ON-LINE MONITORING OF ABSOLUTE STRESS VALUES IN PIPELINES

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Introduction

A wide variety of means are in use to detect, characterize and measure an equally wide range of defects in pipelines. These may arise from pre-existing conditions, errors in construction, effects of corrosion, accidental damage or other causes. Caliper tools, mapping tools, MFL, EMAT and ultrasonic tools are all used to detect conditions that may result in unacceptable stress in a pipeline. The ultimate aim, for all of these detection techniques, is to prove that the inspected pipeline's fitness for purpose is maintained; and where this is not demonstrated, to provide accurate and reliable information on which to base a rehabilitation program.

In recently years, a number of companies have investigated techniques intended to utilize the dependence of the magnetic response of ferrous materials to applied stress in order to make direct measurements of stress. Most of these techniques have been based on the Barkhausen effect, but measurements based on other phenomena such as non-linear harmonics have also been looked at. This paper discusses the use of an alternative technique based on other magnetic properties that have been shown to allow derivation of a quantifiable relation between the level of stress present in material and the magnetic response. This technique, named MAPS by its developers, ESR Technology, has been employed with considerable success out-with the pipeline industry.

Weatherford Pipeline and Speciality Services are presently working with ESR Technology in order to develop a pig-based inspection tool utilising this measurement technology. The initial aim is to provide a tool capable of diagnosing pipeline problems due to ground movement, spanning and other cause of bulk changes in stress. Refinement of the technique may make it possible to detect local increases in stress due to the presence of dents, metal loss defects etc.

Stress In Pipelines

Global expenditure on construction and maintenance of sub-sea pipeline systems runs into hundreds of millions of pounds a year. Securing their operation on a continuous basis is of paramount importance to the oil and gas industry. In order to ensure that a pipeline is built to standard and continues to operate safely and efficiently throughout its planned life, operators run various types of pigs in their pipelines. For many years the pigs run in pipelines have fallen into three main categories:

- utility - cleaning and swabbing
- semi-intelligent - geometry and data logging
- intelligent – primarily metal loss and crack-detection pigs.

Over the years emphasis has been put on the maintenance and efficient operation of pipelines and this has led to the development of more sophisticated pigs covering all of the requirements of operators. The biggest changes have occurred in the area of intelligent pigs with investment made to advance the various technologies used to ensure the integrity of pipelines. Intelligent pigging has as a result come to be considered as a standard operation in the maintenance of pipelines, and the results obtained are delivered in a form consistent with the operating company’s integrity codes of practice.

More recently attention has turned to improving techniques in areas where the typical metal-loss results provided by intelligent pig surveys cannot provide a complete answer. The key parameter is a pipeline's pressure containment capacity, related to the hoop stress present. This defines the limit of operation of the pipeline system. Longitudinal stress, associated with bends and other pipeline features can also play a role. Evaluation of pipeline integrity can typically involve an inspection regime to identify flaws and defects, such as cracks, wall loss, etc, coupled with an engineering assessment of the severity of the defects. The severity assessment will consider known operational parameters (e.g. that pipe-wall operating stresses may exceed 70% of yield), 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. The reliable estimation of residual stress is difficult, and so estimates are necessarily pessimistic. Nevertheless, there remain pipeline failures resulting from wrongly estimated residual stresses.

The direct measurement of pipeline stresses avoids the need to make unduly pessimistic estimates of residual stress, but may also automatically measure the effects of stress-raising defects such as wall thinning on total pipe-wall stress. Therefore stress measurement is a more direct measurement of pipeline integrity than traditional wall thickness measurement of pipe-wall stresses using ultrasonic measurements or magnetic flux leakage, while at the same time having the potential to remove significant uncertainties in the integrity assessment.

Direct measurement of absolute stress levels in an operating pipeline offers the prospect of an alternative means to detect defects, and to quantify the raised stress associated with them. It also promises to allow direct measurement of stress in pipeline out-of-straightness features, removing dependence on relatively inaccurate estimates obtained from measurements of feature shape.

Maps Technology

It has been known for some time that the magnetic properties of ferromagnetic materials are sensitive to internal stress. Based upon a deep and novel understanding of the underlying physics of this effect ESR Technology has developed the MAPS (Magnetic Anisotropy and Permeability System) multi-parameter magnetic system to measure absolute biaxial stress. 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. By measuring information from many magnetic parameters the effects that confound other magnetic techniques such as microstructural changes, poor surface quality and geometry changes can be discriminated and their effects removed from the stress information. It is important to note that this technique measures absolute stress, ie included 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. By taking a series of measurements to different depths at the same position and employing some mathematics, a true stress versus depth profile can be assembled. Figure 1 shows a typical 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) and with care, MAPS resolution is typically an order of magnitude better than this. Results from MAPS compare well to other absolute stress measurement techniques.

Figure 2 illustrates a blind trial against strain gauges. In this test a length of rail was instrumented with strain-gauges and then subjected to a variety of load conditions. Applied stress was measured from strain-gauges. MAPS readings were similarly made at each of the load conditions. Since the MAPS values are for absolute stress, the values for applied stress are calculated as differences between measurements. These results (Figure 3) demonstrate close agreement between the two techniques. Similarly impressive results have also been obtained in comparisons with x-ray diffraction.

The MAPS technology can also be applied for non-contact online measurement of steel products (strip, sheet, plate, tube, pipe, rail, etc) or other applications such as 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.

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.

<u>Dynamic Testing</u>

A demonstration of the MAPS technology for inspection of pipelines has been performed in a length of 24" pipe. The MAPS probes were mounted in a trolley that could be pulled axially through the pipe at speeds of up to 4 m/s. A hydraulic jack was used to induce stress midway along the pipe. Stand-offs between probe and pipe were varied between 2mm and 10mm, and measurements were made at depths of 1.2mm, 1.0mm and 0.8mm.

The principal aims of these trials were to confirm that the MAPS sensors could accurately measure stress in a situation where relative motion existed between the probe and the test-piece, and that minor variations in lift-off would not compromise this measurement to an unacceptable degree. It was also intended to demonstrate that surface preparation of the metal surface was not required.

The test-pipe section (Figure 4) consisted of a 6m length of API 5L-X60 grade, 10mm wall, 24" pipe welded to a supporting structure 500mm from each end. A second section of pipe was positioned directly below the test pipe to provide a jacking platform to which a 10-ton capacity hydraulic jack was mounted. Open sections at either end of the test pipe allowed access to the trolley. An I-beam ran the length of the test-pipe to which the linear drive mechanism was attached. The hydraulic jack was used to induce stress at the centre of the

test-pipe section. A load-cell between the jack and the pipe measured the total force exerted on the pipe wall.
A linear actuator and controller were selected to pull the trolley through the pipe. A trolley was used to support the probe as it moved along the pipe (Figure 5). It provided a means of adjusting the stand-off between the probe and the inner surface of the pipe.

A set of prototype MAPS probes shaped to match the curved pipe surface were used for the pull-through tests. Two orientations of probes were used, one measuring axial stress and the other hoop (if the principal axes of stress can be assumed to be axial and hoop then only two measurements are required to determine the stress components).

The key factors that influence the stress measurement are lift-off, stress, velocity, and material. A maximum speed of 4m/s was selected for use with the MAPS electronic hardware and probes. Figure 6 shows a direct comparison of signal between repeated runs under load emphasizing the consistency, even in fine detail comparable in level with the noise in the system. This detail, away from the point of application of the load represents the residual stress in the pipe material.

For a second set of trials, strain gauges were bonded to the outside of the pipe so as to monitor the applied strains. Finite element calculations were performed to enable, together with the strain gauges, a prediction of the stress levels on the pipe inner surface where the MAPS probe would scan.

FE calculations and the strain gauges can only assess applied stresses, while MAPS measures the total stresses (residual plus applied). Significant manufacturing residual stresses may be present preventing a direct comparison of absolute values. However changes in the MAPS data between loaded and unloaded conditions are directly comparable, and with the calculated and strain gauge (hoop) stress levels for the pipe inner wall at 45° around the pipe circumference (Figure 7). The agreement between these values and the MAPS measurements appears good for both the profile shape and width.

<u>Conclusions</u>

Weatherford P&SS and ESR Technology have performed a series of tests where dynamic measurements have been made inside pipes, covering measurement of applied (bending) stresses. Measurements were made at velocities up to 4 m/s in prototype systems at 24" diameter with stand-offs of 2mm and up. Magneto-dynamic effects from the motion of the sensors past the metal of the pipe-wall have been characterized and variations in signal due to the velocity and instrument stand-off are described.

The aim of this initial work was to demonstrate a realistic expectation of gathering useable results in situations where the instrument was in motion with respect the material. The technology has previously been used extensively only in situations where the material in which stress was to be measured was accessible using a static application. The dynamic situation also raised issues regarding control of instrument lift-off, data-logging, and position determination. The results of testing to date are considered to be very encouraging, and well in line with original expectations raised by results in static applications.

To summarise the MAPS system showed:

- A good sensitivity to stress with excellent measurement repeatability;
- Reasonably good separation of stress measurement and lift-off variation over a range up to 10mm;
- A reduction in resolution with increasing speed as anticipated;

- A very good correlation between the MAPS measurements and values evaluated from strain gauge measurements and finite element analysis;
- Insensitivity to the surface condition of inspected material.

Work is already well advanced on a prototype pig, which, after testing is expected to be ready for field trials in the summer of 2007. Current designs envisage a pig capable of directly measuring absolute pipeline stress. The expectation is that this tool will be capable of making an accurate map of the stress in a pipeline with a resolution of a few tens of millimetres at an accuracy of the order of 10 N/mm or better.

Figure 1 - Typical MAPS Probe

Figure 2 - Validation Testing Set-up

	Applied Stress (from strain gauges)	MAPS result
	(N/mm)	**(N/mm)**
Load Case A	48.9	48.1
Load Case B	19.6	18.9
Load Case C	48.9	49.8
Load Case D	67.7	68.2

Figure 3 - Strain Gauge Validation Results

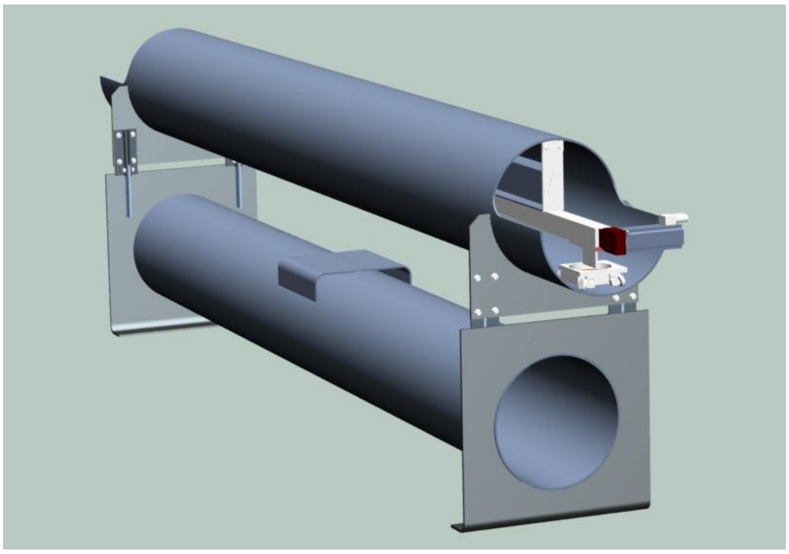

Figure 4 - Test Rig Configuration

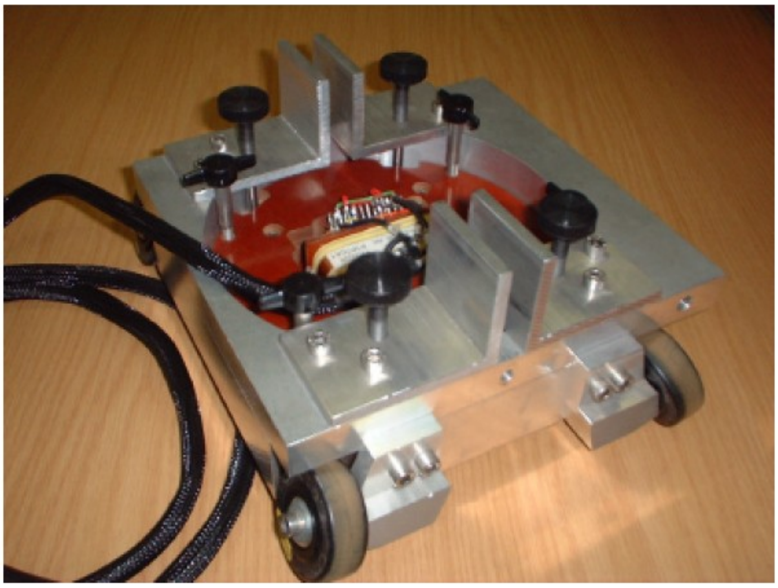

Figure 5 - Probe Support Trolley

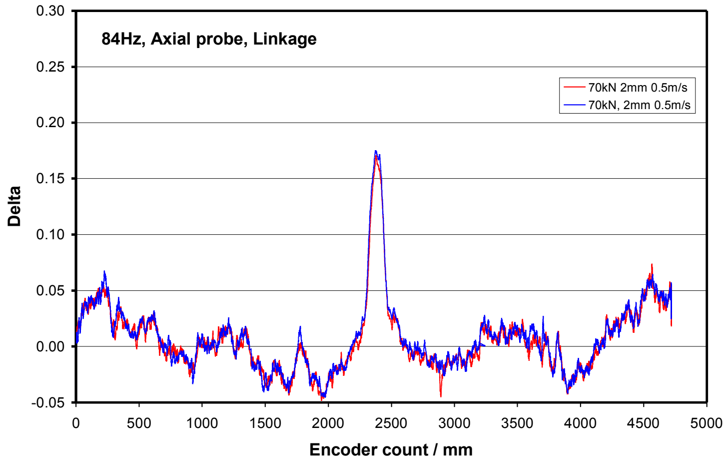

Figure 6 - MAPS Measurement

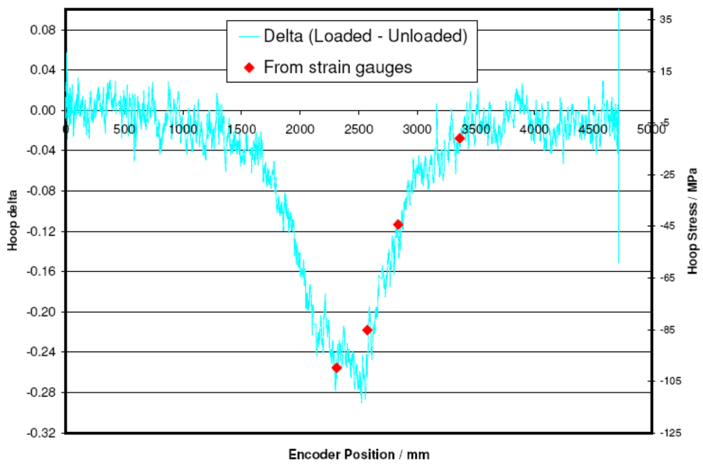

Figure 7 - MAPS Stress Measurement