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Impact of 3D Laser Data Resolution and Accuracy on Pipeline Dents Strain Analysis

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Abstract

Mechanical damage represents a major problem and a threat to pipeline integrity. Even if there is more corrosion typically found on pipeline networks, the number of leaks associated to dents is greater. Dent analysis methods used today are being questioned, being simplistic and very conservative due to lack of confidence in data. This paper presents a new approach to inspect mechanical damage on pipelines by using a 3D laser scanner, dedicated analysis software and a rugged field-pack to optimize deployment in the field. This solution is an improvement over traditional non-destructive techniques such as pit gauging and ultrasounds. Different plain dents will be used in a case study to clearly show the differences between inspection techniques. Depth based and strain based analysis of dents will be discussed. We will see the impact of data point density and interpolation on the ability to accurately regress a radius of curvature used for dent strain analysis. The use of high accuracy 3D laser scanning technique for data collection provides more confidence in depth and radius measurements allowing better failure prediction.

1) 3D laser basics

3D laser scanning is a non-destructing-testing (NDT) technology used to accurately measure surface defects, metal loss or geometrical deformations with a very high accuracy. The surface geometry of an object is acquired in 3D and will be used to take a wide range of measurements. A laser cross is projected on the object and a set of two cameras records the laser lines curvatures following the surface shape in real-time, as illustrated in Figure 1. In the case of pipeline integrity, the 3D laser method is mainly used for corrosion, mechanical damage, pipe ovality and weld profiling.

The Creaform Handyscan3D technology as shown in Figure 2 offers many advantages such as the ability to cover 100% of the scanned surface providing a huge amount of data points. Having such a complete set of data increases the operator’s confidence in the results.

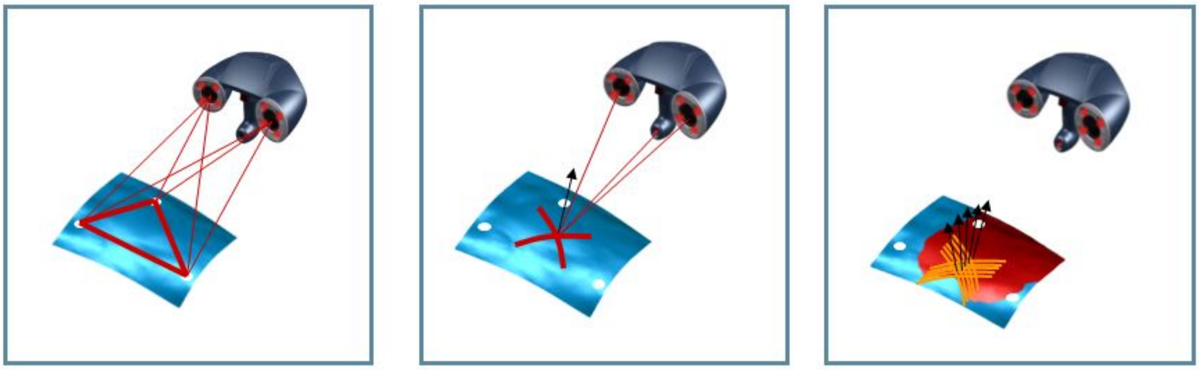

Figure 1 : The scanner position itself by triangulation, cameras read the laser cross deformations as the scanner moves to generate 3D model

Figure 2 : Pipeline inspection with Handyscan3D laser scanner and real-time visualisation on a tablet

1.1 Equipment

The inspection requires the following equipment: Handyscan3D scanner, Pipecheck software and the rugged Field-Pack with wireless tablet.

1.2 Pipe surface preparation

The pipeline surface must be prepared locally prior to the scan. The 3D laser scanner is an optical tool so the surface to be inspected must be visually accessible. Dirt, scale and rust must be removed by sandblasting the pipe surface or using another similar cleaning technique. The scanner will be able to scan the surface in any condition but cleaning it ensures meaningful results, as with any other NDT technique.

1.3 Scanner setup

The 3D scanner does not have to be calibrated to operate but it is recommended before on-site inspection to garantee the accuracy is within tolerance. Calibration takes less than one minute.

1.4 Data acquisition

The damaged area is recorded with the scanner. It takes less than 7 minutes per square meter at 2mm resolution to perform a full (100%) coverage with an accuracy up to 40 microns. The scanner accuracy is a fixed value by scanner design but resolution is defined by the inspector in the software setup. Therefore, accuracy and resolution are not related when using a 3D scanner.

1.5 Data analysis

The inspector simply needs to input the required information for calculation and the report is automatically generated. All parameters can be saved in a template.

2) Mechanical damage analysis from a 3D scan file

The data collected by the scanner is a scaled representation of the outside pipe surface. There are multiple ways to analyse the results. Our objective is to define if the results obtained with the scanner have an advantage over the conventional methods.

2.1 Depth-based analysis

This is the easiest way to analyse dents. With a 3D laser scanner, one can obtain a complete dent 3D shape with a very good resolution. A wide range of measurements can be taken from the 3D scan file including of course maximum depth and depth grid of size defined by inspector. Since the 3D laser scanner can generate millions of points, the results are more accurate and repeatable compared to manual methods.

It is also possible to automatically extract measurements from the data. Here are some measurements that are computed automatically in the software:

- Depth measured with a straight edge along the pipe axis
- Depth measured with a straight edge along the circumferential axis
- Depth measured from a perfect cylindrical fit compared to the scanned pipe
- Dent length and width
- Location of deepest point in the dent
- Pipe ovality with minimum and maximum diameter ratio

We know that depth alone is not a good predictor. It shows the importance of getting more information on the geometry to characterize the dent.

Some measurements like finding the location of the deepest point are difficult to repeat through manual operations. The automated calculation in the software solves that problem and improves repeatability. All calculations are based on geometry within +/- 40 microns accuracy. Depth can be used as a predictor for failure caused by pressure cycles. When the pipe is less likely to fail by fatigue, the shape of the dent needs to be further investigated.

2.2 Strain-based analysis

If one choose to estimate the strain based on ASME B31.8R code, equations 1,2,3,4 and 5 as shown below can easily be applied. This code requires measurement of the smallest radius of curvature at different locations in the dent. This information, along with the size and depth of the dent, are required to estimate strain at a specific location on the pipe. The analysis software can generate a deformation colormap which can be exported in Excel format. Different formulas can be applied on the data, which makes the solution very flexible.

$$\varepsilon_1 = \frac{t}{2}\left(\frac{1}{R_o} - \frac{1}{R_1}\right) \quad (1)$$

$$\varepsilon_2 = \frac{-t}{2R_2} \quad (2)$$

$$\varepsilon_3 = \frac{1}{2}\left(\frac{d}{L}\right)^2 \quad (3)$$

$$\varepsilon_i = \left[\varepsilon_1^2 - \varepsilon_1(\varepsilon_2 + \varepsilon_3) + (\varepsilon_2 + \varepsilon_3)^2\right]^{\frac{1}{2}} \quad (4)$$

$$\varepsilon_o = \left[\varepsilon_1^2 + \varepsilon_1(-\varepsilon_2 + \varepsilon_3) + (-\varepsilon_2 + \varepsilon_3)^2\right]^{\frac{1}{2}} \quad (5)$$

Where :

R0 = ½ pipe nominal OD
R1 = Circumferential dent radius of curvature
R2 = Axial dent radius of curvature
d = maximum dent depth
t = pipe nominal wall thickness
L = dent length

Unfortunately, there is no specification about how the curvature should be estimated. Different algorithms can be used but they will yield variable results. This challenge explains why there is still no standard globally approved in the industry such as the B31G for corrosion. Pipeline owners relate to their experience and historical data to estimate the dented pipe condition to their best. In the next section, we will see how this issue can be solved by using a more accurate tool to acquire the data.

3. Impact of data points density : a flaw in the conventional approach

3.1 Introduction

A conventional approach to assess mechanical damage consist in drawing a grid over the damaged surface and measure the depth for each grid square. Depth measurements can then be used to create a finite element model or they can be used for a strain estimation based on ASME B31.8R code. Inspectors often use a coarse point spacing of 0.5 in or more (12.7 mm) to map the dent geometry and measure its radius of curvature since this procedure is time consuming. In the following test, we will investigate the reliability of this method.

3.2 Case study 1 : Effect of data density on accuracy

To evaluate the effect of data density, dent geometry must be measured at different grid spacing. The goal is to measure the effect of data density alone without being affected by inspector skills or algorithms used to fit a cercle on the curvature.

Starting with a very high density data file representing the dent geometry at 0.5mm resolution, the analysis is performed many times using grids of 2, 4, 8 and 12.7 mm (0.5in). The original data was acquired with an EXAscan 3D laser scanner, and the accuracy of the geometry is therefore within 0.040 mm. This procedure is necessary to exclude other sources of error which will be considered later.

The curvature is evaluated by fitting the smallest possible circle on a longitudinal profile at the deepest point on the selected dent. For each circle fitted, the number of points was chosen to ensure the most accurate fit. The accuracy of each fit can be visualised using avanced metrology software. The procedure has been repeated with three different dent samples.

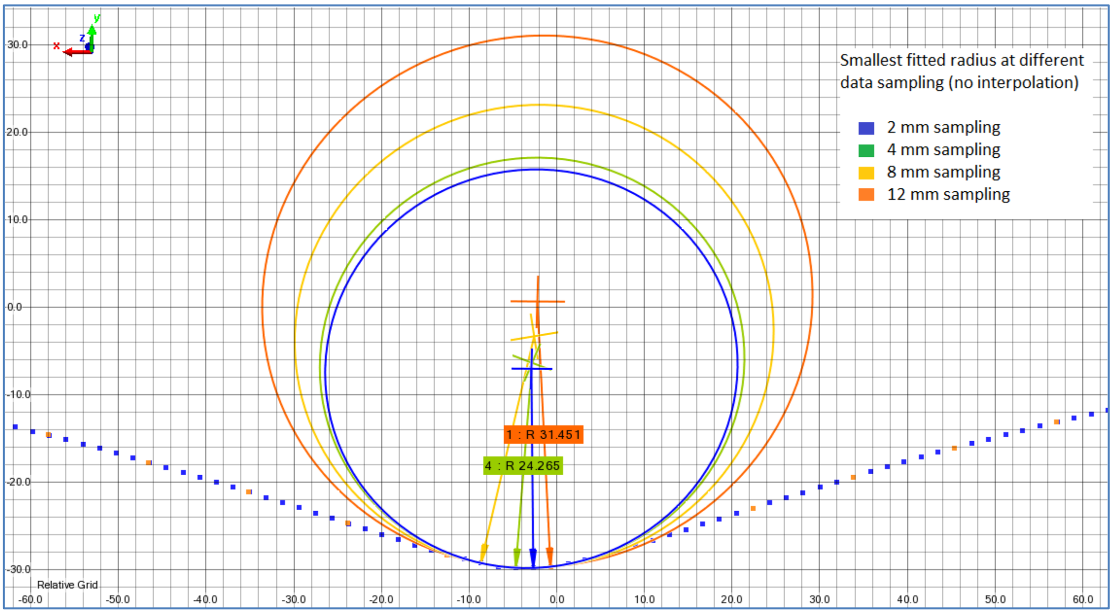

Figure 3: Effect of data density on radius calculation

Table 1: Error on radius calculation at different grid resolutions

Test Sample	Resolution	Radius	Error (%)
Sample 1 - 2mm	2 mm	23.57	5.8%
Sample 1 - 4mm	4 mm	24.265	8.9%
Sample 1 - 8mm	8 mm	27.371	22.9%
Sample 1 – 12.7mm	12.7 mm	31.451	41.2%
Sample 1 - REF	*0.5 mm*	*22.273*	*0.0%*

Test Sample	Resolution	Radius	Error (%)
Sample 2 - 2mm	2 mm	129.226	2.6%
Sample 2 - 4mm	4 mm	132.453	5.2%
Sample 2 - 8mm	8 mm	149.669	18.9%
Sample 2 – 12.7mm	12.7 mm	194.029	54.1%
Sample 2 - REF	*0.5 mm*	*125.9*	*0.0%*

Test Sample	Resolution	Radius	Error (%)
Sample 3 - 2mm	2 mm	33.070	0.2%
Sample 3 - 4mm	4 mm	37.785	14.4%
Sample 3 - 8mm	8 mm	47.898	45.1%
Sample 3 – 12.7mm	12.7 mm	55.710	68.7%
Sample 3 - REF	*0.5 mm*	*33.015*	*0.0%*

3.3 Results

The higher the resolution, the closer we get to the reference radius. At 2 mm of resolution, we get an acceptable error of 5.8% maximum. The radius tend to increase as the resolution increases which create large deviations from the reference at 0.5mm resolution. At the 12.7 mm resolution, the maximal error is of 68.7%. This is 12 times worse than data sampled at 2 mm. We can also observe that radius values converge at the highest resolution. An error of 68.7 % is far from acceptable and therefore explains the use of interpolation algorithms to compensate the error induced by low data resolution.

4. Effect of interpolation on repeatability

4.1 Introduction

The role of interpolation is to compensate for low data density by approximating the profile from the available data. By approximating the pipe surface with mathematics, it is possible to use the curve generated to perform strain analysis. This approximation can be improved with validation on test samples. However, there is always a risk of missing small localized geometry variations affecting the interpolation algorithm.

4.2 Case study 2 : Effect of interpolation in function of scan resolution

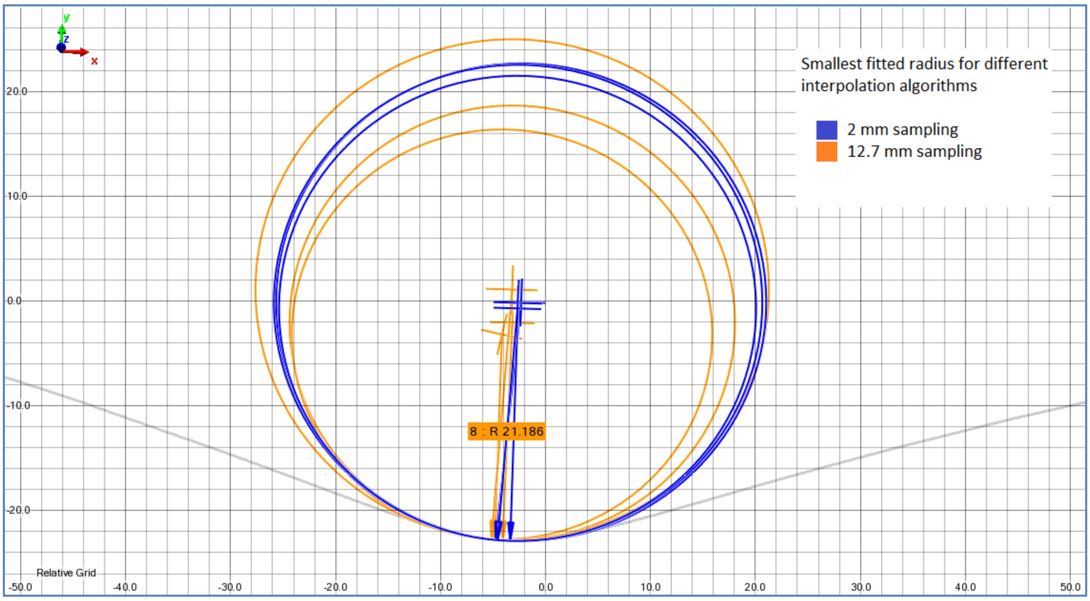

Figure 4: Variations in radius measurement due to interpolation in function of scan resolution

Table 2: Error and variability on radius calculation after interpolation

Test	**Resolution**	**Radius**	**Error (%)**	**Variability (%)**
Sample 1 - algo 1	2 mm	23.307	4.6	2.7
Sample 1 - algo 2		23.227	4.3	
Sample 1 - algo 3		22.691	1.9	
Sample 1 - algo 1	12.7 mm	21.186	-4.9	19.8
Sample 1 - algo 2		19.995	-10.2	
Sample 1 - algo 3		24.418	9.6	
Sample 1 - REF	*0.5 mm*	*22.273*	*0*	
Test	**Resolution**	**Radius**	**Error (%)**	**Variability (%)**
Sample 3 - algo 1	2 mm	33.287	0.8%	9.5
Sample 3 - algo 2		32.263	-2.3%	
Sample 3 - algo 3		30.153	-8.7%	
Sample 3 - algo 1	12.7 mm	37.821	14.6%	29.2
Sample 3 - algo 2		47.152	42.8%	
Sample 3 - algo 3		37.492	13.6%	
Sample 3 - REF	*0.5 mm*	*33.015*	*0.0%*	

4.3 Results

Variability is defined as the difference between the maximum and minimum values. Even after interpolation, the error on the radius calculation is higher with the sampling at 12.7 mm. The variability at 12.7mm resolution compared to 2mm is about 3 to 7 times higher. It demonstrates that interpolation can improve the outcome but lacks consistency.

Sample 1 and 3 at 2mm did not improve with interpolation; sample 3 even got worse. It shows the importance of interpolation is significantly reduced when increasing data density. It could be the solution to disagreements and divergence at approving an interpolation algorithm and at establishing a standard for dent radius calculation.

4.4 Discussion

In the case of low data density, results disparity makes it impossible to apply a correction factor. With high data density, the variability is significantly reduced and consequently allows more consistent failure predictions.

Keep in mind this variability is a result of data density change alone. An error is also induced by a failure to accurately find the location of the smallest radius of curvature. The code defines the highest strain concentration at the location of the smallest radius of curvature which can be difficult to find since it is not necessarily at the deepest point in the dent. With low data density, the smallest curvature point can also be far from a sampled point, and different algorithms will lead to different locations. With higher data density, the location of the smallest curvature point is improved regardless of the algorithm used. In the present case study, the location problem was not factored in the error evaluation.

5. Impact of low repeatability

5.1 Introduction

Repeatability and data reliability are important if we want to predict failures accurately. Some geometric features like dent radius are very sensitive to small changes in the measurement. An offset can occur at the location that we want to measure and the contact surface used as a reference will vary for each node measured on the pipe surface. In this section, we will investigate the consequence of a small incertitude on the final result.

5.2 Case study 3: Effect of low repeatability on dent radius measurement

Four different inspectors were asked to inspect a dented pipe with both a pit gauge and a 3D laser scanner.

With the pit gauge:

- Inspector finds location and depth of deepest point
- Inspector draws a 5x5 mm grid centered at the deepest point and find the depth at each location.

With the 3D laser scanner:

- The inspector scans the same damaged area and input the same grid spacing in the software.
- The deepest point is automatically detected.

5.3 Results

The standard deviation is used to compare results and measure the repeatability between the different inspectors. The average standard deviation is calculated based on the standard deviation obtained from 25 grid points. The pit gauge generated a value of 0.260 mm compared to 0.040 mm with the 3D scanner. It means the scanner measurements are at least 6 times more repeatable. We will see why repeatability is so important in the process of characterizing the geometry and determining the curvature.

Table 3: Results from pit gauge

Highest Disparity					
	x1	**x2**	**x3**	**x4**	**x5**
y1	0.83	0.69	0.57	0.78	0.7
y2	0.41	0.35	0.31	0.43	0.46
y3	0.24	0.24	0.12	0.05	0.1
y4	0.65	0.65	0.45	0.42	0.5
y5	1.23	***1.49***	1.04	0.96	0.89

Standard Deviation					
	x1	**x2**	**x3**	**x4**	**x5**
y1	0.431	0.303	0.260	0.363	0.324
y2	0.192	0.159	0.149	0.193	0.208
y3	0.109	0.102	0.053	0.025	0.046
y4	0.302	0.284	0.210	0.181	0.217
y5	0.571	***0.671***	0.448	0.420	0.396

Table 4: Results from 3D laser scanner

Highest Disparity					
	x1	**x2**	**x3**	**x4**	**x5**
y1	0.08	0.083	0.034	0.053	0.074
y2	0.026	0.048	0.047	0.045	0.034
y3	0.038	0.039	0.032	0.078	0.064
y4	0.064	0.032	0.05	0.029	0.051
y5	***0.098***	0.089	0.067	0.088	0.072

Standard Deviation					
	x1	**x2**	**x3**	**x4**	**x5**
y1	0.039	0.042	0.017	0.024	0.034
y2	0.014	0.021	0.022	0.02	0.019
y3	0.017	0.017	0.018	0.034	0.031
y4	0.029	0.013	0.022	0.015	0.025
y5	***0.044***	0.04	0.032	0.041	0.035

The standard deviation is used to compare results and measure the repeatability between the different inspectors. The average standard deviation is calculated based on the standard deviation obtained from 25 grid points. The pit gauge has a standard deviation of 0.260 mm compared to 0.027 mm with the 3D scanner. Consequently, the scanner is about 10 times more repeatable.

The highest disparity is 1.49 mm with the pit gauge, clearly a manipulation error. The highest disparity with the 3D laser scanner is 0.098 mm, still under its specification of +/- 0.040 mm.

The inspectors were good at finding and measuring the deepest point. The error has more impact on geometric characterization around the deepest point.

The next section covers the importance of repeatability in the process of characterizing the geometry and determining the curvature.

5.4 Mathematical Example

We took a random point on a dent sample and found the longitudinal radius at that point to be 67.10 mm. The sample is a smooth dent with a 6.35 mm thickness. The longitudinal bending strain is calculated at 4.7% using the equation found in ASME B31.8R code. This is a very good example because the decision to repair or replace the damaged section is critical in that range. By changing the center node by only 0.04 mm, the bending strain changed by 5.6%. Changing the same node by 0.26 mm yields a 52.6% variation on the bending strain. Indeed, a small change in displacement can induce a big change in curvature.

This confirms that a small error in measurement can be critical on the calculated strain value. We are considering only one parameter in the equation provided in B31.8R, for only one single point shifted. A worst case scenario, implying many points shifted in opposite directions would yield much worse results.

5.5 Discussion

For the majority of high strain dents, the bending strain has more impact on the effective strain than other strain components. Since bending strain is related to the level of curvature, the accuracy of the measured curvature is very important. Repeatability is the most important factor since an offset in the measurements compensate for itself in the calculation. The use of manual tools proves to have an important negative impact on strain calculation. The tested 3D laser scanner was shown to be 10 times better at providing an accurate value for that purpose.

6. Conclusion

Dent strain analysis on pipelines is directly related to the ability to accurately locate and measure the smallest dent radius of curvature. The conventional approach for dent inspection is characterized by a combination of low density data and low repeatability.

The use of mathematical curves to estimate a given geometry is good practice with low data density but results can always be challenged with interpolation being based on approximation rather than real data points. The use of a 3D laser technique allows very high data density and therefore eliminates the need for interpolation.

This paper showed that data repeatability is important to properly assess mechanical damage and more specifically to estimate strain. The 3D laser scanner performed 10 times better than manual techniques and therefore proves to generate reliable measurements for strain analysis.

References

1. ASME B31.8-2007 code, Gas Transmission and Distribution piping systems, Appendix R
2. Ming Gao, Rick McNealy, Ravi Krishnamurthy from Blade-Energy, ‘Strain-Based models for strain assessment, a review’, IPC conference, Calgary September 2008