

# COMPLEX CRACK GEOMETRIES: HOW TO DETECT AND ACCURATELY SIZE THEM

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## Abstract

Ultrasonic crack technology is based on single transducers operated in pulse-echo mode for liquid lines. This technique uses a piezo-electric transducer generating a 45° shear wave in the steel. For the past 20 years, operators have seen only minor developments and improvements from this technology. The most significant improvement has been the progression from bucket sizing to absolute depth sizing. Pulse-echo limitations have remained for some defect types which are caused due to geometric limitations, e.g. hook cracks where the response of the ultrasonic echo has a direct relationship with the geometry of the flaw.

Since the introduction of absolute depth sizing, the pulse-echo technique has had a limit of 4mm (0.160in) as maximum depth for a feature; at lower depths, the depth accuracy has been fixed to +/- 1mm (0.040in). Such limitations are not sufficient for operators today and have resulted in a need to push ILI providers to enhance the technology. By using high-resolution robots, specialized measurements, and sizing methodologies, recent developments from NDT Global have successfully addressed pulse-echo limitations and opened the door for further improvements.

This paper, will discuss the technological limitations of pulse-echo along with the processes, including research using sophisticated modelling and simulation environments, small scale laboratory testing, and large-scale testing in NDT Global's testing facilities; all in accordance with API1163 to overcome existing limitations with the introduction of a new high-resolution robot development called Evo Eclipse. Furthermore, the authors will share results from commercial high-resolution (UCx) inspections for accurate detection, identification and sizing of defects.

Finally, the authors will present one scenario where high-resolution inspections have helped to address the identification of hook cracks based on data patterns recorded by the ILI robot.

## Introduction

Cracks and linear anomalies are common threats in the pipelines. These anomalies can be found in the base material, the Heat Affected Zone (HAZ) or in the longitudinal weld depending on different factors. Out of these locations, the longitudinal weld including the HAZ normally represents the weakest point of each individual pipe joint. The nature of the cracks and linear anomalies vary depending on their origin. Some of these anomalies grow due to fatigue caused by pressure cycles. Other anomalies were caused during the manufacturing of the pipe joint, such as the lack of fusions in an Electric Resistance Weld (ERW) long seam. Despite the origin of the anomalies, operators face challenges to detect and properly manage, with the goal to operate a safe pipeline while maximizing the throughput.

Inline Inspection (ILI) offers one technology based on a 45° ultrasonic shear wave that allows the detection, identification and sizing (length and depth) of cracks. "The first ultrasonic inspection for inline crack detection providing convincing results was developed in Germany in the early nineties and started practical application in 1994" (Willems, Barbian, Stripf, & Gemmeke. 1995). Since its commercial release, small incremental steps have occurred until the introduction of high-resolution robots in 2016 by NDT Global and with them constant improvements for the crack technology became available to the entire industry.

### Pulse-Echo

ILI ultrasonic crack detection technology is based on an ultrasonic piezo-electric transducer generating a pulse in a coupling medium with a defined angle of incidence. Once the pulse reaches the steel, a 45° shear wave is generated scanning the internal and the external pipe wall. As this wave is traveling in the steel in a "zig-zag" pattern, no reflections are expected unless there is an anomaly (crack) that reflects the wave back to the transducer. The name of this technique is pulse-echo. The Time of Flight (TOF) combined with the wall thickness of the spool enables to discriminate internal and external cracks. Figure 1 shows a schematic of the ultrasonic 45° shear wave technology.

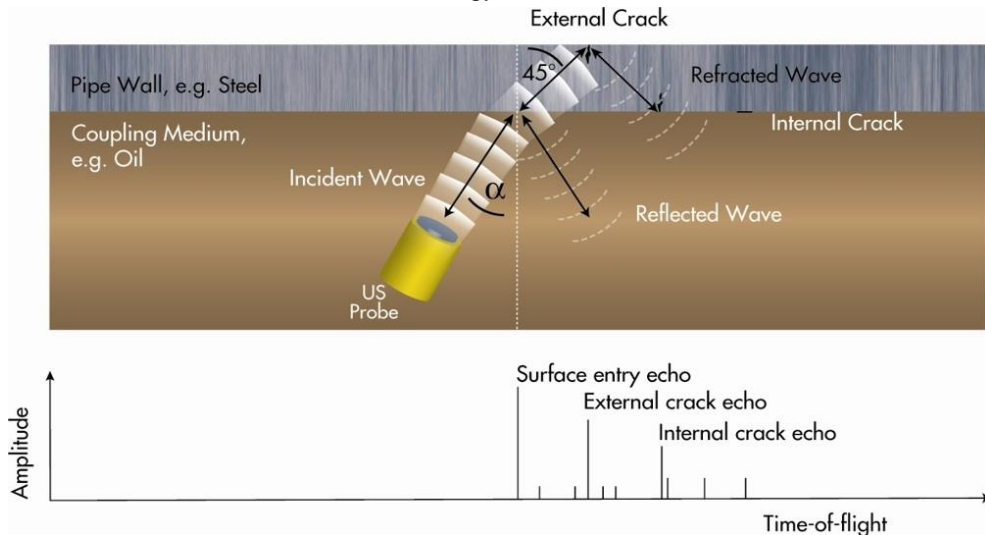


Figure 1 Schematic of 45° shear wave, describing the angle of incidence ( $\alpha$ ) and the 45° refracted shear wave detecting an external and internal crack. The recorded signals are represented in an A-Scan.

When a feature is detected by the 45° shear wave technology, it creates 90° angles between the pipe wall and the crack. These angles allow the transducers to record the maximum amplitude of the feature, used for the depth calculation; this effect is known as Corner Echo (CE). Figure 2 describes the CE of an external crack showing the situation for a radial crack.

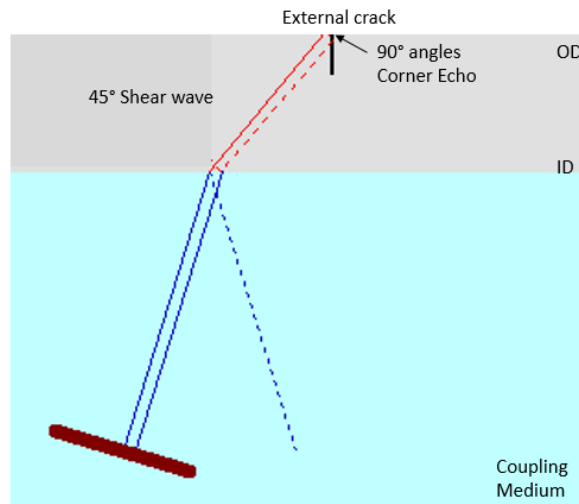


Figure 2 Schematic of the Corner Echo between an external crack and the OD

### Technology Limitations

Pulse-echo has limitations as any other measurement technique. Cracks can show a deviation from the axial orientation, which is called skew and the deviation from the radial direction is called tilt. Figure 3 describes the skewed features to the left and the tilted features to the right. The boundary for skewed ( $\alpha$ ) features is  $\pm 10^\circ$  and  $\pm 45^\circ$  for tilted features ( $\beta$ ). When the feature has a certain disorientation in the axial (skew) and or radial (tilted) direction, the effect on the recorded amplitude with increasing deviation from the optimum crack is a decrease in amplitude. This consequently leads to a reduced calculated crack depth – a severe and non-acceptable limitation. Figure 4 shows the results of modelling and pull tests of skewed features to the left and modelled tilted features with varying depths of 1mm (0.040in), 2mm (0.080in) and 4mm (0.160in) to the right. For tilted features: "As expected, the highest amplitude is obtained at zero tilt for all the three reflectors" (Willems, Kopp, Haro. 2017)

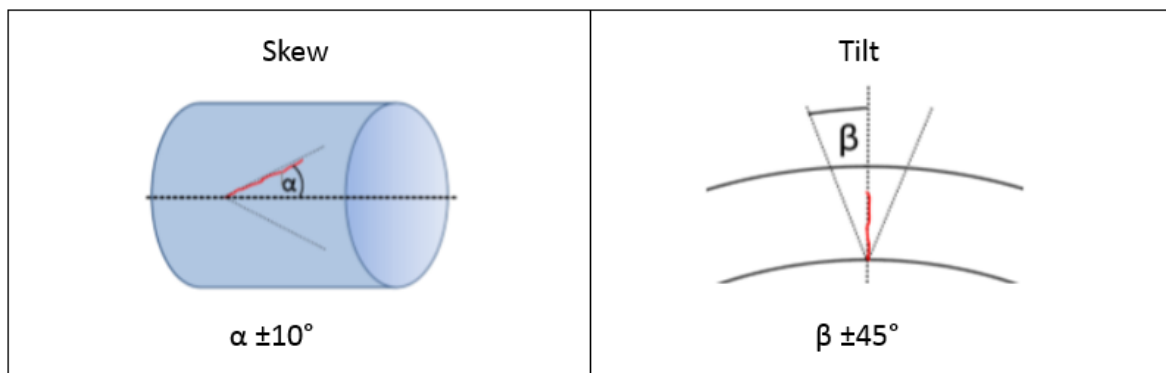


Figure 3 Schematics of pulse-echo limitations for axial misalignment (skewed) and radial misalignment (tilted) features.

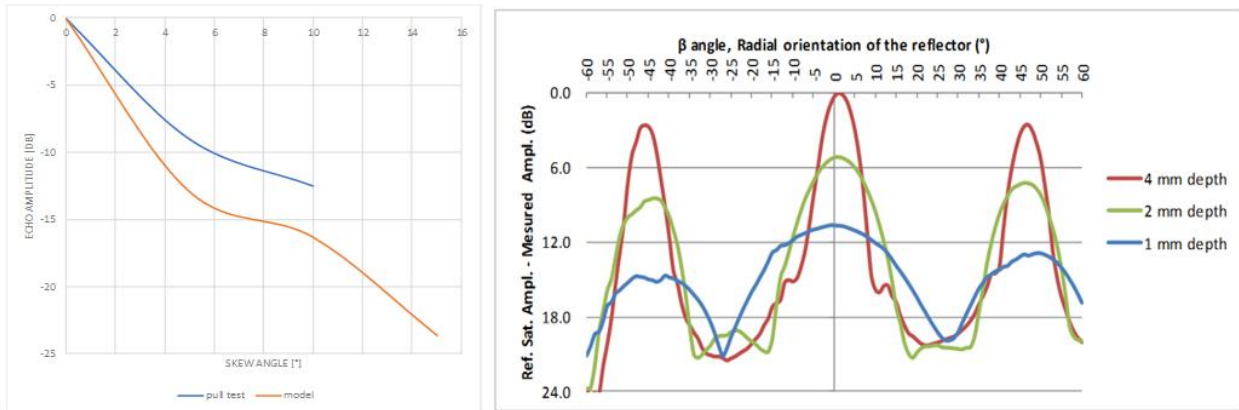


Figure 4 Modelling and pull test results from skewed features with different angles (left) showing the amplitude drop in relation to the angle of skew and modelling results of features with different depths (right) showing the amplitude drop of the features depending on the angle of tilt.

### Depth Sizing

Historically, pulse-echo technology reported the depth of cracks in ranges or buckets where the bucket represented the tolerance of the measurement. The upper bound was used to calculate the Maximum Operating Pressure (MOP) and failure pressure. Table 1 describes typical depth ranges historically used and accepted in the industry.

Bucket	Depth Range (mm)	Depth Range (in)
1	<1	<0.040
2	≥1 ... <2	≥0.040 ... <0.080
3	≥2 ... <4	≥0.080 ... <0.160
4	≥4	≥0.160

Table 1 Historic depth ranges used in pulse-echo

With the introduction of absolute depth sizing approximately 5 years ago by NDT Global, an absolute depth sizing tolerance became available for cracks below 4mm (0.016in). For features ≥4mm (≥0.160in) an open depth interval was provided. Due to a saturation effect on the primary signal response no further sizing capabilities was available. The conventional amplitude vs. depth correlation shown in Figure 5 illustrates the signal saturation at a specific amplitude, in this example 60 dB which would be equivalent to a depth ≥4mm (≥0.160in).

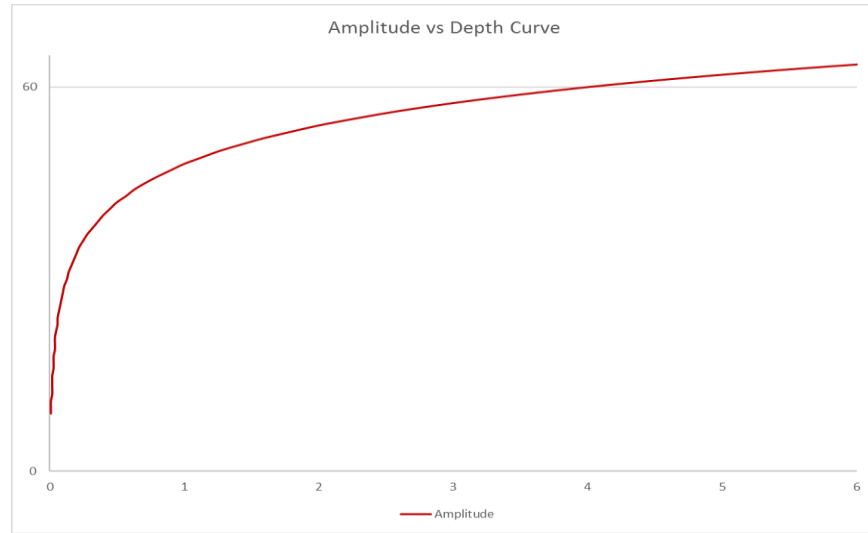


Figure 5 Amplitude vs Depth curve showing the sensor saturation at 60 dB equivalent to a feature with 4mm in depth

### High-Resolution Crack Detection Robots

The improvement of the crack technology has one main goal; provide accurate results reducing the conservatism of the measurement. This directly translates to less dig verifications and more accurate calculation of the MOP, which increases throughput and revenue.

To accomplish this goal, the mechanical robot was modified by increasing the number of sensors on-board. This was only possible by introducing the Evo Series 1.0 "EVO Series 1.0 UC fleet improves speed capabilities and resolution for crack inspections" (Hennig & Lokwani, 2015). Conventional ultrasonic crack robots (UC) have a circumferential resolution of 10mm (0.4in). The circumferential resolution is the distance from the centre of one sensor to its neighbour. High-resolution robots (UCx) at least doubled the number of sensors increasing this resolution to 5mm (0.2in). A high-density measurement grid records the signal from an optimal located sensor. This directly translates to a more accurate crack depth sizing.

Figure 6 represents the sensitivity of the conventional UC technology (top) against the high-resolution (UCx). Each curve represents the sensitivity distribution over circumference of a sensor. Due to the echo dynamics of the sound beam an amplitude drop depending on the area of the sensor that detects the feature will occur. In UC, the amplitude drops between neighbouring sensors observed in simulations is -6dB, this is equivalent as a rule of thumb to  $\pm 1\text{mm}$  ( $\pm 0.040\text{in}$ ). By doubling the number of sensors, the amplitude drops between neighbouring sensors observed in simulations reducing to -2dB, equivalent to  $\pm 0.5\text{mm}$  ( $\pm 0.020\text{in}$ ).

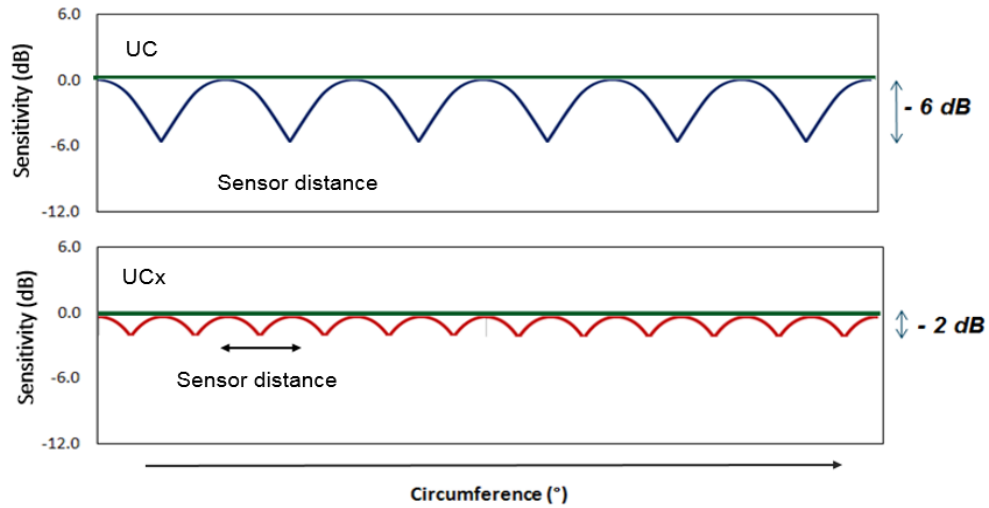


Figure 6 Schematic of the sensitivity between conventional UC with an amplitude drop of -6 dB between neighbour sensors and high-resolution UCx with an amplitude drop of -2 dB.

Further tests in NDT Global's test facilities in Stutensee, Germany included a 12" loop test with artificial features. These feature populations contain flaws with depths from 1 to 4mm (0.040 to 0.160in). The aim of this test was to compare the robot/technology repeatability and the accuracy of the measurement between conventional UC and high-resolution UCx inspections. The sample includes 30 features inspected over 13 laps for UC and 75 laps for UCx. The comparison was performed based on the maximum amplitude of each feature where an interval of  $\pm 2$  dB was used to compare the repeatability and accuracy of the measurement. Table 2 describes the results of the tests for each designed depth and the overall result for each technology. Figure 7 depicts the overall distribution between UC (left) and UCx (right) highlighting the interval of  $\pm 2$  dB.

Design Depth	Conventional UC	High-resolution UCx	Relative enhancement (%)
1mm (0.040in)	74%	92%	24
2mm (0.080in)	71%	81%	14
3mm (0.120in)	57%	86%	50
4mm (0.160in)	50%	86%	72
<b>Overall</b>	<b>58%</b>	<b>85%</b>	<b>46</b>

Table 2 12" Loop test results between conventional UC and high-resolution UCx comparing the robot repeatability and accuracy of the measurement within a threshold of  $\pm 2$  dB

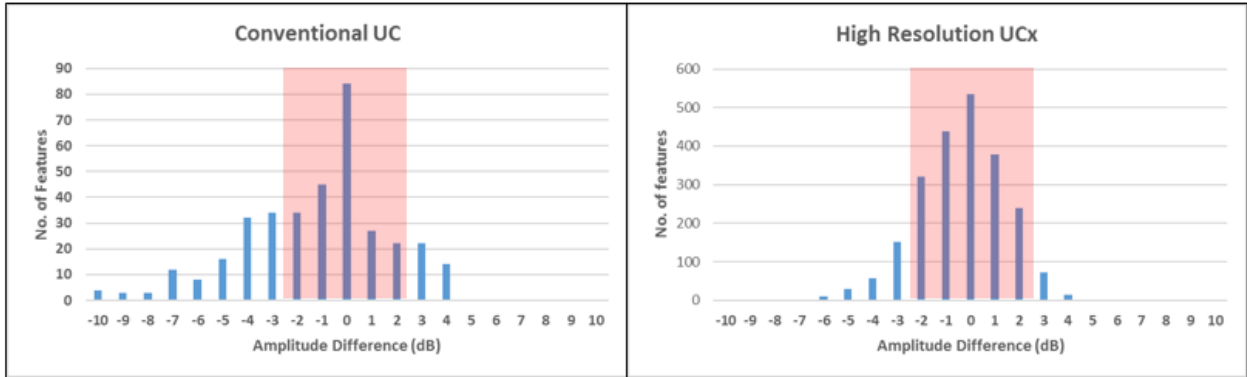


Figure 7 Overall distribution results from the 12" loop test highlighting the threshold of  $\pm 2$  dB. UC (left) and UCx (right)

The results from commercial high-resolution crack inspections with real cracks confirm the results from the loop tests. Consecutive 12" UCx inspections in two pipelines within less than 1 year were evaluated. The results contain over 6,000 reported anomalies of different feature types in both pipelines. Figure 8 shows the depth differences between inspections for each individual feature. 90% of the results are within a  $\pm 0.5\text{mm}$  ( $\pm 0.020$  in) tolerance which confirms the increase in precision and repeatability of the high-resolution robots.

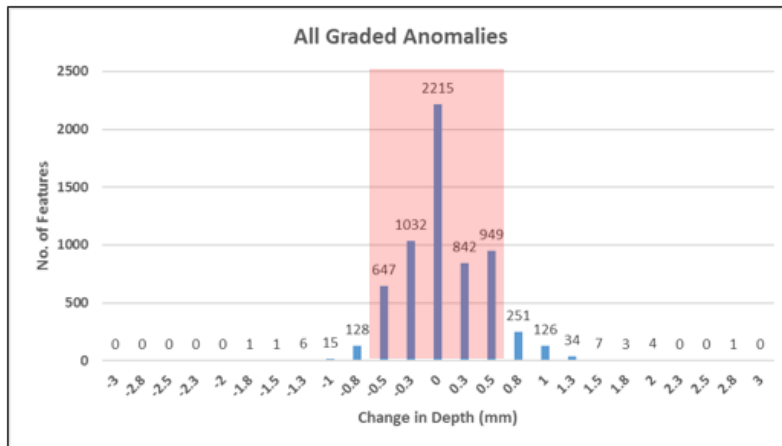


Figure 8 Change in depth distribution chart between consecutive commercial inspections with 90% of the results within  $\pm 0.5\text{mm}$  ( $\pm 0.020$  in)

High-resolution robots have proven to increase the precision and accuracy of the measurement, reducing the depth sizing tolerance compared to conventional UC. Therefore, the depth tolerances for UCx are tighter reducing the uncertainty and conservatism in severity assessment.

Conventional UC @80% certainty	High-Resolution UCx @80% certainty
$\geq 1$ to $< 4\text{mm}$ $\pm 1\text{mm}$ ( $\geq 0.040$ in to $< 0.160$ in $\pm 0.040$ in)	$\geq 1$ to $< 3\text{mm}$ $\pm 0.8\text{mm}$ ( $\geq 0.040$ in to $< 0.120$ in $\pm 0.031$ in)
	$\geq 3$ to $< 4\text{mm}$ $\pm 0.9\text{mm}$ ( $\geq 0.120$ in to $< 0.160$ in $\pm 0.035$ in)

Table 3 Depth tolerance comparison between conventional UC and high-resolution UCx.

UCx enables additional techniques and methodologies to improve further crack depth sizing. The authors elaborate the Enhanced Sizing methodology to overcome the limit in depth sizing in the next chapter.

### Enhanced Sizing

As mentioned before, pulse-echo technique is based on a Corner Echo (CE) amplitude to calculate feature depth. This calculation is limited at 4mm (0.160in). However, the increased circumferential resolution from UCx enabled the development of the Enhanced Sizing (ES) methodology which sizes features for the full depth range.

ES was developed following a systematic approach starting with the idea of improving the depth calculation for cracks and the analyst's feedback. The analysts identified a pattern or additional reflection in the data for "deep" features of approximately ~40% of the wall thickness and deeper. The features that showed this reflection were verified by NDE and confirmed to be beyond the actual depth sizing capabilities from pulse-echo. This observation triggered a systematic study to investigate and quantify these reflections. Figure 9 represents the systematic approach to obtain a methodology that could quantify the reflection and improve the depth sizing capabilities.

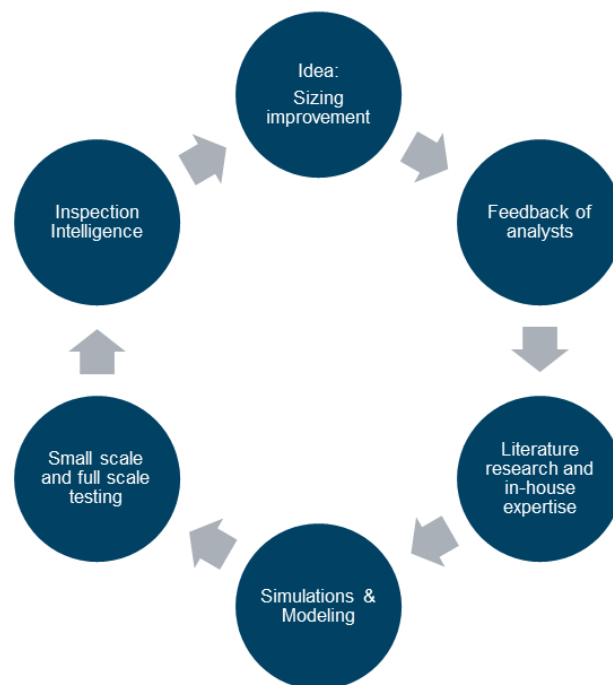


Figure 9 Systematic development cycle

The reflection recorded by the robot is caused by the Indirect Corner Echo (ICE). This is the reflection from the crack itself, but not from the corner echo. There is a direct relationship between the amplitude of the reflection and the depth of the feature. Figure 10 is a schematic of the ICE. The scanning position of the sensor is to obtain the CE of a feature if it is located at the OD, but the feature is further away from the sensor. When the ultrasonic pulse is refracted to detect features at the ID the crack is reflecting the beam back to the sensor. The body of the crack is causing the echo, which the robot records.



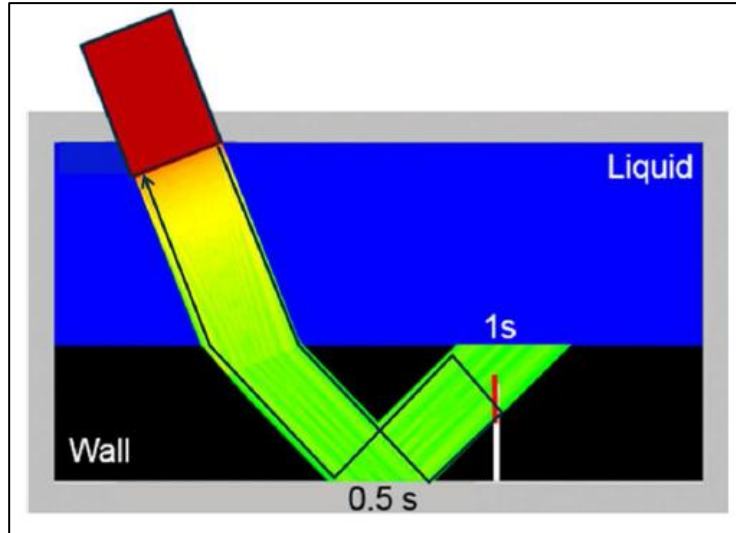


Figure 10 Schematic of the indirect corner echo (ICE) represented by the black vector

Simulations, small scale and large-scale tests show that the magnitude of the ICE increases with the depth of the feature. Figure 11 is a comparison between the maximum amplitude of the CE reflection and the ICE in relation to the depth of the feature. The X axis is the response from test notches from 1 to 10mm (0.040 to 0.400 in) in 1mm (0.040 in) steps. CE (left) is saturated at 4mm (0.160 in); the physical sensor is not able to record higher amplitudes. On the other hand, ICE's amplitude (right) increases with the depth of the feature. From a depth of 2mm (0.080 in) in a wall thickness of 10mm (0.400 in) the ICE becomes relevant, being higher than the noise level and can be used for the depth calculation for the entire wall thickness.

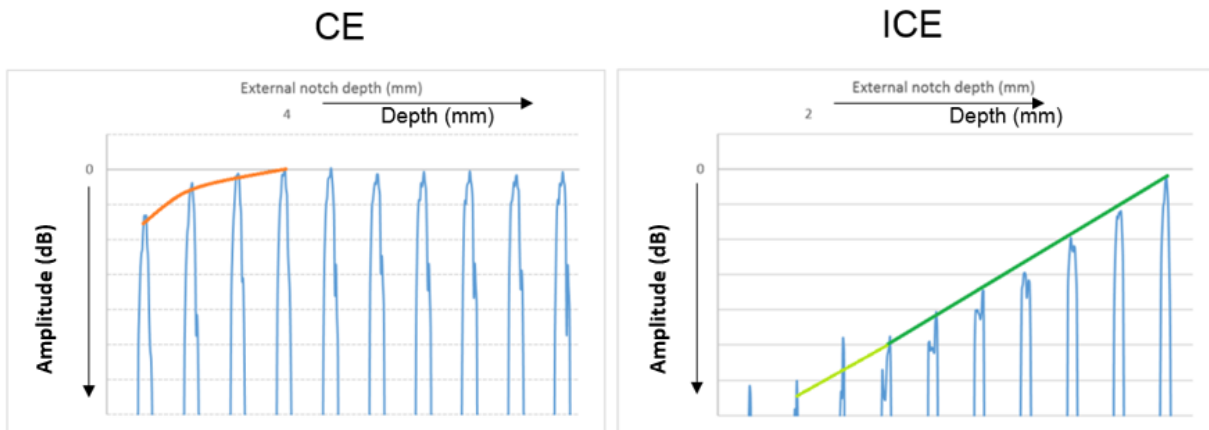


Figure 11 Amplitude response of the CE and ICE in relation to the depth of the feature.

Enhanced Sizing methodology validation was completed in small- and large-scale tests, it was also compared against historic data where NDEs were available. The unity plot on Figure 12 displays the results of the large-scale tests, considering a sample of over 2,000 features with depths between 1 and 5mm (0.040 to 0.200 in). As the results are from high-resolution UCx inspections, the variable tolerances were applied as mentioned on Table 3. 83% of the results are within the high-resolution specification.

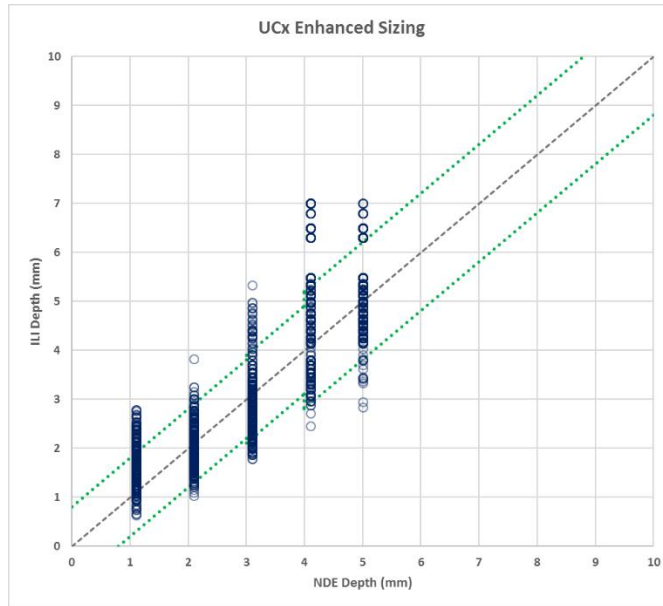


Figure 12 High-resolution with Enhanced Sizing unity plot. 83% of the results are in tolerance at 80% certainty

ES is meanwhile available as standard delivery for all high-resolution UCx inspections. This methodology has proven success in commercial inspections. A reported feature with 18mm (0.710 in) in length and 5.1mm (0.200 in) in depth was reported in a 5.7mm (0.221 in) pipe wall. The diameter of the inspection was 8". During the field verification, the feature was releasing some product as it was through-wall. Figure 13 is a screenshot of the visualization's software B-Scan and a picture of the feature from the field.

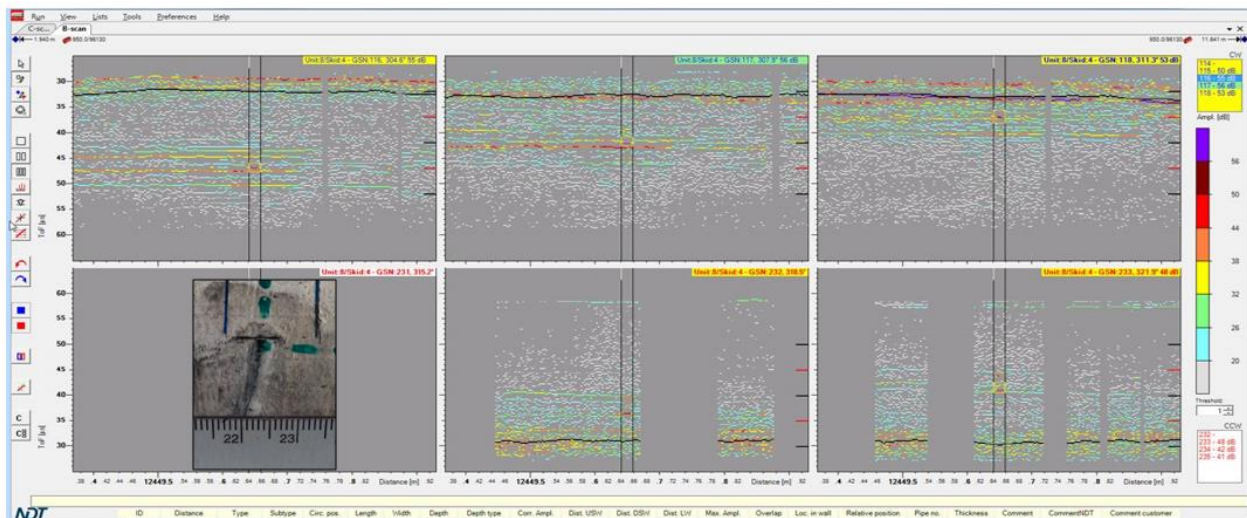


Figure 13 B-Scan of a 90% deep crack and verified as through-wall (bottom left)

Apart from allowing depth sizing for the full wall thickness range, ES provides a depth confirmation for the depth range between 2 to 4mm (0.080 to 0.160 in). In this interval, two depth sizing methodologies provide a depth value. The depth sizing algorithm considers the information from both PE and ES for the reported depth. Figure 14 highlights the area where each methodology is used for the depth calculation.

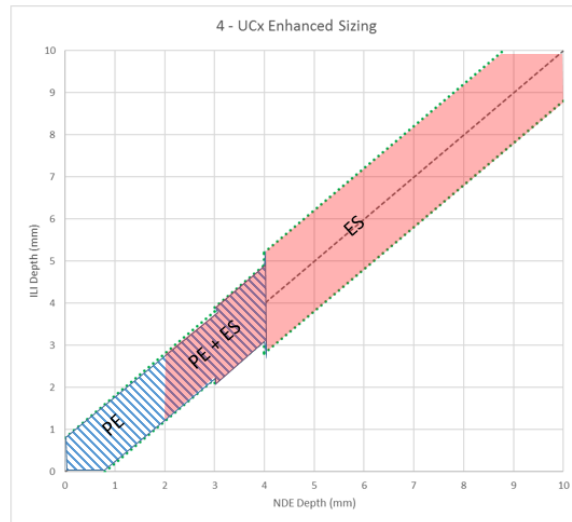


Figure 14 Unity plot highlighting the area where each methodology is used for the depth calculation

### Eclipse

Up to this point, high-resolution has proven to be beneficial to reduce depth tolerances and provide a depth for the full range. There remains two limitations from PE/ES as discussed at the very beginning of this paper. Skewed and tilted cracks are generally undersized - that needs to be addressed. The latest generation of robots utilizes conventional transducers in a completely modified geometrical arrangement. By using the same sensor density and arranging them in pairs clockwise (cw) and counter clockwise (ccw) facing each other it is possible to record an additional signal. Being in pairs, the cw sensors generate a pulse (TX) that is recorded by the ccw sensors and vice versa. In case there is no feature that can shade or block the pulse, it will travel with full energy to the RX sensors (Figure 15, left). On the other hand, if there is a feature that blocks the signal, the energy that is recorded by the RX sensors will be reduced (Figure 15, right).

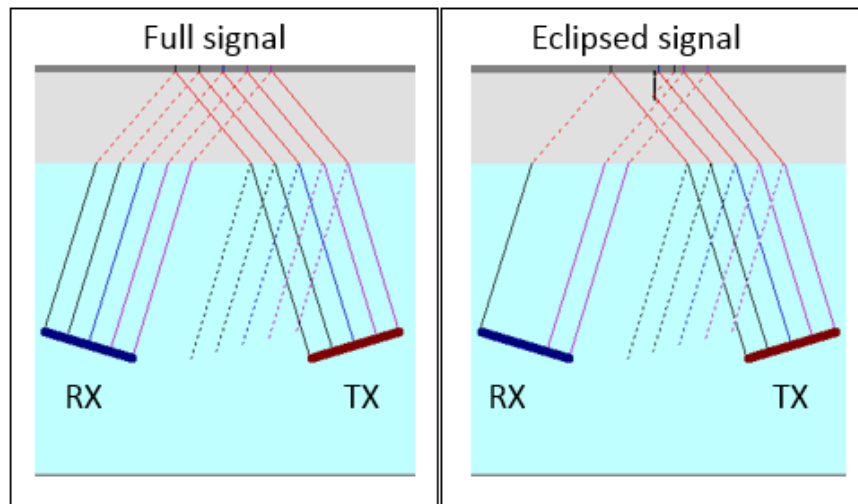


Figure 15 Eclipse technology principle. Full signal with no shading (left) and Eclipsed signal due to a feature (right)

The energy loss or amplitude drop caused by the eclipsed signal has a direct relation to the feature depth, but it is independent to the angle of skew and/or tilt. This sensor configuration in the sensor carrier enables the next generation of high-resolution crack robots called **Evo Eclipse**. This technology includes all the advantages from UCx Enhanced Sizing plus the ability to overcome the tilt and skew limitations.

Following the same systematic approach of Figure 9, modelling and simulations were performed with different feature geometries emulating cross-sections of hook cracks. The aim was to understand the ultrasonic pulse behaviour with PE and Eclipse (EC). Figure 16 displays the schematic of one of the modelled hook cracks and the Eclipse B-Scan showing an amplitude drop based on the colour scale (top). The bottom shows a schematic of PE and the maximum amplitude obtained by the sensor. The simulated depth for this example was 3mm (0.120 in), PE obtained a calculated depth of 1.6mm (0.062 in) and Eclipse a depth of 3.2mm (0.125 in).

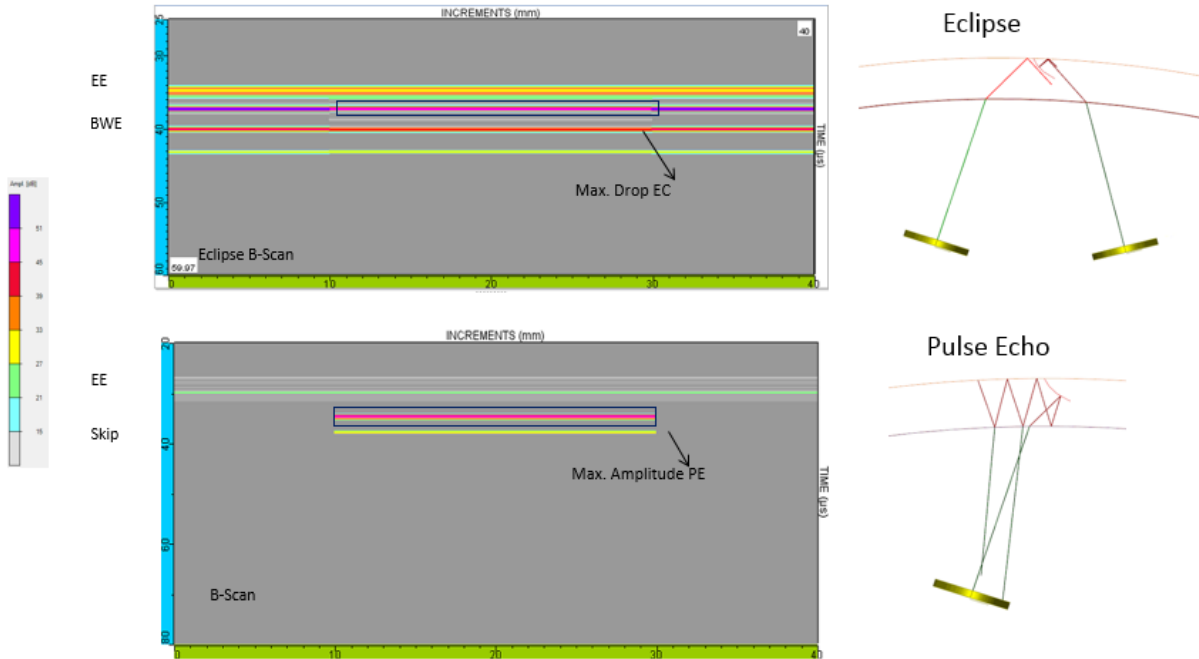


Figure 16 Modelling example comparing Evo Eclipse (top) and PE (bottom)

Figure 17 depicts the working range for Evo Eclipse and PE. The blue diamond represents the depth range in which depth sizing with pulse-echo can be applied. The green diamond represents the same for Evo Eclipse. Features within the green area are detected by pulse-echo but the depth will be underestimated. The 1mm (0.040 in) thresholds (dashed lines) represent the standard minimum depth reporting thresholds. Features with complex geometries that might be changing direction, branching, begin inside the green area but the end of the crack is outside the area will have a bias to be overestimated by Evo Eclipse.

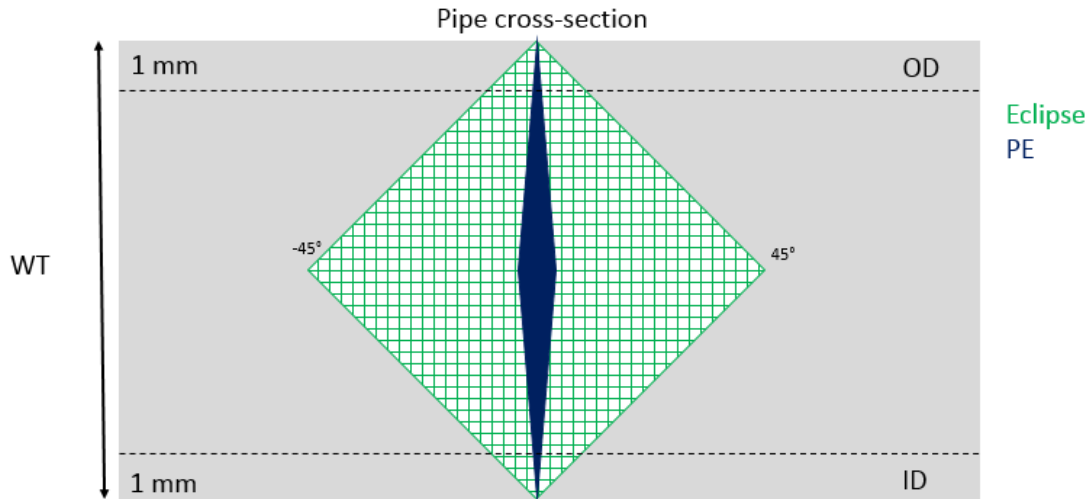


Figure 17 Evo Eclipse (green) and pulse-echo (blue) depth sizing boundaries

Full scale tests performed in a 12" loop containing test notches with different geometries were analysed using an Evo Eclipse robot. The sample of features included:

- Radial features: perpendicular to the surface with depths from 0.5mm (0.020 in) to 5mm (0.200 in)
- Skewed features: with different depths and axial disoriented angles of 2°, 5°, 7°, and 10°
- Tilted features: with different depths and radial disoriented angles of 5°, 10°, 15°, 30°, and 45°

The results from the loop test containing all the features that are perpendicular to the surface are shown in the unity plot on Figure 18. The orange points represent pulse-echo sizing only using the corner echo without ES. The results are as expected. The features are within tolerance with a maximum depth of 4mm (0.160 in). The blue points consider all the benefits of Evo Eclipse, this means three sizing methodologies: pulse-echo, Enhanced Sizing and Evo Eclipse are taken into consideration for the final depth calculation. The data points are within the tolerance lines calculating the depth for the full range.

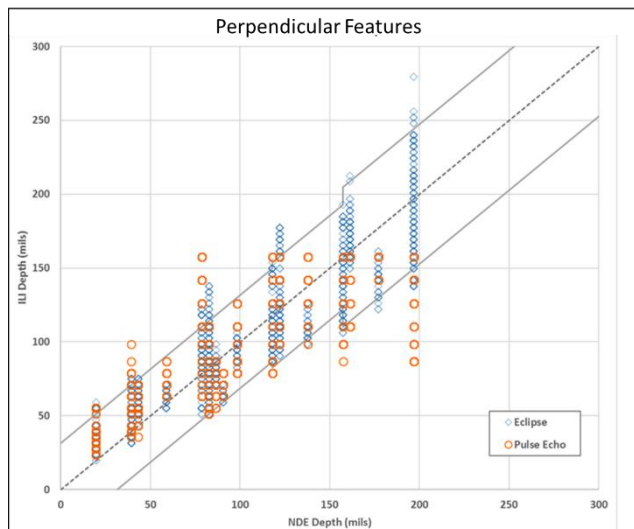


Figure 18 Unity plot of perpendicular features comparing pulse-echo and Evo Eclipse

Skewed features remain a pulse-echo (orange points) limitation as shown on Figure 19. Depending in the angle of skew pulse-echo is capable to calculate the depth within tolerance. This boundary is <math><5^\circ</math> skew angle, despite being in tolerance there is a bias to generally underestimate the depth. The blue points

consider Eclipse based depth sizing methodology only. Using the B-Scans from pulse-echo and Evo Eclipse, it is possible to identify patterns in the data that suggest certain skew angles of the features. Evo Eclipse data points are within the tolerance proving that the technology can overcome the pulse-echo limitation.

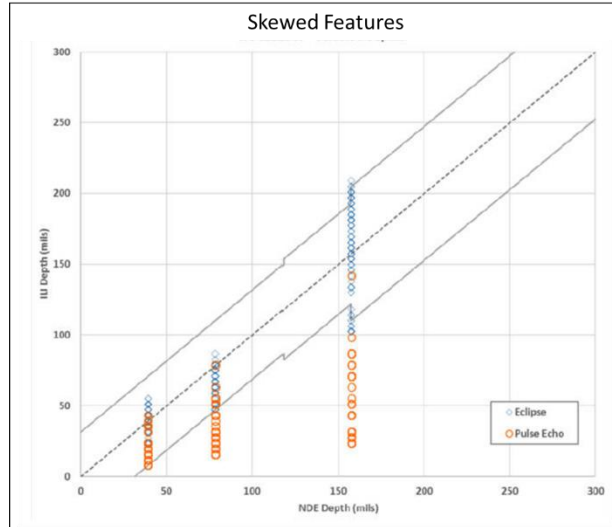


Figure 19 Unity plot of skewed features comparing Pulse Echo and Evo Eclipse

Tilted features (i.e. hook cracks) represent a challenge for operators as they have a bias to be underestimated by conventional pulse-echo. "This example clearly shows that the tilt angle has a strong influence on the reflection amplitude" (Willems, Kopp, Haro. 2017). The Evo Eclipse signal in combination with the pulse-echo B-Scan provides enough information to identify if a feature has a certain angle of tilt. With such information, it is possible to calculate an accurate depth as shown on Figure 20. The orange points represent pulse-echo depth values, where an underestimation exists once the angle of tilt is between  $>10^\circ$  and  $<40^\circ$  (Figure 4). The blue points considering Evo Eclipse have accurate depths, as the shading of the signal is independent to the angle of the feature. Evo Eclipse solves the issue of under sizing tilted features.

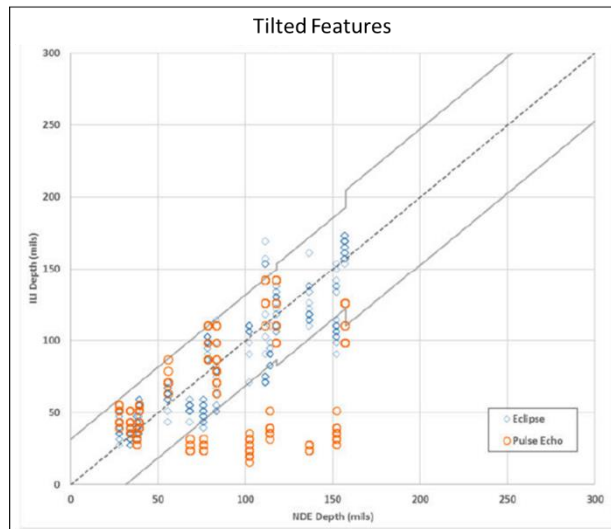


Figure 20 Unity plot of tilted features comparing Pulse-Echo and Eclipse



**Identification and Classification of Hook Cracks**

During this investigation taking high-resolution robots as a basis, we have described the limitations of pulse-echo technology and how these can be overcome. Some of these limitations depend on the sensor arrangement (i.e. resolution & Evo Eclipse) however, if an inspection is performed with state of the art UCx technology only this investigation provides an additional understanding of the data based on the higher number of sensors. This is also true when using Enhanced Sizing, data patterns can be identified to classify a feature as a possible hook crack.

Hook cracks have tilt angles from the tip to the base of the crack  $>10^\circ$ . Showing specific patterns in the data, particularly when the reflections from the cw and ccw sensors are compared. Depending on which side the hook breaks (cw or ccw) the beam is diffracted, and the robot records a specific signal. A schematic of the beam diffraction from the cw sensor is shown on Figure 21. Such behaviour provides reflections at different TOF showing in the B-Scan data. Multiple parallel reflections (top) and single individual reflections (bottom) from the other side as show on Figure 22. Also showing amplitude differences between the cw and ccw sensors due to the beam diffraction. Figure 23 shows an amplitude plot between the cw and ccw sensors of a hook crack breaking towards the cw side.

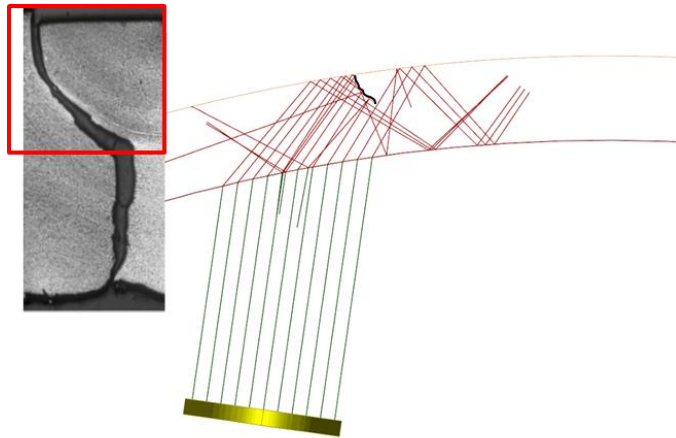


Figure 21 Hook crack simulation showing the beam diffraction from in the cw sensor

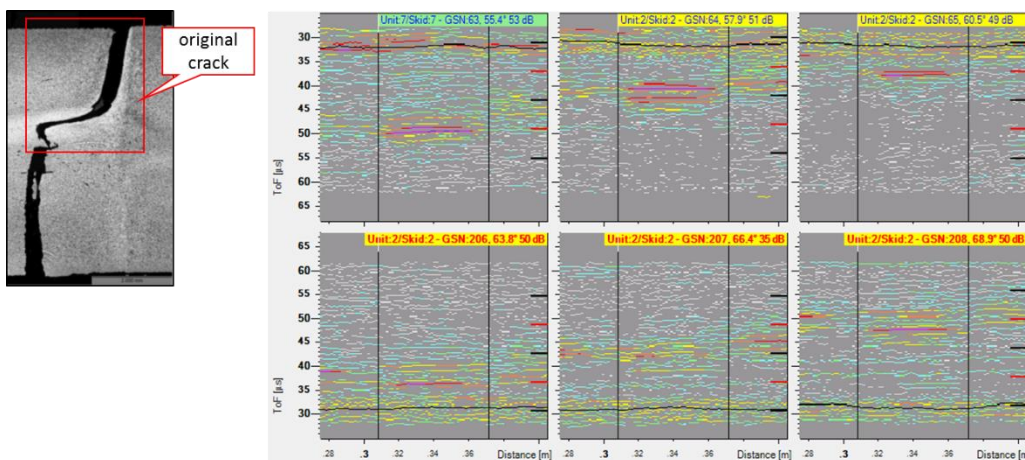


Figure 22 B-Scan of the hook crack from the cross-section to the left. The cw sensors (top) have multiple parallel reflections, while the ccw (bottom) show only one straight reflection.

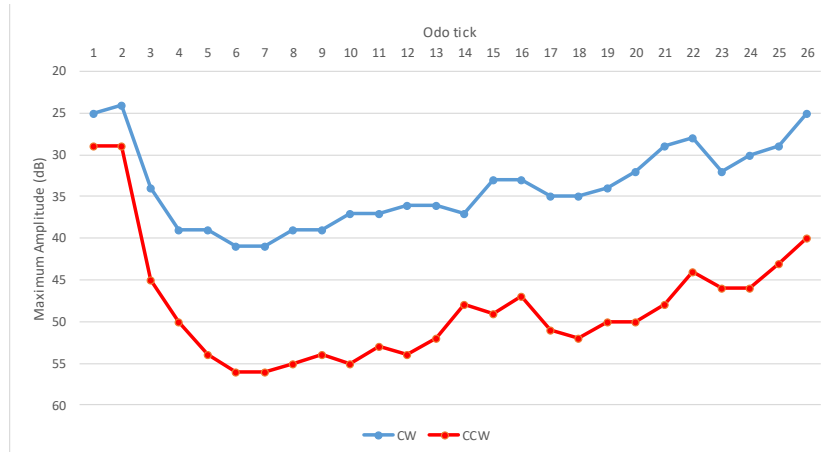


Figure 23 Amplitude profile of a hook crack comparing cw (blue) and ccw (red) sensors. The hook is breaking towards the cw side

**Summary**

High-resolution crack inspections provide solutions to operators as it delivers accurate results with tighter depth sizing tolerances. To accomplish this, the physical robot must be modified to increase the number of sensors.

There are two versions of high-resolution robots, each closing the gaps of pulse-echo limitations.

- UCx Enhanced Sizing: provides smaller depth sizing tolerances and enables Enhanced Sizing allowing to size features beyond the 4mm (0.160in) boundary. It also provides relevant information to identify patterns in the data that suggest the feature is tilted (i.e. hook crack) allowing the analysts to highlight such features.
- Evo Eclipse: in addition to the benefits from UCx Enhanced Sizing, the sensor configuration provides the possibility to identify and size accurately tilted and skewed cracks, e.g. hook cracks or cracks at the bevel of typical DSAW seams

The data that has been gathered so far with these robots allows other investigation areas to continue improving the crack technology with a goal to provide accurate results to the operator so they can manage their integrity management programs.

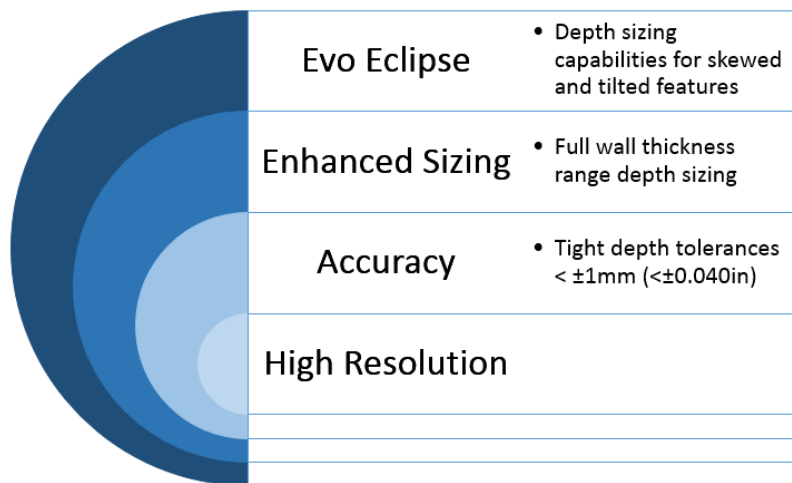


Figure 24 Summary of High-Resolution Inspections for Crack Detection: The Next Level of Accuracy



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