ABSTRACT

For productivity reasons the AREVA-NP/EFF/SAINT-MARCEL factory decided to replace manual UT and radiographic testing, as applied for SG and PZR circular welds, by advanced automated UT based on Phased Array and TOFD techniques.

The new method has to comply with the existing code requirements, i.e. French RCC-M, EN ISO 10863, etc, and has to satisfy severe exploitation criteria such as a limitation of the total examination time.

The presentation gives an overview of the implemented state of the art solutions for the examination of narrow gap submerged welds with thicknesses ranging between 100 and 180 mm. Pulse-echo phased array technique is implemented using 2D matrix probes. The probes can be applied for conventional raster as well as for sector scanning if needed, while their large beam skewing capability allows for optimized detection of misaligned defects. TOFD technique is implemented using conventional probes and linear Phased Array probes. The latter allows perfecting thickness coverage, optimizing signal-to-noise ratio and characterization.

The performance and the flexibility of this solution would make the extension of the work to RPV shell weld examinations (wall thickness of 250 mm) quite possible.

A dedicated scanner has been developed for shop use, and offers flexible installation and operation. A separate calibration bench allows fast verification of the UT parameters during the examinations.

The DYNARAY® system allows applying Pulse-echo and TOFD (conventional and phased array) in parallel, offering a single pass inspection of the welds in all orientations. On-line processing capabilities of the system drastically reduce the data volume.

The extended tools of UltraVision® software, such as the data merge functionality and the assisted analysis, offer a fast analysis solution as well as a comprehensive visualization of the data for final reporting. The developed equipment is intended to be implemented through a demonstration file of equivalence based on trials and justifications (see ref 1).

INTRODUCTION

Manufacturing of Steam Generators (SG) and Pressurizers (PZR) involves Non Destructive Testing of the circumferential welds according to the French Design and Construction Rules for Mechanical Components of PWR Nuclear Islands (RCC-M) code. This includes surface (Magnetic particle and Penetrant Testing) and volumetric NDT methods.

Radiographic Testing is currently applied before heat treatment while manual UT is used in complement for examination of the welds before and after heat treatment.
For productivity and environment reasons the AREVA-NP/EFF/SAINT-MARCEL factory decided to replace manual UT and Radiographic Testing with advanced automated Phased Array Pulse-Echo (“PE”) and TOFD techniques.

The development of the new UT PE method is based as much as possible on the existing manual procedure to demonstrate equivalence since the qualification and acceptance of a completely new method may be very time consuming. This means that the main examination parameters, i.e. beam angles, orientations and probe frequency, are identical to those presently applied for the manual UT method. At this stage the PA beam steering capability is used for reducing the number of probes and for optimizing the beam with regard to the defect orientation.

The TOFD technique is implemented using conventional and phased array probes. This allows a very good depth coverage and flexible adaptation to different weld thicknesses as well as enhanced capabilities in characterisation.

**SCOPE**

The low alloy steel pieces of PZR and SG (Figure 1) are assembled by means of narrow gap submerged arc welds.

![Figure 1: Pressurizer and Steam Generator weld outline](image)

The weld thickness range varies between 100 mm and 180 mm. The bevels are slightly tilted resulting in almost perpendicular fusion faces. The width of the welds is approximately 22 mm. Shell diameters varying between 3.077 m and 5.165 m yield weld lengths up to more than 16 m.

**INSPECTION REQUIREMENTS**

**PE technique requirements**

The UT inspection method has to comply with the French RCC-M code regarding pulse echo techniques. The code requires 0°, 45° and 70° coverage of the heat affected zone of the welds. Following AREVA specifications, a 60° beam is added in the preliminary evaluation stage yielding directions of propagation as shown in the next figure:

![Figure 2: Weld coverage](image)
Longitudinal as well as transverse defects are considered, therefore a total of up to 13 basic beam orientations are used considering a single face weld inspection.

The approach of validation of the new PE method is to demonstrate a level of equivalence with the presently applied manual inspection method (Ref 1) that could be acceptable. As the manual inspection allows for optimizing the indication amplitude by physically turning the probe (up to ±10°), the same capability is required for the automatic inspection. This is achieved by generating skewed beams for each of the considered basic orientations (except for the 0° beam):

![Figure 3: Beam skewing, probe orientations and scanning pattern](image)

A single pass inspection is required for practical reasons and since discrete angles are used, a classical raster scan is performed to cover the weld volume.

**TOFD requirements**
The TOFD technique requirements do not come from RCC-M code and therefore could be those of the ISO 10863 standard with additional requirements concerning the coverage of the different inspection depth zones. Four or more depth zones are implemented based upon a -6dB diffraction coverage criteria while the standard requires a maximum of 3 zones for the considered weld thicknesses.

**Exploitation requirements**
The components to be inspected are horizontally positioned on turning rolls. As they are spread over the shop the inspection system must be mobile. The examination of a weld must be performed within a working day.

**PE PROBE**
Phased array technique has been chosen to generate a skewing beam to replace the manual optimisation process. This is achieved by a 2D matrix probe. The developed probe has similar beam characteristics as the conventional probes presently used for the manual UT inspection. The beam steering allows for generating refracted angles from 45° to 70° SW with a skewing range of ± 15°.

The following images show a 45° SW example of the obtained beams of the matrix probe compared to the beams of the probes used for manual inspection.

![Figure 4: Beam simulation comparison WB45-2 and 7x8 Matrix](image)
As can be observed, the beam similarity with the manual probe is very good, even for the skewed beams. The lobe amplitude is for all cases (45-70°) more than 20dB below the main beam amplitude. Practical measurements on side drilled holes show a very good match of the DAC curves with those of the conventional probes (Figure 5).

![Comparison of DAC curve between Matrix probe and WB conventional probe (DAC on Ø2 mm)](image)

45°: DAC curves for all skew angles

70°: DAC curves for all skew angles

Figure 5: Practical results on SDH

The DAC curves were recorded, for a given skew angle, by rotating the probe in order to orient the beam perpendicularly to the side drilled holes. As can be seen on the figure above the DAC curves for the skewed beams are almost identical.

Besides the generation of discrete angles the probe is capable generating sector scanning practically between 40° and 70°.

**TOFD WITH PHASED ARRAY OR CONVENTIONAL PROBES**

The TOFD technique covers weld thicknesses ranging from 100 to 180 mm by a combination of conventional and phased array transducers (Figure 6).

![TOFD zone coverage](image)

Figure 6: TOFD zone coverage

The thickness is divided in zones that overlap each other. The required number of zones is defined on the basis of a -6dB drop of the diffracted signal as shown in the figure above.

The upper depth range is covered by two conventional configurations. The phased array probe set covers the lower depth range. This offers, besides a reduction of the number of probes, a flexible adaptation of the zone division to fit the weld thicknesses and a good control of the beam spread for a given depth range resulting in a high S/N ratio and reduced back-wall dead zone.

The required TOFD configuration (probe frequency, aperture size, beam angle and probe centre separation) has been defined on the basis of beam simulations with UltraVision® and practical measurements on EDM notches.
The comparison of the UT methods capabilities was carried out from several test blocks containing artificial and realistic flaws such as cracks, lack of fusion, lack of penetration, aligned inclusions and clustered gas cavities.

The scope of the PA PE assessment was mainly based upon a comparison of the results obtained with the new method with those obtained with manual inspection. Additionally, the influences of some essential parameters, such as the scanning resolution, were determined based on acquisitions on different test blocks. Some measurement uncertainties have also been evaluated on the basis of multiple calibration scans spread over a long time period and taking into account all practical variables such as probe coupling and mounting-dismounting of probes, cables, acquisition and scanning system. This will be introduced in the demonstration file (see ref 1).

The PE inspection was carried out following the requirements of EN 583-1 and EN 583-2, as far as possible. The DAC technique is applied for measuring the amplitude of reflectivity of the imperfections. Length sizing is based upon a -6 dB amplitude drop technique.

A typical result obtained on a 120 mm thickness test block is shown for an inspection angle of 60° SW in an end-view below:

The green axis of the end view represents the weld length, the purple axis the depth of the indications. The merged view shows the results of the maximum amplitudes obtained for all skew angles. It can be highlighted that the beam skewing also detects the side walls of the specimen (vertical indications at both sides of the view).

Basically, and independently of the demonstration of the equivalence file, PA PE technique performances have been found equivalent to the conventional manual PE technique. The beam skewing capability of the phased array probe allowed recording identical amplitudes as found manually. For some indications a skew of up to 15° was required for obtaining the maximum reflection amplitude. This will allow being equivalent to the replaced techniques in term of acceptability for these defects.
UT TOFD technique

TOFD examinations were carried out on the same test blocks as those used for PE UT and on specimens with EDM notches. Additionally a qualification of the technique was carried out on a 165 mm thick test block with artificial planar alumina inserts realised by means of hot isostatic compacting and on a clad specimen in order to evaluate the effect of the stainless steel cladding on the back wall echo.

An example showing the excellent signal-to-noise ratio obtained with the Phased Array TOFD configuration is shown for a test specimen containing alumina inserts. Although this kind of artificial defect is known to yield low diffraction amplitudes, the quality of the signal is very good and the obtained S/N is about 16 dB as can be observed from the left side picture below:

![Figure 9: 5 MHz PA-TOFD; Result on a 4mm Alumina insert and on a 2 mm height ID EDM notch](image)

The right side picture shows a 2mm ID surface breaking notch in a 165mm test block illustrating that the back wall dead zone is reduced to a minimum. These results will be used for the equivalence file as support of justifications. A typical TOFD perpendicular scan result is shown below for a test specimen containing real defects:

![Figure 10: PA TOFD, perpendicular scan, specimen with real defects](image)

It was found that the TOFD technique allows detecting all defects with a good S/N in all the considered blocks.

IMPLEMENTATION

Single scan data acquisition
The weld is inspected in sections (3 to 4 m) and each section is covered by a single scan performing PE and TOFD simultaneously. A complete inspection scan of a 1 m weld segment is done in less than 30 minutes. This is achieved thanks to the high data rate capability of the DYNARAY. Acoustic crosstalk is managed by positioning the probes adequately and by firing the laws in an appropriate order. The Firing Sequencer available in UltraVision® is used for this purpose.

On-line data processing
Since the component thickness is big, the weld length long and the number of beams large (4 orientations; 3 angles per orientation; 7 skewed beams per angle + 0° + TOFD) the amount of gathered data is impressive. The inspection of a SG weld with 135 mm thickness and a length of 16 m would generate about 750 GB of data considering all the applied techniques with “normal” data acquisition parameters. Besides the acquisition issue, this huge amount of data must also be analysed and all this within an acceptable time frame.
The DYNARAY system offers on-line compression and multi-peak detection processes to reduce the amount of data. Multi-Peak processing has been chosen since compression still generates too much data and would affect too much the time positioning. The multi-peak process allows storing the amplitude and position of the peaks found in an A-Scan. The picture below shows a comparison of Multi-Peak recording with normal A-Scan recording:

![Figure 11: Multi-peak data reduction process](image)

The advantage of this method is that no time shift is introduced: all peak position data is acquired with the resolution of the initial digitizing frequency of 100 MHz. The major advantage is of course the drastic data reduction: only a limited number of peaks (16 in the present case) for each A-Scan are recorded. Applying this data reduction process allows, for a typical weld, reducing the initial data size of 750 GB to 30 GB (Multi-Peak data reduction is not applied on the TOFD channels).

**Dedicated scanner, calibration and acquisition system**

A dedicated system has been designed and developed to allow for a fast and reliable inspection in the shop. The mobile system is subdivided in 3 main parts. The picture below shows the scanner system positioned on the component, the calibration-manipulation table and the data acquisition unit containing ZMC2 motor controller, DYNARAY acquisition unit, PC and screen:

![Figure 12: Inspection system](image)

The scanning movement is performed by a linear arm on which the probe holder is fixed.

The probe holder is applied on the surface. Contact ball bearings allow the probe holder to run smoothly on the component. Each probe has an independent suspension assuring a good wedge-to-surface contact.

![Figure 13: Scanner with magnetic wheels](image)
The height of the linear movement is such that the scanner can travel over obstacles (nozzles etc) while the position of the legs can be adapted to allow moving between obstacles.

The calibration table holds the calibration blocks and an encoded X-Y axis manipulator (Figure 14). With an easy fixing system of the complete probe pane, the tool allows performing fast and reliable encoded calibration and verification scans. Local liquid coupling and recuperation is also provided.

The laser system can be positioned and oriented in such a way that it projects a line on the component which will guide the scanner system to follow a travel path parallel to the weld seam.

**Data Analysis and reporting**

The weld is inspected with different probe angles, orientations and skews yielding a total of more than 90 PE beams. Analysing the weld data beam by beam would require too much time. For this reason all the data of the PE angle beams is brought together into a new weld zone volume by using the UltraVision® Merge tool. The considered volume is subdivided in unitary cubes. The merge tool calculates, considering all the beams, the maximum amplitude found for each unitary cube by taking into account the time of flight, probe position, angle, orientation and skew of each beam. The principle of merging shall be taken into account in the equivalence file against the step by step study of the trials results (to check all the RCC-M requirements, see ref 1). A typical result is shown in the next picture.

![Figure 14: Calibration + manipulation table](image1.png)

Figure 15: Typical view of Merged Data

The left view of Figure 15 shows a cross section of the weld with all indications found along the weld seam (gate cursors allow for isolating a particular indication). The end view shows a “front” view of the weld (green axis = along the weld length, purple axis = depth). The lower view shows the top view of the weld.

The combination of the Soft Gain tool and the high dynamic range offered by the DYNARAY allow visualizing indications having amplitudes far above the reference level without saturation. Increasing the Soft Gain allows analysing indications at noise level as well if needed.

The resulting volume is analysed with the tools offered by UltraVision®. Indications that cross the reporting level are automatically determined by means of the Assisted Analysis tool. The process automatically draws a contour on each detected indication which gives a visual feedback to the analyst. These functions will also be justified against the basic comparisons made in the equivalence file.

An automatically generated indication table lists all details, such as amplitude related to the reference, position, length size, etc of the found indications.
CONCLUSION

A dedicated system for the UT inspection during manufacturing of large narrow gap submerged welds has been developed and realized. Qualification on blocks with artificial and real defects shows excellent results with PA Pulse-Echo UT and PA TOFD. The acquisition unit and accompanying scanner system allow for a fast inspection of the weld seams.

The performance and the flexibility of the present solution make the extension to RPV shell weld examinations (wall thickness of 250 mm) quite possible. At this stage evaluations have been made regarding probe and system design. A 120-element probe would be required to generate a sufficiently small beam to allow dimensioning flaws located at 250mm depth.

Two DYNARAY acquisition units will operate in parallel in order to deal with a total of more than 500 channels (4 probes of 120 elements + additional PA TOFD and conventional probes). The two instruments will appear as a single unit in the UltraVision® software.

It is expected that this solution will allow full inspections of heavy wall components (single scan) at rates of more than 2m per hour.

All the characteristics and capabilities of the final system are currently being implemented and studied in the equivalence file that will make it possible to use as an alternative to conventional UT and RT in the RCC-M code.

Ref 1
Fredéric LASSERRE et al. Use of combined UT advanced techniques in lieu of conventional UT associated to radiography for end of manufacturing of primary component circumferential welds -- Justification dossier for equivalence demonstration, 10th International Conference on Non Destructive Evaluation, Cannes – France, 2013