Influence of seamless pipes wall thickness variation for the effectiveness of Automated Ultrasonic Testing

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Abstract
Offshore pipelines construction is a technological challenge. Increasing water depth, harsh environments, engineering and commercial constraints are just some of the existing issues. Material selection therefore plays a key role and, for several applications, seamless pipes offer both the best technical and commercial compromise. Typically, NDT inspection of girth welds is carried out using the phased array based automated ultrasonic testing (AUT) zonal discrimination approach. AUT, compared to other techniques, guarantees a higher probability of detection of flaws and it also allows a really accurate assessment of the indications. However, since one of the peculiarities of this technique is that it uses focused beams, it is strictly linked to the geometry of the joint. According to the most credited international codes [1], performing AUT the allowable wall thickness (WT) variation from the nominal one is ±1.5 mm (or less for higher strain applications). Seamless pipes are likely to exceed this limit, particularly taking into account that the WT commonly varies point by point around the circumference. For this reason, several approaches have been developed during the years from AUT contractors such as using dedicated techniques (e.g. multi-shooting) or using multiple calibration blocks. However, all these solutions may deeply influence costs because of the additional qualification tests required and the potential impact on the cycle time.

Starting from AUT validation data to build the model and using simulation software as tool, this study analyses the influence of WT variation on the reliability and accuracy of zonal discrimination approach. Real flaws geometry has been extrapolated from macro-sectioning. Actual focal laws settings have been considered. After validating the proposed model by comparing the simulation results with actual ones, several steps of base material WT variation are considered in order to understand the effect on the ultrasonic response of the flaws in object.

Keywords: Ultrasonic, Phased Array, Pipelines, NDT modelling, AUT

1. Introduction

AUT inspection of carbon steel pipeline girth welds is based on the combination of two different techniques, Phased Array and Time-of-Flight Diffraction (TOFD), used together in order to maximise the capability of detection of flaws typical of the welding process used, mostly gas metal arc welding (GMAW) using a narrow gap J-bevel and automatic or semi-automatic welding machines.

AUT is nowadays a reliable, consistent and extremely accurate method routinely used to inspect girth welds. When examining isotropic material with a “kind” grain structure, such as carbon steel, this technique often leads to a 90% probability of detection with a 95% confidence interval (90/95% PoD) of flaws having a through thickness dimension (the so called “height”) sensibly smaller than 1 mm. This is a remarkable result particularly when compared to other UT techniques.

However, new offshore installation technologies and materials developments allowed pushing the boundaries to new and always more challenging projects and so a continuous technological improvement is required to both welding and NDT.

AUT basic idea is to divide the weld volume into zones (1 to 3 mm height) and for each zone creating a dedicated focal law [2-3]. Ultrasonic signals received by the instrument are
monitored using electronic gates. Both signal amplitude and time of flight in the gated region are taken into account for the scan assessment. Outputs are digitized and displayed in a chart format. The “strip chart” representation helps the qualified technician assessing quickly the integrity of the weld compared to other data visualizations. This is a mandatory requirement in a production-driven environment such as a pipeline construction.

Working with a dedicated and focused channel (focal law) for each zone allows a repeatable and complete 3D sizing of the flaws. In fact, in such conditions, the vertical height of the flaw can be accurately measured, in addition to its length along the circumference and its depth.

Furthermore, the time of flight determines the position of the signal within the gate. This allows distinguishing echoes coming from potential defects from those related to geometrical reflections for example due to the root or cap shape.

Nevertheless, this is also the strong limitation of this approach that, in fact, is linked to the exact geometry of the bevel/weld to be inspected.

AUT most recognized code [1], fixes a maximum wall thickness variation from nominal thickness of ±1.5 mm applicable for pipes exposed for a total nominal strain of less than 0.4%, and ±1.0 mm applicable for total nominal strains equal to and above 0.4%.

This requirement is likely to be exceeded particularly when using thick seamless pipes.

Seamless pipes are often a valuable solution from both technical and economical point of view. The main issues related to this selection, from AUT point of view, are that the fabrication tolerances are wider compared to the welded pipes and also that the thickness is not constant but varies point by point along the circumference.

In this work, the actual WT variation of a group of no. 310 pipes (323.8 mm outer diameter, 25.4 mm WT) has been analysed and, based on the outcome, a series of experimental and simulation tests has been performed.

### 2. Modelling AUT with Civa software

Studies demonstrating that AUT can be reliably reproduced with Civa software are already available in the literature [4-6]. Civa is a semi-analytical software that uses the “pencil-method” [7] to simulate the propagation of the beam and several different models (Kirchhoff, GTD, SOV, modified Born, Specular) to evaluate the interaction between the beam and the flaws depending on the specific conditions [8-10].

In this study, Civa has been used to compute the beam (figure 3) and then to perform the calibration (see figure 4) using exactly the same focal laws (figure 1) used during the experimental tests and the same reference reflectors (figure 2).

<table>
<thead>
<tr>
<th>Zone</th>
<th>Tor/Phi</th>
<th>Name</th>
<th>Type</th>
<th>Config</th>
<th>Wave</th>
<th>Angle Start (°)</th>
<th>Focus (mm)</th>
<th>Elt Start</th>
<th>Active</th>
<th>Index (mm)</th>
<th>Velocity (m/s)</th>
<th>Probe</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tor1</td>
<td>R1 US</td>
<td>Root</td>
<td>Pulse-Echo</td>
<td>Shear</td>
<td>50.0</td>
<td>39.23</td>
<td>40</td>
<td>16</td>
<td>-30.65</td>
<td>3170</td>
<td>Upstream</td>
</tr>
<tr>
<td>2</td>
<td>Tor2</td>
<td>R1 US</td>
<td>Root</td>
<td>Pulse-Echo</td>
<td>Shear</td>
<td>50.0</td>
<td>39.23</td>
<td>40</td>
<td>16</td>
<td>-39.64</td>
<td>3170</td>
<td>Downstream</td>
</tr>
<tr>
<td>3</td>
<td>Tor1</td>
<td>R2 US</td>
<td>Root</td>
<td>Pulse-Echo</td>
<td>Shear</td>
<td>50.0</td>
<td>37.52</td>
<td>41</td>
<td>16</td>
<td>-39.64</td>
<td>3170</td>
<td>Upstream</td>
</tr>
<tr>
<td>4</td>
<td>Tor2</td>
<td>R2 US</td>
<td>Root</td>
<td>Pulse-Echo</td>
<td>Shear</td>
<td>50.0</td>
<td>37.52</td>
<td>41</td>
<td>16</td>
<td>28.24</td>
<td>3170</td>
<td>Downstream</td>
</tr>
</tbody>
</table>

Figure 1. Root 1 (R1) and Root 2 (R2) focal laws
An “angle and depth” focusing has been adopted in order to represent the type of focus used when performing AUT. The dimension of the focal spot at -3dB has been extrapolated running a beam computation in Civa. With a length of 31.5 mm (actual one was 39.23 mm as per figure 3), with the same threshold, the focal spot has a dimension along the z-axis of 6.7 mm.

Calibration reflectors used are 2 notches (R1 and R2), both 5 mm long and 1 mm wide and with a height respectively of 1 mm and 2.5 mm (see figure 2).

Civa as base case brings the highest echo to 0 dB and then the other signals are related to that one. In absolute terms, it accounts for signal amplitude in “points” that can become dB or percentage (A %) of full screen height (FSH) as soon as the user establishes a reference or a calibration target.
3. Results

The influence of seamless pipes WT variation for the effectiveness of AUT has been considered at several levels. First the actual WT variation of the pipes in object has been evaluated (figure 5). Nominal allowed WT variation is -10%+/+12.5% of the nominal WT. The data shows clearly that the average thickness variation is quite narrow even if there is an absolute maximum of 27.82 mm (+2.4 mm or +9.5 % compared to the nominal WT) and a minimum of 23.36 mm (-2.04 mm or -8 % compared to the nominal WT). For each pipe end, 4 WT readings have been done. When considering the average of the four values, the WT variation is widely within ±1.5mm (-0.56 mm/+ 0.42mm).

Taking into account the actual WT variation, the following activities have been performed:
- Qualitative experimental test with the AUT system;
- Simulation campaign with Civa.

3.1 Qualitative test with the AUT system

The first issue highlighted was the understanding of the possibility to detect a flaw if the WT changed by more than 1.5 mm (AUT code requirement). Considering a “worst case scenario” based on the actual pipe thickness range, an additional focal law for each side of the weld (R1 WT) has been created. This focal law, not present in the other calibrations or in the inspections performed, was done only for this purpose, copying exactly the same properties including the same gain of the R1 channel (see figure 6).

To simulate the WT variation, the “element start” (first active element) of the focal law has been changed (R1 WT focal law element start is 42 of 60 elements of the Phased Array probe while, for R1, the element start is 40 of 60). This modification, for a given distance between the probe and the centreline and a given refraction angle, means to simulate a WT variation of 2 mm.
As it can be seen in figure 6, the R1 WT channel has clearly detected the 1 mm root notch. As expected, a WT variation means different paths and so difference in Time of Flight (TOF). This difference in TOF can be noted from the position in the gate of the signal (see column “Pos.(mm)” in figure 6).

### 3.2 Simulation campaign

Three root flaws have been modelled with Civa. The reason why it has been selected this particular region within the weld volume is that, considering the flaws potentially present into the weld, those in this area should be the ones that are more likely to be missed by AUT because of WT variation.

First approach was to model the flaws using the “CAD contoured plan” in the Civa flaw definition panel, starting from the actual macro to copy the exact geometry. However, this option does not allow to “extruding” the profile so that it remains just as a 2D plane. Running the scans the results obtained were not representative of the experimental ones. As it can be seen in the A-Scan in the left part of figure 7, the difference between the 2 echoes (R1 and the flaw) was around 20 dB while it was expected to be sensibly lower than this.

At this point, it has been decided to change approach copying the geometry of the macro directly during the specimen definition using the useful “load image” tool in the Civa CAD scene (see figure 8).
Kirchhoff model involves an automatic mesh of the surface of the flaw (or in this case the “geometry”). It is a surface integral of interaction coefficients depending on incidence and observation angles. This method has some limitations that prevent it to be used to evaluate flaws that are not voids or in general smaller than the wavelength. However, in this case, these conditions are completed satisfied. The flaws in object, considering the 7.5 MHz probes used, are in the range of 2÷3 times the wavelength and they are voids and not inclusions.

For a better understanding of the table 1, a brief explanation of the AUT sizing policy used in this case is given. As general rule, when performing UT inspection, the accurate determination of the depth and of the length of the defects is normally possible whilst the vertical height sizing is much more complicated. This is due to the fact that there isn’t a linear relation between the amplitude of the signal and the height of the flaw. Specific techniques, such as the back diffraction or the TOFD, when used, allow doing this. However, in the specific case of AUT, mainly because focused beams are used, it is possible to accurately size the height of the flaws using the amplitude of the signal.

It is important to highlight also that the 2 root channels are both based on surface breaking notches. So, differently from the fill channels, if an echo is visible on both the channels it will not be considered the contribution of both of them but, with a conservative approach, it will be taken into account the channel providing the “bigger size”.

<table>
<thead>
<tr>
<th>Flaw</th>
<th>Macro</th>
<th>Flaw height [mm]</th>
<th>AUT Result [% FSH]</th>
<th>CIVA result [% FSH]</th>
</tr>
</thead>
</table>
| 1    | ![Image](image1.png) | 1.2 | R1: 56%  
R2: 38%  
Sizing: 1.0mm | A [R1]: 49%  
A [R2]: 34%  
Virtual sizing: 0.9mm |
| 2    | ![Image](image2.png) | 1.3 | R1: 44%  
R2: 36%  
Sizing: 0.9mm | A [R1]: 51%  
A [R2]: 40%  
Virtual sizing: 1mm |
### Table 1

<table>
<thead>
<tr>
<th>R1</th>
<th>R2</th>
<th>Sizing: 0.8mm</th>
<th>A [R1]: 60% FSH</th>
<th>A [R2]: 45% FSH</th>
<th>Virtual sizing: 1.1mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>46%</td>
<td>32%</td>
<td>0.8mm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1 shows that, in the specific case, AUT capabilities were in line with the expectations and that Civa results prediction was reliable and accurate.

At this point, for the flaw no. 2, it has been simulated a WT variation of ±2.5 mm from the nominal thickness at step of 0.5 mm. Results are reported in the figure 9 both in terms of max amplitude and time of flight. The flaw has been detected in the whole range considered.

Comparing the signal received in the nominal WT configuration and the one at -2.5mm, a drop in amplitude of around 25% is visible.

![Figure 9. TOF [µs] vs Thickness [mm] (top) and Max Amplitude [%] vs thickness [mm] (bottom)](image)

### 4. Conclusions

In this work, an evaluation of the correlation between the WT variation and the AUT capability of detection and sizing of real flaws has been performed.

This is a specific issue occurring particularly when performing AUT on seamless pipe.

A mix of experimental and simulated data helped understanding the phenomenon and its influence on the reliability of the non-destructive testing performed.

However, a deterministic quantitative result cannot be extrapolated because it is strictly correlated to the specific probe and focal law used and the “target” reflectors so it’s basically a case by case scenario.

The influence of WT variation on AUT can be considered from three different points of view:

1. Detection of the flaws - within the specific range in object, the effect was not detrimental. Small flaws have been considered and no one of them was “missed” because of the variation of the WT;
ii. Assessment of the flaws - as expected and as verified in both experimental test and simulation, the TOF is affected by the thickness variation because obviously it is directly linked to the length of the beam path. It is an issue when performing AUT because the AUT operator, for linear indications located in the bevel, normally relies on the position in the gate of the signals in order to distinguish the flaw and the geometrical echoes (particularly for the root area). New advanced focusing algorithms such as multipoint focusing or total focusing method [10-12] should be able to help on this and other issues directly or indirectly linked with the amplitude-based sizing;

iii. Sizing of the flaws – since the approach and the sizing policy used are based on the linear relation between height and amplitude, the WT variation influencing the amplitude has an impact on the sizing accuracy. It should be taken into account during the procedure qualification/validation processes [13] in order to include an additional uncertainty factor when determining a sizing accuracy. This is important because it will directly influence the acceptance criteria since in most of the cases pipelines girth welds assessment is Engineering Critical Assessment (ECA) [14] based.

References

13. DNV RP 118, “Pipe girth weld AUT system qualification and project specific procedure validation”, 2010.