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The effect of inspection sizing uncertainty on the maximum corrosion growth in pipelines

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ABSTRACT

Corrosion growth analysis is a vital part of the integrity and risk assessment of corroded pipelines. The results are used to schedule pipeline inspections and maintenance actions. Corrosion growth is often determined from noisy in-line inspection results where the sizing errors can have a significant impact on the measured size and growth of the corrosion features. If the inspection results are on average unbiased, the top percentiles of measured features have a statistical trend of being oversized as shown in the paper. This trend has been confirmed in pipeline practice. The statistical bias effect leads to suboptimal inspection and maintenance requirements if it is not removed in the corrosion growth analysis. Three deterministic and probabilistic models, which account for the sizing bias inherent in in-line inspection data, are introduced for the corrosion growth analysis. The models are tailored toward pipelines subject to internal corrosion with high feature densities. A numerical example is provided based on a subsea pipeline to demonstrate the ramifications of the oversizing bias and the proposed corrosion growth models.

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1. Introduction

Pipelines are major infrastructure systems that transport oil and gas products. They are subject to a variety of natural and manmade hazards including deterioration processes that can lead to pipeline failure with severe consequences. Corrosion, which is considered in this paper, is a significant threat to pipeline integrity [1]. Integrity management of corroded pipelines is often based on the following three steps. First, in-line inspections (ILIs) are regularly performed to obtain information about the state of corrosion in the pipeline. Second, ILI results are used to determine the corrosion growth and (safe) remaining lifetime of the entire pipeline. Third, necessary repairs are executed on the system to avoid unscheduled service disruption and pipeline failure.

ILI tools are based on non-destructive inspection methods such as magnetic flux leakage (MFL), ultrasonic testing (UT), and Eddy current (EC) [2]. ILI results are subject to the following measurement errors [3]:

1. Detection error: The ILI tool does not detect all existing corrosion features. It reports an intact pipeline wall at the feature location.
2. False call error: The ILI tool reports a corrosion feature. However, the pipeline wall is intact, and the reported feature does in fact not exist in the pipeline; this situation is referred to as a false call.
3. Sizing error: If the reported corrosion features are true, the actual feature size is then subject to sizing errors. The reported size in terms of feature depth, length and width differs from the true size of the feature.
4. Location error: The reported feature locations from two or more ILIs are not perfectly aligned due to measurement errors and the application of ILI-specific coordinate systems.

All ILI measurement errors need to be taken into account when the corrosion growth and remaining time to failure of the pipeline are estimated from the ILI results. The paper focuses solely on the sizing uncertainty and investigates the effect of sizing errors on the (maximum) feature size and corrosion growth. In essence, sizing errors lead to differences between actual and measured feature sizes. If the sizing uncertainty is low, the difference between actual and measured values is in general small. In the case of pipeline ILIs, particularly for MFL inspection tools, sizing uncertainty, which can lead to a significant difference between actual and measured

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feature size, is large. The paper shows that for standard MFL sizing errors the top percentiles of measured features are highly affected by an oversizing bias due to sizing uncertainty. Ignoring this bias effect in the corrosion growth and remaining lifetime analysis results in suboptimal decisions for the integrity management of pipelines.

The objective of this paper is to develop models to determine the actual feature size and corrosion growth conditional on the ILI results by taking the trend of oversizing the upper percentiles of the measured features into account. The focus is on estimating the actual corrosion growth between two inspections rather than forecasting future growth. It is necessary to consider the entire population of features rather than an individual feature to make the adjustment for the sizing bias. The deterministic and the two probabilistic models, which are presented in this paper, can be implemented in spreadsheet tools. Without loss of generality, the remainder of the paper is formulated in terms of sizing errors for the depth of corrosion features.

The paper is organized as follows. Section 2 outlines the sizing error model and illustrates the impact of the sizing error on the top percentiles of the ILI-measured features in terms of depth and corrosion growth. The three models, which correct for this bias and estimate the actual feature size and corrosion growth, are introduced in Section 3. A numerical example is provided in Section 4 where the ILI results for a sample pipeline are analyzed considering the effect of the sizing bias on the top features. A subsequent discussion is provided in Section 5, and the final conclusions are presented in Section 6.

2. Corrosion growth and sizing error

2.1. Actual and measured corrosion growth

Corrosion is a non-decreasing stochastic deterioration process. Consider a corroded location in a pipeline, the corrosion depth X_2 at time t_2 can be modelled the sum of the depth X_1 at time $t_1 < t_2$ and the corrosion growth increment ΔX between times t_1 and t_2:

$$X_2 = X_1 + \Delta X \tag{1}$$

If the corrosion process is active, the depth ($X_2 > X_1$) increases with time, and the corrosion growth increment $\Delta X > 0$ is positive. In the case where the corrosion stopped and the feature stopped growing ($X_2 = X_1$), the growth increment is zero. Eq. (1) is valid for both individual corrosion features (e.g. maximum feature depth) and a population of corrosion features in a pipeline or any segment thereof.

Pipeline ILI results are subject to sizing uncertainty. Instead of reporting the actual depth X, a measured depth Y is obtained as the outcome of the inspection. An additive sizing error model is often applied to relate the actual to the measured feature depth [4]. For example, the ILI-measured depth Y_i is the sum of the actual depth X_i and the sizing error ϵ_i for ILI i at time t_i:

$$Y_i = X_i + \epsilon_i \quad \text{for } i = 1, 2 \tag{2}$$

All variables in (1) and (2) are treated as random. It is commonly assumed that the sizing error is independent of the true depth ($X_i \perp \epsilon_i$), which has considerable implications as shown later.

Actual and measured depths are both continuous random variables that have a lower bound of zero and an upper bound of the (intact) wall thickness (wt) of the pipeline. The domains of the three variables in (2) are illustrated in Fig. 1. Consequently, the sizing error is limited due to the bounded domains of actual and measured depths. A feature is referred to as being oversized if the measured depth exceeds the actual depth ($y_i > x_i$). It is undersized in the opposite case ($y_i < x_i$) and free of sizing error if $y_i = x_i$.

The magnitude of the sizing error ϵ_i in (2) depends on the capabilities of the ILI tool (e.g. sensor density and quality) and the quality of the analytical signal processing. Vendors usually specify the accuracy of ILI tools using confidence intervals. For example, high resolution MFL tools, which are of primary interest in this paper, have a standard sizing accuracy of ±0.10–0.15 wt at an 80% certainty level [5]. The sizing error is typically assumed to be normally distributed for a probabilistic analysis of ILI data [3]. The domain of the normal probability distribution is defined from negative to positive infinity that is already a violation of the restricted domain for the sizing error according to Fig. 1. Therefore, proper truncation of the normal probability distribution for the sizing error should be applied [6]. If the ILI tool is (on average over the population of features) unbiased, the sizing error has a zero mean value. The standard deviation σ_i can be determined from the sizing accuracy interval.

$$\epsilon_i \mid \sigma_i \sim \text{normal}(0, \sigma_i) \quad \text{for } i = 1, 2 \tag{3}$$

Based on an 80% certainty level, the standard deviations in (3) are equal to 0.078 wt and 0.117 wt for interval lengths of ±0.10 wt and ±0.15 wt, respectively. The standard deviation usually depends on the type of feature (e.g. pitting, slotting, axially vs. circumferentially oriented), but without loss of generality, this case is not further considered in the remainder of the paper.

The measured corrosion growth ΔY, which is obtained from two ILIs, is the difference of the two measured feature depths Y_2 and Y_1:

$$\Delta Y = Y_2 - Y_1 \tag{4}$$

Inserting (2) in (4) leads to the following results for the measured corrosion growth:

$$\Delta Y = (X_2 + \epsilon_2) - (X_1 + \epsilon_1) \tag{5}$$

and

$$\Delta Y = \Delta X + \Delta\epsilon \tag{6}$$

where $\Delta X = X_2 - X_1$ is the actual corrosion growth between two ILIs and $\Delta\epsilon = \epsilon_2 - \epsilon_1$ is the difference of sizing errors. The actual corrosion growth $\Delta X \geqslant 0$ is strictly non-negative, while the measured corrosion growth ΔY can be negative depending on the difference of sizing errors.

2.2. Impact of sizing error on feature size and corrosion growth

The effect of the sizing error on the measured depth in (2) and the corrosion growth in (6) is investigated in this section. A simulation study is performed to demonstrate the dependence of the measured depth, particularly the top percentiles of the measured depth, on the sizing error.

Corrosion growth ΔX in (1) can be described probabilistically using stochastic processes [7,8] to capture the temporal uncertainty of the growth process. For example, the gamma process [9–11] and the inverse Gaussian process [12] have been applied to model corrosion growth in pipelines. The gamma process is adopted in the simulation study. It consists of independent and gamma-distributed growth increments $\Delta X > 0$ with a probability density function (PDF) $f_{\Delta X}(\Delta x|\Delta\alpha, \beta) = \Delta x^{\Delta\alpha-1}\exp(-\Delta x/\beta)/(\Gamma(\Delta\alpha)\beta^{\Delta\alpha})$ where $\Delta\alpha > 0$ is the shape parameter and $\beta > 0$ is the scale parameter. The actual depth X that is the sum of the growth increments, is also gamma-distributed with the same scale parameter β.

The samples for the actual depth X_1 in (1) are generated from a gamma distribution with a shape parameter $\alpha = 1.2$ and a scale

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