Experimental Comparison of Wave-field Based Ultrasonic Imaging with other Advanced Ultrasonic Weld Inspection Techniques

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Abstract
Non-destructive testing (NDT) based on ultrasonic wave propagation is a known method for detection and sizing of defects in steel components such as girth welds. In this paper, several standard inspection methods, such as time of flight diffraction (ToFD), phased array tandem technique, and phased array sectorial scan, are compared to an ultrasonic imaging technique based on inverse wave field extrapolation (IWEX). The performance of the methods is assessed on plate samples containing artificial defects according to an automated ultrasonic testing (AUT) procedure used in industrial inspections. Measurements obtained with the different techniques are compared in terms of detection, sizing accuracy, and ease of interpretation.

Keywords: Inverse wave field extrapolation, advanced ultrasonic testing, beamforming, imaging

1 Introduction

IWEX (Inverse Wave field EXtrapolation) is an emerging novel ultrasonic testing (UT) technique that shows great potential in both defect detection and characterization, combined with a simplified presentation of inspection results due to an imaging approach. This technique is currently being implemented in the Applus RTD IWEX 3D Imager. In order to quantify its potential and to explore its position in the technological landscape, it is compared in practice to a selection of advanced UT techniques currently available on the NDT market: Time of Flight Diffraction (ToFD), Phased Array (PA) Tandem and PA sectorial scan.

2 Description of current ultrasonic techniques

2.1 Time of Flight Diffraction (ToFD)

ToFD was developed in the 1970s and relies mainly on diffraction signals. The technique includes two single element probes (transmitter and receiver) positioned at each side of the weld. The tip diffraction signals measured at different positions along the weld enable defect sizing in height and length. ToFD is generally known to provide accurate sizing, but relatively poor positioning of the defect in the weld cross-section [1].

2.2 Phased Array sectorial scan (PA sectorial scan)

A phased array sectorial scan is performed by steering the angle, focal depth and index point of ultrasonic beams using phased array probes. Information contained in PA sectorial scans can be of either reflective or diffractive nature. Therefore, caution must be taken when objects with complex geometries are inspected. The information contained in reflected signals greatly depends on the orientation of the defect with respect to the ultrasonic beam, as sizing is done using 6 dB amplitude drop between beams. More background information about PA sectorial scans can be found in [2].
2.3 Phased array tandem (PA tandem)

The PA Tandem technique is often selected when it comes to the inspection of narrow gap welds e.g. in heavy wall components or girth welds [3]. This technique relies on the amplitude of reflected signals to assess the size of defects as well as a zonal concept to size the defects and to determine their position in the weld. A defect can be detected if it is present at the intersection of the transmission and reception beams. In that case, the amplitude of the reflected signal is used to size the defect using sizing curves. It should be kept in mind that sizing based on reflection amplitude assumes a certain orientation of the defect with respect to the ultrasonic beams. If the real defect orientation differs from the assumed orientation, sizing inaccuracies will occur.

3 Inverse wave field extrapolation (IWEX)

3.1 The principle of IWEX

IWEX is a novel ultrasonic testing (UT) method developed by Applus RTD in 2004, as described by Pörtzgen et al. [4] and later by Chougrani et al. [5]. The result of this emerging technique is an actual image of the inspected volume, rather than a plot of the collected signals. The main advantage of this technique is a comprehensive visual representation of the defect, which can be used for accurate characterization in terms of size, position, and orientation. Additionally, the IWEX methodology allows for data visualization in both two and three dimensions as shown in Figure 1.

![Figure 1: 2D and 3D IWEX images (left hand side: inspected steel bar containing an artificial defect; center: IWEX 2D image of the artificial defect; right hand side: IWEX 3D result for the artificial defect)](image)

IWEX is a direct application of the Rayleigh integral for wave field extrapolation. This integral enables the calculation of the sound pressure at any point in an object based on measurements of the sound pressure distribution at the surface of the object. The measurement is typically done by transmitting with each single element individually; and receiving with all elements, see Figure 2. If the multi-element probe contains \(N\) elements, then \(N^2\) A-scans are obtained for one IWEX measurement. This dataset can then be processed by the IWEX algorithm, which effectively corrects the amplitude and phase of the signals for propagation effects and generates an image by focusing virtually on a number of image points in the region of interest.
3.2 Direct imaging

The first applications of IWEX focused at imaging volumes below the probe using direct insonification and hence compression (longitudinal) waves are used, see Figure 3. However, some practical challenges were encountered when applying IWEX to welds:

a) The image resolution close to the probe was relatively poor due to near-field effects.

b) The presence of the weld cap prevented the positioning of the probe directly above the region of interest, i.e., the weld volume.

c) Planar defects oriented more or less perpendicular to the surface were imaged as two tip diffractions instead of showing the flat nature of the defects.

3.3 IWEX over skip

In order to examine areas directly under the probe and to overcome practical limitations, it was decided to process waves that traveled over skip as well; effectively using the back wall as a mirror to image the near surface and to image the lower side of the defects, see Figure 4. In order to differentiate this algorithm from the original direct imaging approach, it was decided to add the number of skips behind the IWEX name: as 2 skips are used in back-wall
imaging, this IWEX variant was named IWEX-2. Following this logic, the original IWEX was called IWEX-0.

The challenge posed by the weld cap and root was solved by using a wedge to the IWEX probe and positioning a probe on either side of the weld, as it is common for other ultrasonic inspection techniques. Using wedges has two main advantages: it directs the beam into the weld volume, but it also allows for using only shear waves by using an angle of incidence beyond the first critical angle. Furthermore, the usage of shear waves has the advantage of almost doubling the resolution of the IWEX approach due to the shorter wavelength in carbon steel.

Another main challenge was encountered when inspecting welds with bevels at small angles. Part of the expected defects follow the weld bevel (e.g. lack of fusion) and are oriented almost perpendicular to the surface. Defects of this orientation cause almost only diffraction signals when imaged with IWEX-0 or IWEX-2 from the top or from the bottom, respectively. The solution to this problem was based on the insight to use a tandem approach for IWEX. In order to have an insonification from the side of the weld, it was chosen to use a sound path from source to an image point via the back wall returning to the receiver (see Figure 5, left hand side). As this approach uses only one skip, it was called IWEX-1. Following up on the lateral insonification, two additional skip can be added to obtain the IWEX-3 algorithm (see Figure 5, right hand side). It has the same advantage as IWEX-1, but has an increased inspection range. Due to reciprocity, the reverse direction of the sound path can be used as well.

To be able to use the IWEX modes with one or more reflections at the back wall, the position of the back wall must be known. If the position of the back wall is not known, it can be determined from the IWEX measurement itself. In this way, even non-parallel or non-flat surfaces can be used for the different IWEX modes as well. Any inaccuracy in the back wall position will result in deviations in the resulting IWEX images. However, the resulting images of IWEX modes 1, 2 and 3 will only be slightly shifted and defocused and will still provide information on the examined volume.

4 Experiments

The study described in this paper aims at comparing measurement results obtained with IWEX with results obtained with ToFD, PA Tandem and PA sectorial scan. The techniques
have been applied and evaluated by operators that had no prior knowledge on the defects in the test sample. The results are compared in terms of detection, height sizing accuracy and ease of interpretation. Defect length assessment was outside the scope of this study.

The test sample designed to compare the different techniques was manufactured following an Automated Ultrasonic Testing (AUT) procedure drafted by Applus RTD for the inspection of CRC girth welds, see Figure 6. In order to have maximum control on the defects made in the test sample and to avoid possible unintended weld imperfections, it was decided to take a solid carbon steel plate. To simulate the geometry of a weld cap and root, one weld pass was made on top and one on the bottom of the plate. The thickness of the plate was 19.1 mm, in compliance with the AUT procedure. As ToFD uses diffraction to detect and size defects, flat bottom holes could not be used as artificial defects. Instead, EDM notches were used of 0.5 mm wide. The plate was sawed in smaller blocks of 35 mm width to be able to machine the artificial defects. Once all notches were manufactured in the sides of the blocks, the smaller plates were tag welded together to reconstruct the original plate; as illustrated Figure 7. It should be kept in mind that because of the side walls of the individual blocks, length sizing of the defects was not possible and hence kept outside the scope of this study.

![Figure 6: Schematic drawing of the CRC weld described in the AUT procedure.](image)

![Figure 7: Perspective view of the test plate design (left) and photograph of the IWEX setup (right).](image)

The test plate contained 17 notches of 3 mm height, all representing possible defects in the weld. The collection of defects represented both common defects, as well as defects that are known to be particularly difficult to detect and size with modern UT, see Figure 8.
Defects BN, BS, and F were manufactured several times with different orientations, to evaluate the sizing accuracy of the UT techniques for varying defect orientations. The additional defects were as follows:

- Defects B1, B2, B3 and B4 are identical to BN, except that they have a rotation of +5°, -5°, +10° and -10°, respectively. The angles are given with respect to the weld bevel and positive angles indicate a clockwise rotation around the defect center.
- BS had variations BS1, BS2, BS3 and BS4 with rotations of +5°, -5°, +10° and -10°, respectively.
- Defect E2 was given a rotation of 90° with respect to E1, effectively giving it an orientation parallel to the back wall.

The ToFD scans were obtained using an Applus RTD PAULIS UT-8 system; while the PA Tandem measurements were performed using an Applus RTD Rotoscan system in combination with an XY-table for accurate probe positioning. The ToFD probes had a center frequency of 10 MHz and provided a nominal beam angle of 60°. The phased array probe used for the tandem measurement had 64 elements with a pitch of 0.85 mm, a center frequency of 4 MHz and a wedge angle of 37°. A calibration block for both ToFD and PA Tandem was designed as described in the AUT procedure drafted for the inspection of the selected CRC weld.

The PA sectorial scans were done with an Olympus Omniscan system. The PA probes had a center frequency of 5 MHz, containing 64 elements with a pitch of 0.6 mm and a wedge providing a natural angle of 55°. Both PA Tandem and PA sectorial scan were performed using one single PA probe, positioned on the side of the weld that contained the artificial (this implies that no information from the other side of the weld was available).

The IWEX inspection was made using the Applus RTD IWEX prototype system, with 2 probes containing 128 elements each (with a pitch of 0.425 mm and a center frequency of 4 MHz); one on each side of the virtual weld, as shown in Figure 7. In order to perform IWEX-1 and IWEX-3 correctly, wedges were used with an angle of 37°. IWEX modes 0 and 2 have been performed from one probe to the other, but also within the same probe individually. The modes IWEX-1 and IWEX-3 were only measured within the same probe. This approach resulted in 10 different images per scan, which were combined into one single image using a color coding scheme.
5 Results

5.1 Comparison of all techniques based on the results obtained for defect BN

The scans obtained for defect BN are chosen to illustrate the typical results that can be obtained with the different techniques, as shown in Figure 9.

When keeping the photograph of defect BN in mind (Figure 9a), an assessment of the different evaluation presentations can be made in terms of ease of interpretation. In the PA sectorial scan (Figure 9b), a drawing of a weld bevel (and corresponding mirror image) is projected over the sectorial scan to provide a reference of the weld geometry. The defect is represented by two diffraction traces (positioned at the intersection of the diagonal black line and the red and blue horizontal lines), while artefacts and geometry (weld cap and root) echoes are also present. Sizing of the defect can be done on screen using the distance between the tip diffractions. In this case, the height of defect BN was measured to be 2.7 mm and hence gave a slight undersizing of the defect. Although the PA sectorial scan provides a graphical representation of the defect and some parts of the weld geometry, its evaluation requires advanced training and experience in UT.

![Defect BN](image)

Figure 9: Results obtained for defect BN; a: macro, b: PA sectorial scan result, c: ToFD result, d: PA Tandem and e: IWEX (IWEX-0 is shown in blue, IWEX-1 and IWEX-3 are depicted in red and IWEX-2 is represented in green).

The scan direction for the ToFD scan (Figure 9c) is parallel to the weld direction, providing a different view of the weld than the macro. ToFD evaluation is typically made using the diffraction patterns for the length of the defect; and using the travel time difference between the tip diffractions for height sizing. For defect BN, a height of 3.0 mm is obtained, which is exactly the size of the artificial defect.
The tandem technique shown in Figure 9d provides a less intuitive representation for defect characterization. The depth of the defect in the weld is given by the zone in which the defect is detected (in the figure: F3 for Fill 3). The size of the defect is deduced from the amplitude of the signal corresponding to the optimum position (black curve). In this case, a value of 4.0 mm is obtained, effectively oversizing the defect. Note that the signal above 100 % FSH was caused by the corner effect at the edge of the plate and was ignored for defect sizing.

The IWEX image obtained for defect BN is shown in Figure 9e. From this image, it can directly be seen that the IWEX approach provides the most intuitive visualization: the front wall, back wall, cap and root are clearly visible; and hence a view comparable to the cross section of the weld is obtained. Defect characterization is relatively simple as well, as the scale is given in distance perpendicular to the weld [mm] and depth [mm]. This means that defect position, size and even orientation can directly be found from the output image. More specifically, two dominating IWEX modes have been used for the sizing of defect BN: the IWEX-1 mode (red) was used to determine the orientation of the defect and IWEX-2 (green) was used to accurately size the defect (intersection of the red stripe with the two horizontal green stripes). The defect height found this way was 3.0 mm; corresponding exactly to the size of the manufactured notch. To further demonstrate the ease of interpretation provided by IWEX, additional IWEX images are shown in Figure 10.

Figure 10: IWEX images obtained for defects A, BN, BS, C (top row, from left to right, respectively); and defects D, E1, F and G (bottom row, from left to right, respectively) (IWEX-0 is shown in blue, IWEX-1 and IWEX-3 are depicted in red and IWEX-2 is represented in green).
5.2 Discussion of the results obtained for all techniques

An overview of the sizing results is given in Table 1. The results are presented as a sizing deviation with respect to the real defect size (3.0 mm). Positive and negative values indicate defect oversizing and undersizing, respectively.

Table 1: Sizing deviation obtained with the various UT techniques and defects

<table>
<thead>
<tr>
<th>Sizing deviation per technique [mm]</th>
<th>Defect</th>
<th>PA Tandem</th>
<th>ToFD</th>
<th>PA Sectorial Scan</th>
<th>IWEX</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>≤ 0.2 mm (green)</td>
<td>≤ 1.0 mm (yellow)</td>
<td>&gt; 1.0 mm (orange)</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>-1.5</td>
<td>Not detected</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>BN</td>
<td>1.0</td>
<td>0.0</td>
<td>-0.3</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>0.0</td>
<td>-0.3</td>
<td>-0.3</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>0.0</td>
<td>-0.3</td>
<td>-0.6</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>B3</td>
<td>-1.0</td>
<td>-0.4</td>
<td>0.8</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>B4</td>
<td>-1.0</td>
<td>-0.5</td>
<td>0.0</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>BS</td>
<td>0.0</td>
<td>-0.1</td>
<td>-0.4</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>BS1</td>
<td>0.0</td>
<td>-0.1</td>
<td>-0.2</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>BS2</td>
<td>-0.5</td>
<td>-0.2</td>
<td>0.3</td>
<td>-0.1</td>
<td></td>
</tr>
<tr>
<td>BS3</td>
<td>-1.0</td>
<td>-0.2</td>
<td>0.0</td>
<td>-0.1</td>
<td></td>
</tr>
<tr>
<td>BS4</td>
<td>-2.0</td>
<td>-0.3</td>
<td>0.8</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>-1.0</td>
<td>-0.4</td>
<td>0.0</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>-1.0</td>
<td>-0.9</td>
<td>-0.9</td>
<td>-0.9</td>
<td></td>
</tr>
<tr>
<td>E1</td>
<td>-1.5</td>
<td>Not detected</td>
<td>-0.5</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>E2</td>
<td>-2.0</td>
<td>Not detected</td>
<td>-0.1</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>-2.7</td>
<td>Not detected</td>
<td>-0.4</td>
<td>-2.5</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>-1.5</td>
<td>-0.1</td>
<td>0.7</td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>

Defect D turned out to be manufactured differently than defined in the design, and hence the real defect size was not 3 mm but 5.3 mm. This implies that the undersizing is larger than reported above, this will be discussed below for all techniques.

When comparing the techniques in terms of sizing accuracy, IWEX provides superior results by sizing 14 out of 17 defects with high accuracy and their correct orientation. The IWEX images for the defects shown in Figure 8 are presented in Figure 10. Three defects were not sized accurately: two were undersized (defects D and F) and one was oversized (defect C). Defect F was interpreted as single point. In the IWEX image, only the lower tip of defect F is visible (imaged with IWEX-2). The diffraction of the upper tip is difficult to detect in the presence of the indications caused by the cap geometry. The height of the defect was not shown by IWEX-1, nor IWEX-3 due to the position up in the cap, so no indication of the extension was imaged. The oversizing of defect C is due to reflections caused by the root geometry: these indications were stronger than the lower tip of the defect observed in the IWEX-0 image, and hence were used to size the defect. This led to oversizing as the geometry indication was deeper than the defect lower tip.

PA tandem showed a tendency to underestimate the size of defects with a position outside its target area or with an orientation deviating significantly from the bevel angle. This is mainly due to the sizing being based on amplitude information and sizing curves for expected orientations. Defects B3 and B4 were undersized due to their orientation. Defects A, C, E1 and F had a position that was not optimal for the used PA tandem setup. Defects E2, BS3 and BS4 combined both challenging orientation and position.
ToFD provided good results in terms of the sizing accuracy. However, it was the only technique that did not detect some of the defects. A possible reason for this might be the notch width (0.5 mm) that might have been too large. It is expected that diffraction signals would have been stronger if a tighter notch had been made. Although IWEX also uses diffraction signals to image the defects, it suffered less from the weaker signal because the phased array probes used for IWEX had a larger aperture than the ToFD probes.

The PA sectorial scan technique used diffraction signals to detect and size the defects instead of reflection signals (which are normally used); combined with the use of measurements over skip. Despite of the complexity of this inspection methodology and its dependency on operator skills and experience, the results were sufficient. In particular, defect F was detected and sized relatively well thanks to this approach.

Defect D formed a special case. When the IWEX results were considered, the defect position diverged significantly from the test plate design. This was later confirmed when disassembling the test plate: the defect had been manufactured in the center of the root instead of next to it, therefore having a different position and size than intended. The total height was measured as 5.3 mm. PA Tandem was not able to size it accurately because it was outside of the sensitive volume of the tandem arrangement. ToFD did not detect it because only a weak upper tip diffraction was visible, yet no lower tip diffraction nor back wall interruption due to the root were detected. The sizing accuracy of IWEX suffered from comparable effects. Characterization with PA sectorial scan was done using reflection signals mainly.

6 Conclusions

By comparing IWEX with ToFD, PA sectorial scan and PA Tandem, it was shown that imaging techniques can provide improved detection and sizing accuracy when inspecting narrow gap welds by taking into account both diffraction and reflection signals. Furthermore, defects with various orientations could be imaged by combining both direct insonification and indirect measurements via the back wall. In contrast to other techniques, IWEX was shown to provide a comprehensive output image allowing for direct evaluation of indications found. The comparison of all techniques on real defects and the criteria for evaluation of the results (preferred modes for certain situations) are recommended for further research. Summarizing, it can be stated that a combination of UT techniques (ToFD, PA Tandem and PA sectorial scan) is recommended for improved detection and sizing of various defects, while IWEX is successful through an inherent redundancy of various modes.

References