Quantitative Defect Sizing on Components with Different Wall Thickness using UT-SAFT

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Abstract:

UT-SAFT is one of the well-known reconstruction tools, which provides information about the defect size. In this work we studied the use of phased array technique in combination with the SAFT algorithm to inspect power plant components. As a first example we inspected a real-sized mock-up model representing a part of a reactor pressure vessel with a 180 mm-thick ferritic base material followed by a 6 mm-thick austenitic cladding layer. The phased array probe was coupled at the outer ferritic surface. We detected and sized artificial cracks within the cladding with a depth ranging from 4 mm to 10 mm. Secondly, we investigated a mock-up model resembling a nozzle including a thermo sleeve inlet and a maximum wall thickness of about 37 mm. Artificially inserted notches with a depth of 3 mm could be detected and sized, where the thermo sleeve is welded at the inside of the nozzle.

1. Introduction:

Nuclear power plant components are inspected during in-service inspections to get reliable information about the actual integrity condition. Fracture mechanical calculations are then needed as decision criterion for possible maintenance processes. Therefore, it is crucial to have quantitative data in case of reflector detection as basis for remaining life time calculations.

In order to get reliable and detailed information about the actual condition of structural and security-relevant parts it is not only necessary to detect possible defect positions but also as a second step to quantitatively estimate the defect size. UT-SAFT is a technique which can meet these requirements. One example of application described in literature consists of an inspection of welds in main gate valves during the in-service inspection of components in Finnish PWR type VVER440 (Loviisa 1 & 2)[1]. A contact technique probe of 2 MHz with a beam angle of 45° was used. Instead of a normal A-scan with low signal-to-noise ratio (SNR) the SAFT algorithm was used to improve the SNR.

In 2004 sizing results have been presented by using phased array data for SAFT reconstruction[2]. It was shown that tip signals could better be detected with longitudinal waves than with shear waves. The SAFT method has a low speed of analysis when comparing it with TOFD technique[3]. Both methods have problems when the detection suffers from the compressive stresses.

In a further publication it is described that the defect detectability could be clearly increased by the SAFT reconstruction compared to conventional B-, C- and D-scan imaging techniques[4]. Longitudinal wave probes were used having insonification angles of 45°, 60° and 70°. All crack-like longitudinal defects at the PWR-nozzle No. 92 of the full scale pressure vessel at the MPA at Stuttgart could be detected and sized. The SAFT sizing was in good agreement with the known defect sizes. There is also an example in literature for a comparative evaluation between ultrasonic phased array and SAFT[5]. At an Al-test block with 1 mm side drilled holes (SDH defects) in different depths measurements were executed using a phased array probe with 64 elements and a frequency of 10 MHz. The SAFT scan made it possible to recognize defect sizes between 0.9 and 1.1 mm.

3D-SAFT is also mentioned in literature as a tool to make more detailed defect description in case of metal plate inspection in the production line, where flaws with a diameter of 2 mm have to be surely detected and resolved in thicknesses between 6 mm and 60 mm[6]. 3D-SAFT was also applied to detect corrosion damages at structures of reinforced concrete[7]. The ultrasonic transmitter had a frequency of 100 kHz and the author used as receiver a laser vibrometer in connection with a scanning unit.

In the primary circuit of a nuclear power plant cracks were detected at a dissimilar weld in the interface between austenitic buttering and ferritic base material. Crack analysis was performed using
SAFT-method and crack sizes well agreed on real crack dimensions as metallographic investigations revealed\[8\]. Thus it is confirmed that the SAFT procedure is a tool for data visualisation and appropriate for objective data evaluation which is needed to minimise human factors\[9\].

The advantages of the SAFT technique are clearly described in the mentioned publications, but there exist no hint to make a useful combination of ultrasonic phased array capabilities with advantages of SAFT reconstruction procedure. The presented investigations will show that there exist possibilities to successfully apply both tools for defect sizing in thin and thick walled components.

2. SAFT reconstruction when testing reactor pressure vessel

Sizing with SAFT is based on a time of flight related measurement method using a reconstruction algorithm of RF signals which are measured by a conventional probe with a divergent sound beam. The original principle of the SAFT technique is shown in Fig. 1.

During the scanning movement of the probe RF signals within the A-scans are digitized and stored. But the angle dependent position of the registered signals within the sound beam is unknown. For this reason a signal processing procedure is applied to arrange the stored signals in a pixel grid. The arrangement takes place as procedure where time of flight dependent circle segments at echo amplitude positions within the sound beam are constructed. At intersections of circles RF signal amplitudes are added taking into consideration its phase position. A defect position is reconstructed by the high number of hits for distinguished pixel positions exceeding there the noise level of.

It is important to have a small distance between adjacent measurement points. That means four measurement points per wavelength have to be registered for a successful application of the SAFT technique. Furthermore full phase information is needed that means the digitization rate has to be high enough to guarantee that at least three amplitude values per period are stored.

In our investigations we have replaced conventional probes by phased array probes with changing angles of incidence during the measurement process. For SAFT the replacement of a conventional probe by a phased array probe means that a divergent sound beam is no longer necessary. At each measurement point the beam angle is adapted to the inspection task that means it is changed in the range between 35° and 60° in steps of 5°. The step of 5° considers the beam divergence. For the reconstruction process the time of flight dependent circle segments are constructed within the enlarged angle range of 25°.

Herewith the circle segments are better adapted to the region where defects are expected. In all pixel elements time of flight dependent signal amplitudes are registered, taking into consideration the related sound paths. At the intersection of circles high resulting RF signal amplitudes indicate a reflector position. They can be distinguished from noisy signal amplitudes. Typical phased array characteristics as for example index point shift in dependence of beam angle and wave mode have to be considered in signal processing.

![Fig. 1. Left: Principle of Synthetic Aperture Focussing Technique using a single transducer. Right: SAFT when using a phased array probe.](image)

For sizing of cracks at the inner surface the SAFT reconstruction technique can be as well applied for measurement data received at thick walled components. In Fig. 2, left the measurement arrangement at a full scale mock up model representing a part of the reactor pressure vessel is shown.
The phased array probe with a frequency of 1.5 MHz is guided by a manipulator on the ferritic side of the model showing a wall thickness of 179 mm and an austenitic cladding of 6 mm. Scanning tracks at the ferritic outer surface were chosen in such a way that selected artificial cracks with different orientations in relation to the cladding stripes could be insonified. Cracks were selected with depths smaller and deeper than the cladding thickness. In Fig. 2, right the investigated cracks with depths of 4 and 10 mm are represented.

Fig. 2. Left: Measurement arrangement with a mock up model representing a part of the reactor pressure vessel. Right: Sketch of cladded back side of mock up model and marked position of artificial cracks ri 4, ri 6 und ri 7 with parallel and perpendicular orientation to the cladding stripes.

Fig. 3 shows SAFT scans reconstructed to size the crack ri1 when using longitudinal waves and changing beam angles between 35° and 60°. Two distinct indications representing the crack can be seen in one of the pictures. The distance between both indications was determined to be 4.4 mm which is depicted in detail in the magnification. In case of using longitudinal waves with an opposite direction of incidence or shear waves in any direction crack sizing was not possible.

![SAFT-scans for sizing crack ri4](image)

SAFT-scans for sizing crack ri1: 4 mm, SAFT evaluated crack depth: 4.4 mm. Right: Known crack depth of ri4: 10 mm, SAFT evaluated crack depth: 10.3 mm.
In Fig. 3, right we depict the detection and sizing of the crack ri4 with a depth of 10 mm. It was possible to size the crack from both directions of incidence using longitudinal waves and the same beam angle variation as in the last case. Even with a 3 MHz phased array probe sizing at the 10 mm crack was possible at least from one direction of incidence.

The cracks ri1 and ri4 have orientations perpendicular to the cladding stripes. The cracks ri6 and ri7 showing both depths of 4 mm have a parallel alignment to the cladding stripes. In these cases it was more difficult to size the cracks. For crack ri6 with a position at the boundary between two cladding stripes the size of 4 mm could be approximately confirmed from one direction of incidence (see Fig. 4).

3. SAFT reconstruction when testing a D-nozzle reference block

The SAFT reconstruction technique was also used for thin walled components. In Fig. 5, left we depict the cross-sections of a full scale mock up model representing a D-nozzle. The investigated part consists of the weld connecting the thermo sleeve to the inner surface of the nozzle. The radial wall thickness in the region of the weld was about 37 mm. The weld itself has an extension of 10 mm in radial direction. In the weld we introduce notches representing artificial cracks in different depth positions. The notches were produced by filling thin ceramic plates to realize small pieces with interfaces before welding again. The investigation’s issue was to clearly distinguish between indications coming from defects within the weld and from defects intersecting the interface of the weld in direction to the base material.

A TR phased array probe transmitting longitudinal waves with a frequency of 3 MHz was used. During the measurement process the beam angles were varied between 17° and 47° in steps of 5°. In Fig. 5, right the SAFT scan shows geometric indications when we take measurement data for SAFT reconstruction at a defect free position of the mock up model. The geometric indications are produced by the interface between base material and thermo sleeve and by the inner boundary of the nozzle. If there exist a defect in the middle of the weld there are added two further distinct indications, which can be observed in Fig. 6, left. In the zoomed picture the distance between the two indications amounts 2.9 mm which well agrees with the intended notch depth of 3 mm.

In Fig. 6, right a SAFT- scan for a 10 mm deep notch is shown. Two distinct indications in the zoomed picture admit sizing. The distance between the two indications amounts 8.5 mm. But to be sure that it is a notch with such a depth of 10 mm and not two separated small defects the shear wave indication produced by the corner effect of the notch at the inner surface boundary helps to distinguish between the two possibilities. This is shown in the B-scan for a beam angle of 35° in Fig. 6, right.
Fig. 5. Left: D-nozzle reference block with the positions of artificial reflectors. Right: D-nozzle-reference block: SAFT-scan of a defect free region.

Fig 6. Left: D-nozzle-reference block, SAFT-scan for sizing notch No.7 depth: 3 mm. Right: D-nozzle reference block: SAFT-scan simulated crack, depth: 10 mm.
4. Summary

As preparation for inservice inspections in nuclear power plants ultrasonic investigation results were represented for the application of phased array measurement equipment on safety relevant components. Investigations were performed at full scale mock up models. For evaluation purposes of measurement data SAFT reconstruction procedures were used for sizing defects at the opposite surface of thick and thin walled components. In case of the thick walled component some artificial cracks were smaller and one crack was deeper than the austenitic cladding layer. It could be demonstrated that in all cases sizing of defects is possible. But it will be a necessary prerequisite to take into consideration possible cases where the crack is smaller than the cladding layer and has an adverse position and orientation in relation to the cladding structure. The orientation of cladding layers may be analysed by the phased array probe when skewing the sound beam until 0°-insonification direction. It is shown that it is necessary to perform a calibration procedure using full scale mock up models to see how phased array and SAFT technique are working together for quantitative sizing.

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6. Literature


