DEVELOPMENT OF A PIG BASED INSPECTION TOOL UTILISING MAPS STRESS MEASUREMENT TECHNOLOGY

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INTRODUCTION

Measurement of pipeline parameters is of major importance in the detection of defects in pipelines, regardless of the means through which they arise. The negative effects of these defects may lead to reduction of throughput in the line, and, if not detected and remedied, unsafe operation may occur. For this reason there has always been a desire to understand in detail pipeline condition.

Over the history of pipeline operations, increasingly sophisticated techniques have been used to make measurements. Magnetic flux leakage and ultrasonic tools can be used to make measurements of wall loss, and other conditions. Caliper tools have been used to measure dents and other mechanical conditions. More exotic tools have been proposed from time to time. All of these techniques make a big contribution to allowing evidence-based decisions on the maintenance and rehabilitation of pipelines to be made.

It has been recognised in the industry that direct measurement of stress in pipelines could be a major tool in toolkit used for pipeline condition assessment. In the relatively recent past, the only reliable means to measure stress were either destructive, or non-portable. Advances in the understanding of magnetic properties of metals, and their relation to stress have allowed a number of potential measurement techniques to be proposed. Many of these have been based on the Barkhausen effect, but other concepts, such as non-linear harmonics have also been investigated.

Weatherford’s Pipeline and Specialty Services group, working with ESR Technology, are in the process of developing a pig capable of measuring the absolute biaxial stress in pipelines, based on ESR's proprietary MAPS measurement system.

MAPS BASICS

It is well-known that the magnetic properties of ferromagnetic materials are sensitive to internal stress. Based on a deep understanding of the underlying physics of this effect ESR Technology have developed a novel multi-parameter magnetic system to measure absolute biaxial stress. This system, known as MAPS, incorporates several techniques into a single unit enabling absolute principal stress levels to be determined non-invasively in a wide range of industrial plant and components made from steel and iron. This measurement of a broad range of magnetic parameters allows effects that can confound other magnetic techniques (such as micro-structural changes, poor surface quality and geometry changes) to be reduced or eliminated. A key feature of this technique is that absolute stress is measured, i.e. including the contribution of residual stresses in the material from manufacture etc.

MAPS is non-contacting with the allowable separation between the surface and probe depending upon the size of probe but typically 0.5-5mm. Measurement is possible through non-magnetic coatings (including paint, plastics, rubber, ceramics, rust, etc) and hence no surface preparation is required. MAPS measures the average stress over a sampled volume of material where the volume is controlled by the size of probe (which typically varies from 4mm to 100mm diameter) and the depth of penetration into the steel. The depth may be altered according to the measurement frequency used and is typically 0.15mm to 7mm. Figure 1 shows a typical MAPS probe head.

Typical measurement accuracy for MAPS can be a few percent of total stress from compressive yield to tensile yield (where the range may be 1000 N/mm or more). The accuracy in any application depends upon many factors including the steel grade, size of probe used, frequency of operation, access to the steel surface and the quality of the MAPS calibration (performed on a steel sample of similar steel type but not necessarily the same form). Results from MAPS compare well to other absolute stress measurement techniques.

ESR presently has a wide range of applications under development. The technology can be applied to non-contact online measurement of steel products (strip, sheet, plate, tube, pipe, rail, etc) or other applications such aside from pipelines (pigging), coiled tubing, wire rope, rail track, etc. The potential benefits include real time warnings of high stresses, feedback control of the manufacturing process, or product quality control documentation. As an example a bearing raceway inspection system was developed to measure the surface compressive stresses (desirable for increased fatigue life) over the complete bearing surface (>1000 biaxial values per hour) as a replacement for x-ray diffraction, which is limited to single points in limited geometries.

MAPS PIG

The stress measured by a MAPS probe aligns with the probe. For general purpose measurements the probe is rotated and measurements made at set angular increments, thus allowing a search to be made for the in-plane principal stress direction. In an application where the probe moves relative to the measurement surface, as in a pig, there is no time for a rotational search to be made. However, this problem may be overcome by having a series of probes at fixed angular positions and combining the signals from these probes to determine the stress direction. Conceptually this consists of a row of probes mounted one behind the other, with each successive probe measuring in a different direction. Three orientations are required to determine the principal axis stress. Figure 2 shows how this works.

Following successful trials of the feasibility of superimposing separate measurement of this type to determine stress, Weatherford's P&SS group have designed and built a prototype pig to make MAPS measurements of the absolute stress level in pipewall material. The design aims were to hold the probes up as close as possible to the metal, while controlling this stand-off distance, and still allowing the pig to transit a pipe in an acceptable manner. This includes the ability to get past dents and other intrusions in the line and to transit bends.

The main design constraints applied were as follows:

- Measure principal stresses: 0, 45 and 90° sensor configuration.
- 1.5D radius bend passing capability, while continuing to measure stress.
- 10% bore-reduction (dent) passing capability, 16% crash bore passing.
- Operating speed - 0.1 to 4m/s.
- Probe standoff – Minimal, 1 - 2mm

Looking ahead to potential field trials, it was also decided to design the pig to a full field environmental specification:

- Compatible with upstream oil and gas pipeline products, with normal levels of CO_2 and H_2S
- Operating Temperature of -10ºC to 50ºC
- Operating Pressure up to 200 bar maximum

- Operating Range of 72 hours

Figure 3 shows the 24" prototype built for testing purposes.

PROBE DESIGN CONSIDERATIONS

The maps probes are mounted one behind the other to build up a map of the absolute biaxial stress in the pipe.

The pig has a conventional wheeled suspension system to support it near the centre of the pipeline, as well as a separate system used to hold the probes up against the pipe-wall.

An important target for the design was to achieve scalability. Although the prototype only gives coverage of about 1/16 of the pipe circumference a fully populated module would increase this to 25% and with the design allowing for up to 4 modules, this would give 100% coverage. Figure 4 shows the coverage of the pipe achieved on this prototype.

CALIBRATION AND VALIDATION

A key consideration for the development of a successful practical tool is the ability to provide meaningful calibration of the sensor system, and independent validation of the results. This is problematic for pipeline stress measuring systems as these are highly stressed (by internal pressure) during normal operation, and systems capable of making highly accurate, non-destructive determinations of absolute stress are largely limited to laboratory use. For example, the 'gold standard' of non-destructive absolute stress measurement is neutron diffraction, which relies on use of a particle accelerator as a source of neutrons. For this reason, in-situ measurement of stress to validate MAPS results by direct comparison is impractical. By the same token, however, digging up a reported weak section of pipeline and removing to a laboratory for examination also fails to provide the required data. Consequently, each material stress to be measured in a calibration is required, covering known levels of applied stress as measured using strain gauges.

DRIVE-THROUGH TEST PROGRAMME

In earlier testing, dynamic trials based on the superposition of readings had demonstrated that even at relatively high speeds (up to 4m/s) the MAPS probes were quite sensitive to applied stress. Also, issues related to the dynamic nature of the measurement, although reflected in reduced resolution and accuracy (by comparison to the static system), were not so great as to preclude getting useful results from a pipeline pig.
Following on from these previous trials, a drive-through rig for a single set of probes was used to make a first assessment of behaviour of the suspension system, and the ability to generate useful information. (Figure 5) Extensive work on the probe suspension system had refined the initial design to the point where it was felt that the pig was capable of moving through a pipe.

The drive-through rig used in previous testing was re-commissioned in order to assess the dynamic behaviour of the probe carriage design. Figure 5 illustrates the test set-up. This rig consists of a 6m length of 24-in pipe based at Weatherford's Musselburgh site which has a linear actuator slide driven by an electric motor. The tests were performed on a carriage assembly and a set of 3 encapsulated sensors, intended for use on the fully functioning 24-in MAPS tool.

The main aim was to verify the satisfactory dynamic performance of the carriage design in maintaining stand-off and in passing welds. In addition, the ability of the carriage to measure stress was assessed and the correct operation of the data-alignment used to register 0°, 45° and 90° probe readings demonstrated.

A set of stress measurements using a single train of probes with the pipe unstressed, and then raised in the centre using a jack, showed that the probes were working correctly to measure stress. Measurements were made at speeds up to 3m/s.

EXTERNAL STRESS MEASUREMENT

An important part of the test programme was to make independent measurements of stress in the line. Two means were used to achieve this.

Firstly, a set of five strain-gauge rosettes were attached to the pipeline. These were all attached to the central of the three test sections. Four of the five gauges were positioned on the top test piece, and the fifth 22.5° radially down the pipe. These gauges provided a measurement of the relative stress at the outer surface of the pipe as it was successively bent and pressured. The gauges were initially zeroed but effects from heating and cooling of the pipe during the day and night caused these values to vary by the order of ±50 □□, equivalent to approximately 10MPa

The second set of measurements of stress were made with ESR's Digimaps equipment. This is a static application of the same instrumentation used on the MAPS pig and is capable of measuring absolute stress, i.e. including residual stresses. The relatively time consuming nature of the measurements limited the number of points taken. The bulk of the readings were taken at the closest practical point to each of the strain gauge locations.

The MAPS readings themselves were made by sweeping the frequency from 3 to 3000 Hz in order to provide a range of depth penetration, building up a picture of the stress in the line.

BENDING STRESS MEASURMENT

A 24-in pigging loop was constructed at a Weatherford site in Aberdeen to enable testing to be carried out. The intention was both to demonstrate the pigability of the design by carrying a representative number of probes down a length of pipe without hanging up, while maintaining the probes close to the pipe-wall. If this was successful the ability of the instrumentation to directly measure applied stress, and the operation of the logging system, could then be assessed. To do this required both a true pigging loop and the ability to apply levels of stress in a representative, safe and quantifiable manner.

After some consideration, two separate sets of tests were proposed. The test-section for both of these consisted of approximately 34m of X60 pipeline, 610mm OD, 14.5mm wt. This was three sections welded together. For the first set of tests, the test loop consisted of this test-section, flanged at one end and attached to a full-bore 24-in ball-valve and a Barrington style pig-trap (designated 'Trap 1'). The other end of the test section was welded to a second ball-valve, with a second pig-trap (' Trap 2') with a GD Engineering band-lock style closure. Motive power was provided by 2-off HL8M Godwin pumps capable of providing up to 4200 gpm of flow at a pressure of 145psi.

The pumps were connected to inlets on each trap via a network of 10-in pipe. Flow could be controlled through these pipes in order to flow from both pumps in either direction, i.e. from Trap 1 to Trap 2, or vice versa. A similar network of pipe-work was used to return water to a break-tank. A smaller pump could be used to fill and drain the line through connection on the bottom of each trap.

This setup was commissioned using a standard bi-di pig to flush out any issues of operability. The range of speeds achieved was from 0.4 m/s up to 1.1m/s. Figure 6 shows the loop setup.

Following this the MAPS pig was run through the loop a number of times. The pig was removed from the pigging loop at the end of each run and examined for wear and damage. Data from these runs forms a baseline for zero-applied stress.

A second set of tests were then performed with this loop configuration, with the test section subjected to significant bending stress. After careful consideration of the best way to achieve this the method chosen was to use a crane to lift this pipe from the centre of the test section, and then use sleepers to prop the pipe up in its new position. Calculation gave a figure of 214mm as the distance through which the centre should be raised to give a peak axial stress of 40% of yield.

Figure 7 shows the lifting operation.

The pipe was then lifted from point 1.5 m to either side of the centre of the test section. The axial reading on strain gauge rosette 'A', nominally at the centre, was used to estimate the pipe position. The pipe position was then measured to determine whether the lift distance was correct. These techniques agreed well and the final position had raised the line by approximately the required amount. Peak stress was measured at approximately 660 □□, compared to an estimated 1550 □□ for yield. After the pipe was propped up and the crane support removed, this figure fell slightly over the course of an hour or two as the pipe settled on its supports.

A further set of tests were run with the pipe in this position, providing data with a known bending stress.

HOOP STRESS MEASUREMENT

A second rig configuration was used to test the measurement of hoop stress in the line. Measurement of hoop stress in the pipeline was considered key to the successful evaluation of the prototype tool capabilities. However, running the pigging rig at the pressures required to impose a significant stress was considered to be impractical from the point-of-view of a drive system providing both the large flowrates required, and maintaining the system at an elevated pressure.

After a significant amount of thought, the idea of using a wireline unit to pull the prototype through the test-section under static pressure was hit upon. This involved removing one of the pigtraps and replacing it with a blank flange into which a tapped hole was machined. This was used to fix the wireline stuffing box and a grease packing system was then used to make a seal. The wire was then attached to the nose of the pig and used to pull it through the test-section. The cups were removed from the tool in order to reduce resistance.

The system operated by using the grease packing unit to maintain a positive pressure around the wire while using a winch to pull the pig. Figure 8 shows the set up. In this picture the wireline winch is on the right of the photograph with the grease packing unit between it and the pipe.

After the equipment was set up, two tests were conducted. The first of these was a pull test for the wireline unit. With the wire securely attached, a pull up to 2000 lbs-force was conducted to demonstrate that the anchoring system was satisfactory to pull the pig. Following this, the loop was pressured up using a Haskell pump to demonstrate ability to hold the intended test pressure of 50bar.

The general procedure adopted was to pull the pig slowly through the first section of line at about 0.1 m/s until the rear of the pig cleared the ball-valve, then to ramp up to the target speed, stopping 20 feet before the end of the line, and pulling the pig slowly to the end maintaining tension. Figure 8 shows the rig in operation.

The lower test pressure of 4 bar was chosen to be sufficient to activate the tool pressure switch with a margin of safety to allow for pressure loss, with the upper pressure of 50 bar being the maximum allowed for safe operation. This pressure is equivalent to a hoop stress of approximately 25% of yield.

CONCLUSIONS

Weatherford's Pipeline & Specialty Services group have performed a series of tests with a prototype 24-in pig designed to make direct measurements of absolute stress in pipelines. Measurements have been made with both applied bending stress (maximum 40% of yield), and applied hoop stress (maximum 25% of yield). The pig performed well throughout the pigging tests, moving freely through the line. The instrumentation system worked well throughout with stress data collected for all of the conditions.

The aim of this initial work was to demonstrate measurement of stress in realistic pipeline conditions.

To summarise, the MAPS prototype under test system showed:

- An ability to move the sensors along the line without significant wear or damage.
- Sensitivity to stress in both the axial and hoop directions.

Work is continuing on assessment of the data gathered with a view to correlating with the independent measurements of stress made using the strain gauges and the static external MAPS system. Following a successful conclusion to this, the next step will be to make the prototype ready for field trials.

Figure 1 - Typical MAPS Probe

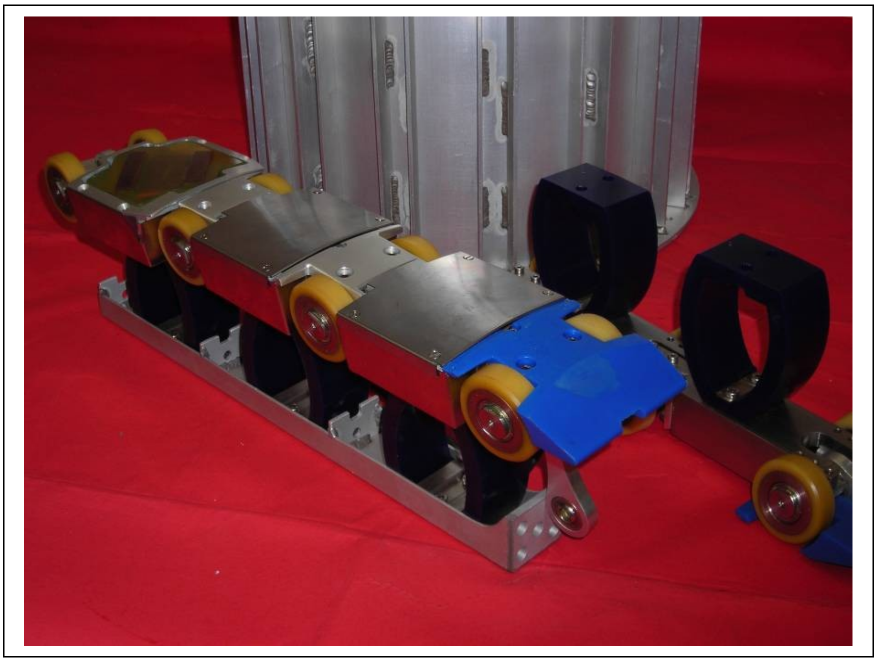

Figure 2 - Probe Carriage

Figure 3- Prototype Pig

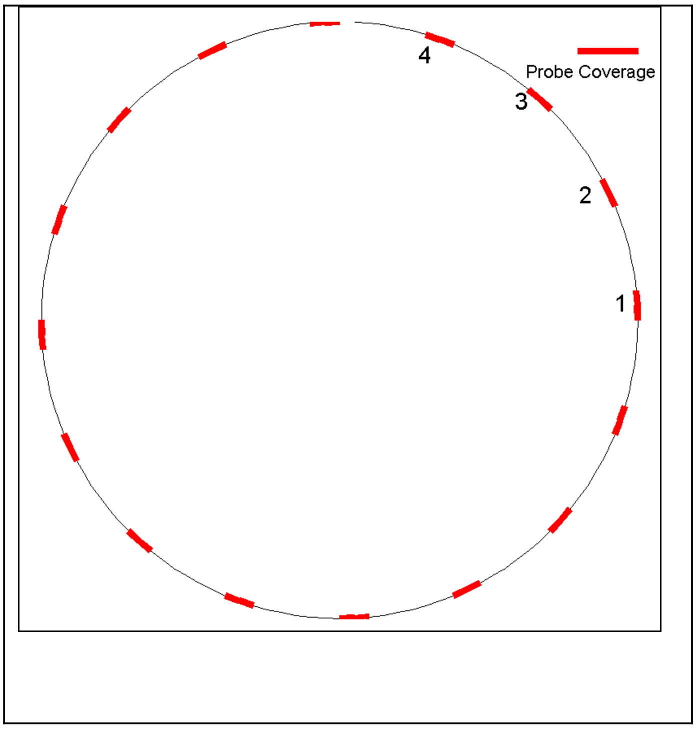

Figure 4 - Sensor Coverage

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Figure 5 - Drive-through test rig

Figure 6 - Pigging Test Loop

Figure 7 - Bending the Pipe

Figure 8 - Hoop Stress Testing