New Use of a 3 Degrees Freedom Encoded Arm for Inspection of Welds with a Phased Array Probe

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Abstract. During a manual ultrasonic testing of a weld, the minimum number of degrees of freedom needed for the displacement of the probe is three: (x, y) are the displacement in the plane and \( \theta_3 \) is the rotation of the transducer around its axis. This allows the controller to search for the maximum amplitude reflected by an indication, an essential parameter to apply the acceptance criteria defined in standards and codes.

The use of phased array probes associated with a sectorial scan is constantly increasing. If such a technique is used to replace X-ray testing, recording information is generally requested. This is commonly achieved by having only a mechanical axis (having at the most 2 degrees of freedom) associated or not with a linear scan. In these conditions, there’s no absolute proof to obtain the maximum amplitude generated by an indication as allowed during manual testing.

To overcome this problem, it is possible to use a 3 degrees freedom arm fully encoded associated with software enabling the reconstruction of the views adapted to ultrasonic testing of a weld. This is a new use for articulated arms originally designed for testing only with straight longitudinal waves.

In this paper, a comparison of the results obtained for weld testing in the three following situations will be presented:
• Conventional manual UT;
• PA UT apply with an electronic scan encoded on a single axis;
• PA UT apply with a sectorial scan encoded on a 3 degrees freedom arm.

The tests have shown that the last situation improves the characterisation of indications in terms of nature and sizing. This can be advantageously used for coarse grains material such as 316L austenitic steel welds.

1. Introduction

During a manual ultrasonic testing of a weld, the minimum number of degrees freedom needed for the displacement of the probe is three: (x, y) are the displacement in the plane and \( \theta_3 \) is the rotation of the transducer around its axis. This allows the controller to search for the maximum amplitude reflected by an indication, an essential parameter to apply the acceptance criteria defined in standards and codes.

The use of phased array probes associated with electronic (sectorial and/or linear) scan is constantly increasing. If such a technique is used to replace X-ray testing, recording information is generally requested. That is the case in ‘Code Case 2235-10’ or in ASTM...
standard. This is commonly achieved by having only a mechanical axis associated or not with a linear scan. In these conditions, there’s no absolute proof to obtain the maximum amplitude generated by an indication as allowed during manual testing.

To overcome this problem, it is possible to use a 3 degrees of freedom arm fully encoded associated with software enabling the reconstruction of the views adapted to ultrasonic testing of a weld. This is a new use for articulated arms which are originally designed for testing of straight longitudinal waves.

2. Conventional Manual Testing

2.1 Description of the Welds

The work has been performed on two ferritic welds, UT2 and UT3. The sketch of the welds is given in the drawing below (Fig. 1). These contain natural built-in defects. Some are planar defects like side wall lack of fusion, cracks or lack of penetration and some are volumetric defects like porosities. These welds are used for training of controllers.

![Fig. 1. Photography of the weld and sketch](image)

2.2 Results of Manual Testing

Manuel testing has been performed in accordance with European standards, NF EN ISO 17640 level B and acceptance criteria of ISO 11666 level 2 with indication characterization according to ISO 23279.

Reference level is set on calibration block with side-drilled holes of diameter 3 mm. For the search of longitudinal indications only, NF EN ISO 17640 requires 2 different angles probes for this thickness from 2 accesses (one side of the plate). We chose 45° and 70° shear waves from accesses C and D.

The results for UT2 and UT3 welds are given in Table 1 and 2.
### Table 1. Results of Manual Ultrasonic Testing of Weld UT2

<table>
<thead>
<tr>
<th>Defect</th>
<th>Side for detection</th>
<th>Probe for detection</th>
<th>Position from origin (mm)</th>
<th>Length (mm)</th>
<th>Position in the weld</th>
<th>Amplitude (dB)</th>
<th>Classification</th>
<th>Acceptation (Y/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>D</td>
<td>45°</td>
<td>120</td>
<td>20</td>
<td>Embedded but on the chamfer</td>
<td>DAC +7</td>
<td>NV</td>
<td>N</td>
</tr>
<tr>
<td>2</td>
<td>C + D</td>
<td>70°</td>
<td>325</td>
<td>20</td>
<td>On the roof of the X weld</td>
<td>DAC-3</td>
<td>NV</td>
<td>N</td>
</tr>
<tr>
<td>3</td>
<td>C + D</td>
<td>70°</td>
<td>235</td>
<td>40</td>
<td>Into the volume, first middle of the thickness</td>
<td>DAX +12</td>
<td>NV</td>
<td>N</td>
</tr>
<tr>
<td>4</td>
<td>C</td>
<td>45°</td>
<td>87</td>
<td>18</td>
<td>On the chamfer, just deeper than X-roof</td>
<td>DAX-3</td>
<td>V</td>
<td>N</td>
</tr>
</tbody>
</table>

### Table 2. Results of Manual Ultrasonic Testing of Weld UT3

<table>
<thead>
<tr>
<th>Defect</th>
<th>Side for detection</th>
<th>Probe for detection</th>
<th>Position from origin (mm)</th>
<th>Length (mm)</th>
<th>Position in the weld</th>
<th>Amplitude (dB)</th>
<th>Classification</th>
<th>Acceptation (Y/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>D</td>
<td>45°</td>
<td>85</td>
<td>20</td>
<td>Embedded but on the chamfer</td>
<td>DAC +7</td>
<td>NV</td>
<td>N</td>
</tr>
<tr>
<td>2</td>
<td>C</td>
<td>70°</td>
<td>180</td>
<td>40</td>
<td>Into the volume, first middle of the thickness</td>
<td>DAC-3</td>
<td>V</td>
<td>N</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>45°</td>
<td>295</td>
<td>15</td>
<td>Embedded but on the chamfer</td>
<td>DAX +6</td>
<td>NV</td>
<td>N</td>
</tr>
<tr>
<td>4</td>
<td>D</td>
<td>70°</td>
<td>295</td>
<td>5</td>
<td>Into the volume, first middle of the thickness</td>
<td>DAX-9</td>
<td>V</td>
<td>Y</td>
</tr>
</tbody>
</table>
3. Conventional PA UT

3.1 Procedure Used

Conventional PA UT has been performed in accordance with European standards. The same electronic and post processing software were used for conventional PA UT and PA UT with 3D freedom arm. But for other parameters, choices were made in order to meet industrial examination strategy that could be applied with the common phased array instrumentation:

- **Probe:** 5L64 used with its S55 wedge
- **1 mechanical displacement at 54 mm from the centre line of the weld encoded with a resolution of 1 mm for each side**
- **3 salvos:**
  - 1 electronic scan with 16 active elements and a 45° Shear wave deviation with a step of 1 element
  - 1 electronic scan with 16 active elements and a 55° Shear wave deviation with a step of 1 element
  - 1 sectorial scan with 16 active elements between 40° and 72° with a 1° step

Reference level is set on the same calibration block with side-drilled holes of diameter 3 mm as manual testing.

3.2 Results on the Welds

Following tables give interpretation results from Conventional PA UT examination.
### Table 3. Results of Phased Array Ultrasonic Testing of Weld UT2

<table>
<thead>
<tr>
<th>Defect</th>
<th>Side for detection</th>
<th>Salvo for detection</th>
<th>Position from origin (mm)</th>
<th>Length (mm)</th>
<th>Position in the weld</th>
<th>Amplitude (dB)</th>
<th>Classification</th>
<th>Acceptation (Y/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>D</td>
<td>45°</td>
<td>111</td>
<td>14</td>
<td>Embedded but on the chamfer</td>
<td>DAC -31</td>
<td>NV</td>
<td>N</td>
</tr>
<tr>
<td>2</td>
<td>C + D</td>
<td>45° and 55°</td>
<td>317</td>
<td>21</td>
<td>On the roof of the X weld</td>
<td>DAC-25</td>
<td>NV (with 1mm height – measured with diffraction echoes)</td>
<td>N</td>
</tr>
<tr>
<td>3</td>
<td>C + D</td>
<td>55°</td>
<td>224</td>
<td>49</td>
<td>Into the volume, first middle of the thickness</td>
<td>DAX -13</td>
<td>NV</td>
<td>N</td>
</tr>
<tr>
<td>4</td>
<td>C</td>
<td>45°</td>
<td>76</td>
<td>20</td>
<td>On the chamfer, just deeper than X-roof</td>
<td>DAX-25</td>
<td>V</td>
<td>Y (due to amplitude)</td>
</tr>
</tbody>
</table>

Below is given an example of results on defect N°4 on Weld UT2.

**Fig. 2.** Observed views on defect N°4 on weld UT2

**Fig. 3.** Observed D-Scan (+12 dB) with cursor on defect N°2 on weld UT 3, access C, 55° E-scan
Table 4. Results of Phased Array Ultrasonic Testing of Weld UT3

<table>
<thead>
<tr>
<th>Defect</th>
<th>Side for detection</th>
<th>Salvo for detection</th>
<th>Position from origin (mm)</th>
<th>Length (mm)</th>
<th>Position in the weld</th>
<th>Amplitude (dB)</th>
<th>Classification</th>
<th>Acceptation (Y/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>D</td>
<td>45°</td>
<td>72</td>
<td>25</td>
<td>Embedded but on the chamfer</td>
<td>DAC -21</td>
<td>NV(with 2mm height – measured with diffraction echoes)</td>
<td>N</td>
</tr>
<tr>
<td>2</td>
<td>D</td>
<td>55°</td>
<td>184</td>
<td>41</td>
<td>On the roof of the X weld</td>
<td>DAC-17</td>
<td>V</td>
<td>Y (due to amplitude)</td>
</tr>
<tr>
<td>3</td>
<td>D</td>
<td>45°</td>
<td>295</td>
<td>37</td>
<td>Into the volume, first middle of the thickness</td>
<td>DAX-7</td>
<td>NV</td>
<td>N</td>
</tr>
<tr>
<td>4</td>
<td>C</td>
<td>55°</td>
<td>303</td>
<td>12</td>
<td>Embedded but on the chamfer</td>
<td>DAX -1</td>
<td>NV</td>
<td>N</td>
</tr>
</tbody>
</table>

All indications were detected, despite sensitivity level not well suited regarding manual UT results.

4. PA UT with a Three Degrees Freedom Arm

4.1 Description of the Arm used for Weld Examination

The arm used is dedicated to longitudinal wave inspection at 0° and was developed for corrosion testing on plate. It has to be used with a specific electronic system with minimum 3 encoders input and specific software able to build new views.

The arm (see Fig.4) have 3 encoders:
- $\rho ; \theta$ : related to the mechanical displacement of the probe on the specimen plan (translate in (x;y) coordinates within software)
- $\theta_3$ : related to the rotation of the probe on the specimen plan (skew angle) and to the orientation of wave propagation

The $\theta_3$ isn’t used and exploited with conventional Phased Array examination, but is very helpful on manual ultrasonic examination.

The software saved all A-scan for each ($\rho ; \theta ; \theta_3$) position and exploit them to build a specific C-scan, called concatenated C-scan. This is a great evolution compared to a traditional C-scan where each point of the cartography represents in colour a level of amplitude or a time of flight at this probe position. Distance between each point/pixel is given by acquisition step in each direction.

In the concatenated C-scan, distance between each pixel is directly related to encoder resolution. But dimension of pixel is equal to the step acquisition defined for the acquisition. Therefore, pixels could be superposed. Furthermore, colour of each pixel
represents signal amplitude taking into account its projection to specimen surface (including refraction angle and tilt angle). It gives a true top view of the piece.

**Fig. 4.** Arm in position for the testing

### 4.2 Procedure Used

To be closed to manual ultrasonic examination, the following equipment for PA UT with a 3D freedom arm was used:

- Probe: 5L16 with a S55 wedge
- a sectorial scan with 16 active elements between 40° and 72° with a 1° step
- a manual encoded displacement on the surface of the test specimen for each side (except on the cap)
  
  Reference level is set on the same calibration block as used for manual testing (with side-drilled holes of diameter 3 mm).

**Fig. 5.** Sketch of the nearest position of the probe with its support regarding to the weld

### 4.3 Limitation for Weld Testing

As this equipment was developed for 0° LW, procedure to reset \( \theta_3 \) encoder wasn’t described. Works have been performed to develop the reset encoder procedure (including verification of encoder parameters).

As all A-scan in all encoded position allowed by the arm are stored, the generated file could become very big quickly. In order to limit data saving size, it’s important to:

- choose carefully the dimension of mechanical C-scan,
- limit the acquired A-scan length,
- optimize the sampling frequency and
- adapt the acquisition step to the dimension of the probe.
Despite all these precautions, a 400 mm length weld generate a 686 Mo file.

The interpretation based on the concatenated C-scan is not easy, because each pixel of the view corresponds to the real position of indication in the top view of the specimen. In other view (B-scan, D-scan, conventional C-scan), each pixel corresponds to the probe position. That is why it’s difficult to observe the A-scan corresponding to a specific indication or point of the concatenated C-scan.

The study also highlighted other limitations of the system. In case the arm is not parallel to the surface to be inspected, errors during reconstructions occurred, the $\theta_3$ axis being miscoded. To correct this error, we should encode the angle of the support arm with the controlled surface (axis $\theta_3$), which is not possible with the current system.

4.4 Results obtained on the Welds

The results for UT2 and UT3 welds are given in Fig.6 and 7.

Concatenated C-scan contains a lot of “noise”. The green points (and some red also) comes for most of them from the top and the bottom of the cap weld (not grind ed). They are geometrical echoes (not significant indications). This phenomenon can make more difficult to detect internal indication (and also due to the dimension of the probe with its support regarding to the weld geometry – see Fig.5)

When the weld is grinded [1], extensive benefits are obtained.
5. Comparison of the Results

The three techniques proposed in this article require some work preparation for sensitivity calibration. For conventional phased array technique, it requires also scan plan drawing to define the examination strategy to ensure the best volume coverage. The work preparation times are quite similar for these three techniques. The main difference in terms of time is about the examination time. Where a manual ultrasonic inspection for this example needs around one hour, the phased array ultrasonic testing with three degree freedom arm requires only a quarter of hour and the conventional phased array ultrasonic testing can be performed in less than 5 minutes.

After examination time comes interpretation time for phased array ultrasonic testing. If there is no indication, this could be rather quick. It takes about few minutes for interpretation when indications are detected.

Excepted than for phased array ultrasonic testing with three degrees of freedom arm, the appropriate choice of ultrasonic parameters (phased array probe and associated / single element probe) was able to detect and characterize indications with a good concordance to manual testing.

Phased array ultrasonic testing with three degree freedom arm wasn’t well suited to this examination for many reasons explained before.

6. Conclusion

Conventional Phased Array examination remains the best solution in that inspection case (carbon steel butt weld with an X chamfer geometry - caps weld not grinded). It was proven that application of standards give comparable results to manual ultrasonic examination in terms of detection and characterization of indications. It was also shown that this particular example is not well fitted to the use of phased array ultrasonic testing with three degrees of freedom arm. This is due to a combination of several limitations:

- dimension of probe holder
- caps weld not grinded

A way to overcome these two limitations could be to develop a procedure able to build a concatenated C-scan with (a) window(s) excluding top and bottom caps echoes.

References