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IN-LINE INSPECTION OF DENTS AND CORROSION USING "HIGH QUALITY" MULTI-PURPOSE SMART-PIG INSPECTION DATA

Steffen Paeper
ROSEN
Technology and Research
Center
Am Seitenkanal 8
49811 Lingen Germany
spaeper@roseninspection.net

Bryce Brown
ROSEN
North America
14120 Interdrive East
77032 Houston, TX USA
bbrown@roseninspection.net

Thomas Beuker
ROSEN
Technology and Research
Center
Am Seitenkanal 8
49811 Lingen Germany
tbeuker@roseninspection.net

ABSTRACT

A new generation of geometry sensor for ILI tools has been developed. This sensor provides highly accurate geometry data of the internal pipe contour. The technology uses the benefits of a touchless distance measurement in combination with the advantages of a mechanical caliper arm. The complementary interaction allow the measurement of accurate data under demanding operational conditions.

The geometry sensor technology can be combined with a navigation unit and the high resolution MFL inspection technology on so called multi-purpose ILI-tools. The merging of different inspection tasks on a single tool is an economic solution to create and add to an ILI-database for integrity management.

Field experience with this new technology will be discussed, based on more than 500 miles inspected pipeline. Most inspections were performed in the US and Canada. The operational performance of the sensors justified the new design.

INTRODUCTION

The last five years have seen some important changes in the requirements for ensuring pipeline integrity and the associated utilization of in-line inspection (ILI) tools as a primary integrity assessment method. This is mainly reflected in the U.S. Code of Federal Regulations for Transportation of Gas and Liquids (parts 192 and 195, respectively) where more prescription has been given to actionable anomalies or threats to integrity. One in particular is that for the minimum geometry required for the detection, sizing and assessment of dents which could have an affect on the integrity of a pipeline.

Knowingly, as recently as two years ago, the so-called "state-of-the-art" in geometry inspection has been redefined. This has changed both the operators' viewpoint, as well as the

regulators, on ILI geometry surveys from one of asset operation and monitoring to utilizing them as a basis for a defect remediation process.

A novel technology for the characterization and sizing of dents has been developed by ROSEN. This high-resolution ILI technology combines the advantage of a touchless electronic measuring system with the advantages of the well-established caliper-arm tools, allowing full compensation of the sensor bounce under highly dynamic operational loads.

Taking this a step farther, combining this new geometry inspection technology with the already established high-resolution magnetic flux leakage (MFL) or circumferential MFL (CMFL) technologies, offers an operator access to the majority of the repair conditions as outlined in the regulations in a single run, and still not compromising such valuable operational characteristics such as 1.5D bend negotiation.

INTEGRITY MANAGEMENT OF PIPELINES

Integrity management of pipelines in the U.S. is regulated by federal codes for both liquid and gas pipelines.

Both rules contain prescriptive integrity management provisions for the pipeline operator. These prescriptions define limits for pipeline geometric anomalies like mechanical damage and dents. For example, the minimum requirement for the sizing of dents is prescribed: a high-resolution geometry tool must be able to detect and size dents with a depth greater or equal to 0.25" (6.35mm). Additionally, a process for inspecting against provisions of a management based rule, rather than inspecting for compliance with a purely prescriptive rule is encouraged [1].

The discussion in recent literature about possible failure modes of mechanical damage in pipelines is strongly recommending: anything but a plain dent must be analyzed

carefully and with relevant expertise. The latest investigations confirm the dependency of failure pressure on the dent shape rather than on the dent depth [2], [3]. This is also reflected in the regulations, recommending engineering analyses wherever needed, and ability to assess the strain associated with dents. A stress riser like corrosion, a gouge or a crack within a dent or between dents, rerounding of unconstrained dents or shape and sharpness of dents, need to be considered within the appropriate assessment method. While the failure assessment process is not prescribed in the new regulations, the (integrity) management measures and management consequences are (refer to figure 1).

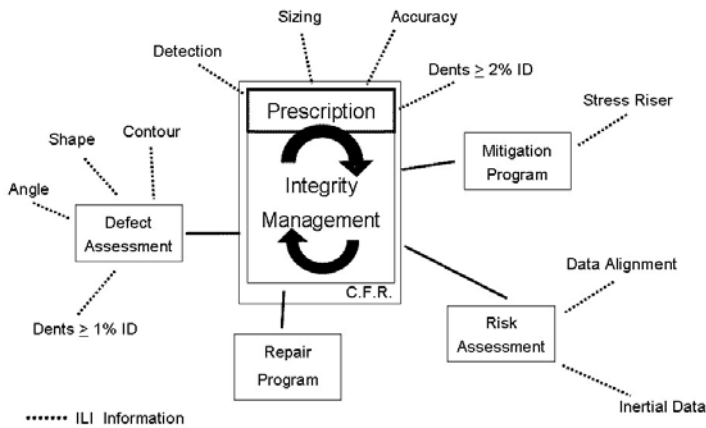


Figure 1: The Integrity Management process typically goes beyond the evaluation of the purely prescriptive information

GEOMETRY ILI TOOLS – HIGH QUALITY APPROACH

As mentioned previously, basic information for dents and ovalities, as we have known it, do not address the necessities for a proper defect assessment.

The state-of-the-art in geometry inspection has changed over the last two years. This is in order to provide pipeline operators better tools to assist them in meeting the intent of the rulemaking when it comes to ILI as the integrity assessment method of choice.

The “classic” geometry inspection for ovalities and large deformation does not provide the required information for a dent assessment as discussed above. This is also indicated in a more recent publication and study on the subject of geometric anomalies, where the probability of detection (POD) was only 32%, based on field verification activities of 78 excavations [4]. With the new regulations, this cannot be accepted.

A “high-quality” ILI process for dents and mechanical damage can provide required information such as the geometry of dents and data on stress risers to start a managed integrity process for the inspected line (refer to Figure 1). The more high-resolution and “high-quality” information that is available about an anomaly found, the better the subsequent failure analysis can be.

It is important not only to size and describe the dents with high accuracy, but also to detect and characterize the before mentioned stress risers. State-of-the-art for the characterization

of the stress riser are high-resolution ILI tools based for example on the magnetic flux leakage principle. In combination with one of these tools, a “high-quality” geometry tool and a navigation unit can be combined on a multipurpose tool (Figure 2), so that the required data can be obtained during a single inspection run.

CIRCUMFERENTIAL RESOLUTION AND COVERAGE

The performance of a geometry inspection configuration for dents can be estimated by using straight forward analytical models. According to these models, the sizing accuracy and the probability of detection (POD) for dents can be determined as a function of the circumferential resolution and the coverage of the sensing area.

Due to the linear equation connecting the pipeline diameter with its circumferential perimeter, the coverage of a single unit tool is linked to the ID-passage of the unit. A fully assembled single inspection plane would also complicate the negotiation of 1.5D bends. As a rule of thumb, the coverage for a single plane geometry tool equals the specified passage minus 15%. Thus, a typical caliper tool with a passage of 75% would cover only 60% of the physical internal pipe surface. This can lead to a significantly reduced POD and to an undersizing of the dent depth as the internal contour is not been sampled completely. (refer to Figure 3).

Therefore, an accurate sizing of dents or other geometric anomalies in a pipeline requires 100% coverage over the circumference by the geometry sensors. To achieve this, the inspection solution must consist of two inspection planes, where the trailing sensor unit is covering the gap of the preceding unit. The tool design for the ROSEN high-resolution geometry inspection system (XGP) consists of two sensor units circumferentially offset to each other and hence guarantee 100% physical coverage of the internal surface (refer to Figures 2).



Figure 2: ILI multipurpose 24” tool. Combining MFL technology with high quality geometry inspection. Two measurement planes for the geometry sensor are required to provide full coverage under all operational conditions.

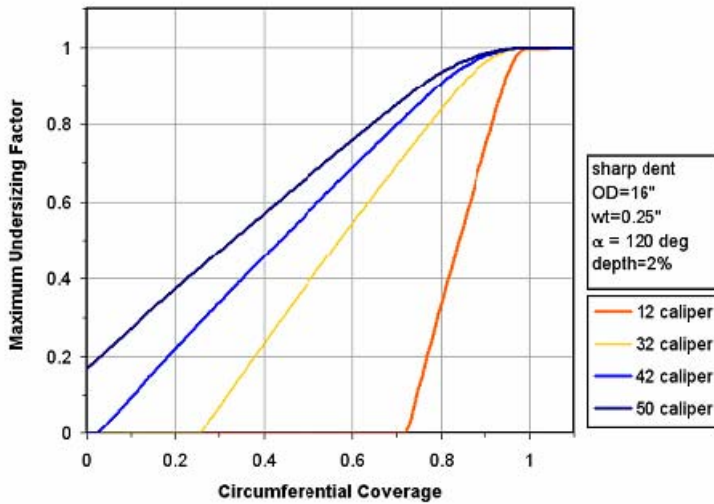


Figure 3: Undersizing of dents as a function of coverage and number of caliper arms for a sharp dent with a tip angle $\alpha=120^\circ$. The maximum undersizing factor is a worst case scenario.

MECHATRONIC SENSOR

A disadvantage of the traditional mechanical caliper tool design, where the mechanical movement of the caliper is transformed into a position signal, is the dynamic behavior of the arms under run conditions. This typically leads to inspection speed restrictions. Above a critical tool speed, the caliper arm starts to lose continuous contact with the internal surface of the pipeline. But also at low speeds abrupt changes at the internal pipe surface may not be monitored correctly.

Pure mechanical designs which try to overcome these problems have to be lightweight and hence are quite fragile. Therefore, these systems do not extend the operational range of this inspection task.



Figure 4: Combination of conventional mechanical caliper concept(B) with a touchless operating proximity sensor (d).

A solution for this problem is provided by a touchless measurement technology. To achieve high measurement accuracy and a satisfying circumferential resolution a mechanical caliper arm system equipped with a sensor to transform the mechanical movement into an electric signal and an electronic distance measurement were combined to a mechatronic solution.

Figure 4 shows the touchless electronic sensor integrated inside the sensor head and a position sensor attached at the base of the sensor arm monitoring the mechanical position. The touchless electronic sensor is used to compensate data obtained from the dynamic behavior of the caliper arm. The unwanted effects of the caliper's inertia is fully assimilated by the touchless measurement. Sharp transitions at the internal surface, such as a pipe misalignment at a girth weld, are monitored very well. Another example explains how the contour of a dent is monitored by the compensation method. Figure 5 shows the result simulated at 6.72mph (3 m/s).

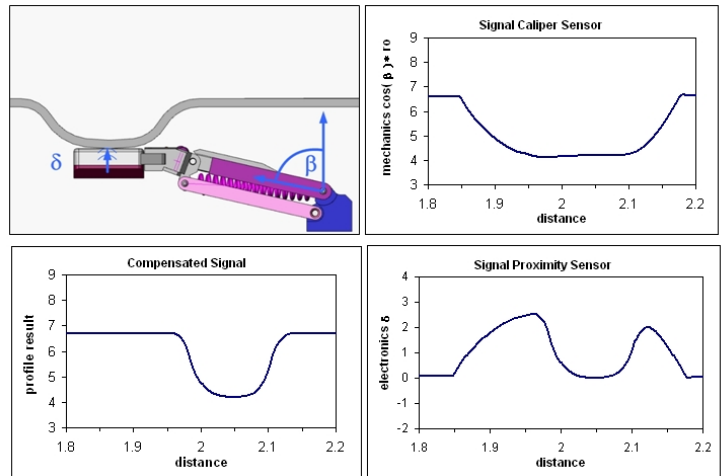


Figure 5: Compensated signal from a dent obtained with the by summation of the mechanical movement measurement and the touchless proximity signal.

This example also emphasizes the tendency of oversizing the dent length by a pure mechanical caliper arm.

Since the electronic sensor is insensitive to non-conductive material, the compensation method is always referring to the internal surface of the pipeline. Scale or wax debris, although detected by the system, will not affect the geometry evaluation of the pipeline.

A single mechatronic unit is designed to cope with a tool-speed of up to 11.2 mph (5m/s) and to provide an accuracy of 0.03" (0.8mm) for radial measurements.

ANALYSIS FOR STATIC DENT STRAIN

The accurate measurement of the dent geometry is the basis for a strain and subsequent stress analysis. For a static analysis of the stress in a dented area the bending strain at the material surface has to be known. With the strain stress curve the static stress at the dent surface can then be estimated. For an analysis of the strain in a dent area, the curvature of the dent surface has to be determined, because the strain at the surface is

directly defined by the wall thickness and the curvature at the area of interest. Mathematically the curvature is defined by the second derivative of a parameterization of such geometry. Therefore the measurement data has to be parameterized or resampled to calculate the curvature in the dent region. It has already been shown that this procedure delivers good results when being compared to FEM calculations.[5]

To perform the needed calculations with the measurement data, the data has to be parameterized or resampled to a suitable resolution. The first challenge is to transform the data, to an equidistant grid. Another issue is the required continuity of the second derivative of the resulting geometry information, since the second derivative is the basis for curvature calculation, like discussed above. 100% circumferential coverage of the measurement system makes this analysis more confident, since it can be assumed that the maximum depth of the dent geometry has been hit. Therefore no extrapolations (overshoots) have to be considered for the transformation.

Therefore well established interpolation methods exist. Generally, cubic splines show continuity of the second derivative, but also show oscillations and overshoots. Cubic B-splines are already used for such calculations [5]. But artificial contour-changes caused by un-wanted oscillations of splines produce non compliant strain results.

For this reason, a combination of spline and Hermite interpolation is used to achieve optimum results for static strain analyses around dents. Moreover, depending on the dent geometry the weighting of the two basic principles has to be designed properly to achieve the right approximation, respectively. The improvement in the resulting curvature can be seen in figure 6. The pure spline interpolation generates artificial curvatures at the border ($\pm 0.06\text{m}$) of a small Gaussian shaped dent.

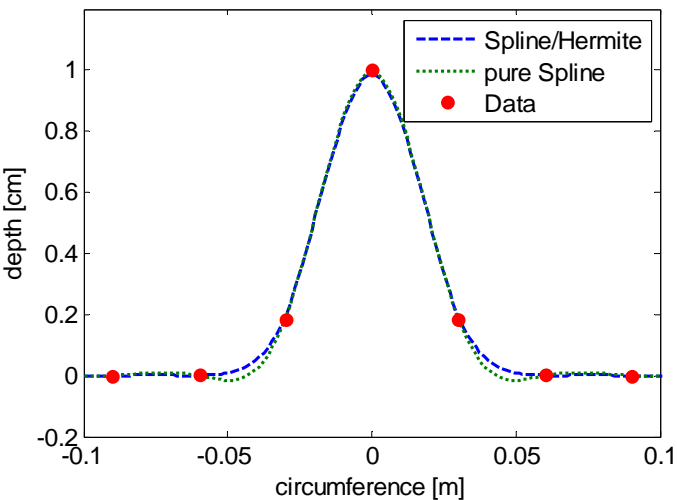


Figure 6: Dent Depth over circumference for a small gaussian defect shape. The spline solution tends to overshoot.

Based on these calculations curvature information can be obtained. Combined with wall-thickness information of high-resolution MFL- and/or CMFL-data a strain analysis can be

performed. With a provided strain stress curve the static stress can be estimated.

MULTI PURPOSE TOOLS

Multi-purpose tools have been common place for some years. For example, high-resolution MFL tools combined with active speed control and an inertial measurement unit are available.



Figure 7: Multipurpose toolMFL, HighRes Geometry and IMU, at the receiver site.

Since their introduction in 2005, ILI tools equipped with the new high-quality geometry sensors have been utilized by ROSEN in more than 500 miles of inspection world wide.

This includes 8", 12", 16" and 24" diameters. The majority of this mileage, more than 300 miles, inspected with the XGP technology has been combined with high-resolution MFL and an inertial measurement unit all on the same tool.

From an operational point of view a compact tool design able to negotiate 1.5D bends and a tool length, not substantially different from conventional "single purpose" tools are demands which need consideration for the selection of adequate multi-diameter tools.

The combination of inspection technologies offers a much more complete picture of the situation at an anomaly location. Combined Data from the same tool offers easier access to dents containing metal loss, as the data is recorded together in the same memory unit and there is no correlation procedure to carry out.

SENSOR PERFORMANCE

Sensitivity

The analysis of inspection data confirmed the sensitivity of the system to shallow dents. Table 1 lists the results obtained with the 16" ILI system on six (6) artificial dents and three (3) "natural" dents found during an inspection.

ID	Depth		Type	Stress Riser
	Onsite	ILI		
1	1.8%	1.9%	artificial	no
2	2.9%	3.0%	artificial	no
3	3.4%	3.0%	artificial	no
4	1.4%	1.7%	artificial	no
5	2.1%	1.8%	artificial	no
6	1.1%	1.2%	artificial	no
7	4.0%	3.8%	field	metal loss
8	2.8%	2.5%	field	metal loss
8	n.a.	4.0%	field	gouge

Table 1: Exemplary results from 16" ILI system. Dent depth is given as a fraction of the OD.

Anomaly Characterization

As discussed above, the mechatronic sensor provides detailed shape information about geometric anomalies in the pipe like dents or wrinkles. The inertial compensation and the touchless measurement between sensor and pipe wall allow small anomalies to be resolved, where the mechanical suspension cannot follow.

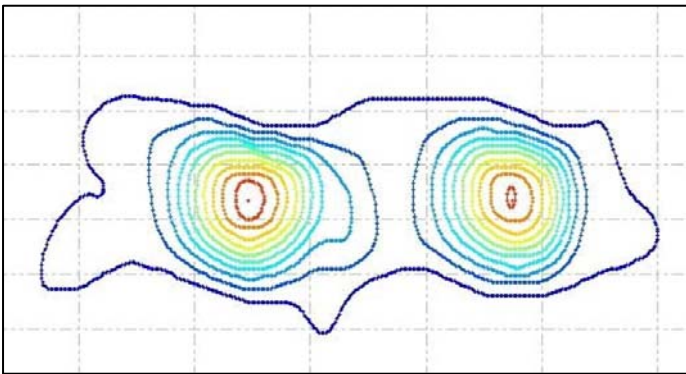


Figure 8: Series of two dents adjacent to each other. Inspection data obtained with the 16" ILI system (below). The maximum depth of the dent was found to be 2.9% OD.

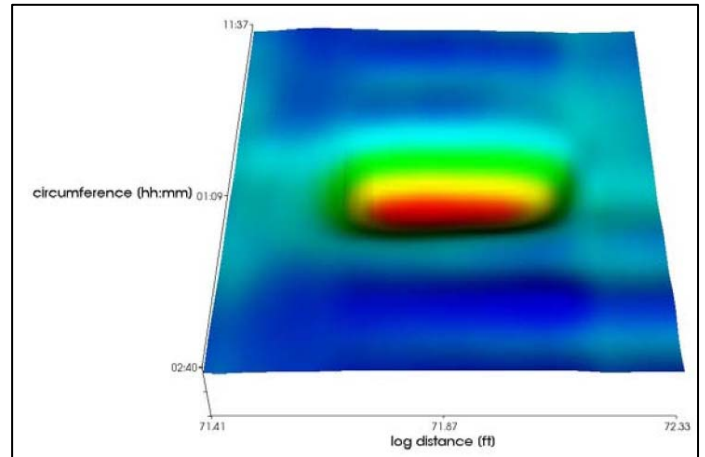
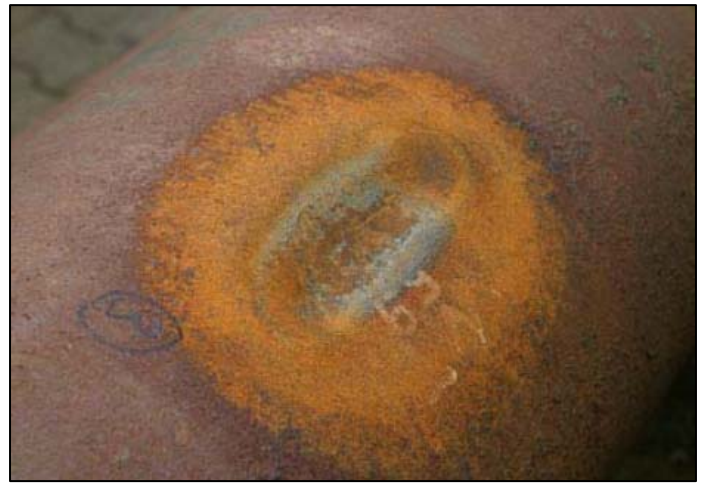


Figure 9: Artificial dent with almost rectangular contour. Inspection data obtained with the 16" ILI system (below). The characteristic shape is well reflected within the data.

Two short dents for example, adjacent to each other in the axial direction are correctly recorded (to figure 8). An artificial dent, with an almost rectangular shape is captured in the data accordingly (figure 9). Wrinkles in the pipeline are accurately mapped by the system. The touchless sensors provide accurate depth information without the requirement of following the contour mechanically (figure 10).

CONCLUSIONS

The demand for reliable dent detection and sizing has changed the scope of existing geometry inspection services with regards to the inspection technology used, as well as the evaluation process of the data. Geometry inspection has entered the "high-quality" inspection market.

Analytical considerations emphasize the importance of both coverage and resolution in circumferential direction of the pipe perimeter.

Measurement of the mechanical position of the caliper arm in combination with a touchless distance measurement provides better accuracy independent from the caliper arms inertia and a wider operational range of the system.

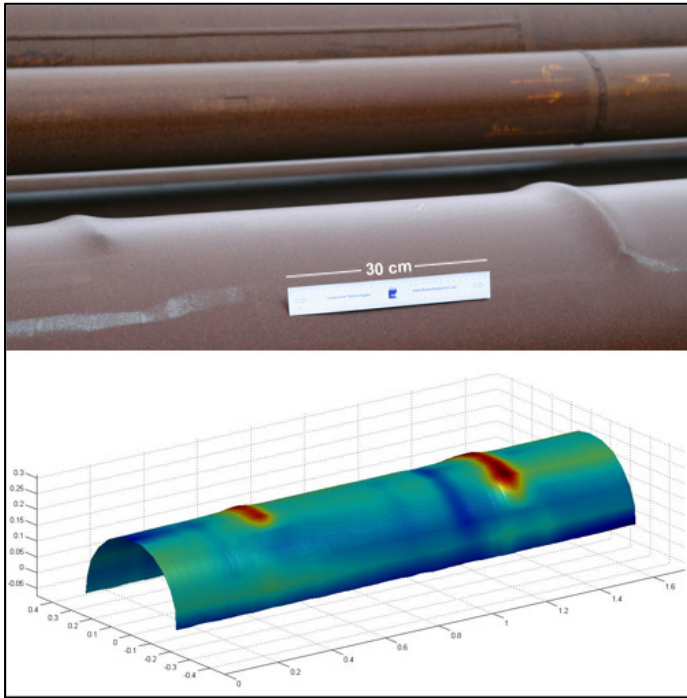


Figure 10: Mapping of wrinkles. Inspection data obtained with the 16" ILI system (below). The touchless sensor provide accurate depth information without the requirement of following the contour mechanically .

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