Adaptive ultrasonic imaging of electric resistance welded pipeline seams

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Abstract

Ultrasonic imaging using the Total Focusing Method (TFM) is a technique which is well suited for the in-service inspection of axial seam welds of pipelines fabricated by electric resistance welding (ERW). For the assessment of flaws in the ERW seam, both the identification of flaw type and accurate sizing play an important role. Initially, the inspection approach used ultrasonic arrays on plastic wedges placed on both sides of the axial weld. However, depending on the quality of the fabrication process, a good mechanical fit between the pipe and wedges could not be obtained for all pipe seams inspected, which affected the quality of the images. As a result, a second approach was developed replacing the plastic wedges with an immersion setup. In this second approach, adaptive processing of the recorded full matrix capture (FMC) data is required to determine the outer pipe surface (OD) and adapt the focal laws accordingly. Using these adapted focal laws, it is possible to determine the profile of the inner pipe surface (ID). The information on the position of the boundaries can then be used to image the weld not only directly through the OD, but also to generate images based on reflections from the ID and OD. Combining these images into one cross-sectional view can then be used for flaw assessment in the ERW bond and surrounding heat affected zone. Results show that accurate knowledge or calibration of the geometrical setup and material parameters is of vital importance for obtaining focused and aligned images. Both inspection approaches are compared, and key parameters for obtaining the required capabilities in terms of characterization and sizing accuracy are discussed.

1. Introduction

A significant portion of the global energy pipeline infrastructure is constructed with pipe materials manufactured using the Electric Resistance Welding (ERW) process. The longitudinal seam of these ERW pipelines may contain manufacturing flaws and anomalies that can grow over time through pressure fatigue and result in a pipeline integrity failure. These flaws/anomalies can be present in both vintage pipe (generally pre-1970) manufactured using a low frequency ERW process and more modern pipe that is manufactured using a high frequency ERW process. ERW seam anomalies are challenging to detect and especially difficult to characterize with current pipeline inspection technologies such as shear wave probes and phased array ultrasonics, which
is driving the industry to better understand current industry performance and to develop new technologies for ERW seam anomaly inspection.

Acoustical imaging is one of the emerging inspection technologies for applications requiring high resolution and low sensitivity to flaw orientation. The Total Focusing Method is a well-known implementation of this approach (1).

An adaptation of acoustical imaging for the seam weld application was initially designed with a setup using arrays on angled plastic wedges, similar to setups typically used for girth weld inspection in automated ultrasonic testing. Using a cylindrical pipe model with constant wall thickness, good results were obtained for flaws in the pipe body, such as stress corrosion cracking (2). However, difficulties were encountered with this approach for imaging of the weld region. These issues were found to be caused by deviations of the sample from the cylindrical pipe model. In particular, misalignment of the plate edges before welding and excessive wall thickness around the weld area caused problems in the generation and interpretation of images.

During recent years, imaging methods like TFM have been adapted to deal with unknown geometry and provide adaptive focusing. Measurements on unknown geometries can be carried out either in direct contact with a flexible array (3) or with an immersion setup (4). Whereas typical immersion setups are based on generating longitudinal waves in the sample, the measurement setup for the seam weld inspection was designed in such a way that primarily shear waves are generated in the weld. This enables the creation of images with higher resolution due to the shorter wavelength in the sample.

In the following, the measurement setup, the calibration of the system, and the process of surface detection are described. Images obtained on representative samples are presented for setups in a water tank and with a flexible, water-filled cushion.

2. Description

2.1 Measurement setup

The basic measurement setup consists of two arrays positioned under an angle to the left and right of the seam weld as shown in Figure 1, with a certain distance between the arrays and the outer pipe surface.

![Figure 1. Measurement setup in the water tank with the two arrays placed under an angle (a); schematic view of the position of the arrays and the pipe surfaces (b).](image-url)
For the tests carried out, the system is set up in such a way that full matrix captures (FMCs) are recorded. This data contains the raw A-scan data of all source-receiver combinations for the elements of the two arrays. This information can be used for calibrating the system, and also for generating images with the setup parameters derived from the ultrasonic measurements.

2.2 Calibration

For the generation of images, accurate knowledge of geometrical parameters is required for the setup as well as the sound velocities in water and the pipe steel. To this end, a calibration routine was developed with the arrays positioned above a flat reflector. From this measurement, the relative position of the two arrays can be established.

The sound velocity in water is determined ultrasonically by measuring the time-of-flight for a known distance. The sound velocity in water can also be monitored during the inspection of a weld, such that compensation for temperature changes is possible.

The sound velocity in the sample to be inspected is found by detecting the outer pipe surface as described in the following section. Subsequently, a number of ultrasonic images of the inner pipe surface are generated for a range of possible sound velocities in pipe steel. The velocity leading to an optimally focused image with the highest amplitude is selected.

2.3 Surface detection

The pipe surfaces can be detected from the ultrasonic data. To this end, an image of the region containing the outer diameter (OD) can be made using the sound velocity in water. The profile of the outer surface can then be traced in the image. A curve may be fitted to the detected points. It is recommended to add criteria to stabilize the result and increase the robustness to noise causing outliers. Furthermore, small parts of the surface may be imaged with relatively weak amplitude due to surface roughness. A smoothness criterion is applied to the detected surface points to obtain a curve representing the position of the pipe surface.

Once the outer pipe surface is known, images of the inner diameter (ID) can be calculated. Subsequently, the inner pipe surface can be traced from the image in a way that is similar to the detection of the outer pipe surface.

2.4 Travel time calculation

Imaging requires the calculation of travel times from the array elements to image points in the region of interest. These travel times can then be used for the focal laws for imaging. For the current application, the travel times are determined using Fermat’s principle (5). Several paths from the array element to the image point are tested, with various points on the interface. The path with minimum travel time is selected.
2.5 Imaging

With the travel times between array elements and the image points known, images can be generated according to the TFM algorithm by picking samples from the A-scans and adding up the contributions for all transmitter-receiver pairs. It can be helpful to apply upsampling to the A-scans to minimize rounding errors when picking samples (4).

The basic TFM algorithm is adapted for immersion imaging by making a few modifications. The A-scan data received contains both shear and longitudinal arrivals from pipe geometry and flaws. Longitudinal arrivals can be filtered out by limiting the range of angles for the acoustic paths used in the pipe. By removing paths below the first critical angle, artefacts in the image are significantly reduced.

Images are generated for various modes including direct, tandem, and indirect paths. For the tandem paths, the direct path is used from the transmitting element to the image point, whereas a reflection at the ID surface is included for the path from the image point to the receiver. The indirect path uses reflections at the inner pipe surface for transmitting and receiving. This way, the region of interest is insonified and imaged from different directions (6). The resulting images can be superimposed for interpretation, allowing for imaging flaws regardless of their orientation or curvature.

An overview of the entire processing chain is provided in Figure 2.

Figure 2. Overview of the chain for A-scan pre-processing, surface detection and imaging.
Aside from the steps described above, Figure 2 shows that there are additional steps for surface validation before carrying out the travel time calculations. It is recommended to rely only on smooth regions of the interfaces. However, the surface profiles may show stronger variations close to the bond line as for the example presented in Figure 1b.

The detected OD and ID profiles are therefore validated before carrying out travel time calculation and imaging. This means that regions with an orientation deviating more than 15° from the horizontal direction are not taken into account for travel time calculation. Furthermore, outliers are removed from the detected surface profiles.

3. Experimental results

3.1 Water tank

A first round of experiments is carried out with two arrays made by Imasonic for immersion imaging positioned in the water tank. Each array contains 64 elements with a nominal center frequency of 7.5 MHz. Figure 3a presents an end view along the seam weld of the sample with a wall thickness of about 8 mm used in the setup depicted in Figure 1. This particular sample shows significant offset between the plate edges before welding and posed difficulties for the inspection with plastic wedges with cylindrical contact surfaces manufactured to fit the nominal diameter of the pipe.

This particular sample did not contain significant flaws. For this reason, a side-drilled hole with a diameter of 1 mm was machined. An image obtained on this sample is shown in Figure 3b. In this case, the shape of the side-drilled hole can be resolved. The combination of the various modes enables imaging of the entire boundary of the hole, with the direct modes showing the top part, the tandem modes revealing the sides, and the indirect modes with reflections at the ID surface showing the bottom part. The hole appears shifted in the image due to the fact that a part of the left side close to the ID is not bonded to the right side, with the overlap due to misalignment indicated by the arrow in the photograph.

![Figure 3. Photograph of the specimen with hole drilled along the weld (a); Imaging result showing the sample geometry and the position of the hole (b).](image)

The direct imaging mode with one array sending and the other receiving is also used to generate an image of the inner pipe surface, whereas the indirect mode is used to show the outer pipe surface. It is also possible to image the outer pipe surface directly, i.e., use the image generated for the detection of the OD surface.
3.2 Flexible membrane

The setup with an immersion tank is only feasible in a laboratory environment. For a more practical deployment of the approach, the arrays are positioned in a watertight housing containing a flexible membrane as shown in Figure 4a. In Figure 4b, the complete system is shown on a test piece of ERW pipeline.

![Figure 4. Flexible wedge with two arrays in a metal housing (a); setup position on a pipe (b).](image)

With the experience obtained from the first round of tests in the water tank, the system is set up and calibrated accordingly. The rubber membrane of the flexible wedge introduces a weak additional echo arriving before the reflection from the outer pipe surface. The strength of the signals from flaws is comparable to the experiments carried out in the water tank. It turned out that the thickness of the membrane can be neglected without significant deterioration of the resulting images.

Figure 5 presents two examples of cross-sectional images for a weld with a nominal wall thickness of 6.35 mm. This particular weld was of interest due to locally increased wall thickness in the area of the seam weld caused by heat treatment after welding. In contrast to Figure 3b, the images for this weld are shown after rectification.

From the small inclusion present in Figure 5a, it can be seen that the different modes are aligned and intersect in one point, resulting in a star-shaped indication in the image. This confirms the validity of the approach used for calibrating sound velocities and geometrical parameters, and for detecting the pipe surfaces.

Figure 5b shows two upturned fiber imperfections. This type of flaw is caused by impurities being present in the plate material used to make the pipe. When the seam is welded, the plate edges are pushed together, and excessive material is ejected outwards. After welding, the protruding parts are trimmed at the OD and ID. This process leads to deformation of impurities in the plate. Laminations tend to turn upwards in the vicinity of the bond line.

In contrast to flaws such as cold welds, upturned fiber imperfections or poor trim of the pipe are considered benign anomalies (7). For this reason, flaw discrimination plays an important role in the assessment of ERW pipeline. The presented approach was shown to have significant advantages over phased array inspection applied to the same samples in terms of interpretation and flaw characterization.
Figure 5. Two cross-sectional images obtained from ERW samples: cold weld at the bond line and small inclusion to the right (a); non-metallic inclusions (stringers) with curved orientation (b).

Figure 6. Overview strip charts generated for a piece of ERW pipe with top and side views revealing different types of flaws along the weld. The scanning direction is shown downward.

From the cross-sectional images produced from a scan of full matrix captures, strip charts can be generated which provide an overview of the weld. An example is shown in Figure 6, with the side views of the weld shown at the left and right side of the figure, and three top views for different layers shown in the center. These three layers allow for a quick assessment of the depth at which an indication is located. For this particular scan, some indications of longer extent can be seen in the upper region of the weld. These are the upturned fiber imperfections as shown in Figure 5b. Other shorter indications at the start of the scan are cold welds close to the inner pipe surface as shown in Figure 5a.
4. Conclusions

A method for the ultrasonic imaging of seam welds has been developed and demonstrated. The approach implements a modification of the adaptive Total Focusing Method for application on seam welds by imaging the outer and inner surface of the pipe sample, followed by imaging of the weld region with shear waves.

Criteria for the detection of the surface from the images were added to increase the robustness of the approach. The accurate calibration of sound velocities and geometrical parameters was found to be essential for the generation of aligned and focused images. In addition to experiments in a water tank, a watertight housing with a flexible membrane was tested successfully. This assembly enables application of the developed approach for larger pieces of pipe in the field that cannot be scanned in a water tank. The extra interface introduced by the membrane was found to have negligible influence on the images.

The resulting images allow for detection and accurate sizing and characterization of indications, enabling also the discrimination between critical and benign flaws.

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