Advancements in In-line Inspection Based Bi-axial Stress Measurement Technology to Manage the Total Stress Landscape of Pipelines

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Abstract

Over 15 years ago, pipeline operators requested the development of an in-line inspection (ILI) axial strain measurement tool to support their geohazard management programs. Since then, Axial Strain Measurement Inspection Service (AXISS™) has been employed on over 15,000 miles of pipeline with many high strain locations successfully identified and mitigated. Like any new technology, it took the axial strain tool a few years to become a unique, established and proven tool for a pipeline operator to assess geohazards, movement and other strain-related threats.

Over the years, the operators' experience has provided key insights as to where the current technology strengths lie and of course where the provision of additional information could further enhance their integrity engineers' more complete understanding of stress and strain-based threats to then develop proactive mitigation strategies and importantly conduct more cost-effective repair programs – ensuring their pipeline's safe and continuing operation.

This paper presents a response to these learned and clearly defined needs. It introduces a new bi-axial stress measurement inspection technology, AXISS™ EPS, that adopts these required advancements by providing detailed information on the entire stress landscape of both active loading and residual stresses. The proprietary sensing technology used by this new tool is an evolution of a mature stress measurement technique that has successfully delivered bi-axial stress measurements for steel structures for the last 3 decades in a range of industries including flexible pipeline riser systems in the offshore oil and gas industry as well as nuclear, automotive, aerospace and rail.

This paper provides a comprehensive overview of the new bi-axial stress tool technology, and a summary of the testing validation and verification program. By focusing on the proven performance, the paper will demonstrate the advancements introduced to the AXISS EPS system versus the previous AXISS system, that provide operators an understanding of their pipelines' total stress and strain status in both the elastic and plastic regions, which in the past would rely on key assumptions to conduct assessments. Using measured condition data will lead to optimized fit-for-service decision-making. In addition, there will be a discussion on how these new advancements will enhance the integrity engineering assessment for high-risk zones such as bends and girth welds.

Introduction

Many pipeline systems cross landslide areas and/or areas of settlement/subsidence (See Figure 1). Techniques for identifying, characterizing, and monitoring these hazards are well established, one of which is the use of inertial surveying (IMU) data in the determination of bending strain both post construction and operation which has become common practice since its introduction in the late 1980's.

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Figure 1: Landslide movement parallel to pipeline

However, the use of IMU for pipeline strain monitoring is limited as it provides strain values due to pipeline bending only and therefore does not represent the total longitudinal strain in the pipeline. Furthermore, given that strains are calculated directly from high accuracy pipeline curvature measurement (out-of-straightness), bending strain measurements in field bends, as operational strain, cannot be determined to the accuracy as expected in “straight” pipe. In such an assessment, the component of pure axial strain that the pipeline is experiencing is needed or must be assumed. Typical practice has been to expose the pipeline for the installation of surficial point measurement pipe monitoring (primarily strain gauges) or destructive testing (such as cut-outs). Methods of stress/strain measurement, including the installation and use of strain gauges, are highly localized and only allow for the determination of change in strain going forward from the date of the gauge installation. This approach can be effective for known areas of developing axial strain as it may provide means to monitor such areas of concern. However “known” is only established for areas of loading as have been determined through risk assessment or through known geohazard events such as flooding and other forms of ground movement.

Given a rising industry focus on Geohazard management and the potential impact on pipeline safety, integrity and operations, four North American pipeline operators and Baker Hughes formed a joint industry program (JIP) in 2006 to develop an in-line inspection tool that could directly measure the axial strain on a pipeline to support the data provided by IMU, and to identify unknown areas of high axial strain from movement or construction thereby enabling more informed integrity assessments. In 2010, the first prototype axial strain tool was introduced and verified [1]. As a result of the successes of the extensive validation program [2], the axial strain tool measurement was commercially launched as AXISS in 2014.

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Learning from Experience

After 10 years of successful axial strain ILI surveys, the tool has been used globally to support operators' geohazard management programs in over 15,000 miles of pipeline. During that time, many pipeline threat mitigation measures have been completed on approximately 1,200 identified features. The application of the AXISS technology successfully fulfilled its objective and it has been utilised in a wide range of applications [3,5,6,7] such as:

- Strain identification and monitoring
- Evaluation of total longitudinal strain demand
- Assessment of the effectiveness of strain mitigation activities
- Circumferential stress corrosion cracking & girth weld cracking susceptibility modelling
- Identification of residual construction stresses

With the considerable experience gained working with stress and geohazard industry experts on real-world scenarios, shortcomings in the first-generation inspection tool were recognized and areas for technology advancement identified. 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 control the entire pipeline stress/strain landscape, integrity engineers need to know the total bi-axial stresses resulting from the following:

- Active operational and external loading
- Residual stresses resulting from historical loading conditions caused by manufacturing and construction processes
- Stresses at geometric deformations (e.g., dents and ovalities)
- 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.

To achieve that, both strain capacity and demand of a given pipeline needs to be known with a higher degree of certainty. 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). Having only bending and axial strains from the inspection tools (specifically in the elastic region) is a known constraint with today's assessment opportunities which leads operators to make assumptions especially at locations subject to residual stresses (from manufacturing or construction) or stress

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concentrators. These assumptions cause risk mitigation uncertainties which will likely be over conservative (extra cost) or potentially underestimated which may lead to pipe failures.

Key Requirements

Resolving the identified remaining needs of the regular users of the technology was the primary objective for the development of a 2nd generation inspection tool for Elastic-Plastic Stress (AXISS EPS) tool. The following targeted improvements were defined as new key system requirements:

Bi-axial Stress Measurement

Measuring total bi-axial stresses in the axial and circumferential directions to provide 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.

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:

- 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.

High-Resolution Inspection for Geohazards

Geohazards typically occur over larger spatial areas relative to the pipe right of way; however, their influences on localized threats due to construction, manufacturing, and stress concentration e.g. girth-welds, dents, corrosion, hard spots etc. can occur over short distances. Where these are critical considerations, a higher axial resolution of stress measurements can be advantageous. An axial resolution close to the defect size being assessed is advantageous from an assessment perspective.

Measurements in Bends

The current generation system design does not ensure full sensor contact on the intrados and extrados of bends in all cases. With the development of differentiation and measurement in both elastically and plastically deformed pipe this capability will provide additional key insight to integrity engineers on known critical zones within their systems.

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Bi-axial Stress Sensor

Applications

Figure 2: Example applications for inspection of stress levels. Upper aerospace bearing robotic scanner, railway wheels, automotive chassis. Lower MAPS-SFT Pig.

At the core of the inspection tool is the proprietary MAPS (Magnetic Anisotropy & Permeability System) [4] technology which was developed initially to non-destructively measure absolute biaxial stress levels within the near surface of industrial plant components. Sensor designs can be tailored for different applications, with defined spatial resolutions, measurement depths, speed of measurement, and stress accuracies within the requirements envelope. The operational specification drives the hardware design using physics-based analytical models. The technology has been successfully applied in the Oil & Gas, Aerospace, Automotive, Rail and Power generation industries for a wide variety of applications. See Figure 2.

Measurement Method

In ferromagnetic materials (e.g., ferritic steels) the magnetic interaction between neighbouring atomic moments in the lattice is sufficient to align them into magnetic domains, the size of these domains being an energy minimization between magnetostatic and magneto-crystalline anisotropy energy. This same atomic interaction results in a small lattice strain (~10 $\mu\varepsilon$), known as magnetostriction, which is positive in steel.

When external forces are applied, the angular distribution (direction) of the magnetic domains changes by the movement of the domain boundaries, such that the fraction of domains aligned along the maximum stress axis increases while that along the minimum stress axis decreases, reducing the total elastic energy within the volume. Consequently, application of an external magnetic field more readily magnetizes (aligns) the domains when it is applied along the tensile stress axis, and thus the

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magnetic permeability is higher in this direction. Conversely the permeability is reduced when the field is applied along the minimum stress direction. Thus, these stress driven changes mean that the magnetic properties are functions of the stress tensor and, as a result, changes in magnetic signature can be used to deduce the underlying state of stress.

Inspection Tool System

The objective with the AXISS EPS tool concept was to re-use proven components of the design wherever possible. The system runs in combination with a Magnetic Flux Leakage (MFL) tool as the previous strain measurement tool to maintain the two benefits of i) ensuring optimised tool accuracy by pre-conditioning the pipeline prior to measurement to limit hysteresis effects and ii) to allow efficient operations needing only one inspection to gather both routine corrosion, caliper and IMU simultaneously with the strain data.

Given the harsh operating environment the tools are exposed to (particularly in gas lines), it is key to mitigate mechanical and electronics reliability risk by the adoption of well proven subsystems whenever possible. In this case, sensor arm and housing, sensor multiplexing electronics, odometer, pressure vessels, suspensions and primary electronics/storage were adopted from MFL tools proven to have >95% run success over many thousands of runs. Furthermore, by capturing the bi-axial stress data perfectly synchronised with the other sensor systems, onboard data integration and alignment is eliminated with the MFL, calliper and IMU which all play a critical role in the interpretation and correct classification of the bi-axial stress data into reportable features.

The tool configuration (See Figure 3) involves 16 stress sensors, with 8 sensors at the front and another 8 sensors will be deployed at the back of the vehicle module, orthogonally mounted to provide bi-axial stress measurement. These sensors are equally separated by 45° and were assessed optimal for accurate geohazard assessment and macro stress features and for the regression models used to estimate maximum hoop stress values.

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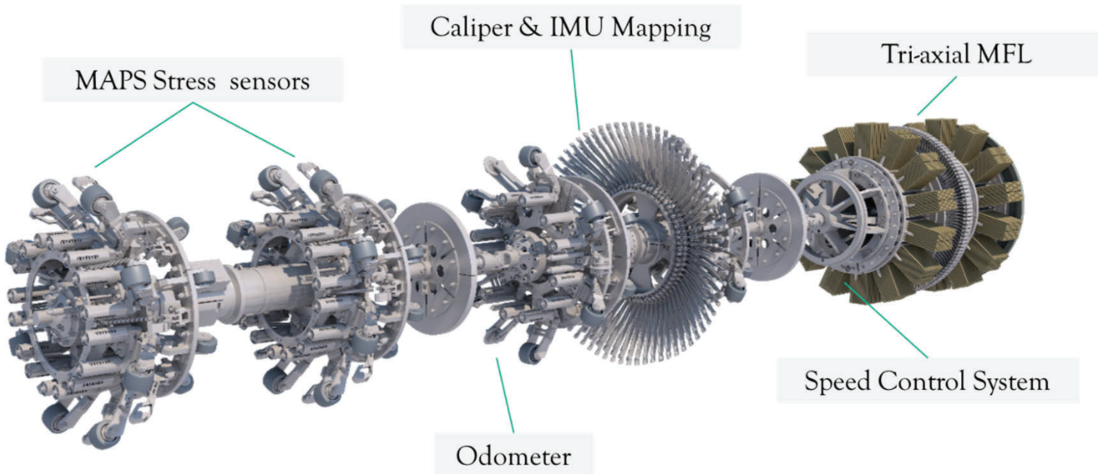

Figure 3: 36” MagneScan™ MFL with AXISS EPS combo configuration

Managing Technical Risk - Essential Variables

Best practice for ILI inspection tool development starts with ensuring a good understanding of the essential variables that could influence the overall system performance and importantly how to control their influence under often varying operating conditions. Prototype testing is aimed at rapidly targeting areas of the tool concept design and associated essential variables that pose the highest areas of technical risk. Conducting these tests early ensures that all identified risks are “solvable” and that the targeted specifications and performance are achievable, or at least any compromises understood early in the program. Overall, this approach typically optimises cost and schedule and the likelihood of success in developing what are highly complex systems.

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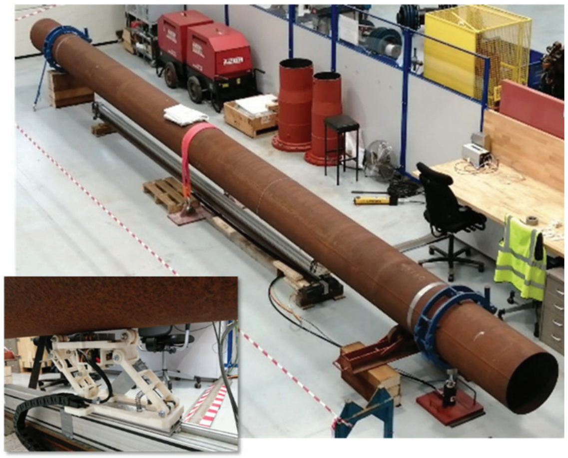

Figure 4: Prototype testing - linear test rig showing -detail (insert) of dynamic sensor carrier

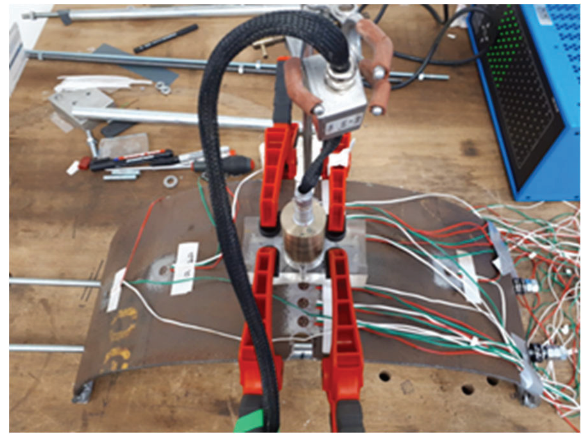

Figure 5: Validation sensor response in elastic and plastic regions

In this case, a number of concept areas and essential variables were identified and addressed through a rigorous prototyping phase of the project. Amongst the variables considered assessed were:

- Sensor design
- Sensor housing
- Sensor Lift-off and tilt
- Static stress measurements
- Dynamic stress measurements
- Material type
- Temperature and Pressure
- Measurement Accuracy
- Maps sensor response in plastic region

Additionally, given the requirement to be able to reliably conduct run to run comparisons between the previous AXISS and new AXISS EPS systems, comparative measurements were collected with demonstrated agreement and functionalities.

Key findings:

- The MAPS sensor was found to be both more accurate than the earlier generation sensor in static performance and demonstrated improved sensitivity in compression.
- Feasibility of calibrating plastic response was confirmed
- Lift-off and tilt calibration was confirmed

Additional details on prototype testing have been previously published. [2]

System Development & Validation

For the overall ILI tool system, a 3 stage validation process was adopted:
Stage 1 – Subsystem testing (sensor assembly performance and durability testing on drum rigs)
Stage 2 – Pull-testing
Stage 3 – Field Trials

Subsystem Testing

The ILI system comprises several subsystems: Mechanical carrier (tool modules), Maps Sensor Probe, Probe excitations electronics, sensor data multiplexing, electronics system and data storage, stress conversion algorithms and visualization, analysis and reporting software. Specific programs of functional performance testing were performed to validate technical requirements and performance specifications were met prior to integrated system testing. Sensor measurement accuracy, sensor durability, signal repeatability (See Figure 6) and software user acceptance testing are examples of subsystem function testing conducted. The stress conversion algorithms include calibration functionalities using the as-measured pipe wall readings for the various essential variables. Detailed calibration experiments were conducted, and calibration libraries established to allow pre-processing of the tool readings into corrected stress values for analysis and determination of strain. Specific material calibration is needed to match the grade, vintage and manufacturer of the pipe. This process is conducted prior to finalizing analysis to ensure stress values are within tolerance.

Given the reliance on the MFL, IMU and Caliper data for the correct interpretation of the stress/strain events, the analysis software has been developed within the existing MFL tool analysis software to simplify aligned data visualization and run-to-run comparison of all data sets in a single environment.

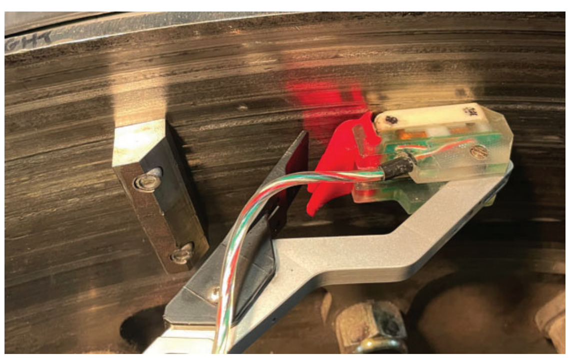

Figure 6: Drum rig testing to establish sensor durability and signal repeatability

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Pull Testing

In August 2024, subsystem validation and tool manufacture of the 36” AXISS EPS system was completed, and the inspection system was ready for initial validation. Pull testing was conducted at Baker Hughes’ ILI headquarters in Cramlington, UK. 36” x 12.7mm wall thickness Grade X65 pipe was chosen for the test. Ten strain gauge rosettes were applied to the top and bottom of pipe to measure change in applied axial and hoop stresses. Three loading conditions were established for the pull-throughs:

- Pipe supported and held level
- Pipe sagging under its own weight
- Pipe unsupported and weighted with 4 tonne weight

Figure 7: Pull rig in unloaded and supported condition.

Figure 8: Unsupported pipe under bending due to 4 tonne static weight

The first generation AXISS was configured with a 36” Magnescan tool and 28 pulls in straight and sagging conditions were performed. The system was then converted into an AXISS EPS configuration and a further 30 pulls made with the same loading scenarios. The system functioned as expected with 2.7Gb of data being collected successfully with data recorded at an axial resolution of 0.8”. Strong agreement was achieved with the AXISS EPS results and strain gauge measurements.

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 system 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.

However, comparison of the old and new technologies turned out to be more challenging than expected for two reasons. First, the sensitivities of the two systems were different (known at prototype testing), and secondly, the fact that the length of pull test was short relative to typical real-world pipe strain features resulting from ground movement. This scenario turned out to be material because the averaging techniques, as typically used to identify features through the dynamic “noise” created as the tools traverse the pipeline, could not be applied effectively thus making a clear comparison of the

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systems very challenging. Fortunately, however, a contingency plan was in place, and an opportunity arose almost immediately with a Canadian operator where we were able to “piggy-back” a field trial on a commercial inspection in a segment of pipe that had been previously inspected with AXISS. This was an ideal scenario to evaluate the requirement to ensure that run-to-run comparisons of the systems were possible, determine accuracy and at the same time carry out a full line system test.

Field Trials

Figure 9: 36" AXISS EPS preparing to launch for first field trial

A 49-mile pipeline segment in Canada was chosen for the Field Trial. The last AXISS inspection was made in June 2023 and this section was ideal due to the active areas of ground movement and previously identified areas of activity that were being monitored. This was an ideal opportunity to establish a true baseline of the run-to-run capability of the two systems and the effectiveness of AXISS EPS to take forward the monitoring of the lines with its advanced deliverables over the single axis measurements.

The inspection tool was launched in late October and was received the following day in excellent condition. Data quality assessment showed some minor data interruptions but did not result in any areas of unanalyzable data. The cause of these interruptions was quickly identified and permanently mitigated.

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At the time of writing this paper the authors are in the process of evaluating the data. Initial investigations are highly promising. As an example, Figure 10 shows area 1, a 0.75-mile segment of pipe where comparable measurements are compared to represent axial strain. As can be seen overall responses are in strong agreement both in terms of the averaged values and smoothed data (used to remove dynamic noise and impact of localized features such as welds.

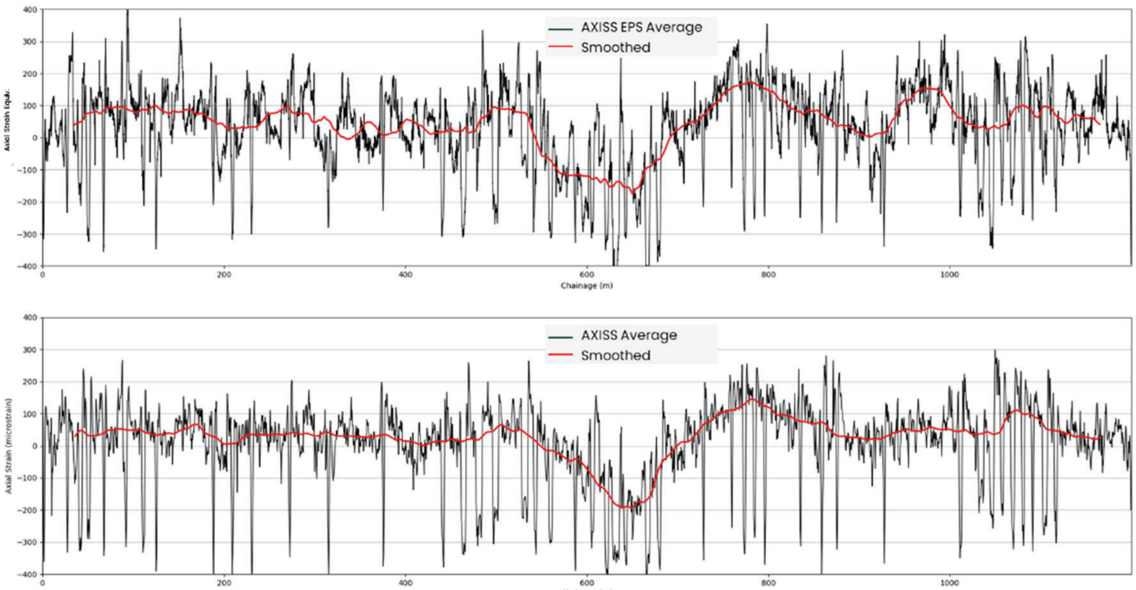

Figure 10: Comparison of run-to-run performance between 1st generation AXISS and AXISS EPS in Area1

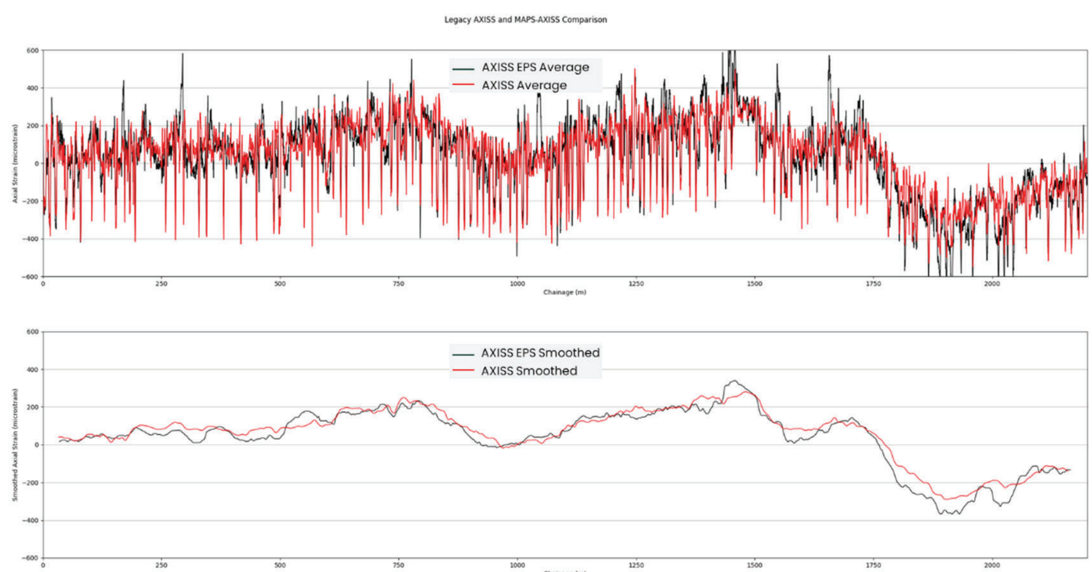

Figure 11: Comparison of run-to-run performance between 1st generation AXISS and AXISS EPS in Area 2

Figure 11 shows Area 2, a specific 1.2-mile area of the pipe. In this case the red line is the measured strain from the generation 1 AXISS run and the black line indicates the new AXISS EPS data. The upper chart is the as-measured data for both inspections. The lower chart is the comparison of the smoothed data sets which better represent the strain condition on the pipeline. As can be easily seen, the overall profiles are very similar with apparent higher sensitivity at a local level with the new system. The repeatability of the two systems was within a range of 100µε which would have been considered very good for the first-generation system.

Detailed evaluation of the data is ongoing, and it is expected that completion of validation testing will complete early in 2025. Currently, additional tool sizes are under development, and it is expected that tool sizes 12" to 48" will be available within the next 6 months.

Conclusion

Over the last 10 years, Axial Strain measurement of operational pipelines using in-line inspection has established itself as reliable means to support integrity assessment and monitoring of pipeline movement and loading. Many important strain features have been identified and either remediated or monitored following assessment.

Real-world experience and customer feedback has led to a second generation of inspection tool being developed specifically to improve the effectiveness of in-line inspection for geohazard monitoring within pipeline operators' integrity programs. By delivering direct measurement of bi-axial stress and differentiation between elastic and plastic stresses, a step change is available in the information pipeline integrity engineers need to remove the unnecessary conservatism applied in the absence of having a complete picture of the stress landscape in their pipelines. With these 2nd generation 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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