Practical Application of Total Focusing for Sizing of Imperfections in Welded Joints

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Abstract. Sampling Phased Array, also called Total Focusing Method is known for about 10 years. This technique uses Full Matrix Captured ultrasonic data which is transmitted and received from several incidence points within the same phased array probe. This data yields an ultrasonic image of very high resolution. New portable and rugged Phased Array Flaw Detectors are now available having this signal processing method onboard. After a short description of this rather new technique, we are pleased to present our experiences in practical applications on welded joints. Our goal is to achieve a reproducible sizing of imperfections in the image plus the evaluation of the recorded data by using additional analysis software. This is also possible, even for flat reflectors not lying perpendicular to the typical beam direction. Our practical results gained from welded joints with imperfections (lack of fusion) using conventional Phased Array will be compared to Sampling Phased Array scans, and a possible alternative to standard echo amplitude evaluation will be discussed.

Introduction

10 years ago A. Boulavinov and others introduced the technique of Sampling Phased Array as a "new technique for ultrasonic signal processing and imaging" [1], described the way of signal processing and demonstrated the advantages of this technique compared to the phased array sector scan. Since this technique implies a huge amount of computing, the development strongly improves with today's fast processors and FPGAs. Commercially, portable phased array units are now available providing sampling phased array, also called total focusing method (TFM) for daily UT inspections. This paper describes the use of TFM for weld inspection – one of the most often found applications for ultrasonic nondestructive inspections.

1. Full Matrix capture (FMC)

A pre-requirement for TFM is the so-called full matrix capture (FMC): In one acquisition cycle each single element of the array transmits a sound wave = n sequential shots. For every single shot, each of the n elements receives an A-scan. Thus n^2 A-scans will now be available, organized in a matrix with the rows for the transmitting, and the columns for the receiving elements, for example for an array with 4 elements we will get 4x4 A-scans A_{ij} (fig. 1). For any reflector in the insonification plane A-scans with the same colors have same time of flights. The A-scans are now further processed in order to create the ultrasonic image within a certain region of interest (ROI).

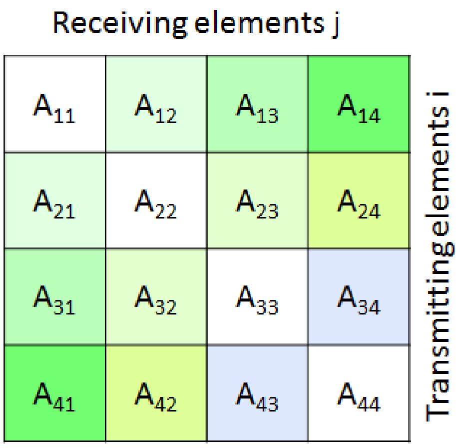


Figure 1: Full Matrix Capture

2. Region of interest

This cross sectional area in the parallel to the array can be defined by the operator, but must lie within the area of sufficient sound pressure of the array (fig. 2a). In addition we assume a reflector at point P(15,30) in the ROI. Element 1 fires, and all elements 1 to 4 receive a signal from point P(15,30) (fig. 2b).

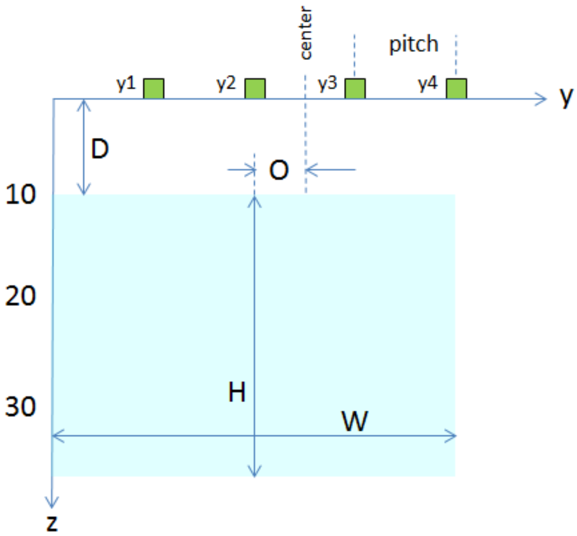
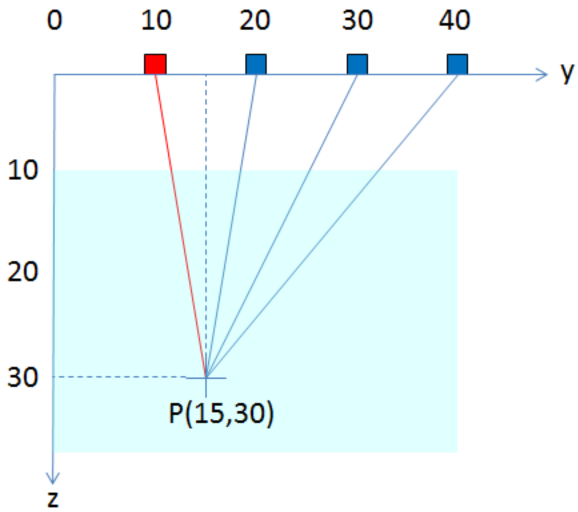


Figure 2a: ROI



2b: Arbitrary target point in the ROI

The time of flight (TOF) values for Point P(15,30) can be calculated [2], and subsequently the relating amplitudes a_{11}, a_{12}, a_{13} and a_{14} for these time of flights can be measured (fig. 3). The procedure is repeated for element 2,3 and 4 sending, which finally yields in 16 amplitudes. The sum of all these amplitudes is the integral response of all signals from P(15,30):

$$A_{15,30} = \sum_{i=1}^{4} \left[\sum_{j=1}^{4} a_{ij} \right]$$

For reasons of simplicity additional values, e.g. caused by the probe delay or wedge are not considered here.

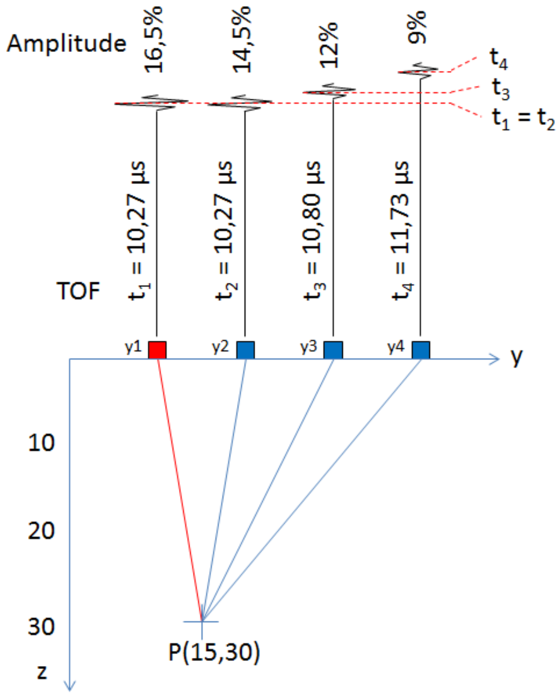


Figure 3: TOF for signals from P(15,30)

3. Image reconstruction

Using a given amplitude color palette, the integral Amplitude for point P(15,30) is converted into the related color, and entered into the ROI at position P(15,30). In total 65536 points of the ROI are filled using the same mathematical algorithm. The system is now ready to start the next acquisition cycle, delivering the raw data for the following image reconstruction. The 64 channel Phased Array Ultrasonic Flaw Detector GEKKO from M2M-NDT/KARL DEUTSCH uses a powerful FPGA for all image processing in parallel to the ultrasonic cycling, achieving a screen update rate of ~30 Hz.

4. Beam coverage

Since with FMC every single element of the array acts as a transmitter and receiver, and due to the small element width, the array will produce a large beam divergence, and with the pitch-catch technique used, the range of the aspect angle increases depending on the total length of the array, providing a much better detectability of inclined reflectors, fig. 4. The area covered with TFM is considerably larger, compared to conventional phased array, e.g. using a linear scan. All these facts will have an important impact on today's ultrasonic applications, not only the improvements on image resolution.

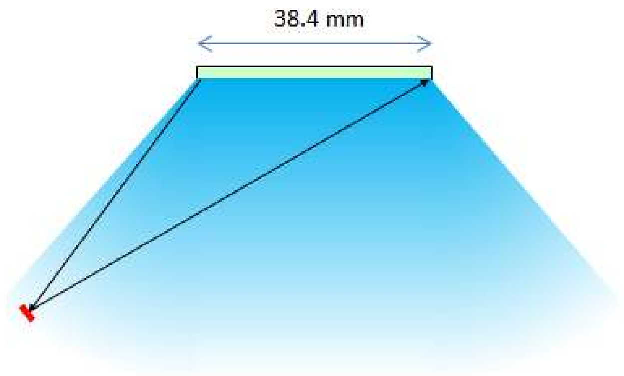


Figure 4: active cross section for the 64 element probe

5. T-joint: Electronic linear scan versus TFM

Our first example describes the inspection of a T-joint (24 x 24 mm) with a total length of 300 mm. The easiest inspection is a straight beam scan from the base plate, opposite to the weld (if accessible). The inspection has been carried out with the same 64-element, 5 MHz probe on a 30 mm Rexolite® delay, (a) applying a linear scan with an aperture of 9.6 mm (16 elements), and (b) a TFM scan with all 64 elements. With the linear scan a fixed scan width of 29 mm results, and with TFM the scan width is flexible and set to 50 mm, fig. 5.

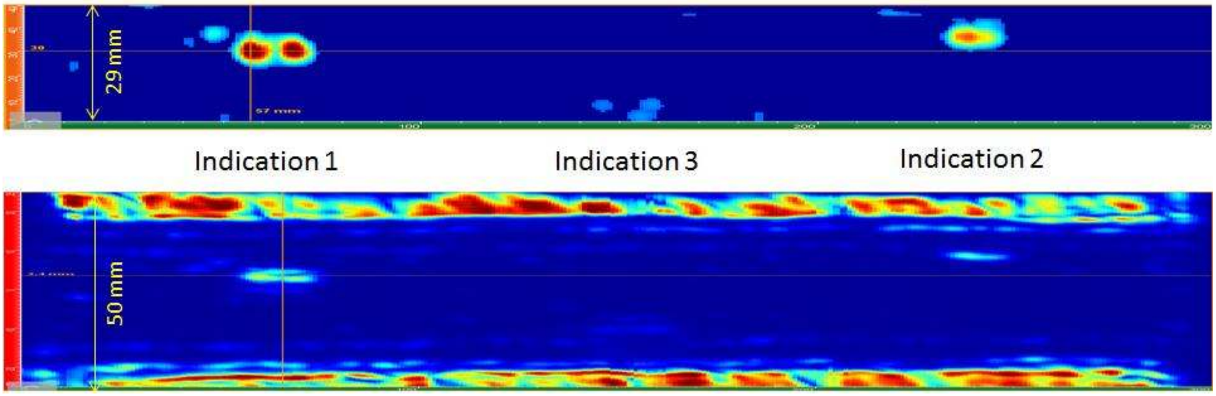


Figure 5: T-Joint 24 x 24 mm

As shown here, the larger scan width for the TFM scan allows the display of geometrical indications from the two weld caps enabling easy control of the probe position and the coupling during the scanning procedure. The indications 1 and 2 in the linear scan show an increased lateral size due to the influence of the beam divergence, whereas TFM focuses the reflectors, thus showing the correct dimension in the index direction. But in both scans, indication 3 is hardly detected! Reason: This defect is a lack of fusion with a slope of ~45°. Since with the linear scan the beam angle is 0° and fixed, we have no option to better "see" this defect, unless we change the wedge delay, and scan again at 45°. With TFM on the other hand it's quite easy to detect the 45° flat reflector be simply moving the probe in the index direction to match the viewing angle to the defect orientation, fig. 6.

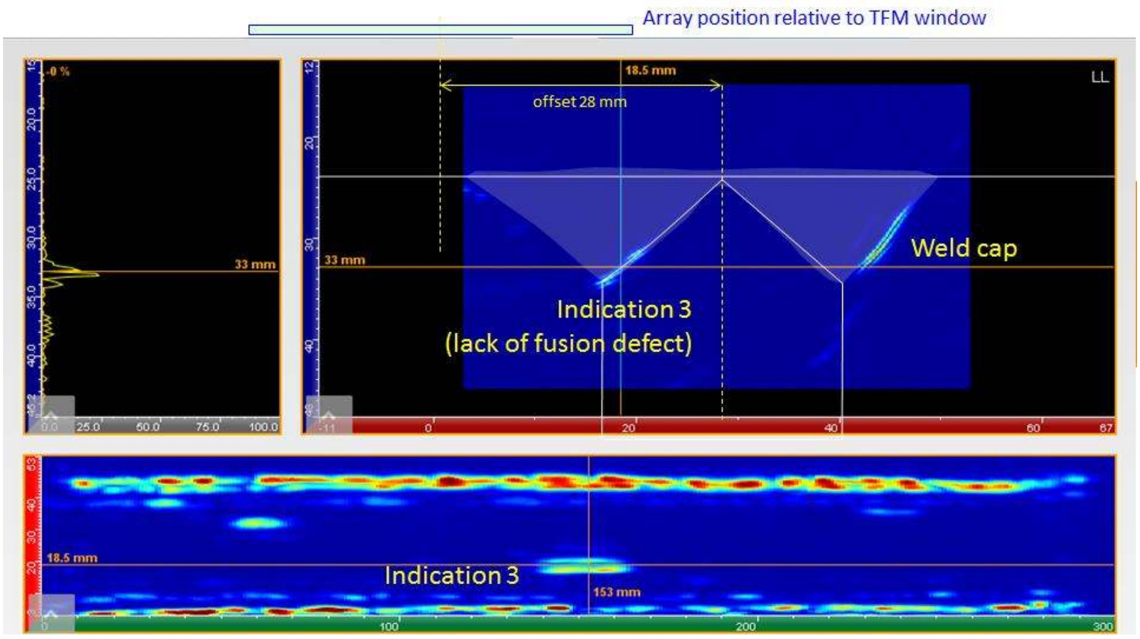


Figure 6: TFM scan with index offset

The probe offset (here 28 mm) relative to the ROI changes the viewing perspective, so that the amount of echo amplitudes from the inclined flat reflector has significantly improved, and a clear indication is shown in the TFM window and the C-scan. Simultaneously also the opposite weld cap is displayed here.

6. Offshore T-joint construction weld

Similar to the previous example, but the T-joints at the offshore windmill construction have a material thickness of 40 mm to 60 mm. Here the TFM remote scan has been shown as the most effective inspection technique, first for safety reasons, and second because of the wide scan width required for the scan path and coupling control. Typical scan lengths of the T-joint sections are ~5m, both when testing from the top side, and the bottom side. The 64-element, 5 MHz probe is fixed in a probe holder for direct coupling via a 3mm water gap, and has a cable length of 30m. The remote controlled Scanner (Jireh: Navic) moves the probe, allowing additional transverse shift for correctly guiding the probe along the scan path, fig. 7 and 8. The scanning speed is 17 mm/s (~1 m/minute) providing a scan resolution of 1 mm, and additionally 4 video cameras are used to control the test procedure. Test results are first stored onto the built-in SSD (128 GB), and at the end of the shift transferred to a NAS mass storage device via the LAN interface. For evaluation and imaging data are further processed with CIVA (EXTENDE).

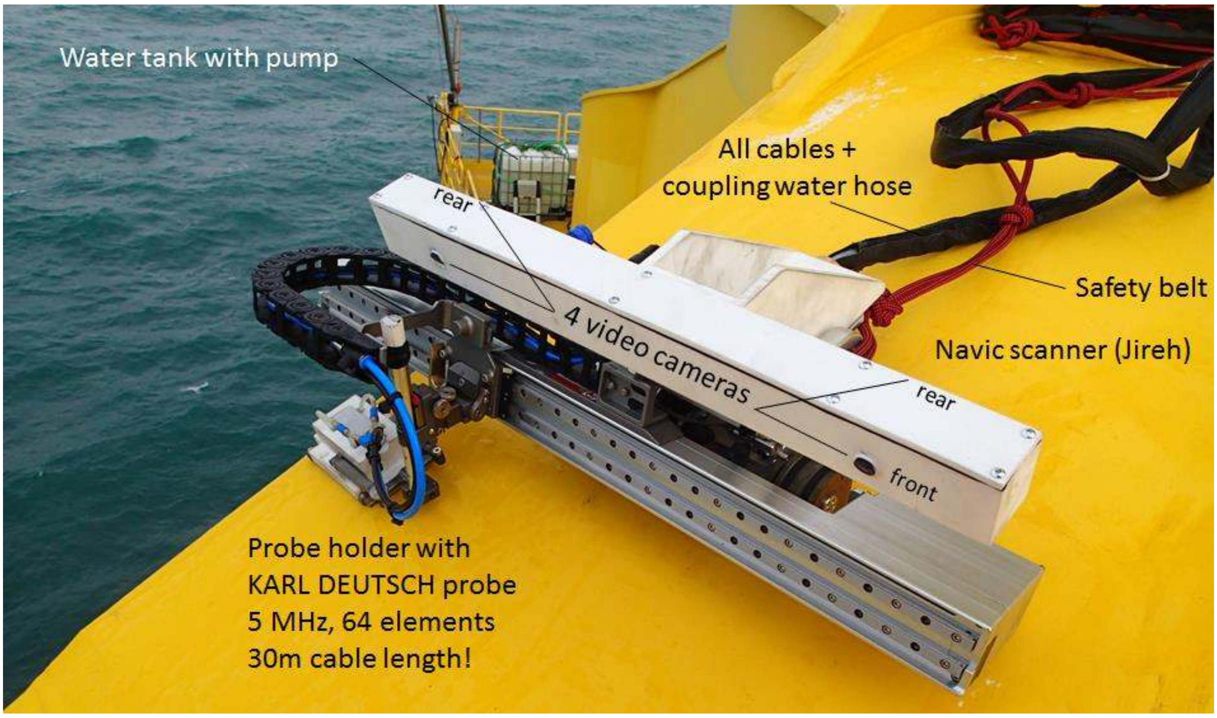


Figure 7: Remote controlled scanner on offshore construction

The operators sit at a safe location and have access to all instruments for the data recording: PA unit, video monitor, coupling water pump, scanner, fig. 9.

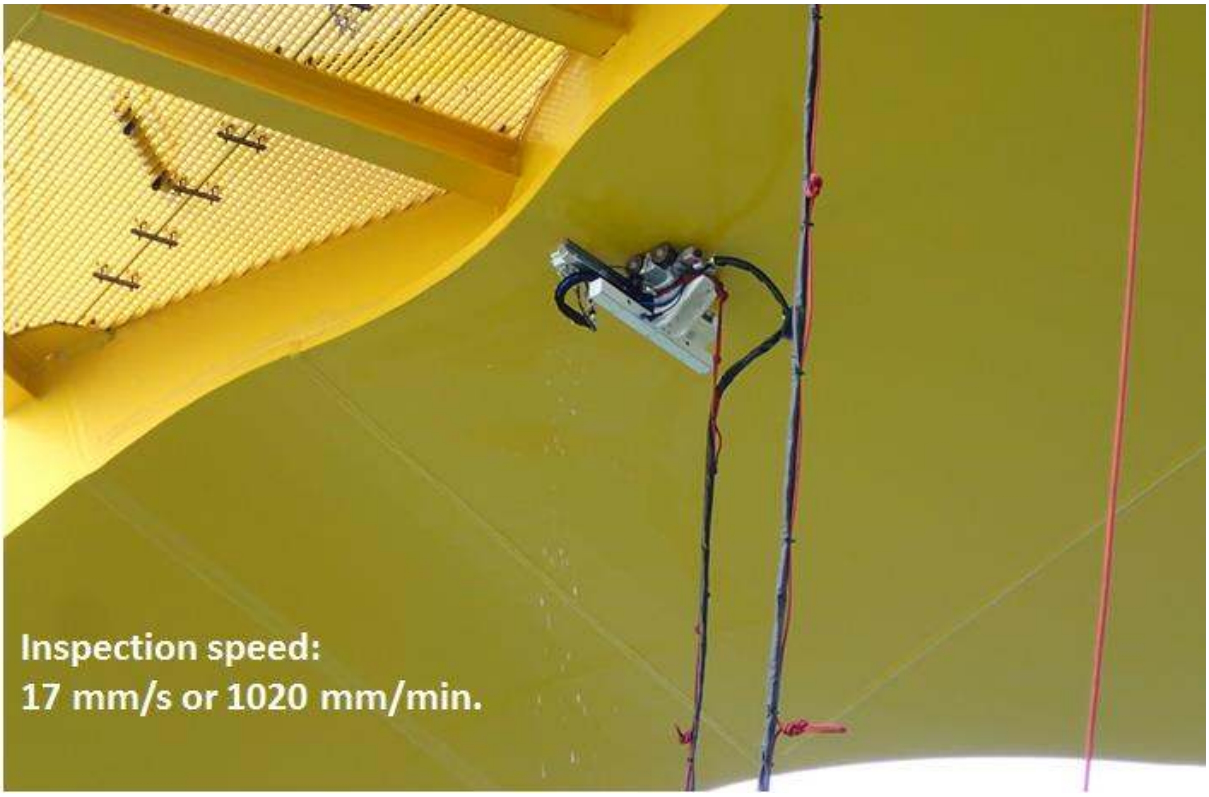


Figure 8: Scanning from the bottom

Figure 9: Control area with PA-Unit (Gekko) and Video Monitor

Examples of a 4.5m section with indications from the weld root are shown in fig. 10.

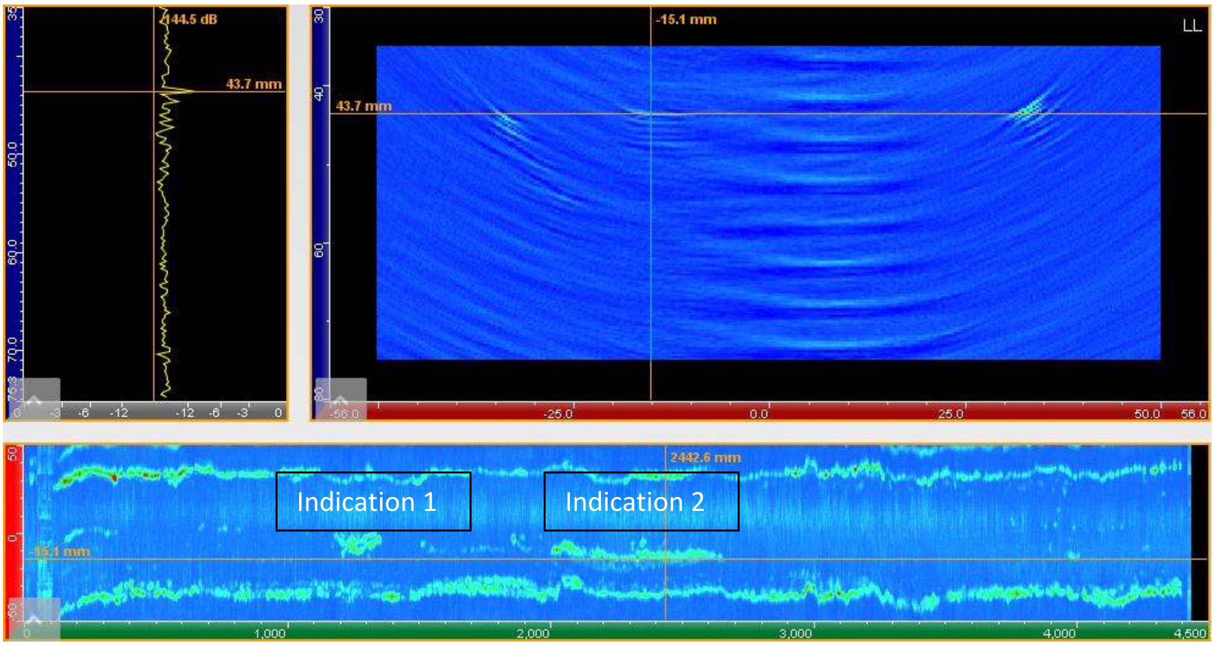


Figure 8: TFM Scan of a 4.5m T-joint (40 x 40 mm) at an offshore construction

Top right is the TFM-window (40 mm x 100 mm) with the two geometrical indications from the weld caps left and right, and at the cursor position an indication from the root of the weld. The A-scan is shown in the window top left. The C-scan (bottom) shows two major indications, and in the zoomed image in fig. 11 the evaluation of the first indication is shown.

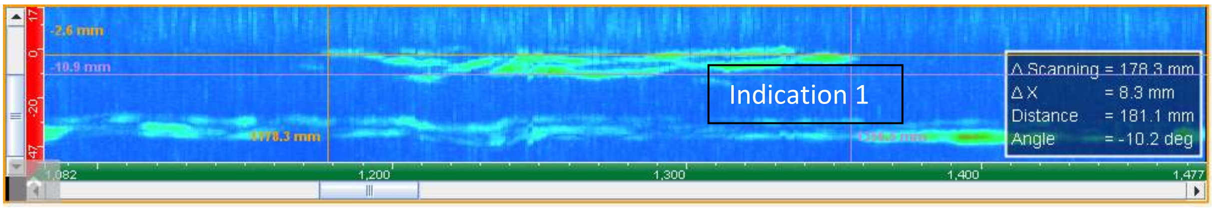


Figure 91: Evaluation of indication 1

This indication at a depth of ~40mm has a length of 178 mm and a width of 10 mm. The test results are used for condition monitoring: Compare the scans taken at different times to document any growth of indications, measure lengths and widths to allow fracture mechanical calculations for decisions on further actions.

7. X-Weld inspection with transverse TFM

A 20mm X-weld with natural defects has been inspected with the 64-element probe on a 36° wedge. The weld has been scanned from both sides using the TT-mode: Standard transmission and reception of shear waves up to half skip (no sound reflection considered), and the TTT-mode where the tandem sound path for the evaluation of flat, vertical reflectors may become useful, fig. 12.

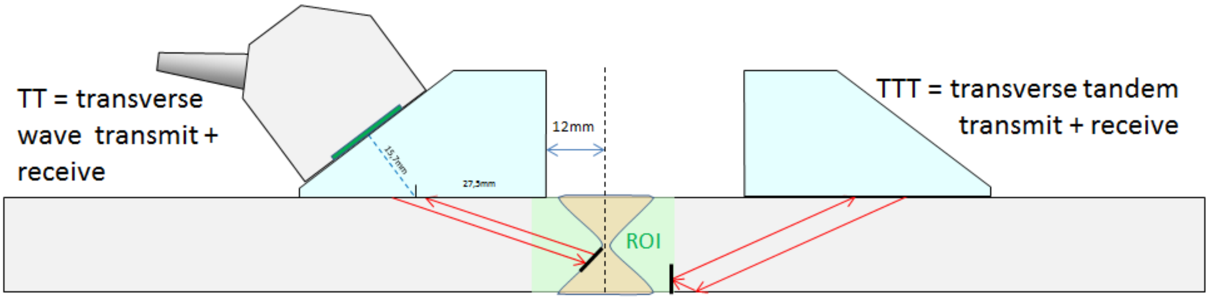


Figure 10: TT- and TTT-mode for TFM inspection of welds

Fig. 13 shows the results of the scan of the 300mm weld section. Indications from left to right are: 1. Incomplete root, 2. Toe crack, and 3. Lack of side wall fusion. Due to the position of the defects, here the detectability is best for the scan from left. For the evaluation of the indications, the TFM scan, the B-scan and the cumulative B-scan is used: The TFM window allows the measurement of depth and the transverse location (index direction) of the indications, the cumulative B-scan allows the measurement of the reflector length and positions in the scan direction (as in C-scan), but also the depth extension of the defect, specifically the TTT-mode allows the precise depth measurement for the toe crack, fig. 14.

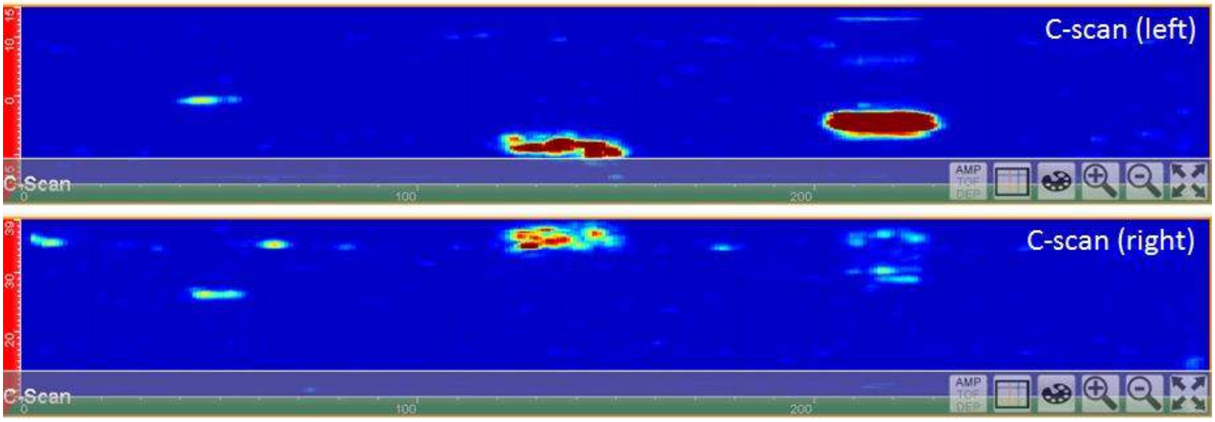


Figure 13: X-weld (20mm) – C-scan from both sides

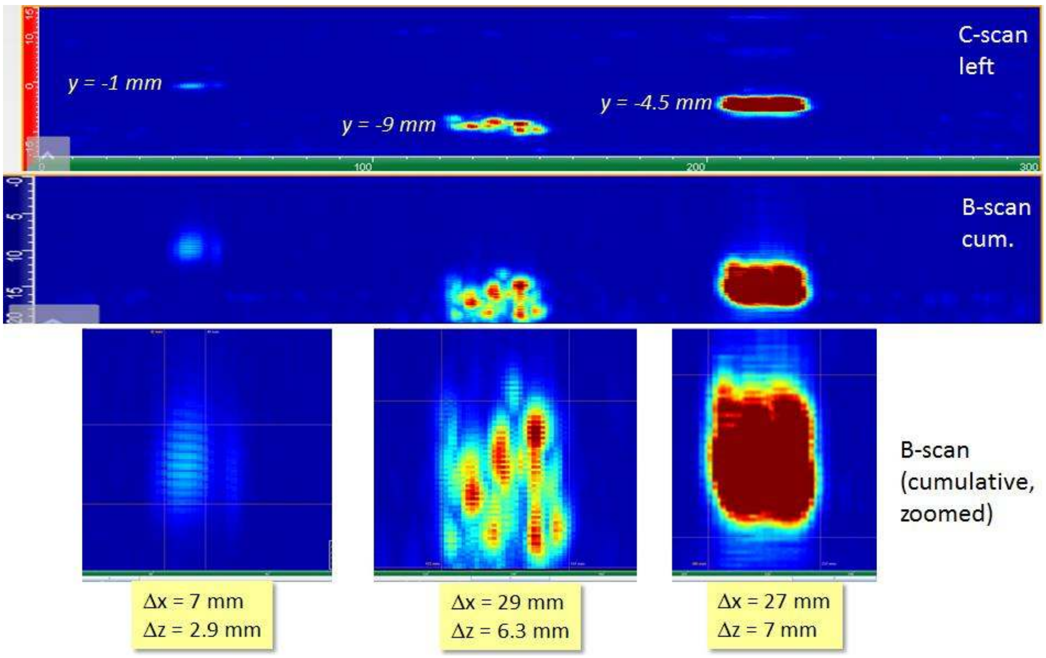


Figure 11: Defect sizing in the image

8. Summary

TFM provides a high lateral image resolution in the array direction almost independent of reflector depth due to focusing to every point in the ROI. It allows the increase of the scan width due to the extreme divergence angle with single element excitation and reception.

TFM allows the measurement of the size of defects using the 6dB drop technique, even for small defects, and works with longitudinal and shear waves, even considering different mode conversion modes with the reconstruction algorithm. It delivers a much higher probability of detection (POD) for inclined defects, and allows the measurement of crack depth or size of vertical defects using the TTT-mode (tandem scan reconstruction).

TFM reduces the dead zone and improves the signal-to-noise ratio.

Using different reconstruction algorithms TFM offers a significant step forward towards defect sizing in the image – a possible alternative to amplitude evaluation techniques. More future TFM applications with destructive control measurements may prove the advantages and applicability of sizing in the image even more, since technical solutions are available now.

References

[1] A. Boulavinov et .al., "Sampling phased array a new technique for signal processing and ultrasonic imaging", Berlin, ECNDT, 2006

[2] M. Jobst, G. Connolly, "Demonstration of the Application of the Total Focusing Method to the Inspections of Steel Welds", ECNDT 2010, paper 1.3.4