Corrosion Growth Analysis - Case Study of MFL-UT Combined inspection

Johannes Palmer, Rosen Technology and Research Center, Lingen, Germany
Thomas Hennig, Rosen Technology and Research Center, Lingen, Germany

Abstract

ROSEN offers a combined inline inspection (ILI) service for Magnetic Flux Leakage (MFL) methodology and the Ultrasonic Testing (UT) with one inspection tool. These two methodologically independent measurements with one ILI run enable to supply a combined inspection service with many operational and qualitative benefits.

The case study presented is based on a representative amount of high quality field verifications, covering a well defined time interval with repeated ILI measurements. This allows to quantitatively analyze the advantages of the combination also in regards to corrosion growth.

The paper will show the enormous benefits of the combination of the robust, indirect MFL and direct UT technology ILI tool. The intelligent interpretative combination of the two ILI information sources exceeds significantly the straight forward statistical combination benefit. The presented approach demonstrates how to identify features not suitable to UT stand alone sizing and how to compensate systematic errors from MFL sizing models. The most efficient method combines for depth sizing the UT shape information with the MFL amplitude, because of its high repeatability. This approach reduces the subsequent sizing tolerance to values, which allow the identification of hot spots and the corrosion prediction based on even short term repeated ILI intervals. Also the MFL/UT combination makes obsolete to rerun similar tools, because systematic errors can be compensated absolutely.

Applied to the identified group of pinholes and embedded pinholes with an average maximum depth of more than 50% the method delivered a depth sizing accuracy in the order of the field verification itself. Such accuracy allows for both the equivalent shortening of the re-inspection intervals and also for the prolongation of the validity of prediction.

The presented combination of the two independent ILI methodologies bears significant useful potential to approach aggressive corrosion mechanisms, e.g. microbial corrosion or CP shielding.

1. Introduction

The pipeline operator experience with Inline Inspection (ILI) techniques increases continuously as their knowledge does about their pipelines condition. As a consequence it becomes more and more evident that the optimization of inspection strategies and methods with regard to specific pipeline problems can have benefit even at higher inspection expenses. More sophisticated ILI systems requiring specialist data analysis become justified for equivalent pipeline use cases. In this context the combination of methodologically independent measurement systems is established increasingly. Where applied to the same type of anomalies
(typically metal loss) the straight forward statistical combination benefit can be exceeded significantly with the intelligent interpretative combination of the two ILI information sources. Interactive semi automated processes allow for sizing accuracy which exceeds the contributing ILI methods significantly.

The combination of the robust, indirect Magnetic Flux Leakage (MFL) methodology with the direct Ultrasonic Testing (UT) ILI tool has well established advantages in this sense (T. Beuker et. al., 2007). The paper will show these basic principles in practice to make plausible the enormous benefits enabling to identify and quantify individual hot spots even of pinhole size.

1.1 Exemplary Test Population of Case Study

The study derives individual spot corrosion growth rates on a concrete, but anonymous case analysis, consisting of 74 corrosion features, which were all thoroughly dig verified.

2. MFL-UT Combination Benefits

Figure 0 – combined MFL-UT pig (RoCorr·MFL/UT®)

The described advantages of two complementary information sources come along without significant disadvantages in the operational behavior: Still a one run set up is regularly achievable. Figure 0 shows a 16” combined UT-MFL pig (RoCorr·MFL/UT®).

2.1 Simple straight forward measurement value combination

The combined probability of detection P can be calculated from the performance of the contributing systems.

Equation 1: Probability of detection P for UT-MFL combined

\[ P_{combined} = 1 - (1 - P_{UT}) \times (1 - P_{MFL}) \]
Individual system performances e.g. of 80% and 80% result in a combined of 96%. Even for specific geometries, where one technology may be significantly stronger, the other still will improve the overall detection performance.

The combined sizing tolerance δ can be calculated for two systems with individual tolerance values according to:

**Equation 2: Sizing tolerance δ for UT-MFL combined**

\[
\delta_{combined} = \frac{1}{2} \sqrt{\delta_{UT}^2 + \delta_{MFL}^2}
\]

This directly require for the simple result value combination the two tolerances deviating up to a certain limit.

**Equation 3: Tolerance combination improvement condition**

\[
\sqrt{3} \cdot \min(\delta_{UT}, \delta_{MFL}) > \max(\delta_{UT}, \delta_{MFL}) \Rightarrow \delta_{combined} < \min(\delta_{UT}, \delta_{MFL})
\]

E.g. assuming depth accuracies of ±0.5mm for a UT system in 6.35mm wall and ±10% for the MFL satisfies the criterion of Equation 3 and delivers according to Equation 2 for the average of the two depth values an accuracy ±0.4mm.

It is evident that even the simple independent final result table combination bears benefits, but these are clearly exceeded by more intelligent approaches, as shown below.

### 2.2 Interpretative MFL-UT data combination

UT system performance usually is most reliable once the reflecting spot has sufficient size and the resolution of the measurement grid is satisfactory to hit it. The UT data provide sufficient information to estimate the quality of the depth sizing by implicit UT information like signal properties or the geometrical steepness around the metal loss bottom.

Once such typical criteria are fulfilled, it is not expected that MFL can contribute more than a plausibility check on the UT sizing. In Figure 1 this case will be called “Type III”.

MFL anomalies are generated by metal surface elements perpendicular to the flux. The resulting MFL signal shapes are not unambiguously invertible. Presumptions which help to parameterize the conditions of inversion are summarized in so called sizing models.

**Figure 1: Flow diagram of MFL-UT combined interpretation**
The shape of the volumetric anomaly causing the same field disturbance can vary - length and width can be found differently for the same signal. This assumed shape influences the MFL depth calculation. To reduce this effect is one of the most beneficiary direct contributions from a combined data interpretation with UT and typically applicable to features with restricted UT peak depth performance, e.g. pinholes or embedded pinholes. This typical scenario will be called “Type I” in Figure 1.

Above it was shown that typical parameters of a MFL sizing model are influenced by assumptions or approximations. Independent information can substantially improve such model on the fly. This can be external supporting information, like calibration digs. But in this case these are implicitly available by the nature of the measurement set up, where UT and MFL both recognize “MFL calibration feature shaped metal loss”. These are called “Type II” in Figure 1.

This continuously refined MFL sizing model will be available for all three types subsequently.

2.3 MFL Repeated inspection sizing
MFL sizing tolerances have different sources. As an indirect measurement system not only the straight technical aspects play an important role, but also weaker defined, as e.g. interpretative. Three principally main components can be summarized:

a. scattering of the measurement system
b. systematic errors from calibration and sizing model
c. ambiguous geometry interpretation.

The latter (c) is a predominant component typically. This is well known in the literature, as this component can be reduced significantly with a homogenized MFL data interpretation, i.e. corrosion growth rate (CGR) assessment directly based on the measurement data and not on tabled values (B. Gu et al., 2003). The second source is the calibration and sizing model originated systematic deviation (b). This is affecting the corrosion growth assessment specifically as systematic errors affect each member of the population in a similar manner, i.e. affect also the average. The lowest error is usually expected from the measurement system (a) as magnetic field disturbances of saturated pipe steel have a high repeatability. Also the geometrical extent of the magnetic field disturbance is large compared to the source geometry itself, hence easier to be resolved satisfactorily.

Figure 2 provides a simple comparative visualization sketch of the expected improvement effect from combined MFL-UT data evaluation compared with tabled MFL results and measurement data based growth calculations. The graph is based on an MFL overall tolerance of 10% and observed ILI depth at the time of the first inspection \((t_1)\) of 17% and 24% at the second \((t_2)\). A straightforward Gaussian error propagation is applied to the a.m. components by weighting the error component a with 0.25 , b with 0.30 and c with 0.45, which are values typically documented from pull tests and field verification re-analyses. The calculation of the extrapolated expected depth and its expected error corridor is also based on straight Gaussian error analysis. This is found still conservative compared to the established FFP procedures applying CGRs, where errors often are applied only to the depth value itself.

The Figure 2 first scene shows the extrapolation in time of the two tabled values with full tolerance as expected from ILI result tables, i.e. error components a,b,c. The second scene illustrates the benefit of a homogenized data interpretation, where only error components a and b affect the same data interpretation. And the third scene is based on an MFL depth calculation from MFL-UT combined data interpretation with interpretational uniqueness delivered from UT shape information and compensated systematic errors from Type II fine calibration, i.e. affected by error component a.
Figure 2: Example Graph to illustrate the effect of error compensation on MFL depth prediction corridors (grey) (assuming constant growth):

2.4 Individual pitting depth prediction

Tabled pitting depth values may scatter significantly between two inspections. UT depth values because of the measurement restrictions in narrow pits and MFL because of a.m. sources. Therefore procedures were established in the literature and in the fitness for purpose (FFP) analyses making use of statistical assessments of the CGR, like averaging. In this context such procedures are not considered. Specifically for individual growth mechanisms like microbial corrosion in pitting, often shaped as sharp pinholes, an individual assessment appears preferable.

3. Case study

This case analysis is based on actual recent data of a European pipeline. The operator preferred to be kept anonymous, but did revise and approve this article. The pipeline shows significant corrosion hot spots of very fast growing pitting, mainly of pinhole size.
The cooperation pipeline operator carried through a thorough and extensive field verification and repair activity at a hundred excavation locations. This huge number allowed to present the MFL-UT combined evaluation approach based exclusively on data later verified. This is not necessary, but does increase the transparency of the presentation enormously.

Exclusively the 74 features unambiguously identified as corrosion were used for the investigation. 13 of these show the restricted UT reflection, because of small size and judged to meet the “Type I” shape criteria. 61 are “Type III”, i.e. have a UT standalone depth sizing. 7 of these are suitable to contribute to the refinement of the MFL sizing model. (The depth position of the 7 Type II within the 61 Type III is displayed in “Annex a”).

3.1 MFL Sizing Model Refinement (Type II)

For both ILIs at \( t_1 \) and \( t_2 \) UT and MFL data sets indicate the same 7 features, which satisfy the Type II criteria. Typically this is a diameter larger than 20mm and simple symmetric shape. A typical example is shown in Figure 3.

The refinement, i.e. mainly compensation of calibration assumptions, is shown in Figure 4. Both values tend into the same direction and have similar order. This case is more probable, because most of the calibration assumptions are repeated, but one can imagine the effect of different directions on statistical growth assessments, which would be compensated successfully here as well. Once these values are derived, they will be available for the further MFL sizing.
3.2 Sizing isolated and embedded small sized pitting

Small sized features or small steep parts of larger corrosion are challenging geometries for both UT and MFL sizing. For UT mainly the reduced quality of the deepest point reflection affects the quality. For MFL the maximum amplitude has much higher significance and repeatability, but the depth sizing suffers the weakly defined flaw volume estimation.

The tolerance $\delta$ of depth $d$ sizing in MFL is a function $F$ of the effective (eff) contributing metal loss length $L$ and width $W$ and the MFL amplitude $A$ of the feature. For small features $L$ and $W$ can be replaced by better defined information from an independent source like UT.

Equation 4 summarizes this simple effect, which can have enormous benefit. This is not always identifiable, when looking at the UT data alone, because a maximum depth can be missed even without a missing reflection occurring, i.e. even a “maximum” depth value still is worth to be plausibility checked as outlined in Figure 1, Type III work flow. Where UT suffers such poor peak depth reflection the resulting accuracy in equation 4 is even better than the combination ($\delta_{combined}$ outlined in Equation 3).

Equation 4: MFL Tolerance improvement

$$d_{MFL} = F[L_{MFL}, W_{MFL}, A_{MFL}]$$

for $L_{eff}, W_{eff} < 15\, mm$

$$\delta(L,W)_{MFL} > \delta(L,W)_{UT} \Rightarrow$$

$$\delta(d_{MFL}[L_{MFL}, W_{MFL}, A_{MFL}]) > \delta(d_{MFL}[L_{UT}, W_{UT}, A_{MFL}])$$

The findings of a typical pinhole type and also general corrosion location are visualized in Figure 5. The two pinholes are visible upstream in the lower right corner, the pitting developing to general corrosion in upper left part of data shots. The depth values of the UT data display are standalone estimations, whilst values displayed in the MFL data are based on MFL sizing making use of the UT shape information.

The reported result 52% depth and growth of 35% within $\Delta t$ for the upstream pinhole has high reliability, which could not be achieved with a comparable quality neither for UT nor MFL standalone data. The larger extent downstream corrosion is sizeable.

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1 Dimension classification according to POF 2009 [POF 2009].
Figure 5 – Data example of pinhole and pitting developing to general corrosion based on UT sizing on the one hand and MFL sizing making use of UT shape information on the other (Feature No. 22&23):

with UT standalone sufficiently (Type III). A similar example of pinhole fast growing pitting is displayed in Figure 6.

Figure 6 – Example of typical fast growing pinhole Type I sizing based on MFL amplitude and UT shape Feature No. 17&18):

Figure 7 displays an even more challenging feature type of complex corrosion with embedded pinhole type character. This feature developed rapidly and shows a steep embedded pinhole in a complex general corrosion area. The ILI findings easily identified the hot spot character of this location, but also made it exactly predictable making use of the above outlined approach.
Figure 7 – Embedded pinhole in complex corrosion – rapidly growing (Feature No.30) Field photograph plus data display of ILIs at recent and previous inspection.

Figure 8 summarizes the 13 Type I sizing results. On the one hand the UT standalone and on the other the MFL sizing, based on combined data interpretation. The dig verification dates were close to t2. The observed confidence of sizing is ±6.0% at 80% certainty. This value is already in the range of the field verification itself and therefore perhaps even better.

Figure 8 – Summary display of all 13 Type I sizing results, based on MFL sizing making use of UT shape compared to UT standalone sizing.

4. Final ILI Result
Figure 9 visualizes the significant contribution of the MFL information to the overall quality of the ILI inspection report based on the combined MFL/UT data interpretation. The deepest features where identified and sized with the essential use of the MFL data. And these features also were identified as the fastest growing: 8 of the 10 identified hot spots were “Type I” features of pinhole or embedded pinhole shape.

The quality of the final achievable result with the presented approach reaches the quality of the field verification sizing itself, i.e. it could be even better. Assuming the field results to have absolute correctness delivers an achieved accuracy for the 61 UT sized features of ±4.3% at 80% certainty and ±6.0% for the Type I combined MFL/UT sizing, having in mind that this challenging test population has an average depth of more than 50%.

Figure 9 – Differentiation of the data sources contribution to the final ILI result:

5. Summary

The combination of the robust, indirect Magnetic Flux Leakage (MFL) methodology with the direct Ultrasonic Testing (UT) Inline Inspection (ILI) tool has well established advantages. This study shows the intelligent interpretative combination of the two ILI information sources exceeding significantly the straight forward statistical combination benefit. The presented approach demonstrates how to

- identify features not suitable to UT stand alone sizing
- apply MFL amplitude based depth sizing
- compensate systematic errors from MFL sizing models
- introduce UT shape information as major improvement to MFL sizing.

The quality of the final result reaches the quality of the field verification sizing itself. Corrosion growth assessments with the combined technology are drawing benefit from the MFL for certain features without the necessity to rerun similar MFL tools,
because systematic aspects from sizing models and calibrations are compensated fully.

This case study demonstrates the reliable individual identification of hot spots even of very small or complex shape, i.e. pinholes or embedded pinholes. The fact, that even smaller corrosion growth rate values become resolvable, allows for the equivalent shortening of the re-inspection intervals, where the circumstances require such initiative. Also the results show, that a prolongation of the prediction intervals can be possible.

6. Abbreviations

A  Amplitude
CGR  corrosion growth rate
δ  sizing tolerance
d  depth
Δt  time between previous and recent ILI
FFP  fitness for purpose
ILI  inline inspection
L  length (axial extent)
MFL  magnetic flux leakage
P  probability of detection
t₁  date (time) of previous ILI
t₂  date (time) of recent ILI
UT  ultrasonic testing
W  width (circumferential extent)

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8. References


Thomas Beuker, Johannes Palmer, Manuel Quack, Magnetic-flux leakage (MFL) and ultrasonic testing (UT) for enhanced detection of metal loss and pipeline wall features, 3R international (46), p.718-722, Oldenbourg Industrieverlag GmbH, München, November 2007

Appendix

Depth distribution and result quality of 61 Type III UT sizing results covering 7 UT sizing results suitable for MFL on the fly sizing model refinement: