ALGORITHMS AND SOFTWARE DEVELOPMENT FOR WELDS AUTOMATED ULTRASONIC INSPECTION BASING ON PHASED ARRAYS

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Introduction

Improvements in technology of ultrasonic array probes and multichannel ultrasonic hardware manufacturing lead up to developing of relative low-cost flaw detectors with phased arrays (PA). Implementation of PA allowed to obtain B-scan (S-scan) of inspected object with refresh rate more than 10 Hz and arouse interest between UT engineers [1, 2, 3]. PA implementation allows to detect flaws, measure its height and length, with identification of real welded joint geometry. PA implementation requires UT procedure development. However for a number of practical cases, application of PA can appear insufficiently effective. It is necessary to notice that besides a traditional mode of use array probe as PA, it is possible to acquire full raw batch of signals by each antenna element and to use algorithms constructed on ideology of multibeam distribution of ultrasound in inspected object.

In the report outcome of the test blocks and real welded joint inspections is resulted, obtained data allows to get the information not only about the flaws size and position, but also about a configuration of weld, its shape and chamfer.

Thin-walled welds inspection

The conventional probes for UT have near field length parameter. The PA has the same. As effective focusing is possible only in a near field, so border value of near field further defines the concept of thin-walled and thick-walled objects. For the PA with 5 MHz operating frequency with 32 elements (pitch 0.8 mm) placed on the 35° wedge, the near field distance is about 145 mm or $145\cos 60° \approx 77$ mm projected to the vertical plane. Frontal resolution at the depth 77 mm is about 4 wavelength. Object with wall thickness less then half of near field we will refer as thin-walled and other as thick-walled. In the table 1examples of thin-walled objects resulted.

Table 1. Thin-walled objects

Inspected object	Outer diameter, mm	Wall thickness, mm	Base metal material
Du300	321-329	15±4	austenitic steel
Du500	521-535	28±7	austenitic steel

Du300 welded joints inspection with PA

For austenitic welded joints Du300 of RBMK-1000 power plant SPC “ECHO+” developed UT procedure (840.44 M) [4] which provides flaws detection having reflecting ability, equivalent to the notch in length of 10.0 mm and height 2.0 mm, including cracks of intergranular stress corrosion cracking. Procedure also provides flaw height and length measurement accuracy ±2.0 mm and ±10.0 mm, accordingly, while inspection from the side of weld where flaw located. During acceptance tests of a procedure with use of Harfang X-32 and OmniScan MX the declared parameters of detection and measurement have been confirmed.

There were declared two modes: high-frequency with PA with operating frequency 5 MHz and low-frequency with 2.25 MHz PA. The linear array should have not less than 16 active elements and beam steering range from 50° to 80°. Incremental encoder should be used for scanning along weld axis. The pulse-echo technique only used from both weld sides (Fig. 1).

The inspection progress is as follows. At the first step low-frequency mode used for detection of longitudinal flaws. These flaws are exposed to measurement procedure in high-frequency mode. The welded joint Du300 acceptance criterion is absence of flaws with amplitude equivalent to longitudinal notch with length 10 mm and height 2 mm. The inspection datasheet remains with the inspection data in a database.

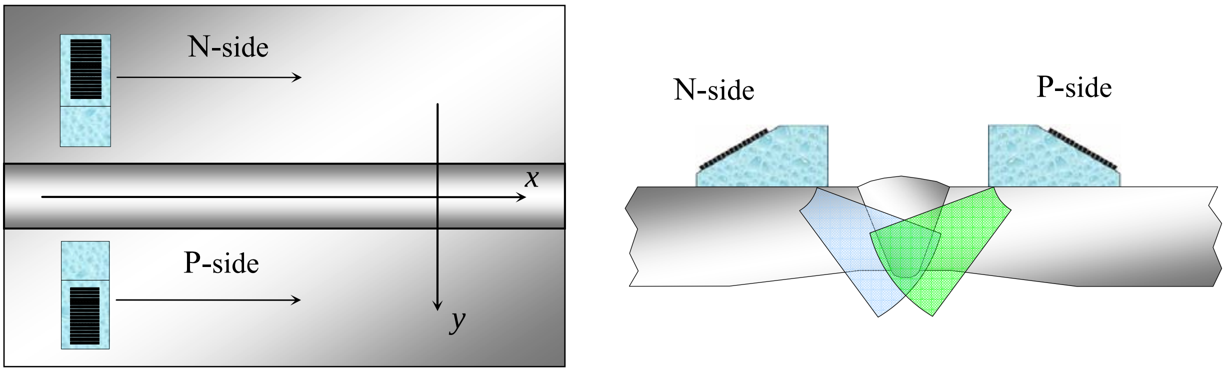


Fig. 1. Scanning scheme plan (left) and cross-section (right) for thin-walled weld

At the figures 2, 3 the results of test block inspection in low-frequency and high frequency modes demonstrated. All artificial flaws were detected; the loess's height is 1.5 mm. At the Fig. 3 demonstrated S-scan image of this one, measured height is 3.0 mm, conforming ±2 mm height sizing accuracy. Other flaws were measured with admissible absolute error.

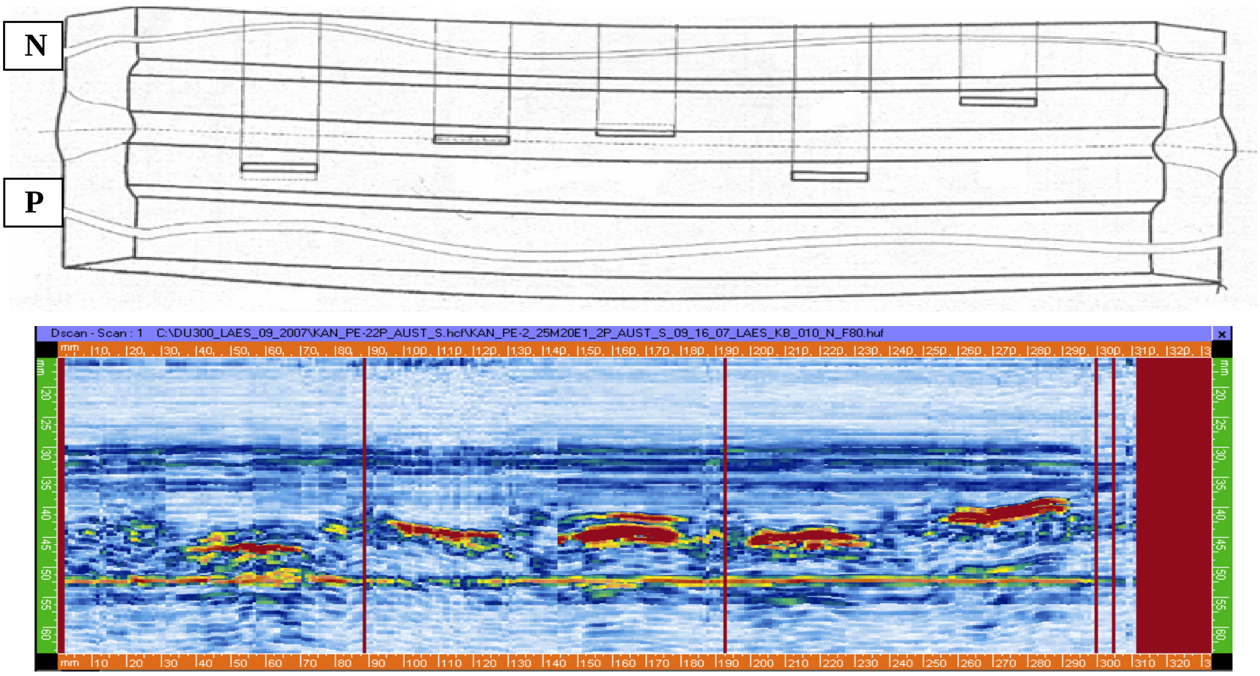


Fig. 2. C-scan of austenitic weld Du300 weld test block. Inspection from the N-side. Operation PA frequency 2.25 MHz.

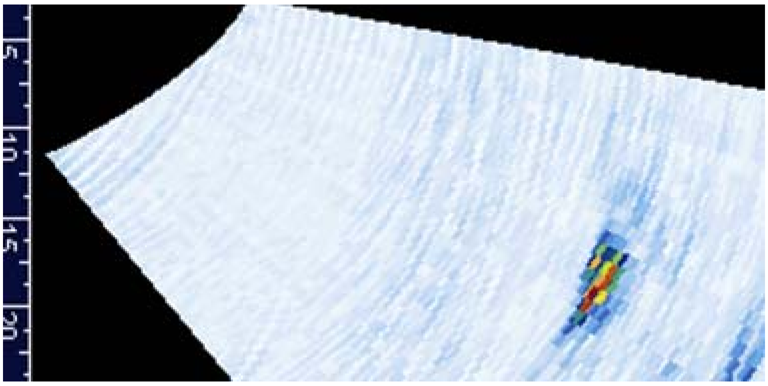


Fig. 3. S-scan of 1.5 height notch in austenitic weld Du300 weld test block. Operation PA frequency 5 MHz.

For acknowledgement of an 840.44 procedure were used the real cut out Du300 welds with a priory known flaws. Inspection with tested procedure allowed to detect all flaws. The length and height sizing has been confirmed by results of the automated ultrasonic testing with use of system AUGUR 5.2 [5]. At a Fig. 4 results of the Du300 weld in turbine branch inspection are shown. Revealed flaws are located in a weld root and were described as sagging. These flaws are not dangerous but their size is under monitoring during scheduled preventive maintenance carrying out. It is necessary to notice that images received by PA flaw detector are converted in a database on the inspection data which is under maintenance of AUGUR systems since 1997 and which can be analyzed by means of the software module ANALYSIS of AUGUR 5.2 system.

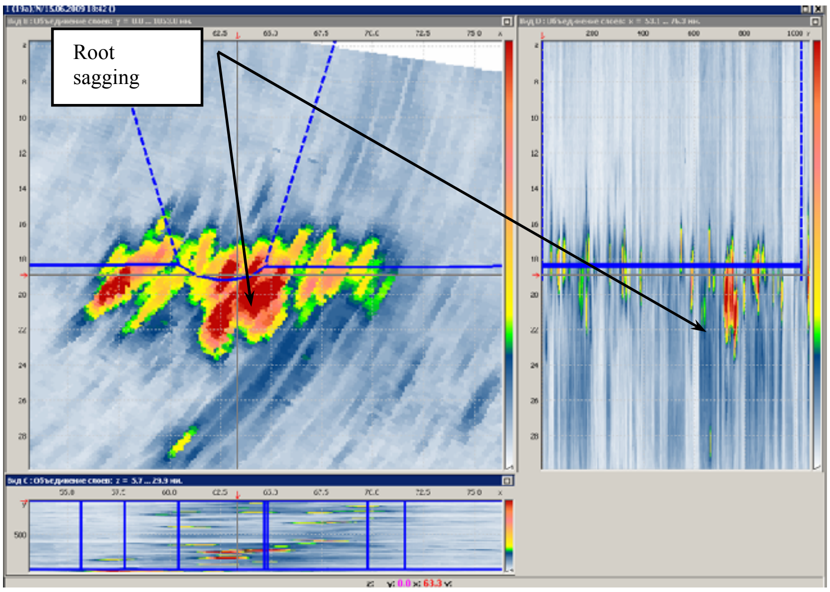


Fig 4. Three views of real Du300 weld root part. Operation PA frequency 5 MHz.

Du300 inspection with antenna array in double scanning mode

For accounting of reflexions from rough object borders the signals processing in a double scanning mode [6], by method C-SAFT [7, 8, 9] rather prospective. The given inspection mode also is a part of a 840.44 M procedure.

At a Fig. 5 the Du300 inspection setup is shown. The cycle of measurements consists in pulsing of ultrasonic impulses by each array elements from the N-side and reception by each array element from the P-side (two yellow arrows), in pulsing and reception full raw data from the N-side (a blue arrow) and from the P-side (a green arrow). Measured signal writes into three files –NP-file, N-file, P-file, and then arrays moves to the next point along weld for repetition of a measurements cycle.

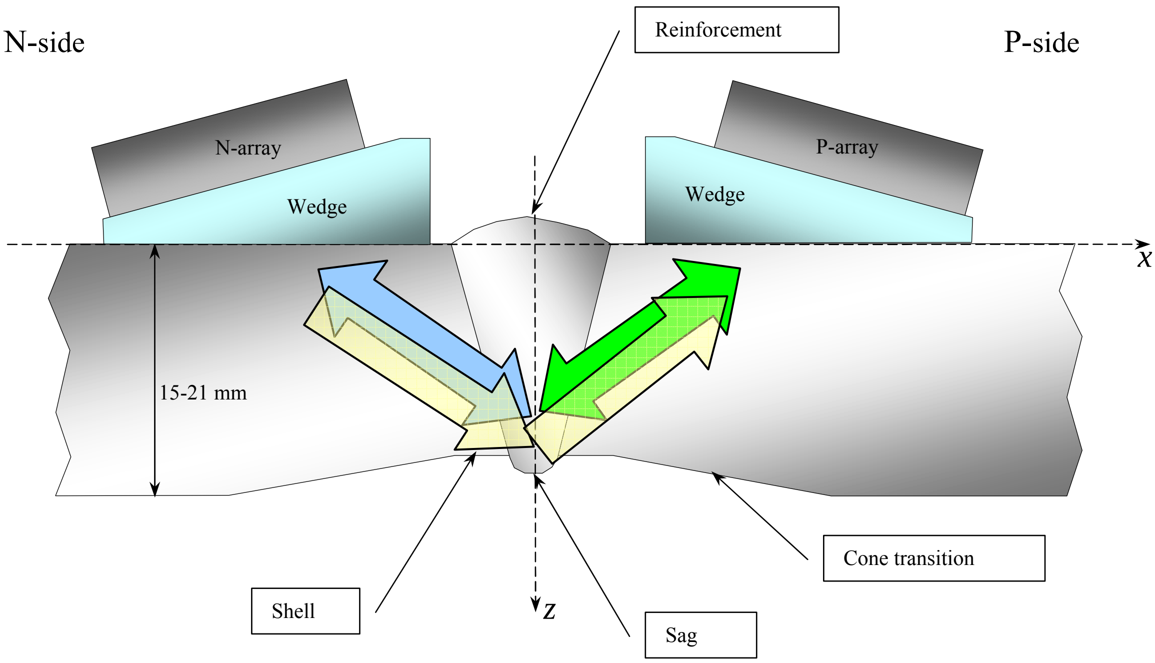


Fig 5. Measurement setup of thin-walled weld with rough bottom.

Unlike the classical scheme of the pulse-echo technique with cross scanning probe, array is motionless and acquires signals in a double scanning (bi-static) mode when all pairs of pulsed and received by array elements are used. In a Fig. by 6 black small squares are sixteen array elements, by a red line the beam on which the impulse radiated from the first array element to the flaw (a grey circle) is schematically shown. At reflexions from flaw received by all sixteen elements is noted by green arrows. Then the second element pulses and all elements receive. Finally 256 A-scans will be acquired with 16 element array. This A-scans provides various techniques simultaneously – half-skip, full-skip data with wave type conversion etc. For this paper signals acquired with 5 MHz 32 elements with 0.8 mm pitch array PE-5.0M32E0.8P.

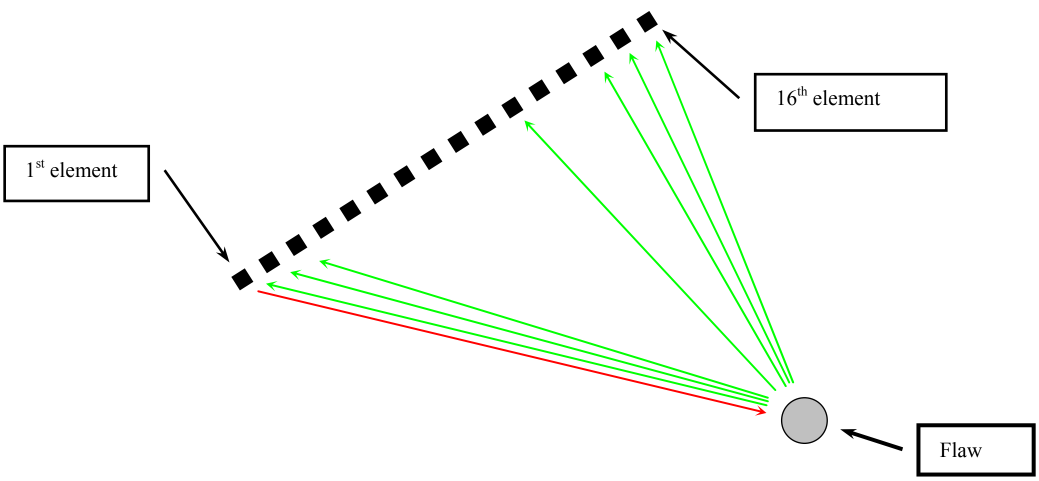


Fig 6. Measurement setup with antenna array (16 elements) in double scanning (bi-static) mode.

One of algorithms which allow to process this richest bulk of information is a C-SAFT (Combinational SAFT) method. With its help images on which indications are not displaced on *xz* axes and better focused on all region-of-interest (ROI). Mentioned drawbacks are characteristic for images received by PA flaw detectors. As for refreshing rate, for example handheld flaw detector with C-SAFT A1550 IntroVisor of “ACS” [5] forms C-SAFT image with a speed commensurable with PA flaw detectors.

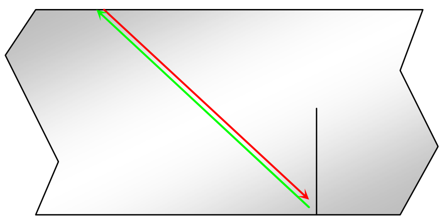
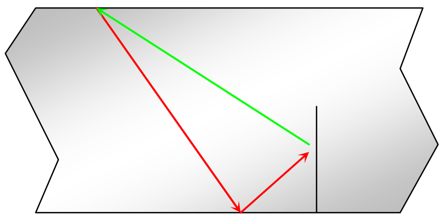
As further the important role will be played by acoustic schemes with reflexion of ultrasonic impulses from a bottom and a top surface of object we will use following designations: refraction or reflexion on outer (top) surfaces will designate letter **T**, reflexion from bottom surface will designate letter **B**. Wave mode after refraction or reflexion will be L (longitudinal) or S (shear). So the full-skip technique with wave mode conversion from shear to longitudinal at bottom surface and the same way to receiver will be designated as **TB(SL)-TB(SL).**

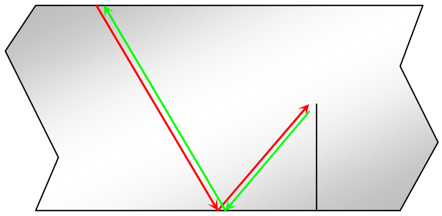
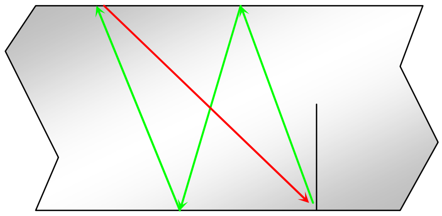
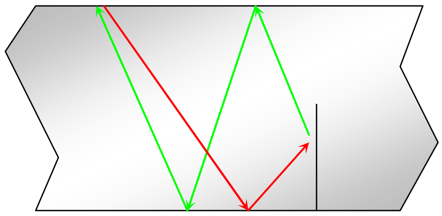
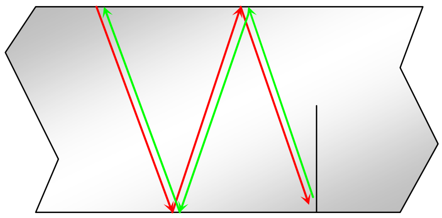
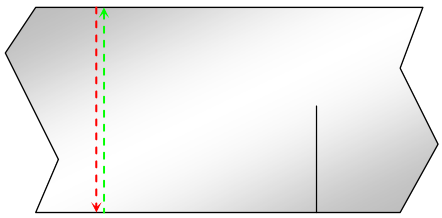
So, after raw A-scans acquisition in NP-file, N-file and a P-file it is necessary to obtain from them images by C-SAFT. At first pitch-and-catch data in NP-file processed (yellow arrows at a Fig. 5). The obtained images allows to receive the information on the form of a bottom surface of Du300 and to find out shadowed zones which are specified confidently as outer surface crack indication of height more by than 4.0 mm. With use of three acoustic schemes **TB(SS)-TB(SS), TB(LL)-TB(SS)** and **TB(SS)-TB(LL)** it is possible to restore the bottom image in a wide range from -50.0 to 50.0 mm and to estimate its profile.

At the next stage N-file and P-file data proceeded. C-SAFT method allows to reconstruct flaw image taking into account reflexions from rough bottom surface and top surface. The T(S)-T(S) scheme means half-skip technique with shear wave, TB(SS)-TBT(SSS) means full-skip way to the weld and one-and-a-half-skip vice-versa (all is shear wave). The table 1 contains techniques label and schemes practically used in inspection. The red lines means a path of pulsed beam and green ones a received beam path. Solid lines are shear (S) waves and dashed are longitudinal (L) waves. Comments describe what part of a crack is reconstructed better at image.

Totally six schemes used for flaw image reconstruction from each weld side. "Illumination" of flaws in a wide range of angles (about 130.0 degrees) allows to obtain the qualitative combined image of flaws. In the elementary case combination is summation of modules of all six partial images. Higher quality of the combined image allows to automate sizing and recognition of flaws. At a Fig. 7 shown the result of summation of all of six partial crack images on which it is possible to define confidently type of flaws and its geometrical sizes. For demonstration of the high signal/noise relation (SNR) contrast of the image is increased to 300%. It is necessary to notice that the array was on distance about 50 mm from the weld reinforcement centre, therefore with a half-skip is possible only is detect crack, but it is impossible to define its height.

Table 1. List of techniques used for flaw image reconstruction. The red line is a path of pulsed beam and green one is a received beam path. Solid lines are shear (S) waves and dashed are longitudinal (L) waves.

#	Technique label	Technique scheme	Comment
1.	**T(S)-T(S)**		**Shear wave** – root part and crack tip
2.	**TB(SS)-T(S)**		**Shear wave** –crack body

#	Technique label	Technique scheme	Comment
3.	**TB(SS)-TB(SS)**		**Shear wave** – root part and crack tip
4.	**T(S)-TBT(SSS)**		**Shear wave** – root part and crack tip
5.	**TB(SS)-TBT(SSS)**		**Shear wave** – crack body
6.	**TBT(SSS)-TBT(SSS)**		**Shear wave** – root part and crack tip
7.	**T(L)-T(L)**		**Longitudinal wave** – image of bottom surface under the antenna array

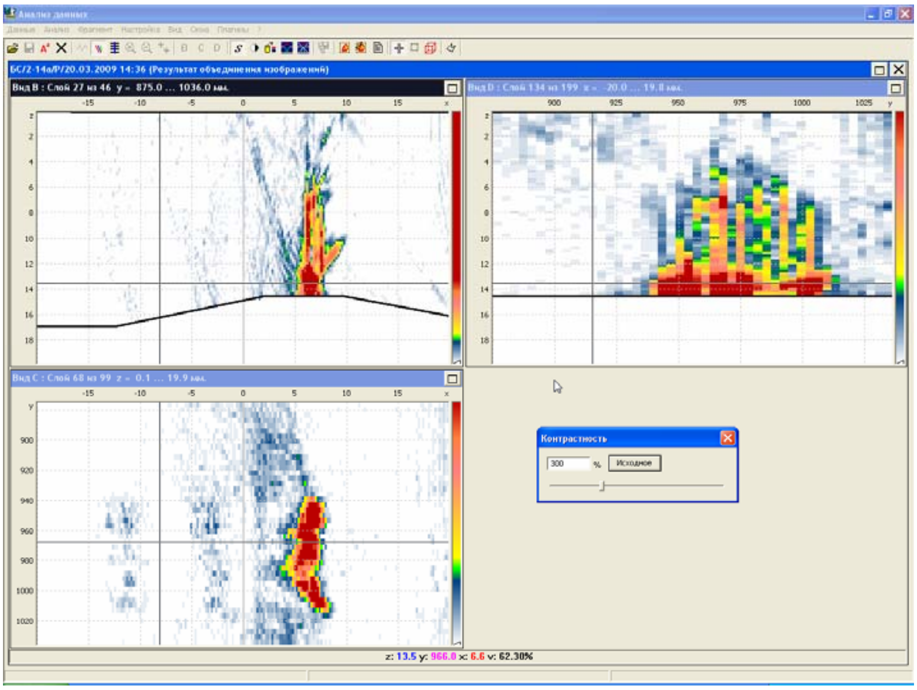


Fig. 7. Combined image from six partial C-SAFT images of real crack in Du300 austenitic weld. Used array with 32 elements and operating frequency 5 MHz.

Processing of the same data with C-SAFT under scheme T(L)-T(L) (see table 1), allows to obtain the image of a bottom surface and to estimate acoustic coupling quality. The wall thickness at N-side and P-side calculated automatically by the images of a bottom surface after multiple reflexions between object borders. At a Fig. 8 the result of a wall thickness definition on which it is well visible is presented that the thickness of a pipe from the N-party varies on 0.6 mm throughout a circle.

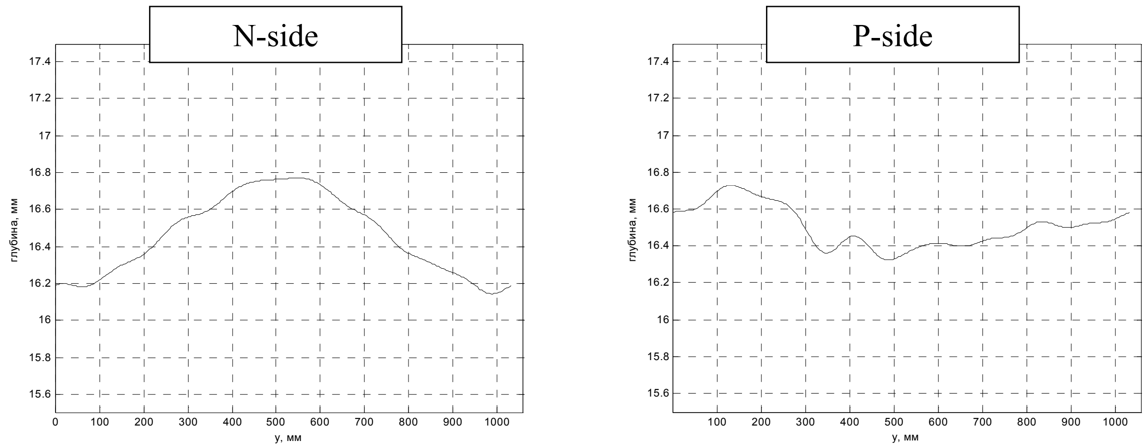


Fig 8. Wall thickness measurement result from both sides of Du300 weld.

Thus, three files are measured in each point along weld on which it is possible to obtain **seventeen images** totally. However the operator does not have necessity to analyze all these images as almost all processing occurs in the automated mode. Such approach allows to obtain high-quality images of defects that in turn raises reliability of flaws sizing and recognition process.

Researches have been conducted according to reliability of cracks height sizing by combined image. At a Fig. 9 are presented result of definition of a profile of almost through wall crack on bottom surface, calculated by combined image in comparison with metallographic investigation. Comparison of a five real I.D. breaking cracks profile measured by the images obtained by a prototype of system AUGUR 6, with metallograpy has shown that the maximum error of height sizing is 1.5 mm.

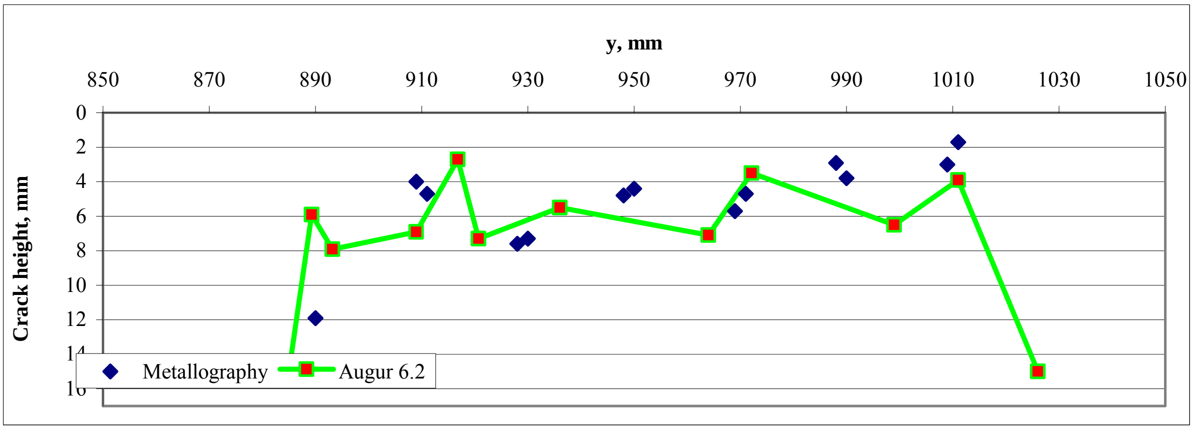


Fig. 9. Results of crack height measurement by combined image with comparison of metallography investigation.

At the moment AUGUR 6 system for Du300 inspection developed which includes scanner T300 which can work as in manual, and the automated mode, the electronic block for signals acquisition in a double scanning mode, the personal computer with the software which under the scenario spends stage-by-stage processing practically without intervention of the operator. The basic stages of the scenario are listed below:

- acoustic coupling quality evaluation and shadow zones detection
- obtaining of information on the cross-section bottom surface profile by pitch-and-catch data by images **TB(SS)-TB(SS)**, **TB(LL)-TB(SS)** и **TB(SS)-TB(LL)**
- wall thickness measurement along weld from N-side and P-side by images **T(L)-T(L)**
- partial images reconstruction under techniques **T(S)-T(S)**, **TB(SS)-T(S)**, **TB(SS)-TB(SS)**, **T(S)-TBT(SSS)**, **TB(SS)-TBT(SSS), TBT(SSS)-TBT(SSS)**
- partial images combining into one image by data from N-side and one from P-side
- automatic flaw zones detection
- automated flaw sizing under the operator`s management
- inspection datasheet generation

All data including flaws description is moving into database.

Thick-walled object inspection

The table below describes examples of thick-walled objects, according to classification rule declared before

Inspected object	Outer diameter, mm	Wall thickness, mm	Base metal material
Du700	790	55±4	perlitic steel
Du1200	1335	72±5	perlitic steel

Inspection with PA

Inspection procedure 840.44 M described before was expanded to thick-walled welded joints taking into account acoustical and constructive objects characteristic. The PA inspection results was confirmed by AUGUR 5.2 system. At Fig. 10 the PA inspection of perlitic weld into turbine NPP branch results shown. One can see the volumetric flaw at the weld chamfer in the mid-height and small indications at the weld root.

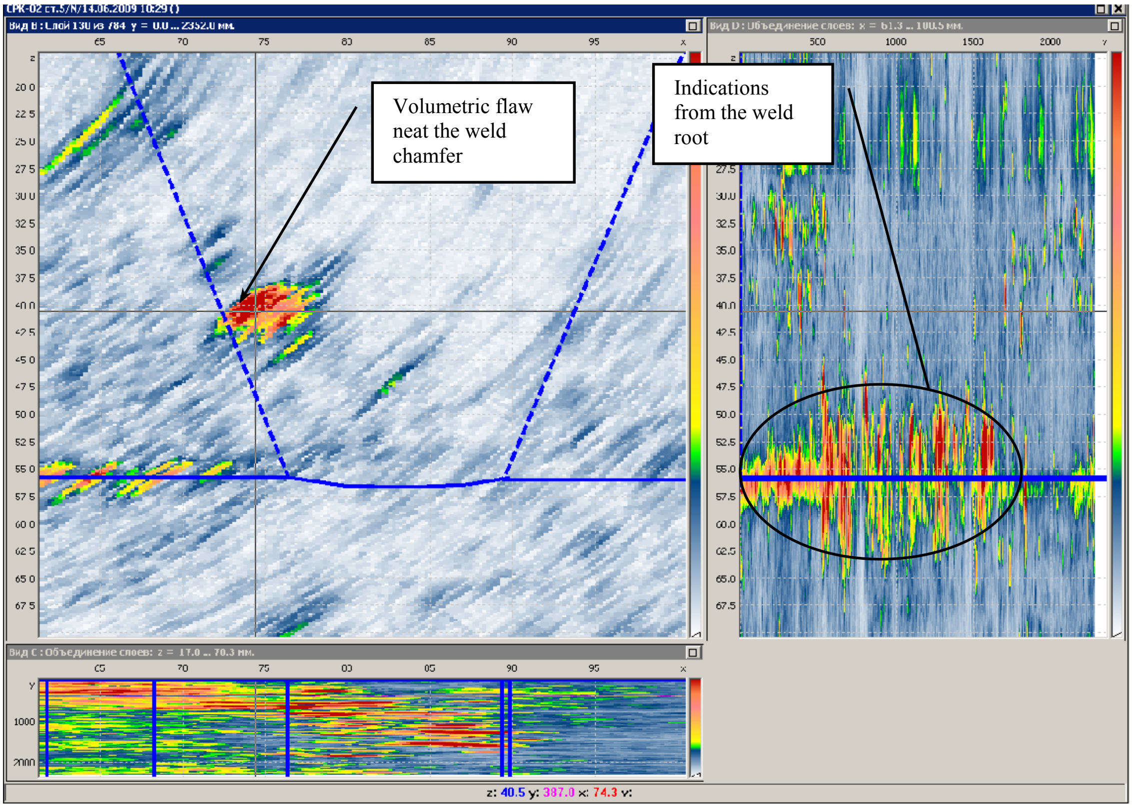


Fig. 10. Du700 weld inspection with PA. The volumetric flaw and small indications was detected.

Inspection with array in triple-scanning mode

PA application for detection of flaws on depths bigger, than antenna near field, will not allow to obtain the image of flaws with the high resolution. For flaws on depths of 50.0 mm and more the frontal resolution worsens. To improve resolution it is possible to make a cross-section scanning with relative coarse steps, reconstruct a set of C-SAFT images and finally combine them together coherently. The combined image has a resolution defined not by the array size but the scanning area size. It is logical to designate such acquisition mode like a triple-scanning mode. At a Fig. 11 images of four Ø 0.5 mm SDH with distance 2.0 mm from each other, obtained by C-SAFT method with one array position (left pane) and C-SAFT images with antenna array scanning at the aperture 42 mm (right pane). The scanning aperture is almost twice more than PE-5.0M32E0.8P equal $32\times 0.8\cos(2.7)/\cos(3.22) = 19.3$ mm array aperture.

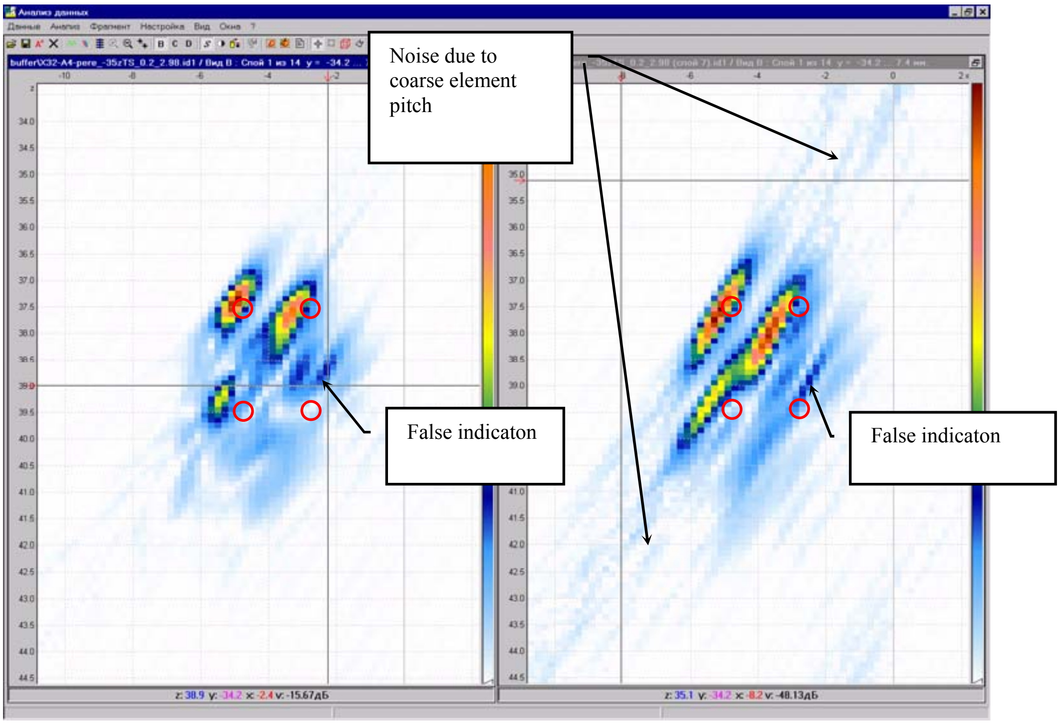


Fig. 11. C-SAFT images of four SDH with single array position (right) and in triple-scanning mode (left).

Contours of SDH are represented in figures by red circles. The frontal resolution has increased twice in a triple-scanning mode, the noise related with coarse elements pitch in 0.8 mm, has decreased more than on 6 dB. However, amplitude of the false indication generated by rereflections between holes, practically has not changed, as it is defined by size of the spatial aperture on which signals are registered in a double-scanning mode. Because of effect shadowing effect the most distant SDH is not visible. It is obvious that the ideology of combining image with use of different techniques (see table 1) is easily generalised on a case of triple-scanning mode.

Thinned array inspection with triple-scanning mode

Objects like austenitic cleft welding repairs at Du800 pipeline (RBMK-100 power units) or main shutoff gate valve weld (VVER-440 power units) needs a long ultrasonic path (more than 200 mm) with bottom surface reflection, therefore longitudinal waves practically used due to smaller attenuation. Longitudinal waves results “parasitic” wave mode transformed indications, particulary on the full-skip. This indications makes difficult the flaws sizing and even flaws detection.

It is possible to reduce the “parasitic” indications and provide high frontal resolution with two ore more rigidly connected conventional probes with several plates each one. This construction is called thinned (or subsampled) array. By analogy to the previous section it is possible to designate such operating mode as a **thinned array inspection with triple-scanning mode.** The obtained image will have high frontal resolution due to large scanning aperture and suppressed “parasitic” indications due to coherent summation of the images batch. The cross-section scanning will reduce the noise related to coarse (above 5 mm) thinned array element pitch.

At the Fig. 12 two probes with constant distance *b* between ones showed. First probe has two plates and second probe has three plates. Probes’ independent suspension allows tuning to the rough surface which could be critical for monolith large antenna array. In every scanner cross-section position 32 A-scans recorded for all pulsing/receiving combinations. After full raw data acquisition with small scanning step (approximately half of wavelength) 32 images by SAFT method will be obtained and coherently combined together.

Though for effective implementation of this technique the coherent images combination should be strictly cophased. Special combined calibration procedure for thinned array was developed.

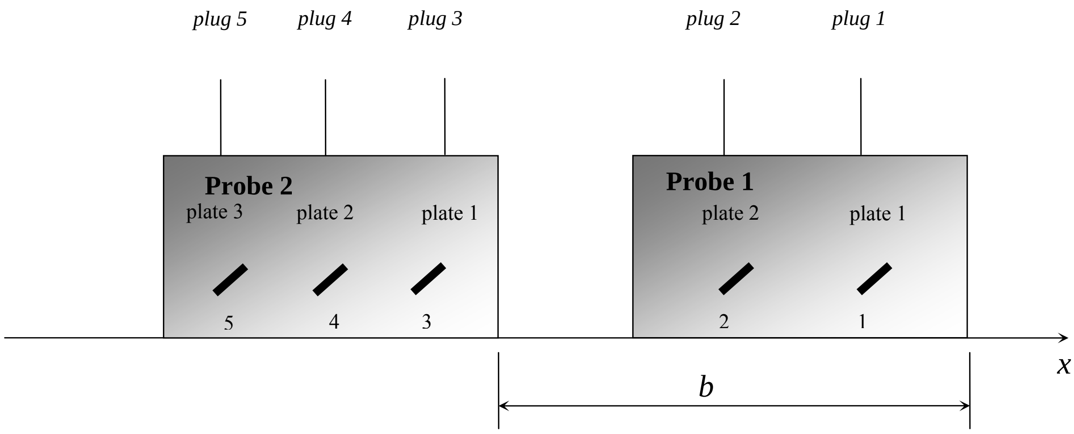


Fig. 12. Example of sampled array combined from two cases with five plates.

Conclusion

The inspection procedure 840.44 M was developed for the thin-walled welded joints, in which possible application of the PA inspection, and by antenna array in double-scanning mode. Modification of C-SAFT method developed considering reflexion of ultrasonic impulses from a rough bottom and top surfaces of object, and allowing to obtain the high-quality combined flaw images. The prototype of AUGUR 6 system has passed successful tests on weld cuts with real cracks.

For the thick-walled object inspection (with a wall thickness more than 50 mm) it is recommended to acquire data in a triple-scanning mode, that considerably raises frontal resolution of the image obtained by C-SAFT method. The perspective technique of inspection of very thick objects is a thinned array inspection with triple-scanning mode.

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