RECENT IMPROVEMENTS REGARDING ULTRASONIC CRACK INSPECTION OF PIPELINES

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ABSTRACT

Crack inspection of pipelines using conventional ultrasonic technology has become a standard application for in-line inspection (ILI) of liquid pipelines. Crack inspection tools have proven very successful for the detection of various types of cracks (e.g. SCC) or crack-like anomalies present in many pipelines worldwide. The first inspection tools were developed for axial crack inspection (UC), as most cracks or crack-like defects in pipelines are axially orientated. In some cases, however, circumferential cracking can occur prompting the development of tools for circumferential crack inspection (UCc). Standard crack inspection tools can be applied in most liquid pipelines transporting typical crude oils or products (e.g. diesel).

Over the years, specific inspection requirements came up that were not covered by the first tool generations. These requirements are related to different aspects of the inspection process ranging from tool-related characteristics to inspection-related challenges such as crack inspection in liquid gas. Consequently, those challenges are addressed by the latest tool developments allowing an inspection performance not possible before with regard to inspection speed and measuring resolution. In the paper, the achieved progress including enhanced depth sizing is described and illustrated by examples from inspection runs.

1 INTRODUCTION

The first ultrasonic inspection tools for inline crack detection using the 45° shear wave technique were developed in the early nineties and their commercial application started in 1994 [1]. The development was driven by the increasing demand for an alternative to hydrotesting as a means of proving the integrity of a pipeline. The minimum crack size to be detected was determined from fracture mechanics calculations. As a result, a minimum length of 30 mm and a minimum depth of 1 mm were defined ensuring a sufficient safety margin with regard to critical crack sizes. Inline crack inspection proved to be quite successful over the years and has become one of the standard applications for ILI. Nowadays, several vendors are providing ultrasonic crack inspection tools for a wide range of pipelines. As an example, NDT Global offers ILI tools for axial crack inspection as well as circumferential crack inspection covering all relevant sizes from 6" upwards with an inspection track record of more than 100,000 km as per today (starting 2003). These tools use conventional, piezoelectric sensors which limits their application to liquid pipelines. Gas pipelines can be inspected, too, by using a liquid batch, which however requires considerable additional efforts including a shut-down of the line.

2 INSPECTION METHOD

The main target of inline crack inspection is the reliable detection of surface-breaking cracks or crack-like anomalies with predominantly radial orientation. The detection limit was initially defined by a minimum length of 30 mm and a minimum depth of 1 mm where the limit size typically refers to a probability of detection (POD) of 90 %. Secondly, precise sizing of the crack dimensions (length and depth) is equally important in order to provide suitable input data for crack assessment. As a viable solution complying with the restrictive conditions of inline inspection, the well-known 45° shear wave method [2] was chosen when the first crack inspection tools were developed [1]. Even though this method has some inherent limitations regarding depth sizing [3], it is still the standard method applied with current ILI tools for crack inspection in liquid pipelines.

2.1 Principle

The principle of the 45° shear wave method is explained in Fig. 1. A piezoelectric transducer generates a longitudinal ultrasonic wave (center frequency ≈ 4 MHz) which propagates through the liquid coupling medium into the pipe wall. The angle of incidence in the medium is selected such that a refracted shear wave is obtained propagating through the wall at an angle of approx. 45°. Using water as a couplant, the angle of incidence is then approx. 18°. If the pulse hits a radial crack a strong reflection is obtained (corner reflection) that is received by the same sensor (pulse-echo method). Depending on the time-of-flight of the crack signal relative to the surface signal one can readily determine whether the crack is internal or external. The received signal is displayed as an A-scan showing the measured reflection amplitudes as a function of time-of-flight or distance (Fig. 1).

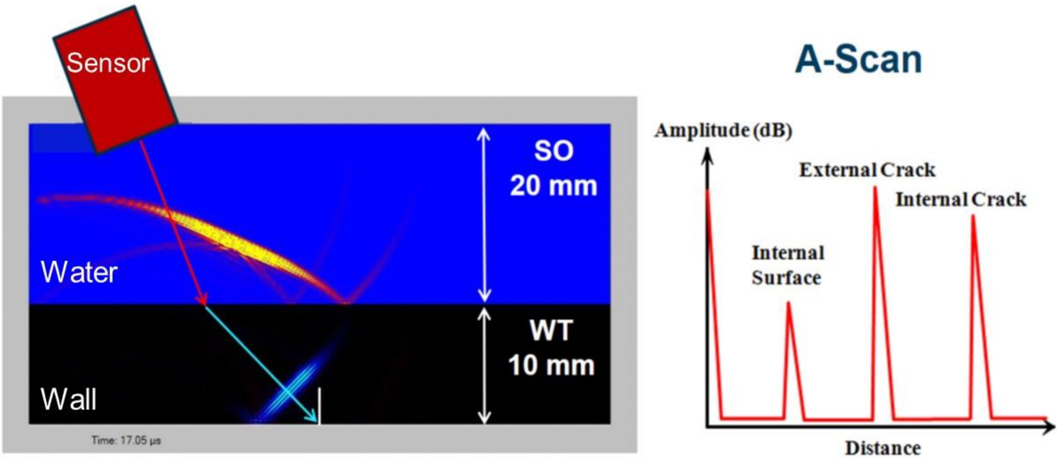

Figure 1: Inspection geometry and A-scan signal (schematic)

The amplitude of the crack signal depends on the propagation angle of the refracted shear wave. The path of the reflected signal includes the refraction from the liquid medium into the wall and vice versa as well as the reflection at the backwall and the reflection at the crack. This sound path is depicted in Fig. 2a together with the result of the calculated reflection amplitude for a (deep) crack as a function of the refraction angle β (Fig. 2b). The calculation is based on the plane wave approximation using formulas given in [2]. Fig. 2b also shows the result of modelling using the finite difference (FD) method. The agreement between both calculations is quite good. Some deviations become noticeable for refraction angles above 60° (dashed line) where the plane wave assumption is limited due to the finite wall thickness.

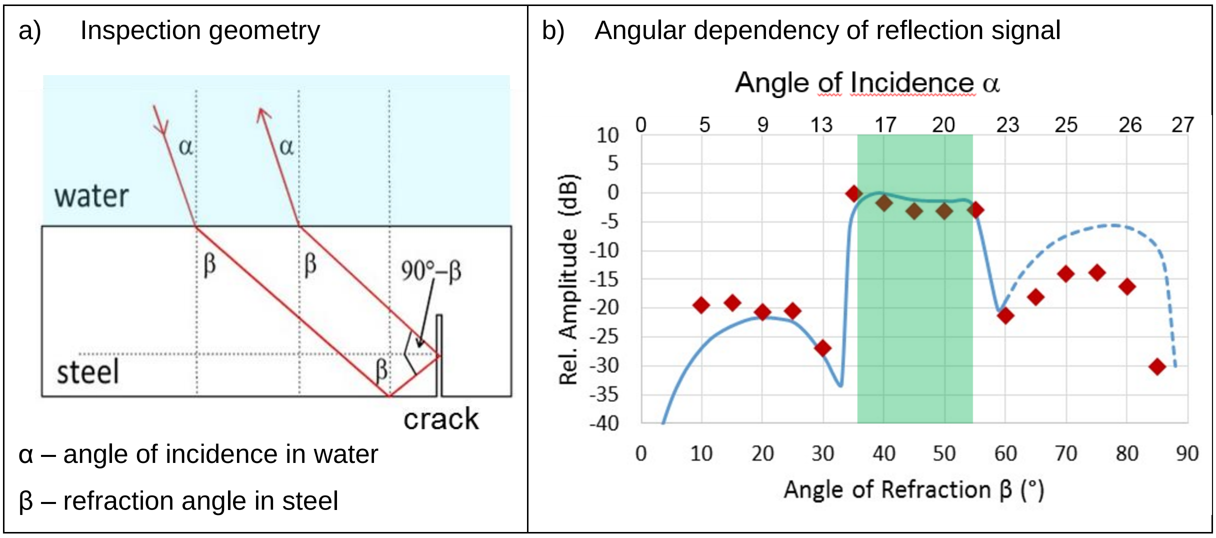

Figure 2: a) Sound path of crack signal b) calculated signal amplitude as a function of refraction angle β for shear wave in steel (blue line: plane wave calculation; red dots: modelling using the finite difference (FD) method)

As can be seen from Fig. 2b, the amplitude of the reflection signal is rather constant within an angle range from approx. 40° to 50°. The amplitude dips around 30° and 60° are caused by the mode conversion from shear wave to longitudinal wave taking place at $\beta \approx 30°$ at the backwall and around $\beta \approx 60°$ (= 90° - 30°) at the crack. Inspection angles outside the angle range indicated in Fig. 2b by the green shading have to be avoided.

2.2 Pipeline Medium

Most liquids transported in pipelines can be used as coupling medium provided that the liquid is free of amounts of gas that might impede ultrasonic propagation. These liquids include most crude oils, products and even liquid gases (e.g. propane or butane). The ultrasonic properties (ultrasonic velocity & attenuation) of the medium need to be known prior to the inspection in order to ensure optimum inspection settings. The ultrasonic velocity in the pipe wall is considered to be constant which is in particular true for ferritic pipeline steels (the velocity of shear waves is normally in the range from 3200 m/s to 3260 m/s). In a standard sensor carrier the angle of incidence is fixed by the mechanical design of the sensor holders. The standard angle of incidence for crack inspection in crude oils is 17°, which can be used for medium speeds from approx. 1200 m/s to 1500 m/s. In contrast, crack inspection e.g. in propane would require an incidence angle of 11° (based on a velocity of 850 m/s) and thus a modified sensor carrier has to be applied. Especially for crack inspection in liquid gases, the dependence of the ultrasonic speed on temperature and pressure needs to be taken into account in order to ensure proper inspection conditions (see section 3.3).

3 RECENT IMPROVEMENTS

The progress of in-line inspection tools is strongly correlated to the progress in electronics, data processing and data storage capacity. Highly integrated electronic components allow for compact size and reduced power consumption at the same time. As a result, an increased number of sensor channels can be accommodated in less space which is in particular important for small diameter tools. In general, the corresponding improvements regarding the quality of the inspection data are:

- Enhanced axial resolution
- Enhanced amplitude resolution and time resolution
- More sensor channels thus providing better circumferential solution
- More parallel processing of receiving channels enabling higher inspection speed

It should be mentioned that also improvements of ultrasonic transducers have taken place over the last two decades. In particular, composite transducers are nowadays applied, which offer an increase of sensitivity by typically more than 10 dB compared to standard piezo-electric transducers when used in a liquid environment.

3.1 Resolution

In general, the resolution of an ultrasonic ILI tool can be described by the following four components:

1. Axial resolution: The axial resolution is defined by the axial distance between two consecutive measurements of the ultrasonic sensors.
2. Circumferential resolution: The circumferential resolution is defined by the circumferential distance between two adjacent ultrasonic sensors. Both, axial & circumferential resolution determine the scanning grid.
3. Sampling frequency of ADC: The sampling frequency determines the resolution of the time-of-flight measurement of ultrasonic indications as well as the maximum amplitude error of the peak amplitude measurement.
4. Sampling depth of ADC: The sampling depth determines the resolution of the amplitude measurement of ultrasonic indications. It also relates to the dynamic amplitude range that can be covered.

Fig. 3 shows the scanning grid for the standard crack inspection UC (Fig. 3a) and for the latest high-resolution version UCx (Fig.3b). Here, the scanning grid is defined by the axial resolution and the circumferential resolution. The ultrasonic shot density is by a factor of four higher for the UCx inspection, which in turn increases the data volume by the same factor. The improvement of the circumferential resolution can also be recognized from the increased sensor density (Fig. 3c,d). Doubling the number of sensors requires considerable efforts on the construction side as the amount of cabling and transmitting channels needs to be doubled as well.

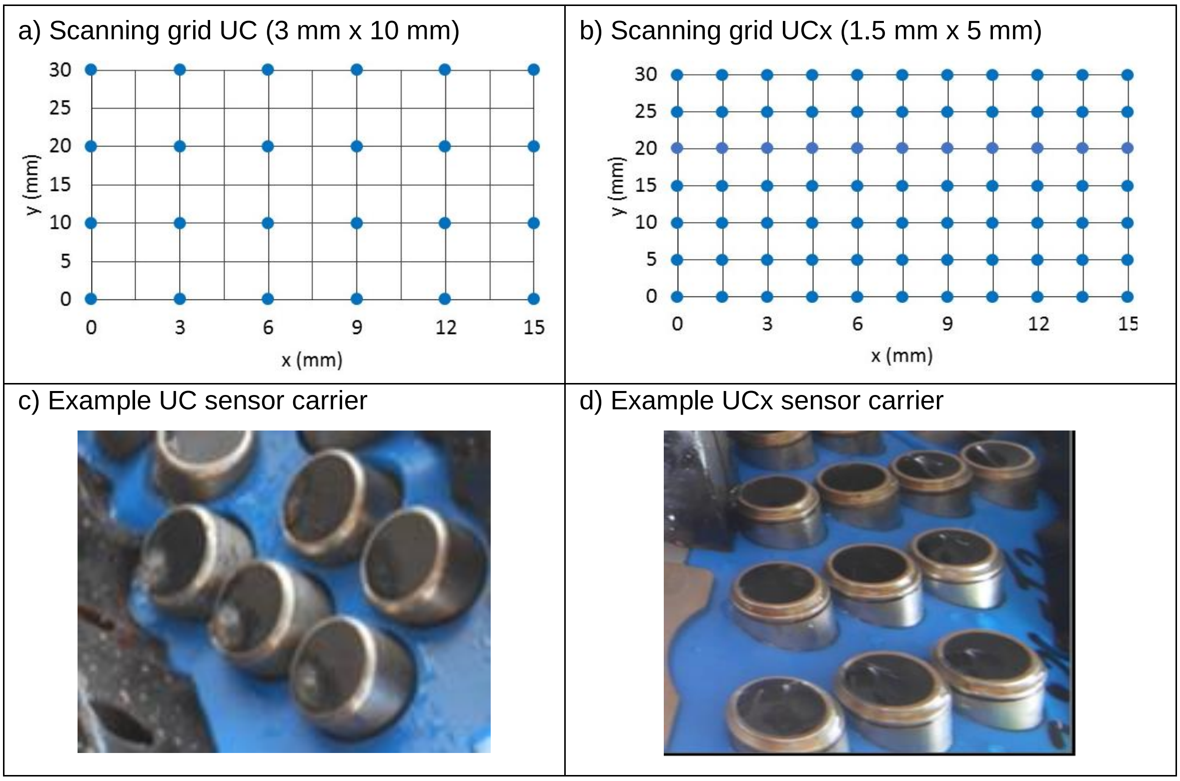

Figure 3: Scanning grid for UC and UCx and corresponding examples of sensor carriers

The higher circumferential resolution also provides a more homogeneous sensitivity distribution over the pipe circumference as illustrated in Fig. 4. Here, the maximum sensitivity drop is reduced from - 6 dB (UC) to approx. -2 dB (UCx). As a result, the measuring error regarding the maximum reflection amplitude from a crack is reduced.

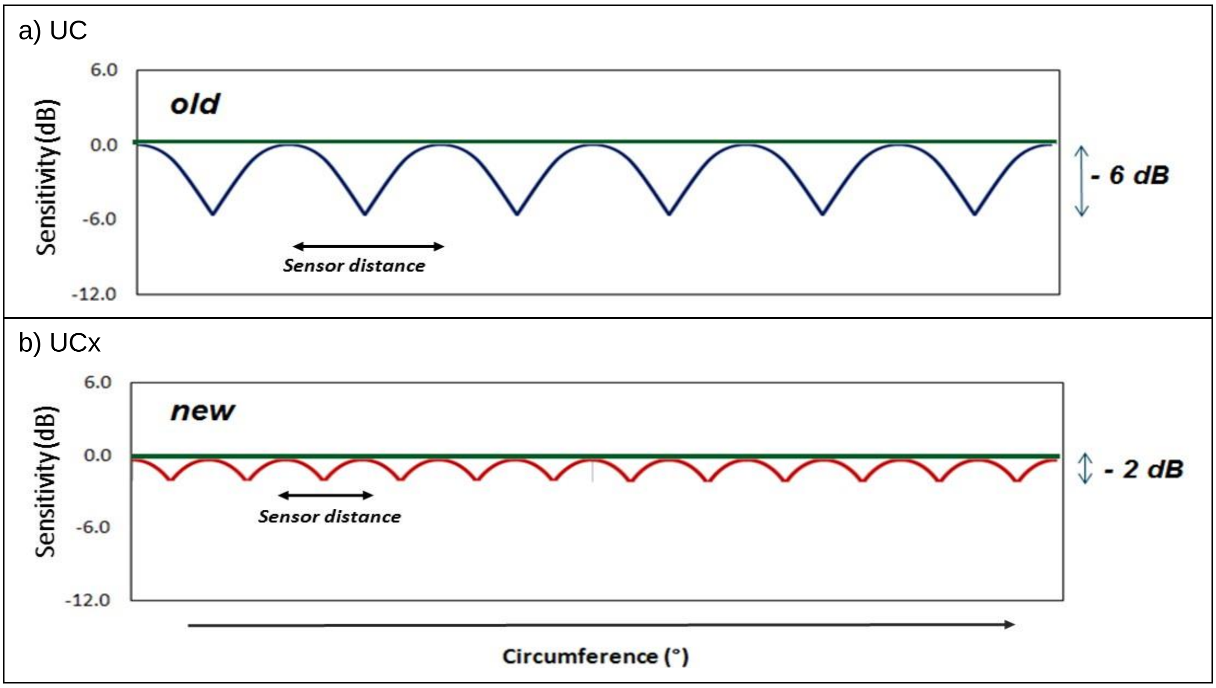

Figure 4: Improvement of circumferential sensitivity for axial crack inspection

The advantage of the increased sensor density is demonstrated in Fig. 5 showing B-scans from a crack-like anomaly located at the longitudinal weld as recorded during two different inspections. Using standard resolution UC the anomaly is picked up by three sensors while the same anomaly is detected by six sensors when the UCx resolution is used. The improved resolution not only ensures a higher POD but also provides more detailed information allowing for better signal classification as well as for more accurate sizing.

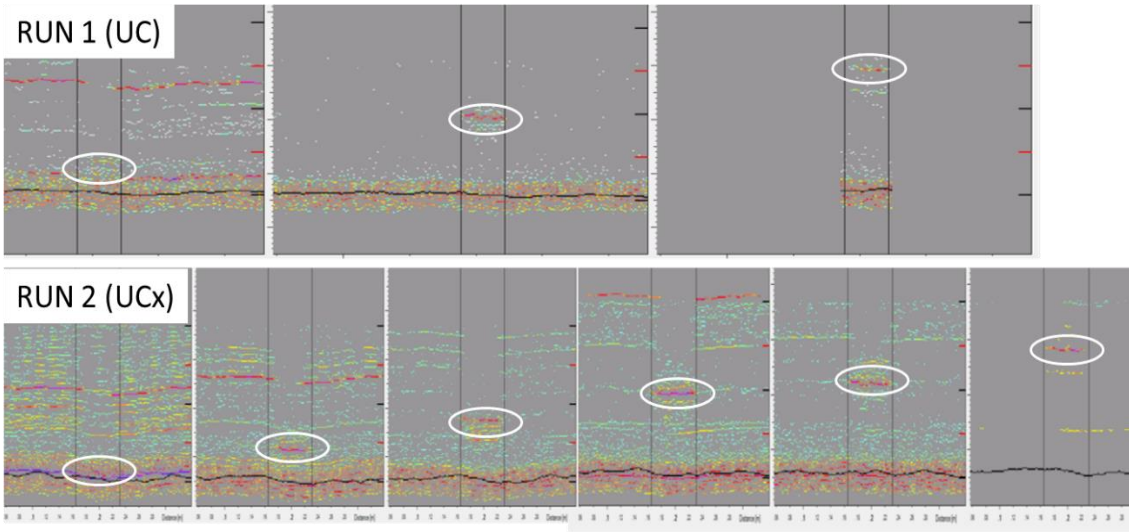

Figure 5: B-scans from two different inspections showing indications from a crack-like reflector located at the longidudinal weld: run 1 (UC) – 3 sensors; run 2 (UCx) – 6 sensors

Fig. 6 shows a result from a special inspection that was carried out in a gas pipeline by running the tool in a water batch. Here, the inspection task was to find in particular very short stress corrosion cracking (SCC) located near the girth weld. The minimum crack length to be detected was 20 mm, which was achieved by appropriate settings of the detection criteria together with an axial resolution of 1.5 mm. The example shows a single crack starting next to the girth weld. Here, the verified length was 20 mm and the depth was already 5.2 mm.

a) .Axial SCC at girth weld

b) B-scan showing crack indication

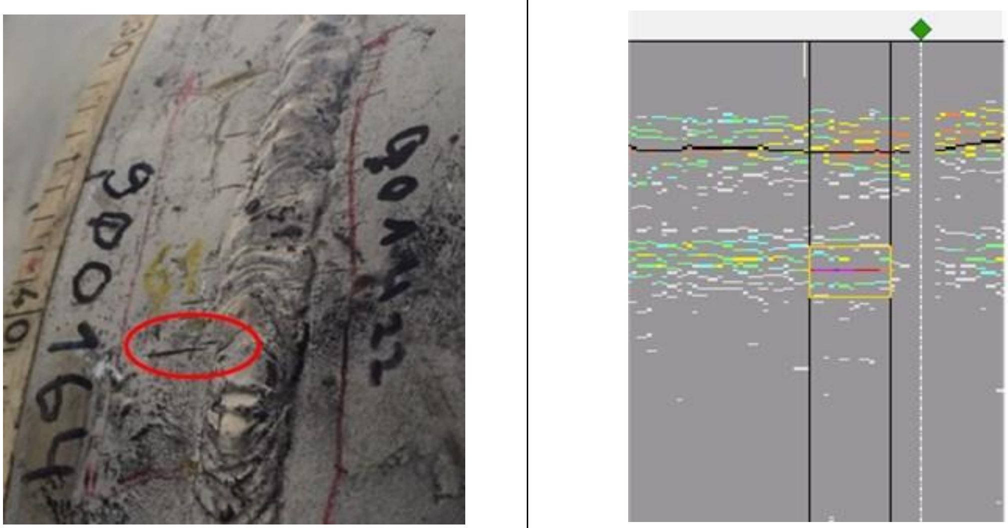

Figure 6: Axial SCC near girth weld (length: 20 mm, depth: 5.2 mm) and corresponding B-scan.

Table 1 summarizes some characteristics indicating the improvement of the inspection resolution from the first tool generation to the latest tool generation.

Table 1: Improvement of resolution characteristics for crack inspection

Variable	First Generation	Latest Generation
Axial resolution (mm)	3 (1.5 opt.)	1.5 (0.75 opt.)
Circ. resolution (mm)	10	5
Sampling frequency (MHz)	40	80
Time resolution (ns)	25	12.5
Max. amplitude error (dB)	1	0.2
Sampling depth (bit)	8	14
Dynamic range (dB)	60*	78**

*using logarithmic amplifier **using one bit for sign

3.2 Inspection Speed

The relationship between axial resolution a_R and the maximum inspection speed that is acceptable to ensure a specified axial resolution is given by the relation

$$v_{max} = a_R / (N_m * t_{us})$$

with:

v_{max} – max inspection speed at given resolution a_R

N_m – no. of multiplexed ultrasonic receiving channels / unit,

t_{us} – time window for recording a single A-scan.

As the time window to record the ultrasonic signal is more or less fixed (typically 60 µs to 100 µs), the main option to increase the maximum inspection speed for a given axial resolution is to parallelize the data processing on the receiving side; i.e., to reduce the number N_m of multiplexed channels. The corresponding design is implemented in NDT Global's new EVO Series 1.0 electronics. Compared to the old design the new design allows for an increase of inspection speed by a factor of up to four depending on the total number of sensors used. Consequently, the high resolution tools can now be operated at inspection speeds that in most cases do not require the pipeline operator to reduce the pumping speed and thus the throughput of his pipeline.

Table 2: Maximum inspection speed obtained with EVO Series 1.0 as depending on axial resolution for axial crack inspection UC and UCx and circumferential crack inspection (UCc); old values shown in brackets.

Type of Inspection	Axial Resolution (mm)	Max. Inspection Speed (m/s)
Axial cracks (UC)	3.0 1.5	4.0 (1.6) 2.0 (0.8)
Axial cracks (UCx)	3.0 1.5	2.0 1.0
Circ. cracks (UCc)	1.5	2.0 (0.8)

3.3 Medium Properties

Ultrasonic ILI requires a liquid couplant, which is usually provided by the pipeline medium itself (crude oil, products etc.). The ultrasonic properties of the medium (ultrasonic velocity, ultrasonic attenuation) need to be known prior to inspection in order to ensure optimized tool settings. During an inspection, these properties used to be treated as constant in the past although it is known that there is some temperature & pressure dependency. However, knowing these dependencies allows for reducing uncertainties in the inspection data otherwise ignored.

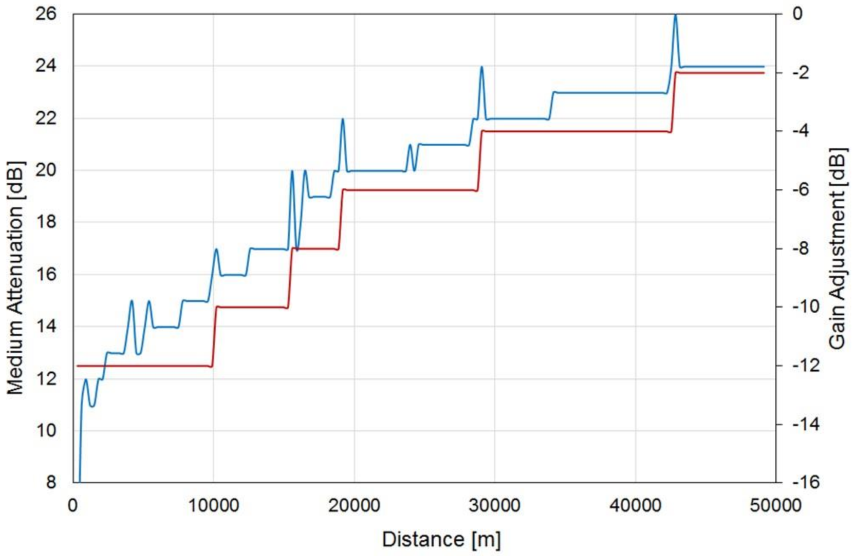

Figure 7: Change of medium attenuation during inspection run (blue line); the resulting amplitude change is compensated by proper gain adjustment (red line).

In order to monitor the medium properties during an inspection run the new generation of inspection tools are equipped with reference sensors. These sensors together with attached reference reflectors are immersed into the liquid medium allowing for a continuous recording of its ultrasonic velocity and attenuation. Based on this data, the saturation amplitude used for crack depth sizing can be corrected, if necessary. An example is shown in Fig. 7. In this case, the medium attenuation has changed during the inspection by an (unusual) amount of approx. 12 dB caused by larger temperature and pressure variations. The change in attenuation was compensated in real time by an automated gain adjustment (see Fig. 7). One of the benefits of this improvement is the fact that the same saturation amplitude required for the depth sizing of crack-like indications is readily available for data analysis without further post-processing of the data. Furthermore, the automatic gain control prevents the risk of degraded data quality due to a loss of inspection sensitivity caused by increasing medium attenuation during an inspection.

3.4 Enhanced Depth Sizing

The determination of the crack depth from ILI data mainly relies on the recorded amplitudes from the corner reflection (see Fig. 1). The typical amplitude behavior of the corner reflection as a function of crack depth is shown in Fig. 8 where the inspection geometry is similar to the situation illustrated in Fig.1, i.e., using EDM notches in a plate and water as coupling medium.

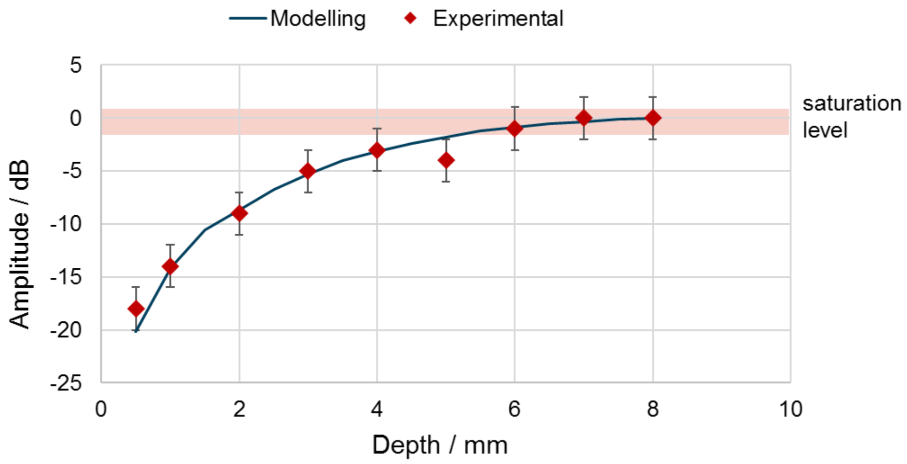

Figure 8: Amplitude of corner reflection as a function of crack depth for external cracks (EDM notches in plate with 10 mm wall thickness; transducer diameter 15 mm)

The measured dependency is very well reproduced by the 2D - FD modelling results also shown in Fig. 8. In the depth range between 1 mm and approx. 4 mm an amplitude change of about 10 dB is noticed. For depths larger than 4 mm the amplitude of the reflection signal levels off approaching a saturation level. The actual shape of such an amplitude vs. depth relation depends on properties of the ultrasonic probe (e.g. diameter) as well as on diameter and wall thickness of the pipe. In order to size crack indications detected by ILI, the saturation level and the actual depth dependency need to be known. Then, a depth can be recalculated from the measured amplitudes at least in the depth-sensitive range below 4 mm. As the deeper cracks, however, are most relevant for safe pipeline operation, it is of utmost importance that such cracks shall be detected with highest priority by in-line crack inspection. One of the characteristics of ultrasonic pulse-echo inspection that is in particular sensitive to deeper cracks is related to the reflection taking place via the wall side opposite to the crack. In contrast to the direct corner reflection, we refer to this echo in the following by the acronym ICE (indirect crack echo).

The approach of using this type of signal is explained in Fig. 9 assuming an external crack. If the crack is located at the half skip distance, the usual corner echo is obtained (see Fig. 1). The ICE signal becomes visible at the full skip distance when the crack is extending into the sound beam (Fig. 9a).

a) Principle of indirect crack echo (ICE)

b) Signal amplitude vs. crack depth (modelling results, wt = 10 mm)

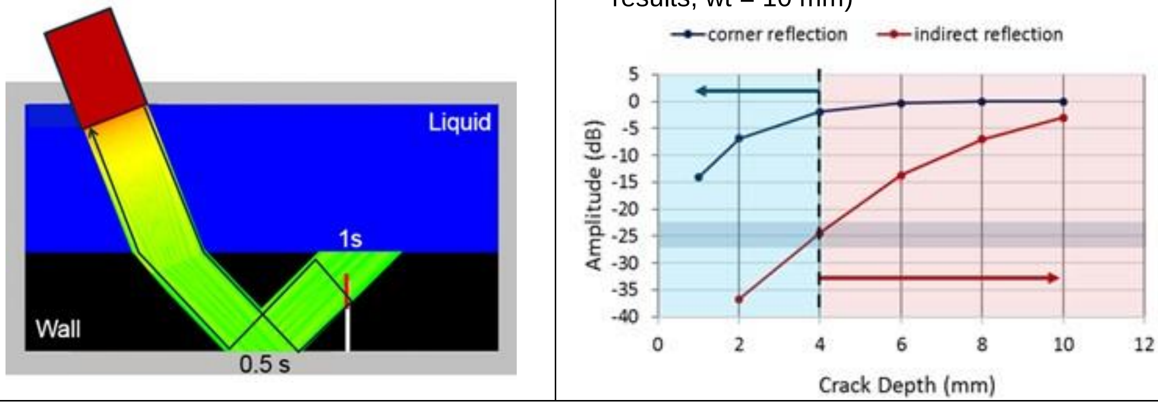

Figure 9: a) Explanation of the indirect crack echo (ICE) b) ICE amplitude as a function of crack depth (echo amplitude from corner reflection for comparison)

The modelling results for the amplitude of this signal are shown in Fig. 9b using a wt of 10 mm and a probe diameter of 15 mm. At a sensitivity level of approx. - 20 dB, the ICE becomes visible for depths above approx. 4 mm. The amplitude of the corner reflection is shown for comparison. While the corner reflection is sensitive in the depth range below 4 mm, the ICE is sensitive over the depth range from 4 mm to 10 mm thus covering in particular the range where the corner echo is saturated. It should be mentioned that the practical applicability of the ICE is subject to certain constraints regarding transducer diameter D, wall thickness wt and a sensitivity related minimum crack depth d_{min}.

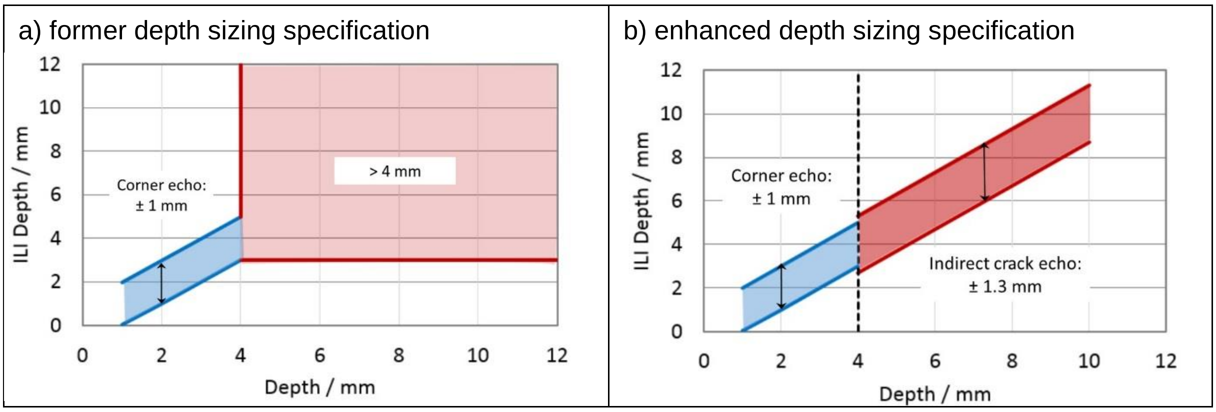

Figure 10: Old (a) and new (b) specification range for crack depth sizing

By exploiting the amplitude of the ICE signal, the range of crack depth sizing can be extended over the full wall thickness (wt) where the covered wt range is mainly depending on the probe diameter. This new approach was verified by modelling studies as well as by comprehensive experimental work including a variety of different pipe diameters and wall thicknesses [3]. As a result, a tolerance of ± 1.3 mm at a certainty of 80 % was determined (Fig. 10b). Compared to the old sizing specification (Fig. 10a), where the depth range is limited to the saturation depth of approx. 4 mm, the enhanced sizing approach represents a major step forward regarding the reliability of inline crack inspection.

The enhanced sizing was applied using inspection data from a blind test performed earlier [4]. The test pipeline contained a large set of fatigue cracks which were generated at the circumferential side of welded-on anode pads. Such anode pads are used for corrosion protection e.g. in offshore flowlines. The test pipeline was inspected by a tethered tool equipped with standard UCc technology for crack detection and with a TOFD unit for precise crack depth measurement [4]. The true depth of the fatigue cracks was verified afterwards by destructive examination. A typical example of this type of fatigue crack is depicted in Fig. 11a showing the surface indication as well as the cross section of a 62 % deep crack as determined by destructive testing. The ultrasonic B-scan recorded for this crack including the amplitude dynamics of the reflection signals are illustrated in Fig. 11b.

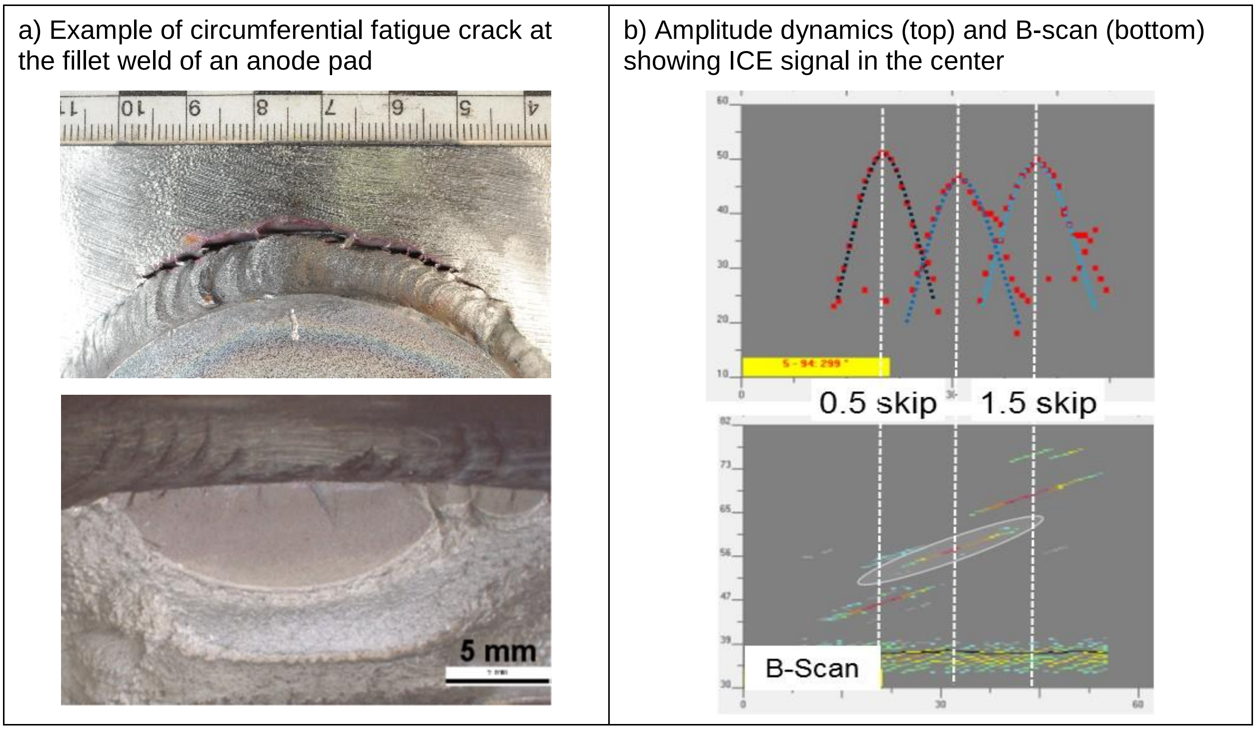

Figure 11: Example of fatigue crack showing surface indication and cross section (a) and ultrasonic B-scan (b) with corner echoes and ICE indication in the center

The ICE signal could be identified for 13 cracks (out of 14) having a depth above approx. 30 % wt at a wall thickness of 12.9 mm. One crack with a verified depth of 36 % wt did not exhibit an ICE signal. The reason was probably that this crack had an intermittent shape where the length of the deeper section was below the specified minimum length of 20 mm. Based on the modelling result presented in Fig. 9b, the crack depths were determined from the maximum amplitude of the ICE signal. The results are shown in Fig. 12 together with the TOFD results. All the depth values determined by this procedure are lying within a tolerance band of ± 10% wt, which is in agreement with the specified tolerance of ± 1.3 mm (see Fig. 10b).

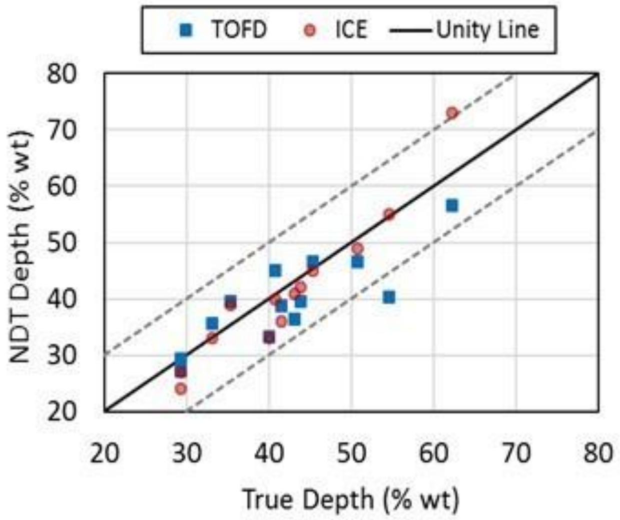

Figure 12: Unity plot showing results of crack depth sizing using the ICE amplitudes. Results from earlier TOFD measurements [4] are shown for comparison.

4 PERFORMANCE SPECIFICATION

The performance specification for ultrasonic crack inspection is indicated in Table 3 comparing some actual characteristics with the preceding ones. In particular, the minimum crack length for UC inspection has been reduced and the enhanced depth sizing has been introduced (see section 3.4).

Table 3: Excerpt of performance specification for crack inspection (old values in brackets)

	Axial Inspection (UC)	Circ. Inspection (UCc)
Min. Crack Length* @ 90 % POD • *Axial Resolution 1.5 mm* • *Axial Resolution 3.0 mm*	 20 mm (30 mm) 25 mm (30 mm)	 30 mm /
Min. Crack Depth @ 90 % POD • *Base Material & at Weld* • *in Weld*	 1.0 mm 2.0 mm	
Length Sizing @ 90 % Certainty	± 10 mm	± 15 mm
Depth Sizing @ 80 % Certainty • *Depth range 1 mm – 4 mm* • *Depth range > 4 mm*	 ± 1.0 mm ± 1.3 mm (new)	

*smaller length optional

5 SUMMARY

Ultrasonic crack detection has become one of the standard applications for the inspection of liquid pipelines. Today, inspection tools are available that allow for the reliable inspection of most crack issues present in pipelines including in particular axial cracking but also circumferential cracking.

Although the inspection technology itself, which is based on using 45° shear waves, is still the same as used in the first tool generation, the technical progress achieved by a variety of new developments is remarkable from many perspectives. The main improvements coming with the latest crack tool generation and the related benefits are summarized in Table 4. Further improvements are already available today by combining more than one inspection technology in one tool (e.g. crack inspection & metal loss inspection). Future progress of inline crack inspection will address the implementation of additional testing modes to reduce current uncertainties that may affect POD, POI and sizing.

Table 4: Latest technical improvements of inline crack inspection and related benefits

Improvement	Benefit
Enhanced axial resolution	• More detailed crack profiles • Smaller minimum crack length
Enhanced circumferential resolution	• Increased POD & POI • Reduced risk of incomplete coverage • More accurate maximum reflection amplitude
Higher signal dynamics	• Wider range of medium attenuation • Better sensitivity & signal quality
Increased inspection speed	• Reduced costs by avoiding loss of throughput during inspection run • Less operational interference
Enhanced depth sizing	• Full wall coverage of crack depths • More accurate and less conservative crack assessment • Reduction of excavation costs
Online monitoring of medium properties	• Reduced risk of failed run due to change of medium properties during inspection • Better data quality by adaptive signal gain

6 ACKNOWLEDGMENT

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