A picture-perfect inspection

Niels Pörtzgen, Applus+ RTD, the Netherlands, explores improvements in full matrix capture-based ultrasonic imaging for pipeline girth weld inspection.

Since the development of welding processes for the construction of pipelines, there has been a need for a quality assessment of girth welds. In the early days, radiography was developed to obtain a basic assessment of the weld quality and to establish good workmanship. Although radiography is still successfully in use for many new construction pipeline projects where good workmanship is required, safety issues due to radiation and operational limitations such as film development time have been drivers for the development of other inspection strategies.

Ultrasonic testing (UT) provided a solution to avoid radiation and to obtain instant results. Initially, ultrasonic testing was performed manually by an experienced and skilled inspector who would move an ultrasonic probe in a meander pattern along the weld, searching for potential weld imperfections. This inspection strategy was further improved by mechanised or automated UT (AUT) systems. The first systems were quite bulky and heavy (Figure 1) due to the size of the manipulator, and also due to the number of ultrasonic probes required for a complete coverage of the inspection volume using the zonal discrimination concept (ZDC).[1]

With improvements in engineering, the size of the manipulator of AUT systems could be reduced. Furthermore, due to advances in computer and sensor technology, the need for single fixed angle probes could be reduced by using ultrasonic phased array (PA) probes. With PA probes, ultrasonic beam parameters such as the angle of incidence, the focal spot and beam width can be controlled with a computer up to a certain extent.

Although the practical and economic benefits of PA technology for girth weld inspection are evident, the inspection strategy based on the ZDC has not changed much. Therefore, inherent limitations caused by the use of narrow directional beams have also remained. Furthermore, the typical display of data in so-called 'strip charts' and the interpretation require experience and expertise. Nonetheless, the introduction of PA technology opened up an opportunity for the introduction of a new inspection concept, whereby representative 2D and 3D images from the girth weld and possible indications are generated.

Generation of an 'ultrasonic fingerprint'

One of the main conceptual differences between the traditional ZDC concept and ultrasonic imaging is the way in which ultrasonic waves are applied to perform the measurements. With the ZDC, groups of individual elements are fired in a certain timing sequence referred to as a 'delay law', generating a narrow directional ultrasonic beam. The properties of the ultrasonic beam (angle, focal spot, beam spread) are determined by the number of elements in the group and the delay law.

For the use of ultrasonic imaging, the elements of the ultrasonic array are treated as individual sources and receivers. Hence, no delay law will be applied to a group of elements. Instead, a single element will be fired, starting with the first element, and the upward travelling wave fields will be received by all available elements of the entire array (Figure 2). The time-signal responses from the receiving elements, referred to as A-scans, are all recorded. Then, the second element is fired and again all A-scans from the receiving elements are recorded, until all elements have been used as a source. As such, A-scans have been recorded from all possible combinations of sending and receiving elements of the array. Because the combinations of sending and receiving elements can be arranged in a matrix notation, the resulting data set is often referred to as a 'full matrix capture' (FMC).

Figure 1. The first automated ultrasonic testing systems were rather bulky and not computerised.

The FMC data set contains responses from ultrasonic waves that have been reflected and/or diffracted at the geometry of the weld (back wall, front wall, cap and root reinforcements, high-low etc.), and also at possible indications (lack of fusion, porosity, root concavity, undercut etc.). When the ultrasonic array is large enough and positioned correctly, the FMC data set will thus contain responses obtained from waves which have reached a possible indication from different directions, including travel path from waves reflected at the back wall or even from waves that have undergone a wave mode conversion (e.g. from transverse waves into longitudinal waves). As a result, not only information related to the presence of an indication but also the geometrical information (orientation, depth positioning, and height) will be captured in the data. Therefore, the FMC data set is much like an ultrasonic fingerprint. Intuitively, it can be understood that the sequence to measure such an ultrasonic fingerprint does not require any a-priori knowledge (such as the design of the weld bevel) as opposed to the ZDC. Once the FMC data set is recorded, the next step is to process the data into a 2D image.

Imaging by time reversal

In order to process an image from the FMC data, first an image space consisting of pixels must be defined. Obviously, the image space should be sufficiently large to cover the entire area of interest. This is usually the full weld area and the heat affected zones (HAZ). The positions of the array elements relative to the locations of the pixels are inputs for the calculations. Because the sound velocity and the locations of the elements and the pixels are known, the travel times from each element to each pixel location can be calculated by applying wave field physics. Hence, as illustrated in Figure 2, the signal responses corresponding to an indication located at a certain pixel can be predicted.

All the recorded responses are then shifted back in time with the corresponding time duration from sending element, to the pixel location, to the receiving element. When done correctly, all amplitudes are lined up at t = 0.

This process can also be explained mathematically in terms of backwards or inverse wave field propagation (IWEX).[2] In fact, the time shifts required to line up all responses in the A-scans at t = 0 for a certain pixel, are the same as the delay laws required to create a focused beam at that pixel location. Because this applies

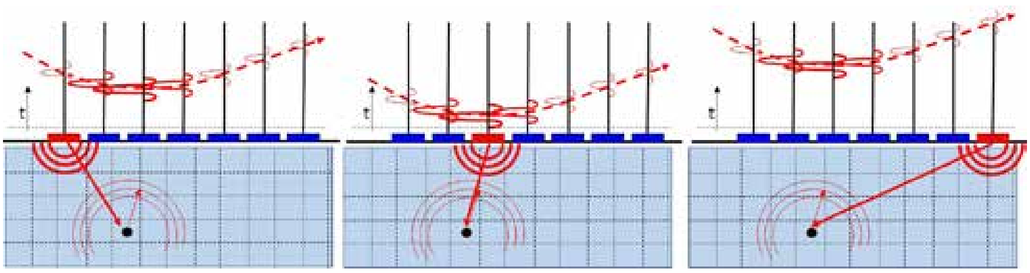

Figure 2. A full matrix capture (FMC) data set contains recorded A-scans from all possible combinations of source and receiver elements.

to all pixels, the imaging strategy is also referred to as total focusing technique (TFM).[3]

Finally, all the responses at t = 0 are summed and the resulting value is assigned to the pixel location and displayed with a coded colour pallet. The process must be repeated for all pixels in the image space, resulting in a 2D image. The image obtained in this way, will contain the information from a single travel path of the waves, e.g. direct from source to pixel and direct from pixel to receiver. Such travel paths are referred to as modes. The modes have different sensitivities depending on location and orientation of possible indications. Therefore, 2D images from multiple modes must be calculated and combined for a full coverage and orientation independent inspection.

The concept of ultrasonic imaging based on FMC data has been explained and illustrated. However, the step from concept to an accepted industrial application requires the development of hardware and software integrated into a system. For this purpose, the IWEX system was developed.

Figure 3. **The IWEX system applied for girth weld inspection in a spoolbase.**

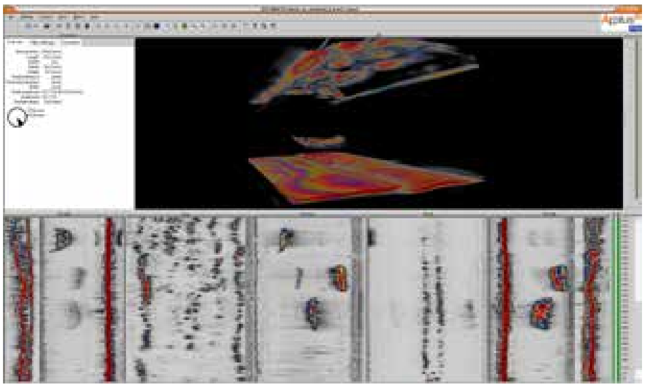

Figure 4. **Example of an IWEX scan from a girth weld with small and larger imperfections. The upper part of the display shows a 3D presentation of a selected area of the weld. The lower part displays the projection views.**

Ultrasonic imaging with the IWEX system in practice

Although the concept of ultrasonic imaging based on FMC data was already known, the development of the technology for real-time inspection applications and the step towards industrial acceptance have taken more than a decade, and it is still ongoing. The IWEX system developed by Applus+ RTD is the first AUT system for girth weld inspection based on FMC ultrasonic imaging. A feature of this system is its ability to generate images from multiple modes simultaneously. The IWEX system has been qualified for the inspection of carbon steel welds and CRA welds for offshore pipelines according to DNVGL-ST-F101:2017, and also for carbon steel onshore welds the system has been validated by TÜV in Germany.[4]

The IWEX system is a modular system containing the following components:

- A robust 19 in. rack with a standard industrial computer and a power supply unit.
- A winch with a 50 m umbilical cable as standard length carrying a network connection and power supply.
- A scanner bug which can be placed onto a removable and adaptable guiding band.
- The IWEX ultrasonic hardware unit with connections for array probes (2 × 64 elements), conventional probes, positioning encoder and temperature sensors. The IWEX ultrasonic hardware unit can be mounted on top of the scanner bug.

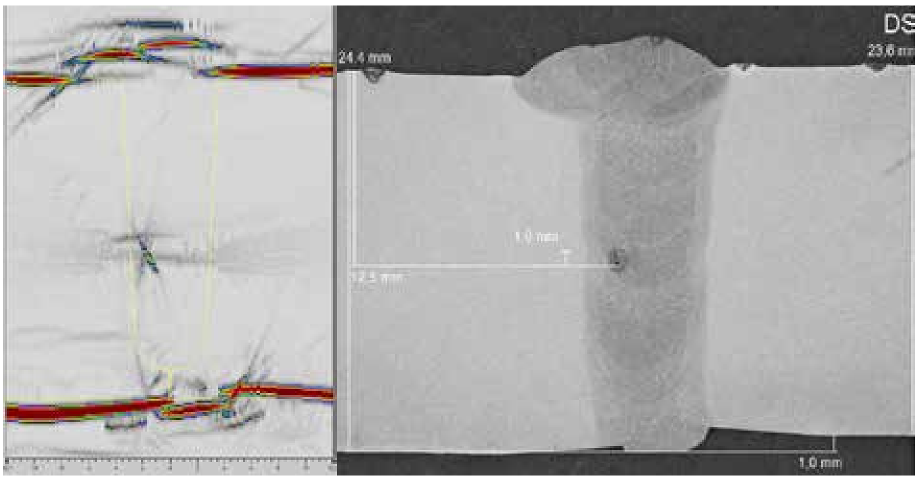

Figure 5. **Examples of 2D IWEX images showing welding imperfections with a comparison to the macro section from the actual indications.**

Depending on the application and design of the pipeline, a typical IWEX set-up contains two 64 element array probes and a pair of ToFD probes. Sometimes, additional transverse wave probes and/or creep wave probes are also used.

In a spoolbase facility, pieces of pipe are welded in station along a production line. The ultrasonic inspection is performed in a station right after the weld has been completed. When a new weld arrives in the station, the guiding band is placed at a certain distance from the weld

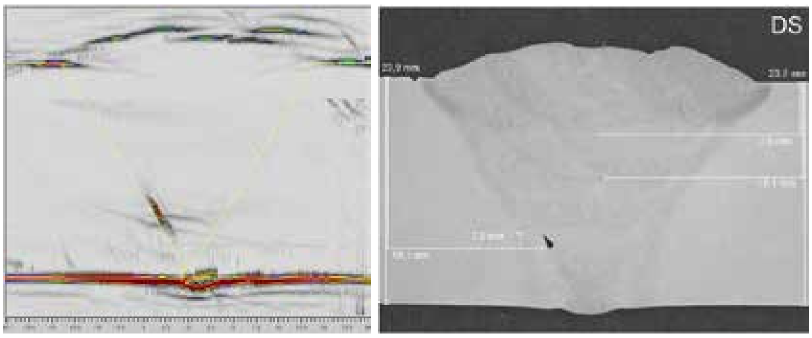

Figure 6. **Examples of 2D IWEX images showing welding imperfections with a comparison to the macro section from the actual indications.**

centre line, usually indicated by a pre-set scribe line. Then, the scanner bug is mounted onto the guiding band and placed at a start position which is indicated on the pipe (Figure 3). When the scanner is positioned correctly, the inspection starts, whereby the scanner bug moves around the entire circumference propelled by an electromotor. A 2D image is then generated in real-time at every circumferential position with a resolution of 1 - 2 mm. The 2D images can be viewed on the screen while the scanner is moving. The 2D images can be rendered into a 3D image, which can also be displayed during the scan.

When an inspection is started from the software, all the 2D images over the entire circumference – including an overlap at the zero point – are stored. Once the scan is finished, the user can start the interpretation of the results. Typically, the interpretation consists of two steps: detection of indication and, in the case of their presence, sizing of indications. For the detection of indications, the data display was designed to have a similar appearance to the well-known strip-chart display; however, the information presented in the strips is different from the ZDC. The number of strips used for detection is fixed and the information represents projection views from different sides and directions of a 3D volume (Figure 4):

- A side projection to the upstream and downstream side of the weld.
- A top down projection from the cap, volume and root area of the weld.

By means of pattern recognition, the user can easily recognise the presence of a possible indication. The initial location of the indication can be obtained from the projection views.

In case an indication has been identified, the user can view more details by moving a cursor line to the location and scroll through the area where the indication has been found. When the cursor line is moved, the 2D images will appear corresponding to the circumferential position (Figures 5 and 6).

Also, an area can be selected and a 3D image can be displayed from the selected area. In order to apply the acceptance criteria, the length and height of the indication can be assessed. For this, the software has built-in tools based on -6dB drop off and tip diffraction. Once the sizing of the indication has been completed, the indication can be added to a report in PDF format. At the end of each shift, a report can be generated from all inspected welds with the 2D and 3D images from the evaluated indications. It is also possible to open the scan files later on with a viewer program for further analysis if required.

Benefits and future potential

As opposed to traditional girth weld inspection based on the ZDC, IWEX imaging does not make use of small directional beams. As a consequence, many limitations that are related to the use of directional beams and zones do not apply. For example, the positioning of the guiding band is much less influential, depth positioning of indications is more accurate and the probability of detection is less dependent on the orientation of indications. As a result, the design of the reference block can be generalised so that it can be used for both J- and V bevel designs, reducing the costs.

Because the image presents defects in the context of the weld, it is more straightforward for non-NDT experts to understand the results. Defects can be visualised in a rotatable 3D image so that the depth, height, and length can be determined. This enables the welding crew to optimise the welding procedure and identify possible improvements in welding parameters in an efficient feedback loop.

Furthermore, because the detection is tolerant to defect orientation and position, and sizing is calculated based on the defect's image dimensions, characterisation and sizing accuracy can be more unambiguous compared to the ZDC. An improved sizing accuracy can be incorporated into the engineering critical assessment of the acceptance criteria. As a consequence, the conservatism in the acceptance can be relaxed, leading to fewer unnecessary repairs.

IWEX imaging also offers future potential. The availability of 2D and 3D digital images opens up the possibility of applying advanced (post) processing strategies for improved visualisation, pattern recognition and software assisted interpretation through machine learning. In combination with the ongoing developments in robotics and computer technology, it is possible that further benefits will be seen in the future, helping to make the inspection of new construction girth welds safe, accurate and cost-efficient.

References

1. Ginzel E.A., 'Automated Ultrasonic Testing for Pipeline Girth Welds, A Handbook', Olympus NDT Canada (2006).
2. Pörtzgen N., 'Imaging of Defects in Girth Welds using Inverse Wave Field Extrapolation of Ultrasonic Data', PhD thesis, Delft University of Technology (2007).
3. Wilcox P.D., 'ULTRASONIC ARRAYS IN NDE: BEYOND THE B-SCAN', 39th Annual Review of Progress in Quantitative Nondestructive Evaluation, AIP conf. Proc. 1511 (2013), pp. 33 - 50.
4. DNVGL-ST-F101:2017, 'Offshore Standard for Submarine Pipeline Systems', Appendix E.