DEFINING DEPTH SIZING PERFORMANCE

Abdullahi Atto, Lukas Klinge, and Stefan Bauer, ROSEN Group, Germany, offer an introduction to the extended depth sizing of UT crack inspection and show the performance validation.

The depth sizing of the ultrasound crack detection (UTCD) is generally based on the signal amplitude of the ultrasound echo reflected by the linear anomaly in the pipe wall and received back by the transducer (pulse-echo technique). The larger the reflecting anomaly surface (depth), the stronger the received signal.

Conventional UTCD depth sizing was originally based on depth classes and only limited to up to 4 mm depth because of the direct corner-echo signal saturation. Anomalies with a signal amplitude saturation were classified as 'depth ≥ 4 mm' without discrete depth sizing.

Recently, the UTCD technology has been further improved, especially regarding depth sizing. An 'extended depth sizing' approach using an indirect echo allows continuous depth sizing for anomalies above 4 mm depth.

The extended depth sizing for crack-like anomalies, has been made available recently for large diameter ILI tools. For small diameter pipelines (OD ≤ 12 in.) additional challenges to the measurement performance had to be considered and addressed by the inspection tool design, before an extended depth sizing can be provided in a robust and reliable manner.

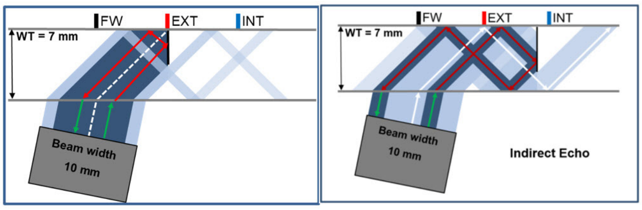

Figure 1. Sketch showing the specular shear wave reflection angles of direct (left) and indirect echo (right).

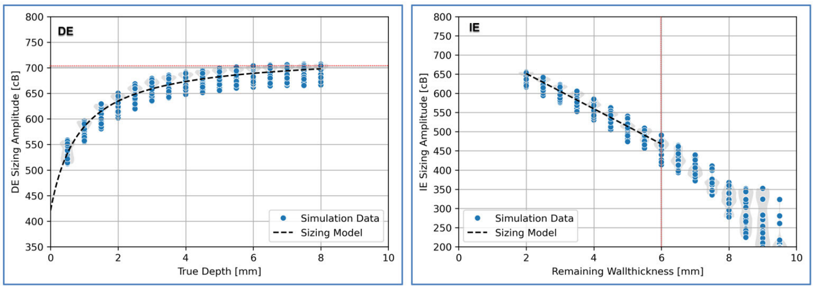

Figure 2. The DE amplitude distribution (left) shows an amplitude saturation level (about 70 dB) for anomalies above 4 mm depth. The IE amplitude distribution (right) shows an amplitude saturation and a linear correlation between amplitudes and depths for anomalies with a remaining WT of up to 6 mm.

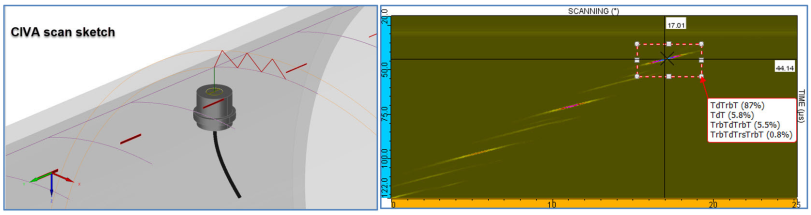

Figure 3. CIVATM simulation sketch of UTCD pipe measurement (left) and B-scan of the measurement data (right).

Extended depth sizing

The conventional UTCD depth sizing uses corner echo directly reflected over the closest pipe wall surface. The direct corner echo is usually the strongest signal and can be easily and robustly identified in the gathered data. The deeper the anomaly the stronger the 'direct echo' (DE) – but only up to a certain amplitude saturation level. Therefore, depth sizing based on DE cannot be applied to anomalies deeper than 4 mm.

A deeper part of a linear anomaly can indirectly reflect a part of the shear wave beam over the pipe surface opposite to the anomaly wall surface. External anomalies reflect the indirect echo over the internal wall surface whereas internal anomalies reflect IE over the external surface. The shear wave reflection over the opposite pipe wall surface is designated as 'indirect echo' (IE).

The deeper an anomaly and the smaller the remaining wall thickness (WT), the stronger the indirect echo. Hence, the depth of anomalies deeper than 4 mm can be discretely sized according to IE amplitudes.

IE amplitudes are generally weaker than DE and cannot reach the amplitude saturation threshold. See Figure 1 for an illustration of DE and IE.

The UTCD extended depth sizing is based on a combination of DE and IE amplitudes (see Figure 2):

- Linear anomalies with a depth of up to 2 mm can only be sized by DE.
- Linear anomalies with a depth between 2 mm and 4 mm can be sized by both DE and IE.
- Linear anomalies with depths above 4 mm can only be sized by indirect echo approach (IE).
- Indirect echo sizing can be reliably applied if the anomaly remaining WT is not larger than 6 mm.

Performance qualification

According to API 1163, the UTCD performance qualification applies a comprehensive approach consisting of four stages for each of the included pipeline diameters:[1]

- UT simulation is based on the essential variables of the UTCD tool and operational conditions.
- Laboratory measurement of pipe coupons with test anomalies by applying ILI tool components.
- Full-scale pump test consisting of repetitive UTCD runs in a test loop with a large test population.
- Recent and future field validation results will also be added to the performance qualification.

UT simulation

CIVA^{TM} is a renowned simulation, processing, and analysis software for non-destructive testing (NDT). It is widely used in different industries for research, design, and qualification studies.

ROSEN applied UT simulation during the development phase for design, improvements, and comparison of different measurement system configurations. The simulation results are compared to and qualified with the results of high-resolution laboratory measurements applying the ILI tool components and configurations.

UT simulation is also applied for the performance qualification process:

Table 1. Overview of the test anomaly populations and number of test runs per pipeline diameter

Nominal OD (in.)	Number of notches			Number of test runs	Total of anomalies in features lists
	External	Internal	Total		
6	453	450	903	24	21672
8	817	532	1349	24	32376
10	202	200	402	12	4824
12	100	100	200	12	2400
	1572	1282	2854	72	61272

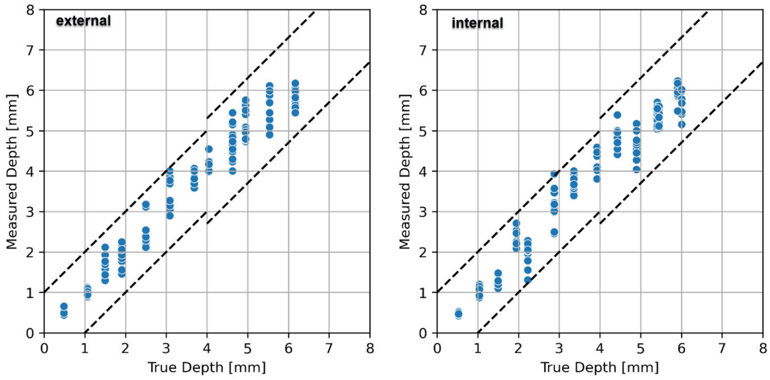

Figure 4. Unity Plots of the 6 in. UT-C performance qualification with extended depth sizing (full scale pump test).

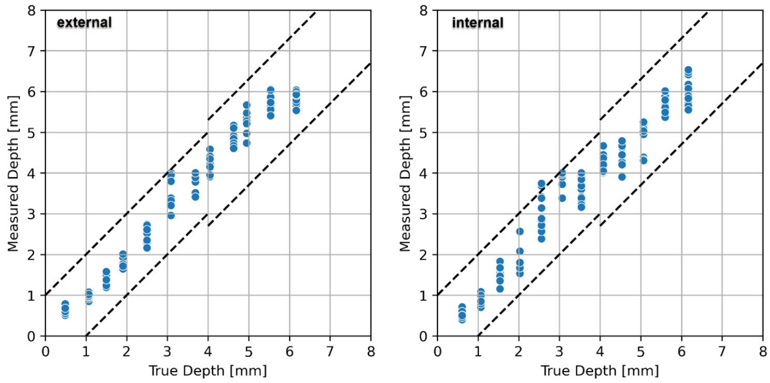

Figure 5. Unity Plots of the 8 in. UT-C performance qualification with extended depth sizing (full scale pump test).

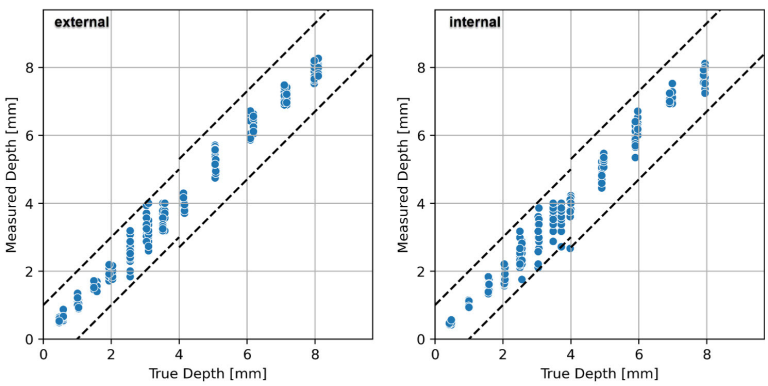

Figure 6. Unity Plots of the 10 in. UT-C performance qualification with extended depth sizing (full scale pump test).

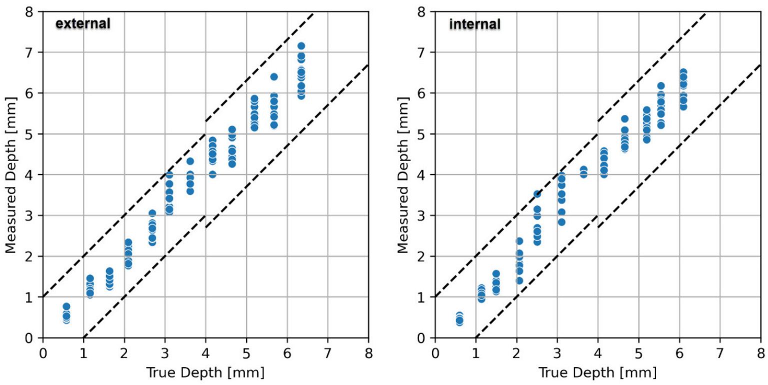

Figure 7. Unity Plots of the 12 in. UT-C performance qualification with extended depth sizing (full scale pump test).

- The configuration of the UTCD measurement system and the main pipe parameters are configured in the simulation.
- Dimensions and shapes of the test anomalies are configured for the pump test spools.
- A novel approach of an ILI tool-like data sampling method is used for the UT simulation so that the gathered data corresponds to the resolution of a random UTCD inspection or pump test run.

The depth sizing model based on the CIVA simulation results and qualified through corresponding laboratory tests is applied to the performance qualification process of the pump tests. For each pipeline diameter and WT, the UT simulation data is used to train the depth sizing model, and the pump test results are used as test data for the performance qualification process.

This qualification approach has the main advantage of avoiding a bias occurring if the same pump test data is used for both sizing model training and testing the performance qualification. Eventual deviations of individual test anomalies and irregular pipe geometries of some test spools will also not influence the depth sizing model.

Full scale UTCD pump test

To create a representative database for each pipeline diameter, one or two full-scale pump test series, each consisting of twelve repetitive UTCD runs, are performed in a test loop with a large population of linear test anomalies:

- Test spools with nominal WTs between 4 mm and 13 mm are used for each pipeline diameter.
- As linear test anomalies, notches with a depth of 0.5 mm to 80% of the nominal WT are manufactured into the external and internal surfaces of both pipe body and longitudinal seam welds.
- The verified anomaly dimensions are used for the comparison with the ILI anomaly dimensions measured by the UT-C tools for the purpose of performance assessment.

Table 1 shows an overview of the test anomaly populations and the number of test runs for each pipeline diameter from 6 - 12 in.

After data processing and the related data quality check, the pump tests were deemed as successful. The gathered inspection data of the pump test runs were handed over to the data analysis team. Since the data analysis team had no information about the actual/design dimensions of the test anomalies, ‘blind’ data analysis was performed as follows:

- An ‘automated feature search’ (AFS) was applied to the inspection data to create ‘feature boxes’.
- The data analysis team classified each feature and checked the amplitude values and lengths.
- A senior data analyst performed a quality assessment and validated the analysis results.

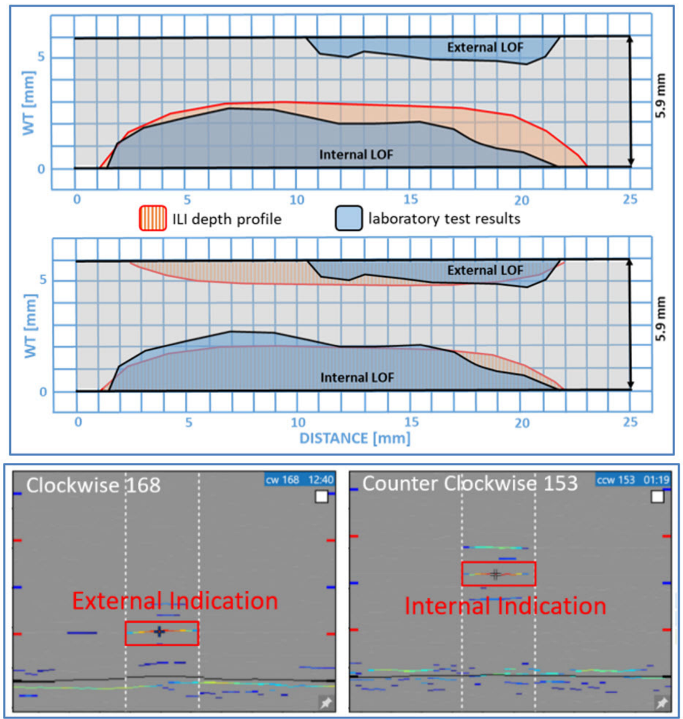

Figure 8. **Comparison of depth profile of stacked LOF between UT-C inspection data and destructive metallurgical test.**

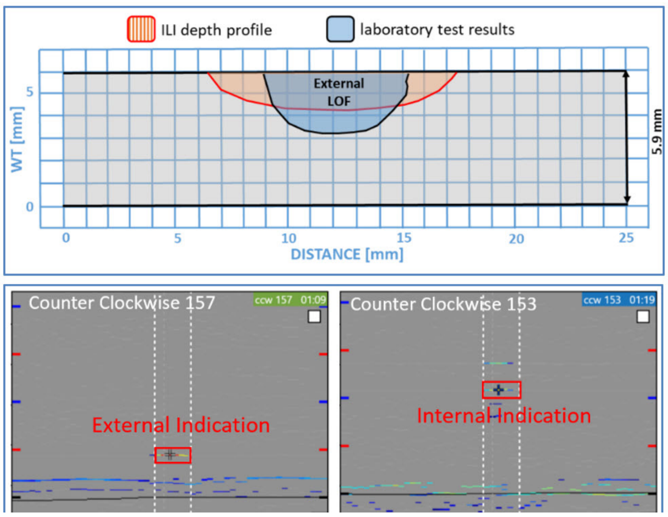

Figure 9. **Comparison of depth profile of stacked LOF between UT-C inspection data and destructive metallurgical test.**

The final feature lists have been handed over to a different analysis team to correlate the ILI results with the actual test anomaly dimensions and to assess the performance capabilities.

Performance qualification of extended depth sizing

An extended depth sizing based on both DE and IE amplitudes was applied for the performance qualification of small diameter UT-C tools (6 - 12 in.) based on a full-scale pump test.

The results of the performance qualification can be summarised as follows:

- All linear test anomalies with a length ≥ 20 mm and a depth ≥ 1.0 mm were detected by the ILI tools and identified during the data analysis. Additionally, more than 95% of the test anomalies with dimensions below the specified detection thresholds were also detected (depths below 1 mm, lengths below 20 mm).
- Depth sizing accuracy ≤ 1.0 mm is calculated for test anomalies of up to 4 mm depth.
- Depth sizing accuracy ≤ 1.3 mm is calculated for test anomalies with depths above 4 mm.
- The extended depth sizing is only valid for anomalies with a remaining WT of up to 6 mm.

Confidence levels significantly above 90% were calculated for POD and depth sizing accuracies.

Figures 4 to Figure 7 show the results of the full-scale performance qualification pump tests as depth unity plots of 6, 8, 10, and 12 in. UT-C tools.

Field validation

The new generation of UTCD small diameter tools with 5 mm circumferential resolution was recently introduced. Therefore, only a limited number of field validation results are meanwhile available. Results of two field validation measurements of lack of fusion (LOF) in ERW longitudinal seam weld are included as examples in this article.

The reported flaws were detected during a baseline survey of an 8 in. pipeline of a nom WT = 5.9 mm. The anomaly locations were first verified in the field and then cut out for destructive testing and laboratory measurement. The destructive testing with anomaly profile measurement has accurately revealed the actual length and depth profile of the anomalies. Two of the three verified anomalies have lengths significantly shorter than the specified minimum length threshold of 20 mm.

The first reported anomaly consists of two overlapping stacked LOF anomalies at the external and internal pipe surfaces. The pair of stacked LOF anomalies are identified by the UT-C data analysis and reported as one internal anomaly (Figure 8):

- The similarity in length and profile between the main internal signal and the overlapping external signal suggests that the external indication would be an indirect echo caused by the internal anomaly. Therefore, the anomaly was reported as 3.1 mm deep to the indirect echo sizing.

- The destructive testing has revealed that the major anomaly is at the internal pipe surface and has a length of 18.9 mm and a peak depth of 2.85 mm. The minor part of the stacked LOF is at the external surface and has a length of only 11.5 mm and a peak depth of 1.2 mm.

The second validated anomaly is significantly shorter than the specified minimum length for detection and sizing of the UT-C Performance Specification. The anomaly has been reported as 1.9 mm deep (DE sizing) and 11 mm long. The destructive testing revealed a length of only 6.2 mm long with a peak depth of 2.8 mm.

Conclusion

As part of the extended depth sizing to apply discrete depth sizing to linear anomalies deeper than 4 mm, ROSEN has implemented further improvements of the essential variables influencing the depth sizing performance of small diameter UTCD tools:

- UTCD transducers are optimised/tailored for the specific challenges of small diameter pipelines and implemented to UT-C tools of 6 - 12 in. nominal OD.
- Circumferential resolution of the small diameter UT-C tools is enhanced from 7 - 5 mm sensor spacing.
- Depth sizing methodology is improved with the application of CIVA modelling and lab testing.
- A detailed full-scale pump test with a large population of test anomalies is performed to validate and qualify the UTCD performance specification.

Extensive performance qualification tests have proven a clear improvement in the reliability and accuracy of the UTCD depth sizing in general and particularly in small-diameter UT-C tools.

References

1. API, In-line Inspection Systems Qualification, API STANDARD 1163, 3rd Edition, September 2021.
2. ATTO, ABDULLAHI et al., 'Continuous Depth Sizing of ILI Ultrasonic Crack', International Pipeline Conference Sep 2016, Calgary, Paper IPC2016-64409, 2016.
3. POF, Specifications and Requirements for In-line Inspection of Pipelines, Standard Practice POF 100, November 2021.