# ILI AXIAL STRAIN MEASUREMENT – SHARING OVER 10 YEARS OF OPERATIONAL EXPERIENCE AND TECHNOLOGY ADVANCES FOR THE FUTURE

**Phil English, Jeff Sutherland, Inessa Yablonskikh, Baker Hughes**

## Abstract

Pipeline systems experience a range of strain conditions along their length. These are either factored into the pipeline design as known operational strains or present themselves as strain resulting from additional external loadings that are potentially unknown during the design or construction phases. Detecting, monitoring, and understanding these additional strains in combination with operational strains are a key part of a pipeline integrity management program. Surveying with inertial mapping tools has been commonly used since the late 1980's for accurate measurement of bending strain, which unfortunately only provides a part of the picture.

Development of the ILI axial strain measurement tool (AXISS™) was to fulfil pipeline operators' need for axial strain measurement in combination with available bending strain information to enhance their geohazards risk management programs.

After an extended period of comprehensive field testing and validation, supported by a number of partner customers, Axial Strain Inline Inspection transitioned from a developmental to commercial service more than 10 years ago. Since then, over 25,000 kms (about 15,534.3 mi) of data has been collected with many high strain locations successfully identified and mitigated. And, while axial strain inspection is now established as a proven and important tool for a pipeline operator to assess geohazards and other strain related threats, that experience has provided key insights as to where the current technology strengths lie and of course where we need it to go next to provide the level of information truly needed to optimize our full understanding of strain in the assessment of pipeline threats.

This paper gives a detailed overview of some of those experiences discussed, examples of the applications of the technology, case studies and the types of strain events identified. Secondly, and importantly, this paper provides key insight into the latest developments of the technology that will address the remaining unmet needs of the geohazard and stress and strain engineers tasked with establishing firstly a complete picture of pipeline strain condition and secondly allowing them to effectively optimize any mitigation measures or repair programmes. Advancements in tool development including bi-axial and plastic measurements of longitudinal stress in the pipeline are also discussed in this paper.

## Introduction

The expenditure on construction and maintenance of pipeline systems runs into billions of dollars a year. Securing their continuity of operation is of paramount importance to the oil and gas industry and to broader society for energy availability and security. In order to ensure that a pipeline is built and remains FFP and continues to operate safely and efficiently throughout its planned life, operators run various types of ILI inspection surveys in their pipelines. For many years the ILI inspections in pipelines have fallen into four main categories:

- geometry such as calipers,
- metal loss
- crack-detection,
- mapping and bending strain.

A wide variety of technologies and methods are in use to detect, characterize and measure an equally wide range of defects in pipelines. These defects may arise from pre-existing conditions, errors in construction, effects of corrosion, accidental damage or other causes. Caliper tools, mapping tools (IMU), MFL, eddy current and ultrasonic tools are all used to detect anomalies and conditions that may result in an unacceptable stress or strain level in a pipeline leading to failure. In using any or all these techniques, their ultimate aim is to justify the inspected pipeline's continued fitness for purpose, and where this is not demonstrated, to provide accurate and reliable information on which to base a rehabilitation program to achieve fitness-for-purpose levels of integrity.

## Background – ILI Axial Strain Tool Development

Many pipeline systems cross landslides and/or areas of settlement/subsidence. These were either not identified during the original pipeline routing, occurred since pipeline construction or were triggered by pipeline construction. The current state of the art geotechnical techniques for identifying, characterizing, and monitoring these hazards are well recognized and have been readily available for a few decades. The use of in-line inspection high resolution inertial survey tool (IMU) data in the determination of bending strain in operating pipelines is well developed and understood. The missing component in determining the total longitudinal strain in the pipeline was to understand the component of pure axial strain that the pipeline is experiencing without the need to expose the pipeline for the installation of surficial point measurement pipe monitoring (primarily strain gauges) or destructive testing (such as cut-outs). Many methods of stress/strain measurement, including the installation and use of strain gauges, only allow for the determination of change in strain going forward from the date of installation, whereas the ILI axial strain tool measures total strain at the time of inspection.

Given the significant impact on pipeline safety, integrity and operations, in 2006, four North American pipeline operators and a pipeline inspection company formed a joint industry program (JIP) with the objective of developing an ILI pipeline/geotechnical tool that could directly measure the pure axial strain on a pipeline as a result of soil/structure interactions to allow for better integrity-based decisions [1]. For 2 years, the JIP focused on the proof of concept through performing extensive lab testing and static measurements at selected dig locations. In 2008, the first trial ILI axial strain tool was released. Many field test runs for different pipeline sizes were successfully performed from 2008 to 2014. As a result of the success of the extensive validation program that took place from 2006 to 2014, AXISS™ was commercially launched in 2014. Now, after 10 years of successful axial strain surveys, the tool is established as a critical component of the geohazard management programs for many operators in different regions around the world.

## Summary of Ten Years of Operational Success

Since 2014, the tool has been successfully run by many operators in many regions around the world. Table 1 summarizes overall tool inspections since commercial launch.

**Table 1 Summary of Commercial Runs Since 2014**

| | **Summary** |
|---|---|
| Number of inspections since 2014 | ~200 runs |
| Total inspected pipeline length in kms | ~25,000 kms (about 15,534.3 mi) |
| Total number of axial strain features detected | 1150 features |
| Main causes of axial strain features | 1- Geohazards and pipe movement<br>2- Construction and manufacturing defects<br>3- ROW characteristics (e.g., rail and road crossings, river crossings, etc.)<br>4- Local features (e.g., dents, ovalities)<br>5- Pipe characteristics (e.g., wall thickness transitions, valves, tees, etc.) |

The tool has been successfully used by many operators, in multiple applications in addition to Geohazard management to assess pipeline safety conditions with the following benefits:

- Reduction in the number of digs needed to install strain gauges and to check strain conditions.
- Elimination of the need for destructive tests and associated cut-outs.
- Reduction in costly surface and geotechnical surveys.
- Measurement of current total axial strain (strain gauges only measure strain difference from the time of their installation).
- Improved confidence in pipeline integrity assessments by getting a fuller picture of the strain condition measuring both bending and pure axial strain components.
- Improved safety by complete pipeline assessment for potential injurious geohazards and resulting axial features before they become critical.
- Reduced repair costs by minimizing unnecessary mitigation.

The following examples summarize some of the tool applications that operators utilized to solve their lines' risks from strain-related threats.

### Identification

Results of the inspection have been successfully utilized as a screening method to proactively locate high axial strain features before being injurious. As shown in Figure 1, identification of unknown strain features mainly focused on locating unknown geohazards, assessing high risk zones (e.g., girth welds under high strain) and defining the real extent and effect of already known geohazards on different pipeline systems.

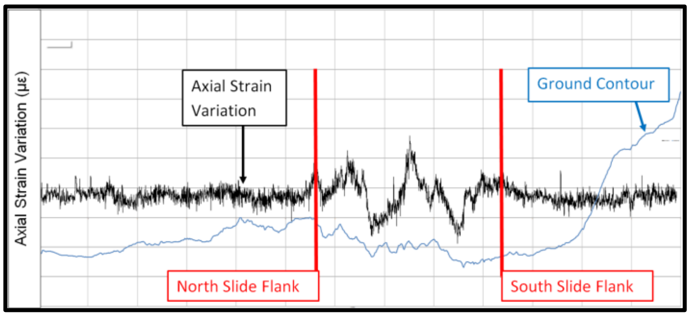


**Figure 1: Defining the Extent of a Translational Landslide on 13 km section of pipeline**

## Monitoring

Run-to-run inspection for axial strain condition became an important application and this is evidenced by the growing number of run-to-run analyses carried out year on year. The importance of this application lies in the ability of providing key information to evaluate and monitor the condition of the pipeline. Monitoring the variation of axial strain over time provides operators with a clearer picture of the progression of identified geohazards and its effect on the pipelines in the ROW. Figure 2 provides an example of run-to-run analysis results comparing axial strain values of 2 inspections carried in 2014 and 2019.

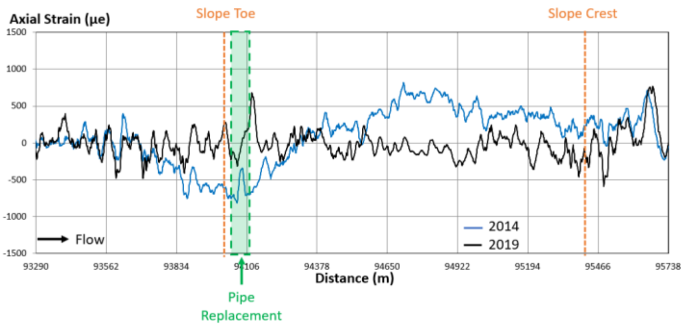


**Figure 2: Axial Strain Profile on a Pipeline for 2014 VS 2019**

## Different Geohazards

The AXISS strain inspection system has been geared towards geohazard management and deployed to survey pipelines to assess the effect of diverse types of geohazards such as landslides (longitudinal and transverse to the pipeline), hydrotechnics (e.g., erosion, river crossings), excavation and subsidence. Before AXISS, IMU (bending strain) monitoring was the only effective ILI technology used to assess the effect of ground movement/landslides on pipelines. IMU strain monitoring is an optimal approach for the cases of landslides which move in a direction perpendicular to the pipeline (e.g., Figure 3b) since the majority of the strain induced will be bending strain. On the other hand, the AXISS axial strain tool is more broadly applicable for cases of longitudinal landslides which move in a direction parallel to the pipeline (e.g., Figure 3a) since significant strains induced will be axial strains. The combination of technologies is optimal, as in reality, ground movements are random and, in most cases, they will induce both longitudinal and perpendicular load components generating both axial and bending strains in pipelines.

**Figure 3a Landslide movement parallel to pipeline**

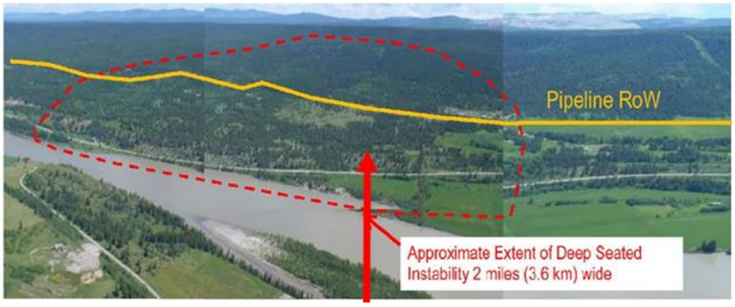


**Figure 3b Landslide movement perpendicular to pipeline**

**Residual Stress from Manufacturing and Construction**

The AXISS tool measures the total axial strain that affects pipelines through their entire history. A key aspect of identifying residual stresses, is analysing the circumferential distribution of strain for the pipeline. Analysis techniques allow for identification of whether the localized strains were caused by the pipe forming process, from specific construction and laying techniques, or by an active operating load. The AXISS system has been successfully utilized to identify residual strains resulting from various sources such as pipe formation techniques, pipe characteristics (e.g., seam and spiral weld), construction processes (e.g., HDD, tie-ins) and pre-commissioning testing (e.g., hydro testing). Figure 4 illustrates the axial strain variation measured over the long seam of a pipeline. Higher than average strain readings located within +/- 15º of the seam weld are shown. Uncalibrated axial strain variations as high as 900 µƐ were measured in this example.  These values are significant and may increase when applying calibration. 90% SMYS stress may be in the order of 2000 to 2500 µƐ for most pipelines.

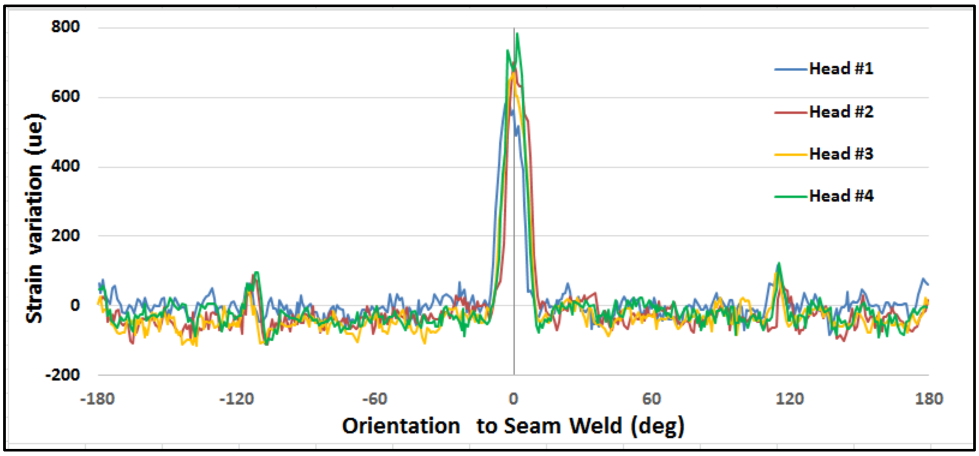


**Figure 4: Average strain variation relative to seam weld orientation demonstrating the seam weld effect for 9.55mm WT X-52 grade for 30" pipe (circa 1957)**

### Total Longitudinal Strain Demand

Both IMU and AXISS tools provide data to identify strain due to geotechnical events, but neither can independently provide the full total longitudinal strain condition (axial and bending strain together). Figure 5 illustrates distributions of both pure axial and bending strains across cross-section of a pipeline. Combining data from both tools enables estimating the total longitudinal strain demand (active strain) at any point along the pipeline.

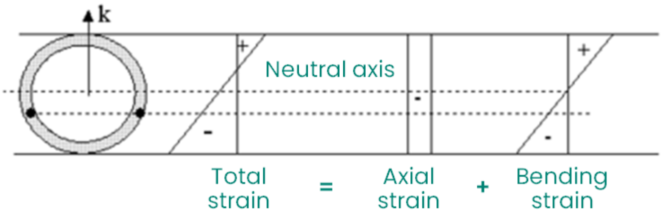


**Figure 5: Total Longitudinal Strain Distribution**

### Assessment of Applied Mitigation Measures

Geohazards can apply significant stresses/strains that can increase the risk factors beyond acceptable limits in some areas within the pipeline under investigation. In such cases, operators shall apply mitigation measures to reduce stress/strain values and subsequently risk factors to acceptable levels.

Since AXISS (in combination with IMU) can deliver total longitudinal strain demand, operators can select the optimum mitigation measure by:

- Either reducing strain demand (e.g., strain relief operations)
- Or increasing strain capacity (e.g., using stronger pipe, sleeves).

In addition, operators can use AXISS and IMU to measure the total longitudinal strain demand after applying the mitigation techniques to assess their impact and success.

Figure 6 represents a situation when the operator used an anchor to stabilize the ground to reduce the longitudinal strain demand as a mitigation measure. In this case, it was deemed that the measured axial strain values had been stabilized which enabled the operator to conclude the success of the anchor.

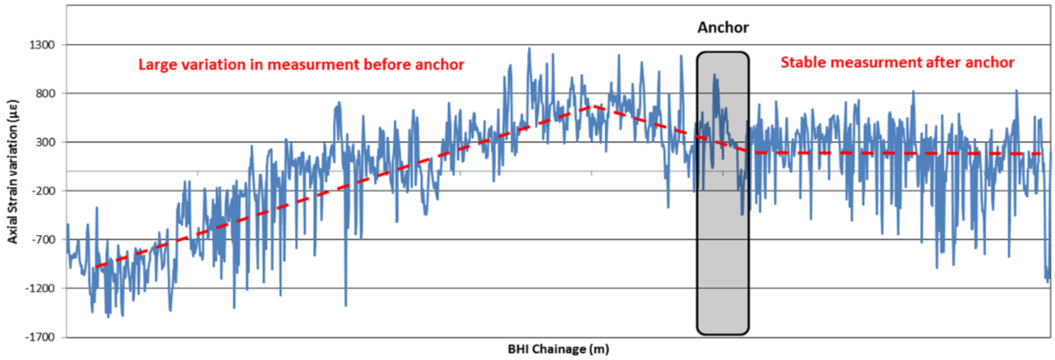


**Figure 6: Axial Strain Trend Illustrates Ground Movement Stabilization after the Anchor**

## Augmenting Susceptibility Models for Select Local Features

Despite being developed to primarily evaluate macro level strain events like those typically experienced with geohazards, over the years, analysis and reporting deliverables have been customized to assess the impact of some local features such as girth weld (GWD) defects. Current tool configurations do not provide for direct measurements and assessment of local features; however they do provide key parameters that enhance the performance and precision of susceptibility models developed to assess CSCC and GWD with cracking issues.

In case of pipelines having CSCC susceptibility, AXISS can be used to identify areas where tensile longitudinal stresses have been higher than hoop stresses. These high tensile stress values can be entered in operators' risk models as a key threat indicator. Areas where longitudinal tension is higher than hoop stress are areas of high susceptibility for CSCC.

In the case of GWD with cracks, it is beneficial to identify the welds under high tension. Many girth weld defects can be detected through high-resolution MFL inspection; however, some girth weld defects, including narrow cracks, cannot be reliably detected by MFL survey alone. The introduction of axial strain measurement, IMU bending strain and high definition MFL inspection when considered with other contributing risk factors in a specific threat assessment model has been able to improve the effectiveness and efficiency of dig programs targeted at mitigating the risk of girth-weld failures in mountain pipelines [5]. Figure 7 shows a comparison between cracks identified by the abovementioned threat assessment model and the original X-Ray photos taken during construction.

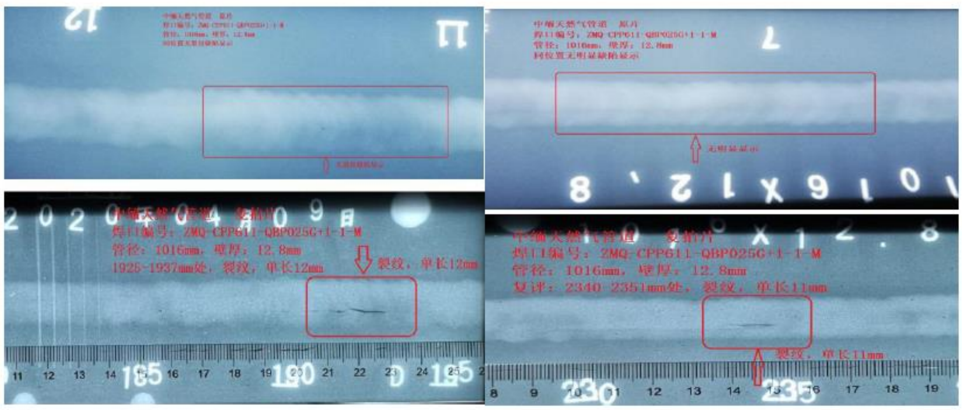


**Figure 7: Example of Cracks Identified Via Threat Assessment Model Vs Original X-Ray Photos during Construction**

**Transition of current infrastructures for Hydrogen**

With the introduction of hydrogen into existing pipeline networks infrastructure, there is ongoing work to determine the longer-term effects of the presence of hydrogen and its influence on existing damage mechanisms [Ref 17-,18-]. Within existing damage models, hydrogen ions permeate into steel causing an embrittlement of the material. This embrittlement effect alters, and potentially accelerates time-dependent defects such as cracking.

While current practices of integrity assessment may use conservative values for material and fracture properties such as toughness, the applicability of altered stress concentration factors for defects become forefront because the material properties themselves may require consideration of embrittlement as well as the more extensive presence of external loading factors leading to non-trivial longitudinal strains within the defect. Conventions in growth modelling for time-dependent features may revert into fundamental "change" detection and monitoring of defects in the near term because of assumptions made for the localized defect as well as an extended consideration of multi-faceted stress/strain conditions.

**Use in advanced integrity assessments and role in Engineering Assessment**

Engineering Critical assessments (ECA) are recognized to be a method to justify maximum allowable operating pressures and safe operations of a pipeline. Within basic threat assessments, defects may be considered as isolated or under influence of the hoop stress due to the pipeline operating pressure. With other loading conditions, non-conventional stress/strain distributions result from more than just the stress concentration of the defect (Figure 8), and require a more detailed analysis and assessment that includes the influencing factors of the environment and conditions around the threat.

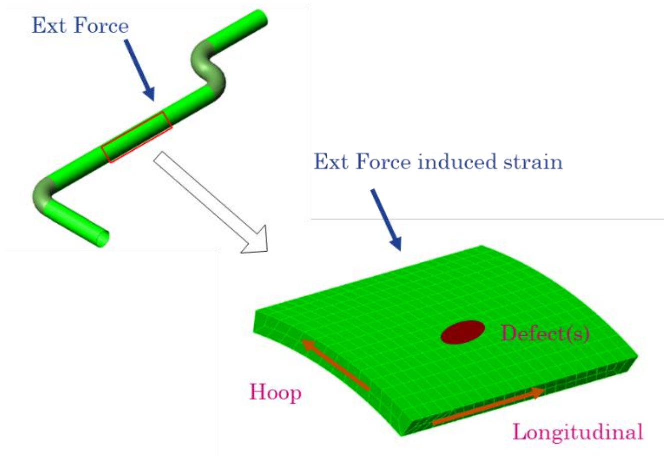


**Figure 8 Schematic of loading conditions and strain consideration around a conventional defect**

Existing comprehensive methods for Fitness for Service provide guidance for "Level 3" assessments which is considered the highest level of comprehensive review and assessment of the threat situation and is intended to have all expected influential factors considered, including for interacting threats and conditions. Finite Element modelling and analysis (FEA) and related analysis is noted as a practice. As such, all loading factors, localized material properties, allowances for residual stress distributions (prior loading histories), pipe geometry as well as the defect(s) geometry are included in the assessment.

## Feeding Learning Forward

### Pipelines Stress Landscape

The AXISS system is a primary component in the geohazards risk management toolbox of many operators in different regions around the world. But it is clear that the more an inspection can do to enhance understanding of the pipeline condition at all locations in all circumstances, the better will be our ability to guarantee effective and efficient structural health monitoring.

From the experiences and learnings gathered over ten years of running AXISS, it is observed that pipeline operators are expanding from critical feature flaw identification towards methods that include a more refined understanding of their pipeline system's stress/strain landscape. To achieve that, both strain capacity and demand of a given pipeline needs to be known with a higher degree of certainty. Strain capacity is a structural/mechanical characteristic that can be calculated using the information, such as as-builts or similar highly detailed representations of actual pipe conditions and material/fracture properties.

In general, pipeline strain capacity is as-designed except for locations suffering stress concentrators (e.g., corrosion, cracks) or geometric deformations (e.g., ovalities, dents). Total stress/strain demand is dynamic and is usually unknown because it is the result of all the loads acting on the pipeline of which some are known (e.g., operational loads) and some are unknown (e.g., environmental loads, residual stresses from manufacturing and construction defects). Knowing both stress/strain capacity and demand enables operators to perform fit for service assessments accurately with limited assumptions. Measuring strain components in the longitudinal direction only (specifically in the elastic region) is a known limitation with today's assessment opportunities which leads operators to make assumptions especially at locations subject to residual stresses (from manufacturing or construction) or stress concentrators. These assumptions cause risk mitigation uncertainties which will likely be over conservative (extra cost) or potentially underestimated which may lead to pipe failures.

The main focus of recent development programs at Baker Hughes targets the advancement of the AXISS service to measure total bi-axial stresses in both elastic and plastic regions. Measuring total bi-axial stresses in the axial and circumferential directions provides a full and accurate knowledge of the total stress/strain demand, which, in turn, enables operators to have the complete picture of their pipeline system's stress landscape.

The pipeline industry has looked to improve methods, technologies and techniques to encompass all forms of threats and ensure overall pipeline integrity throughout the pipelines' lifecycle. The key parameter for a pipeline's pressure containment capacity, relates to the hoop stress that is generated because of the pressure loading. Across all segments and locations, this then generally defines the limit of operation of the pipeline system as MAOP. Anomalies or conditions that effectively reduce the pressure containment capacity are of primary interest as threats.

To that end, the evaluation of pipeline integrity typically involves an inspection regime to identify flaws and defects, such as cracks, metal loss, etc., then data is utilized in conjunction with an engineering assessment to determine a basis of the severity of the defects. Assessment methods for such flaw-based defect centric "stress concentrators" will consider known operational parameters including pressure and related hoop stress capacity limits, but it must also include a significant degree of conservatism (a safety margin), in order to account for unknowns such as residual stresses. These residual stresses arise from the material history, fabrication, ground movement, and in-service damage.

A reliable estimation of residual stress is difficult, and so estimates are necessarily conservative. Further, the equations used by defect assessment methods are generally based on correlations between hoop stress and burst pressure and make no allowance for longitudinal stresses. Longitudinal stress/strain resulting from operational and external loading (e.g. geohazards) plays a role. Where such loading may be present, further conservatism is then required and a fundamentally expanded approach for assessment of severity of localized defects.

Establishing some basis or representation of multi-component loading cases provided a strong motive to develop a new technology that would be an extension to the ILI axial strain measurement tool and at the same time fulfil the industry call to enable operators to understand total bi-axial stress in pipelines. Therefore, the focus of recent development program targets is the advancement of the axial strain tool to measure total bi-axial stresses in both elastic and plastic regions. Measuring total bi-axial stresses in the axial and circumferential directions provides a full and accurate knowledge of the total stress/strain demand, which, in turn, enables operators to have the complete picture of their pipeline system's stress landscape.

**AXISS System Advancements**

To control the entire pipeline stress/strain landscape, integrity engineers need to know the total bi-axial stresses resulting from the following:

1. Active operational and external loading
2. Residual stresses resulting from historical loading conditions caused by manufacturing and construction processes
3. Stresses at geometric deformations (e.g., dents and ovalities)
4. Stresses at stress concentrators (e.g., corrosion, GWD and cracks).

As a result, development of a tool configuration that targets both active operational and external loading, and residual stresses is ongoing. The following sections will summarize the advancements introduced to the configuration of the new generation of tools geared towards geohazards, active operational/external loading and construction/manufacturing residual stresses.

**Bi-axial Stress Measurement as ILI**

With the next generation of the AXISS system, bi-axial stress technology will deliver predicted bi-axial stresses in both axial and circumferential directions in the pipeline wall. This capability will enable accurate estimates of equivalent active and residual stress along the pipeline and enable more informed decisions concerning integrity of a pipeline in cases of combined pressure and geotechnical loading.

**Measurement in Both Elastic and Plastic Regions**

It is evident that pipe sections that are under active plastic deformation are prone to be elevated risk zones. Over the years, operators have expressed the need for the following additional capabilities as requirements:

- Ability to measure stresses in plastic region in addition to the elastic region.
- Ability to quantify strains in plastic region in addition to the elastic region.
- Ability to demark between stresses/strains in elastic and plastic regions.

The new AXISS sensor measures bi-axial stresses in both elastic and plastic regions.

Elastic-Plastic measurement is a new advancement that will achieve the three operators' requirements mentioned above and will also enable more information to be reported and evaluated by the operator:

- Identification of plastically deformed regions

- Threat quantification and prioritization of high-risk zones within plastically deformed pipe sections
- Understand the influence of the stress history of the pipeline through manufacturing and construction
- Quantify residual stresses and understand their influence on operational active loading and stress concentrations.
- Assessment of high stress concentration zones upstream and downstream of GWD
- Prioritize and optimize repairs or mitigation actions for the above.

**High Axial Resolution**

Geohazards are macro features that extend over long distances; however, they result in threats that can occur over short distances due to construction, manufacturing and stress concentration. Where these are critical considerations, a higher axial resolution of stress measurements can be advantageous. The axial resolution will be increased to approximately 25 mm (dependent on tool speed), which will:

- Enabled refined girth weld strain assessment.
- Enable more precise integration and alignment with other inspection data for critical flaw integrity assessment – including level 3 fitness for purpose assessments.
- Increase Probability of Detection (POD) and Probability of Identification (POI) of higher risk conditions from operational and residual stress areas interacting with other stress concentrators.

**Change Monitoring**

Monitoring high strain features through run-to-run analysis is essential in many situations, especially geohazards. One of the main product requirements of the next generation of stress and strain measurement systems is to ensure backwards compatibility in reported results and comparisons. This will enable run-to-run analysis of historic axial strain values delivered through legacy monitoring programs and allow valuable comparisons of critical changes in key parameters and conditions, while taking advantage of the more advanced capabilities and deliverables of the new AXISS technology.

**Conclusion**

Over the last 10 years, combination strain measurement in-line inspection to determine bending and axial strains has proven to be the most effective means to assess the impact of pipeline movement and loading due to geohazards and other causes over the entire line length. Through the operational experience gained working with the reported strain data and the real-world decisions that needed to be made, operators have provided valuable insights into technology refinements and advances that will further improve the effectiveness of the application of the technology within their integrity programs.

A new ILI bi-axial stress tool has been developed with advanced performance and specifications to remove remaining gaps in necessary information, that currently have to be estimated in order to complete comprehensive fitness for service assessments. Furthermore, with these capabilities, it is fully anticipated that ILI stress and strain measurement of pipelines will play an increasing role in regular pipeline monitoring, validation, and in the energy transition.

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