 52 of 64 lengths of interlinked cracks were within the +40/-20 mm black dashed lines. This means, that the depths measurement of the inline inspection complies with the 90% certainty statement (with 95% confidence, according to API 1163) of the tool specification. The certainty of the length measurement seems to be near to 90% - for the clarification of this case, the interaction rules applied in field and with the ILI data need to be considered.

*Fig. 10: Predicted depth vs. field depth*
*Fig. 11: Largest interlinked crack: deviation from field measurement*
9.3 Comparison Between UltraScan DUO and UltraScan CD Data
The minimum defect size that the Phased Array tool can detect is specified with a length of 25 mm and a depth of 1 mm. The conventional UltraScan CD tool detects defects with a minimum length of 30 mm and a depth of 1 mm. From the 64 defects detected by the Phased Array tool, the conventional UltraScan CD tool detected 58. The other 6 were either between 25 mm and 30 mm or just above 1 mm depth.

Also regarding sizing accuracy, the Phased Array tool performed better than the conventional tool. The tolerance for 90% certainty is $\pm 1$ mm for the Phased Array and $\pm 1.2$ mm for the UltraScan CD.

Fig. 12: Depth sizing comparison between Phased Array tool and conventional tool

10 Summary and Way Forward
The extensive analysis of the performance of the Phased Array technology on the UltraScan DUO inspection tool from these two case studies indicates that the Phased Array is the more accurate technology compared to the technology using single crystal oscillator (piezo) transducers.

The Phased Array provides more flexibility than the single crystal oscillator transducer which has a fixed angle and focal length. Phased Array allows a flexible adaptation of the ultrasonic sensor properties like sensor width, distance between sensors or shot angle - just by changing software parameters. This leads to improved results, especially on the defect detection and the depth sizing.

The next step for the Phased Array technology is to take advantage of this flexibility in ways which bring even more value to the pipeline operator through enhanced sizing accuracy. Some projects underway in this area include pitch and catch studies, paint brush, and varying firing angles in the same inspection as a way to deliver the highest reflected signal amplitude.

Further improvement of defect detection and depth sizing will also be subject of the next steps of improvement in crack detection: Besides shooting at a spot with only one angle, two different angles could be applied. Instead of one sensor shooting and listening, one virtual sensor can shoot and another can listen. For inline inspection, Phased Array is the only reasonable technology for these advanced measurement methods.