Methods for Consideration of ILI Measurement Tolerance

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Abstract

The deployment of In-Line Inspection (ILI) tools plays a key role in pipeline integrity management helping ensure reliability and safety of a pipeline system. ILI tools employ various technologies to gather data used to detect and characterize anomalies including but not limited to metal loss, cracks, or deformations in the pipe wall.

Determining and appropriately considering ILI tool measurement tolerances is critical in the interpretation of the data collected. ‘Determining' is how the tool tolerance is estimated and quantified, whereas 'considering' is the process decision on how use tool tolerance is used in a program. Measurement tolerance (or tool tolerance), in this context, denotes the range of error or deviation between the true value and the measured value reported by the ILI tool. ILI vendors define specific tolerances for each measurement parameter accounting for the tool's design, calibration, and intended application.

Various methods exist for considering measurement tolerance, varying from the deterministic addition of pre-determined values based on prior tool performance and desired safety targets to reliability methods using statistical techniques that consider the sources of uncertainty individually. Each method has certain practical advantages and challenges that must be understood.

Background

The determination of safe operating pressures for pipelines must include the evaluation of diverse factors that impact the integrity and reliability of the pipeline system. Prudent methodologies are employed that address uncertainties and potential risks some of which may not be entirely comprehensible or quantifiable. These uncertainties are commonly integrated within design codes, standards, and engineering protocols.

49 CFR 192.921(a)(1), 192.937(c)(1)(iii) and 192.710(d) include the following language with respect to the treatment of tool tolerance:

> *“... an operator must analyze and account for uncertainties in reported results (e.g., tool tolerance, detection threshold, probability of detection, probability of identification, sizing accuracy, conservative anomaly interaction criteria, location accuracy, anomaly findings, and unity chart plots or equivalent for determining uncertainties and verifying actual tool performance) in identifying and characterizing anomalies”*

And 49 CFR 192.712(e)(1):

> *“An operator must explicitly analyze and account for uncertainties in reported assessment results (including tool tolerance, detection threshold, probability of detection, probability of identification, sizing accuracy, conservative anomaly interaction criteria, location accuracy, anomaly findings, and unity chart plots or equivalent for determining uncertainties and verifying tool performance) in identifying and characterizing the type and dimensions of anomalies or defects used in the analyses, unless the defect dimensions have been verified using in situ direct measurements.*

and 49 CFR 192.632(c)(5) states:

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> *"...must conservatively account for the accuracy and reliability of ILI, in-the-ditch examination methods and tools, and any other assessment and examination results used to determine the actual sizes of cracks, metal loss, deformation and other defect dimensions by applying the most conservative limit of the tool tolerance specification."*

Response to features identified by ILI surveys is based on the depth of a feature and the results of predicted failure pressure analysis. Depth-based response is based on depth alone such as a feature exceeding 80% of the nominal wall thickness. For predicted pressure-based criteria, a failure model is used to establish a predicted failure pressure. Several established and validated limit state models are widely used such as ASME B31G, modified B31G, RSTRENG, API-579-1 for corrosion, and NG-18, modified Ln-Secant, MAT-8, API-579-1 and CORLAS for cracking. These models require input parameters including wall thickness, depth, length, outside diameter, yield strength, and toughness (for cracking).

Sources of Uncertainty

All measurements contain some degree of error. Characterization and quantification of tolerance ensures that discrepancies between the reported measurement of a value and the true values for such characteristics as type, size, shape, and location are understood.

ILI performance is evaluated based on three primary metrics. These are Probability of Detection (POD), Probability of Identification (POI) and Sizing Accuracy. POD represents the likelihood that an ILI tool will correctly detect the presence of an anomaly, POI represents the likelihood that, if an anomaly is detected, that it will be correctly identified or characterized. Sizing accuracy is the likelihood that the feature will be accurately sized.

Factors that affect POD, POI, and sizing accuracy can vary based on the specific technology, pipeline conditions, and the nature of the features being assessed. Several key factors affecting detection, identification and sizing include: the nature of sensors utilized, the level of expertise of the analyst reviewing the data, operational conditions (including speed of the tool and the cleanliness of internal surfaces), the type, geometry, aspect ratio, and proximity of defects to adjacent features. Metallurgical variations (such as cold expansion or bending) may influence the magnetic properties, particularly where Magnetic Flux Leakage (MFL) technology is used. Several factors are discussed in further detail below.

Tool Speed

The speed at which an ILI tool operates impacts the accuracy of the measurements and data collected. The relationship between ILI tool speed and accuracy can be complex and depends on various factors including:

- Resolution and Sampling Rate: Higher tool speeds might lead to lower data resolution, where smaller defects or anomalies might be missed or inaccurately represented.
- Signal-to-Noise Ratio: Higher tool speeds can increase the noise in the collected data.

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- Measurement Precision: Higher tool speeds might result in less precise measurements due to the shorter time available for data collection.

Feature Orientation

Feature orientation plays a significant role in an ILI tool's ability to detect and accurately characterize features or defects.

Sensitivity to Geometry: Different ILI technologies are sensitive to specific orientations. For example, traditional MFL tools are well suited for inspection of volumetric defects but may have reduced sensitivity to narrow features oriented in the same plane as the inspection, thus an axial MFL tool may not be best suited for narrow axial metal loss, and a circumferential tool may not be well suited for circumferential slotting. Ultrasonic testing tools might have varying sensitivities depending on the orientation of the feature relative to the ultrasound beam.

Signal Strength and Quality: Feature orientation can influence the strength and quality of the signals received by the ILI tool's sensors. When a feature is oriented favorably, the signals produced by the feature might be stronger and more distinct, leading to accurate detection and characterization.

Sizing Accuracy: Feature orientation can impact the accuracy of sizing measurements. If the feature is oriented in a way that affects the interaction with the sensors, sizing errors may occur. For example, narrow axial corrosion (NAC) may not be sized accurately by an axial MFL tool.

Data Interpretation Complexity: Some features might require more sophisticated analysis techniques to accurately determine their characteristics.

Feature Morphology

The geometry of a corrosion or cracking feature significantly influences the ability of ILI tools to accurately detect and size the feature.

- Size: The size of the corrosion or cracking feature can impact ILI accuracy.
- Aspect Ratio: The aspect ratio, defined as the ratio of the feature's length to its depth or width, can affect the sizing.
- Curvature and Shape: Features with complex geometries, such as those located on curved surfaces (dents) or with irregular shapes and interacting with seams or girth welds, can pose challenges for certain technologies.

Methodologies for Consideration of Measurement Tolerances

Deterministic

A deterministic-based assessment of ILI-reported features involves evaluating the structural integrity and potential failure modes of the pipeline system using a safety factor or maximum expected error designed to account for all potential uncertainties. In this approach, assumptions are made for many or all the parameters in the analysis. For pipeline characteristics nominal values are used, and for ILI

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measured values, consideration for tool tolerance is required which may include directly applying a specified tolerance supplied by the ILI vendor.

A typical performance specification for depth measurement of MFL ILI is +/- 0.1t at 80% confidence level, where t is the wall thickness of the pipe. This, simply put, states that the actual value of the measured features will be within 10%t of the measured value 80% of the time.

Figure 1 illustrates a confidence interval for a population of features. In this case, if the confidence is 80%, the measured value 'x' (the mean) is in the middle at the peak of the plot and 80% of the actual values are between the upper and lower bounds (green shaded area). The remaining 20% of the population would have actual values outside the interval (orange shaded areas). This "two tailed" normal distribution would expect to have up to 10% of features exceeding both the upper and lower bounds. In this scenario, the features below the lower bound (i.e., tool measurements indicate the feature is deeper than its true size) are already conservative. Establishing an ILI response plan based on the mean plus the tool tolerance effectively could provide a 90% confidence that the actual depth of the feature does not exceed the upper bound.

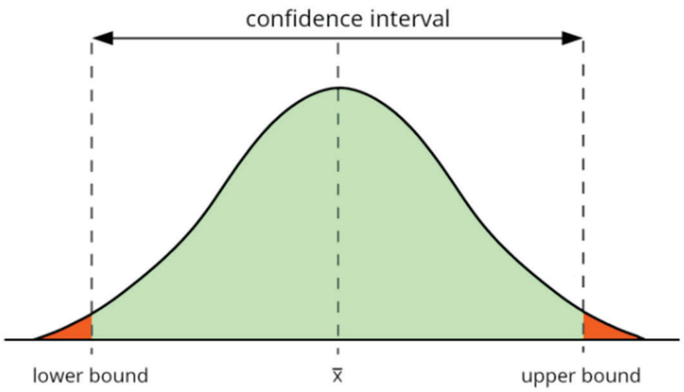

Figure 1: Illustration of a Confidence Interval

Advantages

This method is the simplest approach and achieves a certain level of reliability by "adding" the potential error at a desired confidence interval to each measurement.

Limitations

Applying the confidence level provided by the ILI vendor assumes that the measurement error can be modeled as a normal distribution and the measurement does not have bias. If the distribution of error is not normal, the error may increase or decrease conservatism based on the skewness of the distribution. (Figure 2)

A deterministic assessment uses conservative values for many or all input parameters to account for variability and uncertainty in measurement accuracy, environmental conditions, material properties, and operational factors. The use of "worst case" or conservative inputs for all

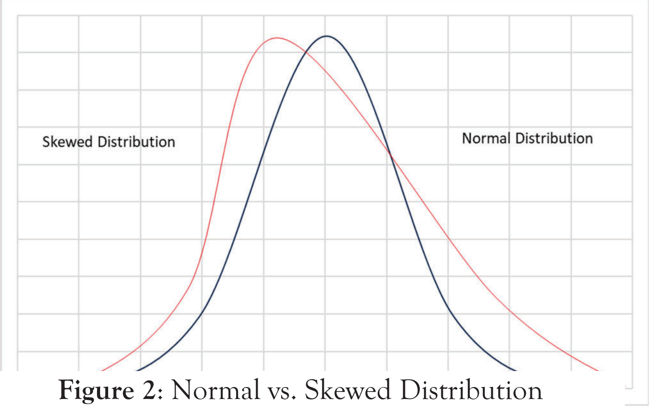

Figure 2: Normal vs. Skewed Distribution

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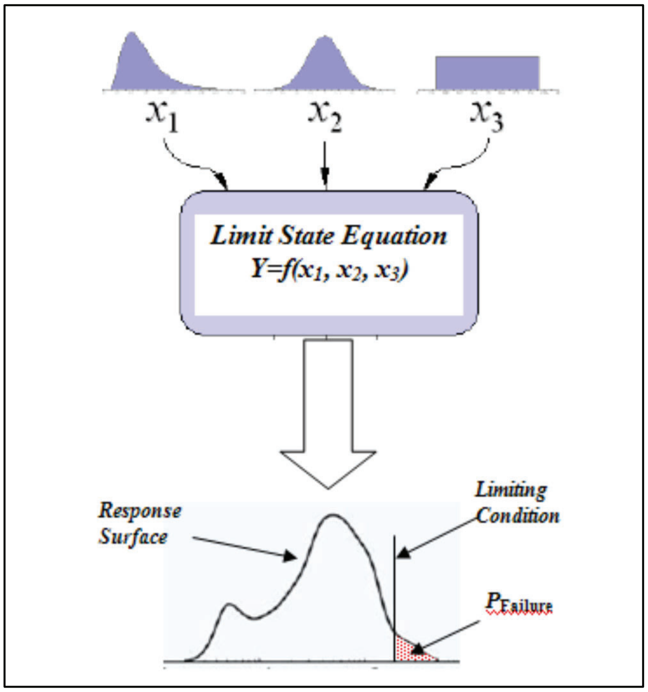

Figure 3: Reliability Approach

parameters simultaneously in the failure models is an unlikely scenario and is likely to result in excess conservatism and decisions that do not improve pipeline safety (e.g. Applying resources to work that may not be impactful to improved pipeline safety).

Conversely, a deterministic assessment can result in over-confidence in integrity management decisions. The limitation of the deterministic approach is evident in its reliance on a fixed confidence interval. For example, in the MFL scenario previously noted, the lower or upper bounds of an 80% two-tailed confidence interval are 1.28 standard deviations from the mean. The application of a 10% depth adjustment to the ILI-measurement based on this metric does not correspond to a fixed level of reliability, rather it is a relatively rudimentary approach that inherently accepts a variable and often unquantified level of risk.

To illustrate this point, consider two hypothetical pipelines, Pipeline A and Pipeline B, both have similar attributes and operating conditions. Pipeline A contains 10 anomalies, with a maximum depth of 40% metal loss and a minimum Failure Pressure Ratio (FPR) of 1.39 x MAOP. Pipeline B contains 10,000,000 anomalies, also with a maximum depth of 40% metal loss and a minimum FPR of 1.39 x MAOP. Based on deterministic criteria, both would appear identical, however in the latter case, the likelihood of an outlier (a feature outside the confidence interval) is virtually assured. In large datasets, the likelihood of encountering outliers (features that deviate from expected behaviour or fall outside the confidence interval) is significantly higher. In Pipeline B's case, the probability of an outlier is significant, potentially representing a severe anomaly that could compromise pipeline safety. A deterministic approach, which evaluates pipelines based on fixed criteria without considering the statistical variability of large populations, may fail to account for such extreme cases, leading to unconservative and overly optimistic risk assessments.

This example demonstrates how the deterministic method may lead to unconservative results.

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Reliability Based

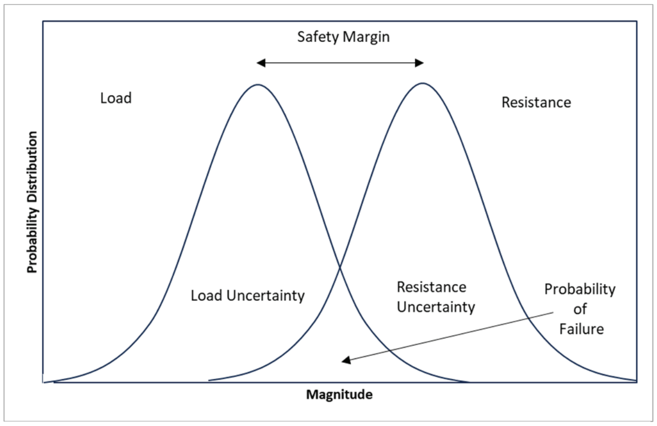

Figure 4: Failure Probability Concepts

A reliability-based assessment of ILI features involves considering the uncertainties associated with the inputs to limit state equations. In this approach, a probability density function (PDF) is utilized to model the uncertainty in the input parameters. Figure 4 is a conceptual representation how a reliability method uses limit states equation inputs as probability density functions. The **load curve** reflects the uncertainty or variability in the demands or stresses applied to the system (i.e., the pressure that can be sustained before failure). The **resistance curve** shows the variability in the system's capacity to withstand these loads (i.e., wall thickness, outside diameter, yield strength). The area of overlap between the two curves represents the **probability of failure**. This is the likelihood that the applied load exceeds the system's resistance, leading to a failure event.

Reliability methods have been widely adopted in the nuclear and aerospace industries where they are used to identify and manage threats. Some North American operators in the pipeline industry have already adopted this approach as a tool for integrity management. Pipeline industry research organizations such as PRCI and EPRG have spent significant time and resources developing reliability-based models for various purposes. Reliability models, in many cases, employ the same limit state equations as the deterministic methods however the load and resistance variables are characterized in terms of probability density functions (Figure 4).

Advantages

Adopting a probabilistic methodology addresses the previously stated inadequacies by incorporating statistical analysis to evaluate the distribution, frequency, and uncertainty of anomalies. This approach allows for a more nuanced understanding of risk, ensuring that outliers and rare events are adequately accounted for in integrity management plans. For operators, this shift can translate into more accurate risk assessments, targeted maintenance strategies, and ultimately, enhanced pipeline safety and reliability. The probabilistic method provides a clearer picture of the true risk landscape, enabling operators to make more informed decisions and allocate resources effectively to prevent potential failures. Therefore, reliability methods provide a powerful tool to support accurate, quantitative predictions on the likelihood of failure and expected lifespans, and, when used correctly, achieving consistent levels of reliability when compared to deterministic methods.

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Limitations

The limitations of reliability methods are primarily associated with the challenges of selecting appropriate input parameters and the complexity of the approach. The complexities could include available modeling expertise, data quality requirements and computational limits or delays. Reliability models have the potential for introducing bias in different ways. For example, the models and/or targets can be adjusted for certain use cases. Results can be misinterpreted, and care must be taken in setting up the model(s).

Variability and uncertainty in the parameters will also increase over time. Corrosion and cracking threats levels would be expected to increase over time if operating and/or environmental conditions are conducive to feature growth and mitigation systems are not effective. Conversely, over-estimated growth rates could result in overestimation of the likelihood of failure.

Conducting reliability analysis on ILI data, particularly with a significant population of features, can require the utilization of advanced computational tools and personnel that can require the utilization of advanced computational tools and demand advanced modelling expertise.

Additional Factors

Accounting for tool tolerance in the interpretation of ILI data entails a level of nuance that includes considerations beyond the features reported by the ILI tool.

An 80% confidence level is widely accepted, however other confidence intervals (e.g. 70%, 75%, 90%, 95%) can be achieved using different tolerances. It is the operator's responsibility to identify and use an appropriate confidence and corresponding tolerance for each scenario. Consideration must be given to the values and tolerance for such factors as relevant material attributes and operating conditions of the pipeline segment, ILI tool sensor parameters and performance during the ILI survey.

Discussion

Pipeline operators, regulators, and the public all share similar goals of ensuring pipelines are operated safely. Pipeline operators want to ensure that the right work – and only the right work – is done at the right time to ensure safety of people and the environment. This is more important than ever in a world of increasingly limited resources, personnel, service interruptions and cost pressures. When ensuring the right work is done, some extra activities (additional excavations and analysis) will be included to ensure appropriate margins of safety. The challenge is to minimize any inefficiency to ensure the available resources can be applied in areas that have the greatest impact on increasing safety.

Each method of accounting for tool tolerance has advantages and disadvantages. If the method chosen is not suitable for the intended purpose, unintended effects may result including but not limited to unnecessary excavations and inefficient resource allocation. Overly conservative ILI tool tolerances can result in pipelines being taken out of service for repairs or inspections that may not

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be necessary. This can lead to unnecessary downtime, maintenance costs, and operational disruptions.

For pipeline systems with relatively few anomalies, a deterministic approach can provide an acceptable level of assurance of pipeline fitness for service while minimizing resource demands (i.e., personnel, pipeline repairs and remediation). For systems with a large population of features, deterministic methods can lead to unconservative responses or require significant resource inputs to achieve desired levels of pipeline reliability. In such cases achieving the prescribed margins of safety requires more fieldwork, some of which may be unnecessary. Increased conservatism is achieved by assuming that the tool error occurs in every measurement and includes more anomalies in the response, many of which are already measured accurately or conservatively.

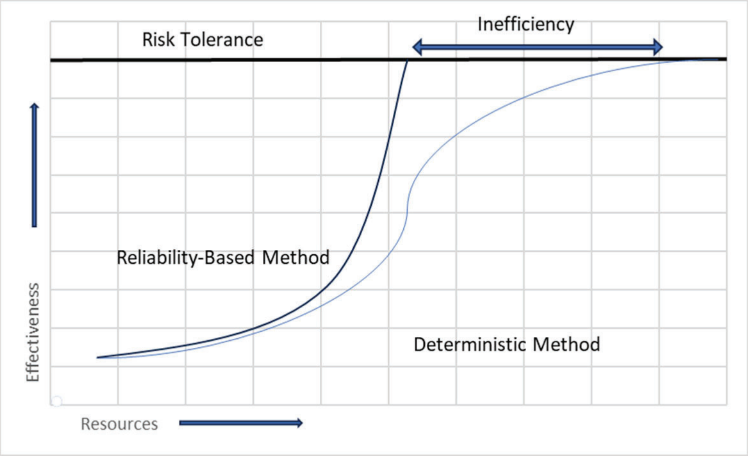

Figure 5: Concept Plot of Effective vs. Resource Requirements

Figure 5 is an illustration of the potential advantages of reliability-based methods for consideration of tool tolerance vs. deterministic methods.

In this concept plot, a reliability-based method provides the pipeline operator a method to achieve the desired outcome (risk tolerance) by performing remediation and repairs with targeted resources and specific activities rather than increasing the number of excavations and repairs as a result of adding conservatism to reduce the potential for outliers.

Sources of Conservatism in Pipeline Design and Fitness for Service

It is recognized that the consideration of tool tolerance is required to ensure appropriate levels of safety are achieved. While this is a key consideration, it should be noted that conservatism exists in many aspects of pipeline engineering models and tools and compounding conservatism can obscure pipeline safety objectives. Some of the sources of conservatism are discussed below.

1. A primary purpose for use of ILI tools in pipelines is identification of defects that could lead to rupture. The calculation of failure (i.e., burst) pressure using an established failure model such as ASME B31G or other can be used in evaluation of a ratio of failure pressure to MAOP (failure pressure ratio or FPR). These failure models have been shown to be conservative due to the assumed geometric profile (i.e., more metal loss is assumed than actual).
2. Yield strength is not the primary consideration for evaluation of limit states of potential defects in steel pipelines – rather this is flow stress or ultimate tensile strength (UTS). Flow stress is

an intermediate value between the yield and ultimate tensile strength that governs the behavior of collapse controlled ductile failure. UTS is always greater than YTS therefore basing MAOP on YS inherently creates conservatism in the calculation.

Conclusion

There are multiple ways to consider ILI tool tolerance. Methods can range from calibrating based on outliers, to deterministically applying a vendor stated tool tolerance at a certain confidence interval, to a comprehensive analysis that considers probability of exceedance and reliability modeling.

Deterministic methods can be simple and easy to apply and use, however they may, in certain scenarios, lead to excess conservatism resulting in wasted resources or unconservative conclusions. This is shown by a typical dig to repair ratio for an operator's integrity program. Reliability methods consider tool tolerance by representing the inputs to the limit states equations as probability density functions and provide a powerful tool to make accurate, quantitative predictions on likelihood of failure that can achieve higher levels of reliability than deterministic methods particularly when a large population of features exists.

Based on the risk tolerance set by a pipeline operator and factors such as operating conditions, populations of features, and confidence in data sources (both pipeline material data and inspection data) an operator may choose the best method to achieve desired results.

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