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High-Speed Phased-Array Ultrasonic Testing of Standard-Walled and Heavy-Walled Seamless Tubes with Improved Oblique Defect Detection

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Abstract

Since its introduction in the early 2000's, the PAUT technique with linear arrays has demonstrated to be a robust, highly versatile solution to cope with the high-performance requirements (in terms of sensitivity, repeatability and productivity) for many mills producing OCTG and Line Pipes. Combined with precise mechanical scanning in a testing portal (gantry) configuration (rotating tube, linear probe movement), this solution eventually became the standard, adopted by major ultrasonic system suppliers and tube manufactures.

One novelty of this technique, was the possibility of ultrasonic beam steering for oblique defect detection. This could be performed by means of the same probe used for longitudinal defect detection in a narrow angle-range and by separate arrays for higher angles. Depending on the throughput requirements, the oblique defect detection capability was restricted to a number of definite directions and/or to a narrow range.

The manufacturing process, especially for quenched and tempered heavy-walled tubes, could potentially generate discontinuities of every orientation requiring to extend the oblique defect detection angular range. A novel extension of the linear Phased Array technique for oblique defects up to ±75° on standard and heavy-walled steel tubes is presented in this paper. Excellent test results with high sensitivity and reliable SNR could be achieved on the whole extended defect orientation and dimensional ranges. For heavy-walled tubes, the optimization of the incident angles and the use of mode-converted waves for the detection of internal/external defects is essential. The best-possible acoustical solution, particular highly-sensitive Phased Array probes and probe clusters with fast coupling capability where developed. A specific scan-plan for wall thickness measurement and for transverse and laminar defects detection was also afforded.

Several parallel modules of a state-of-the art PAUT electronics are employed. Parallel firing and multiple parallel computations in the reception mode are key features that consent high testing speed. Therefore, high sensitivity, repeatability and productivity is provided for the entire extended defect orientation and dimensional ranges.

A Testing Machine is being developed by KARL DEUTSCH and will go into operation at TMK-ARTROM in the second half of 2021.

Keywords: Phased-Arrays, Ultrasonics, Seamless, Tubes, Oblique, Heavy-Walled

1. Introduction. ECHOGRAPH-RPTS PAUT. Phased array testing of seamless tubes at TMK-ARTROM

TMK-ARTROM, a leading global manufacturer of seamless tubes based in Slatina, Romania, continues to develop its production facilities focused on premium products. In 2018 a new state-of-art heat-treatment plant with a production capacity of 165,000 to/year was incorporated. The new advanced plant covers the dimensional range: diameter 60 – 273 mm / wall-thickness 5 – 60 mm, having the capacity to quench and temper extra heavy-walled tubes.

Fig. 1 TMK-ARTROM facilities at Slatina. New Heat-Treatment plant, Quenching Tank

These high-steel-grade tubes, target demanding applications in the machinery, automotive, heavy duty hydraulics and energy fields between others. The safe use of these tubes demands more stringent non-destructive testing. In consequence, a significant upgrade of TMK-ARTROM non-destructive testing capacity and capability was required to complement the new heat treatment plant in the premiumization and flexibilization of its mechanical tubes' facilities.
Along the manufacturing process, seamless tubes undergone transformations and stresses which can lead to discontinuities. Due to the high elongation characteristic of the forming process, most of the surface imperfections are oriented in a predominantly longitudinal way. However, especially during the manufacturing of quenched and tempered heavy-walled tubes, potentially discontinuities of every orientation may happen, which raises the need to test the tubes for a wider defect angle range.

Currently, testing for flaws with a few preferred oblique orientations is already recommended or required by international standards and major users' specifications for seamless pipe UT. It is envisaged that these standards will eventually demand gapless randomly oriented flaw detection.

The new ultrasonic testing system is expected to test for discontinuities oriented between ± 75° and 90° (transversal) from to the tube axis, placed on the external and Internal surfaces. Supplementary, the detection of laminar imperfections and the wall-thickness measurement is required. The test shall be performed in a single run of the tube through the unit (notably for heavy-walled tubes), with 100% coverage over full length of the tubes, and perform a productivity compatible with the new heat-treatment plant.

The company KARL DEUTSCH (KD) was commissioned to develop this highly sophisticated ultrasonic testing system that has to be put it into operation in the second half of 2021.
The project is supported by Solutii CND in Bucharest, Romania for the after-sales service.

2. Evolution of the Linear Phased-Array testing technique for medium size steel tubes

2.1 Linear Phased-Array application on medium-size tubes

Multi-element transducers arrays with electronic focusing and steering capabilities present interesting advantages for on-line inspection. Indeed, a great flexibility is obtained by using a transducer array to generate a beam focused at any specified angle and range. One- or two-dimensional transducer arrays are connected to electronics performing delay-laws calculated to achieve focusing in transmit and receive modes.
An arrangement of linear UT Phased Array probes aligned to the tube axis has proven to be a robust and extremely versatile solution to insonified a tube in multiple directions. Each Phase Array probe implements determined ultrasonic beam direction(s). The length of the probes defines the scan helix of a precise and flexible 2-axles geared scan system, where probes are displaced along the tube length while it rotates.
The original configuration was introduced in the early 2000s ([1], [2]) to cope with high-performance ultrasonic testing requirements (in terms of sensitivity, repeatability and productivity) for medium sized OCT tubes.
The arrangement consists of a minimum of 3 linear phased array probes placed parallel to the tube axis. In the minimal configuration, one probe facing the tube axis, while the other two displaced and symmetrically tilted at ± 17° ca. facing a common sound entry line one the tube surface.
The probe facing the tube axis was dedicated to Wall-Thickness measurement, the detection of Laminar type Defects and Transverse defects in both forward and backward directions by means of electronic beam steering.
The two tilted probes consent the detection of Longitudinal defects in the clock-wise and counter-clock-wise directions but also, a novelty of this technique, Oblique defects through electronic beam steering.
Extending the probes length and repeating the same focal laws along them (electronic scanning) increases the UT coverage (helical inspection pitch) and so the productivity without affecting sensitivity. The electronic scanning also gives flexibility to adjust the “virtual probes” overlap (scan step) required to optimize repeatability in function of the reference reflector geometry and orientation.
Digital beam-forming modular instruments permitted a cost-wise efficient industrial implementation of high capacity and high capability systems.
Matching focal laws were applied in transmission and reception. Even when each element was digitized before computation (typically up to 32 elements per virtual probe), the evaluation was carried out in a classical analog way after conversion of the summation result. Some parallel evaluation capacity was possible (up to 4 virtual probes per probe, limited by electronics size and cost) when scalability features were added to electronics. The complete electronic scan of the probe required several sequenced cycles shifting the same focal laws.
This concept eventually became the standard adopted by the leading OCTG (Oil Country Tubular Goods) and Line Pipe tubes manufactures and consequently by the main ultrasonic testing system suppliers.

2.2 Extension of the oblique defect detection capability

The basic concept of three linear arrays was extended by the addition of probes (and probe holders)

- Increasing testing speed, by distributing test functions
- Improving resolution, by separating Transverse and WT/Laminar functions
- Extending the oblique range, using narrower specific tilting angles, dedicated to higher inclination defects.

Typically, 2-3 orientations were covered by each pair of tilted probes. On most testing machines, the oblique defect detection was limited to either ±11°, ±22° and/or ±45°; occasionally ±67°.

The development of full digital beam forming and evaluation electronics, made possible the digital reconstruction in reception of several defect orientations from a single transmission pulse. This technique saves most of the ultrasonic waves traveling time associated with a sequence of multiple transmission pulses and so lead to the achievement of gapless defect detection (regardless of their orientation) up to ±45° at industrial speed ([3], [4], [5]), occasionally adding other specific orientations up to ±67°.

Up to 7 probe-holders are used in a system performing this oblique-defect angle range.

2.3 2D Phased-Array Implementations

The use of 2D phased-array probes has the theoretical potential to integrate all test functions, as the ultrasonic beam can be swivel 360°. A sequenced electronic beam swiveling and scanning is not practical due to the number of cycles required. Multidirectional or omnidirectional insonification is used, aiming to cover the complete angle spread with a single or reduced number of shots and multiple reconstructions. This is achieved using linear pulsers to conform the ultrasonic beam, being the draw-backs of these implementations the high cost of the (high number of elements) matrix probes and parallel electronics with linear pulsers required, and a higher energy dispersion with a consequent loss of sensitivity. [6] [7]

These testing techniques has been implemented for the standard walled tubes range (Wall Thickness / Diameter ratio > 0.2).

2.4. Heavy-walled tubes

The classic way to test heavy-walled tubes is using different tilting angles for longitudinal internal and external, either dedicating separate probes or running two mechanical scan cycles using different probe tilting angles.

1.5D phased-array probes has been used to provide both required angles in a compact way. The implementations have been done with relatively large axial element pitch (to keep the total number of elements small), thus, steering the ultrasonic beam for oblique defects detection ins not possible ([8], [9]).

3. Implementation of ECHOGRAPH-RPTS PAUT. Phased array testing of seamless tubes at TMK-ARTROM

3.1 Requirements

The new system shall test for discontinuities having any orientation between ±75° plus 90° from to the tube axis, on the external and Internal tube surfaces. Additionally, the detection of laminar imperfection and wall-thickness measurement is required. The test shall be performed in a single run with 100% coverage for all test functions, and perform a productivity compatible with TMK-ARTROM's new heat-treatment plant. The tubes end condition can be either cold-cut or uncut (as-rolled).

3.2 ECHOGRAPH-RPTS PAUT Mechanics

3.2.1 Testing portal for seamless steel tubes in the medium diameter range

The principle preferred for a precise mechanical scanning of the tubes surface is the proven testing portal. It consists of a 2-axis gantry plus a roller bench placed bellow it. A test carriage is moved along the gantry (box-type) girder, lengthwise above the tube. The tube is rotated at constant (servo-controlled) speed on the roller bench at a stationary axial position.

The carriage precise linear displacement, over the horizontal ball rail system, is driven by an onboard servomotor through a rack-and-pinion link and geared by the tube rotation.

This coordinated process is programed to warranty a precise mechanical scan helix of the probes over the OD tube surface. In the stationary regime the helix width reaches the effective probe length minus the overlap required to ensure 100% UT coverage for all the test functions.

The tube rotation speed is adjusted based on the UT pulse repetition frequency (PRF) and circumferential pulse density required.

The test mechanics (that holds the UTPA probes), the UTPA electronics, the pneumatics and water systems and the related automation modules are integrated on a the second (vertical) axis on the carriage.

The vertical movement of the assembly over the vertical ball rail system, is driven by a servo-motor through a quick ball-screw. It is raised to release space for loading/unloading the bench and lowered to place the test mechanics at the testing position, determined by the tube diameter.

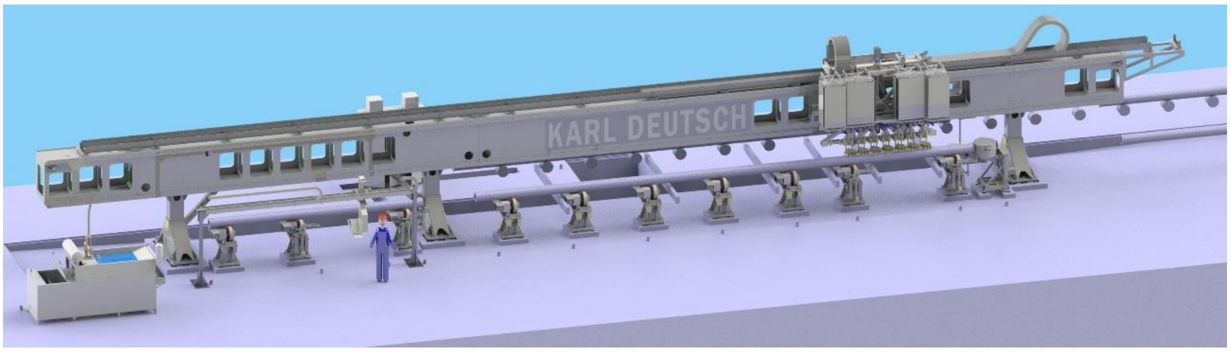


Fig. 2 High-Speed Tube Testing Portal with a length of 32 m.

Fig. 3 Assembled tube testing system before shipment

The inspection sequence is automatically executed and controlled by PLC, being the main steps:

1- The tube length is measured in the loading conveyor

2- The tube is transferred to the roller bench while the carriage is aligned with the tube end

3- One by one each cluster is released on the tube border, where it stays until good UT coupling is established and a complete revolution of the tube finishes.

4. Once the end of the pipe is tested by all clusters the carriage is displaced at constant speed until the pipe end is reached; a similar sequence is then applied to fulfill full-length inspection.

3.2.2 Transforming Stopper

The axial position of the tube is assured by an adaptable stopper.

For cut tubes, it places a vertical axis free rotating wheel in contact with the tube end face and the lowest point (6 o'clock).

For uncut tubes (having uneven ends), the stopper employs free-rotating disks, concentric with the tubes axis and having a diameter somewhat bigger than them.

The different diameter disks plus the wheel are integrated in a single mechanism that performs automatic changeover (disk/wheel selection and height positioning), based on the tube diameter and its ends condition.

3.2.3 Test Mechanics

The test mechanics consists of up to eight modules. Each of them holds a cluster with one or two Phased-Array probes.

A sophisticated follower mechanics provides dynamic alignment of the cluster to the tube surface. It consists of a gimbal joint in combination with a pneumatically-driven lowering and lifting axis for fast probe cluster positioning. The joint allows three degrees of freedom what is essential for a smooth following of the tube surface. Especially for tubes with higher straightness tolerances, the design of the joint is challenging. The lowering-and-lifting axis is implemented with recirculating-ball bushing linear guides and a pneumatic actuator and also provides a 4th, cushioned, degree of freedom. The pneumatics is adjusted to shorten the lowering lifting but safeguarding the cluster from mechanical damage.

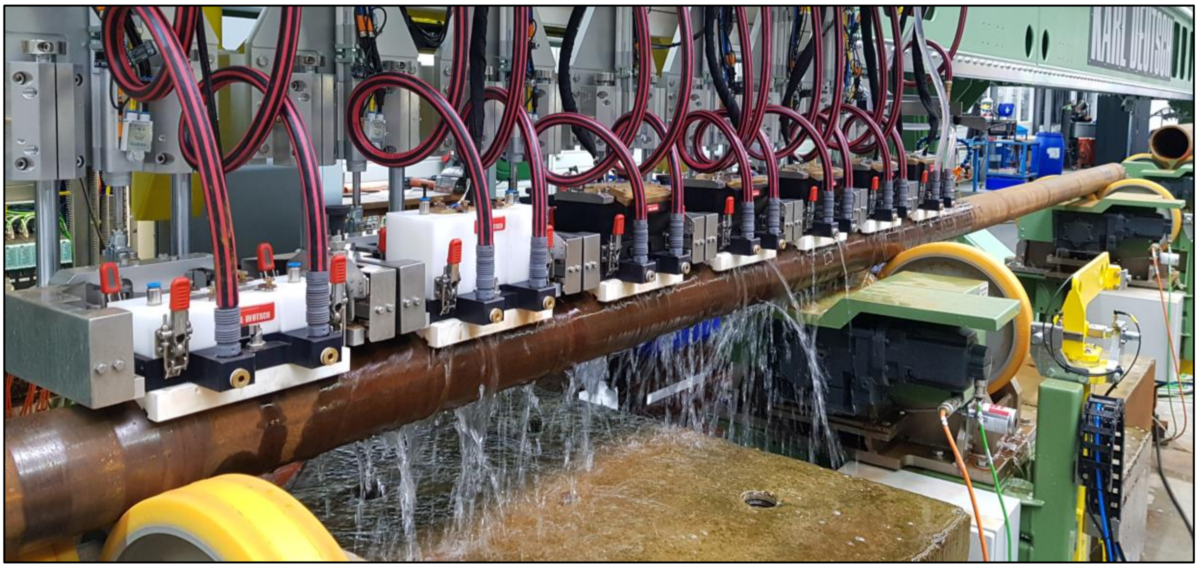


Fig 4 Probe holders (clusters) for longitudinal, oblique, laminar and transverse defect detection and for the wall thickness measurement

3.3 Probe Cluster for the Multiple Test Functions

In order to implement the required test functions, a completely new series of probe clusters had to be developed. Longitudinal, transverse, oblique (±75°) and laminar defects have to be detected reliably. Also, the wall thickness must be measured.

The probe clusters have a modular design. They contain a stable closed water chamber, sealed in the base with an acoustically transparent membrane just above the tube surface. Therefore, only a narrow water gap is required for optimum ultrasonic coupling. After lowering the clusters onto the pipe surface, reliable, bubble-free and fast coupling is achieved. This solution also contributes to shorten the untested ends length.

The probe cluster consists of three main components: guiding shoes, central body and probe holder.

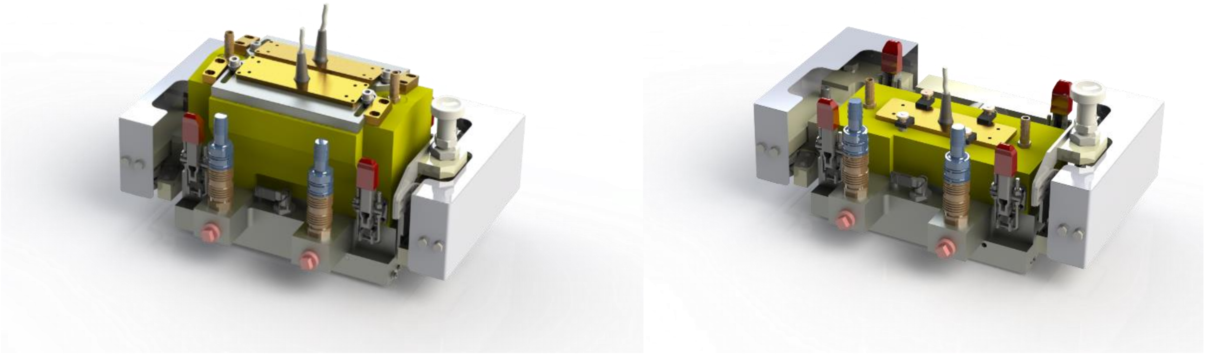


Fig 5 Probe Clusters with Guiding Shoe (bottom plate, not fully visible), Probe Holder (green color), aluminum Central Body conforming the close water chamber and Gimbal Joint (aluminum yoke).

3.3.1 Guiding shoe

The guiding shoes ensure the proper cluster alignment with the tube, also in case of roundness and straightness tolerances, following the tube off-center displacements. They and are also key components for reliable and fast coupling. During the rotational test of a seamless tube, its off-center position might reach 10 – 20 mm!

A highly flexible gimbal joint and a light-weight probe cluster are then required.

In addition, the lowest possible number of shoes must be carefully chosen. The entire production matrix of the pipe mill must be considered. The curvature of the shoe should match the outer tube diameter, but a few mm. off-range can be covered. For small pipe diameters, more shoes are required for a reliable testing machine operation. For large pipe diameters, the diameter range can be covered with a smaller set. The wear of a shoe shall be limited as possible for convenient maintenance and for low wear part cost. Therefore, hard-metal elements are part of the shoe design for an increased lifetime.

Changing the guiding shoes is a fast tool-less operation, what reduces the diameter change-over time.

Special attention was placed on avoiding air bubbles to be trapped bellow the membrane. If bubbles arise, there must be a reliable way for their removal. For this purpose, suitable channels were made in the guiding shoe.

3.3.2 Central Body

The central body of the probe cluster contains the water chamber, integrates the quick connectors for the water hoses (that fill the gap between the membrane and tube).

The central body is invariant for the entire pipe range and also the same for all clusters, independent of the test function and number of probes. It has never to be changed. It is linked to the test mechanics through gimbal joints.

The probe holder is attached to this central body by quick-release clamp.

3.3.3 Probe Holder

The probe holder is used to fix the probes at the required position. Using an integrated insert, the probe position can be adjusted precisely to the pre-calculated required tilted angle and water- path. It can be quickly removed – again, without tools, and by means of fast-locking pins.

3.4 Phased Array Probe design and development

The process of probe development involved several steps resulting in an optimization of the already established ECHOGRAPH immersion phased-array probes for this special application. In general, probe development at KARL DEUTSCH starts with pre-defined parameters based on well-established cases that are then adjusted via modelling taking into account the actual conditions of the test setup. Since all probes are developed and built at KARL DEUTSCH, the performance of preproduction samples can be quickly evaluated in the testing machine creating agile interactional optimization cycles before serial production is launched.

In the first modelling step CIVA simulations are carried out to evaluate the impact of aperture size, probe frequency and face curvature radius along the dimensional tube range.

For Transverse, Longitudinal and Oblique flaw detection the optimum aperture size for this project is a compromise of test speed, sensitivity at long sound paths and prevention of grating lobes for high steering angles. Giving the probe a radius of curvature in the passive axis focuses the sound beam allowing the performance optimization for the specific tube dimensional range. The probe frequency was adjusted to obtain a good performance on all tubes within the dimensional range, but especially on the higher wall-thicknesses'.

Fig. 6 PAUT Probes for seamless tube testing.

A few pre-production samples with different frequency in the range anticipated by modelling were built and test on final use conditions. Although the application tests show a qualification for all of the probes, the optimum probe frequency was defined as a compromise between a small divergence of the sound beam and a good performance on the higher attenuating cases.

The wall thickness and delamination probes keep the same effective width as the probes used for transversal, longitudinal and oblique flaw detection. Further optimizations on the element size, frequency, damping and mechanical focus resulted in an improved sub-surface resolution for thin-wall tubes and high signal to noise ratio for the tubes with thicker wall.

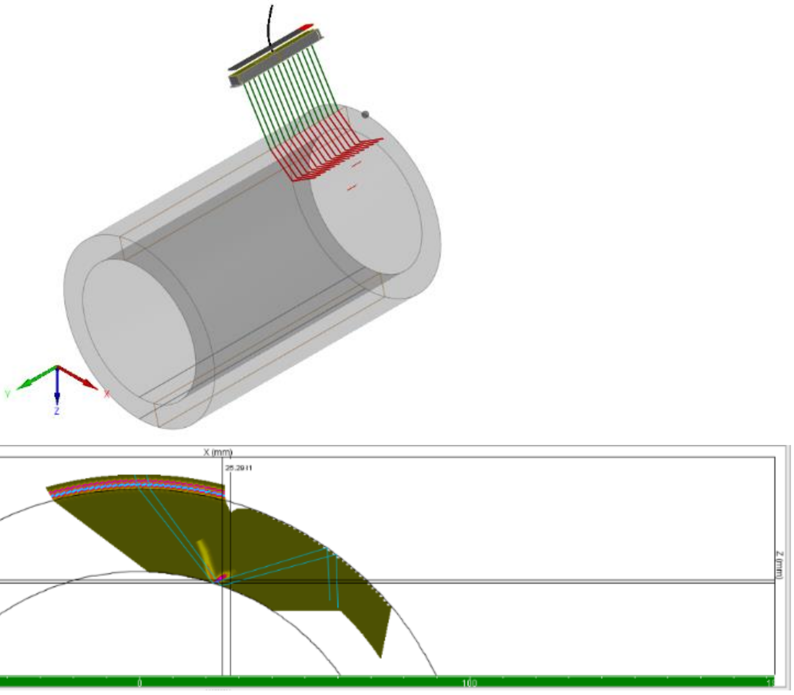


Fig. 7 CIVA Visualization of Longitudinal Defect Detection

3.5 ECHOGRAPH Phased Array Ultrasonic Testing Electronics

Fig. 8 ECHOGRAPH-PAUT Parallel Test Electronics (Module 128/128)

The evaluation of the ultrasonic signals according to flaw type and position is carried out with the ECHOGRAPH-PAUT electronics. This advanced full parallel electronics combines the advantages of the Phased-Array technique with enhanced evaluation methods and offers high-speed testing as well as improved SNR capabilities.

The ECHOGRAPH-RPTR-PAUT system operates up to 12 electronic modules in parallel for the different test functions. More than 1000 Parallel Phased Array channels make possible advanced inspection modes such as parallel firing and scalable parallel evaluations. Around 10000 test functions, synchronized with encoder pulses are implemented for this application. Up to 320 MB/s data transfer rate is achieved.

Various amplitude thresholds, individual programmable DAC (TCG=time-corrected gain) and multiple evaluation parameters are available allowing to meet common and advanced inspection requirements.

The electronics is mounted and well-protected in a shielded electronic cabinet onboard the carriage (see Fig. 9).

Fig. 9 ECHOGRAPH-PAUT electronic modules installed in a cabinet

3.6 Application

3.6.1 Testing Requirements

The new ultrasonic testing system is expected to test for discontinuities having any orientation between ± 75° and 90° (transversal) from to the tube axis, placed on the external and Internal surfaces. Supplementary, the detection of laminar imperfection and Wall Thickness measurement is required.

The test shall be performed in a single run of the tube through the unit (notably heavy-walled tubes), with 100% coverage over full length of the tubes, and perform a productivity compatible with the new heat-treatment plant.

3.6.2 Application Development brief

An extension of the Linear Phased Array technique was developed making viable the testing in an angular range of ±75° on standard-walled and heavy-walled steel tubes. In addition, specific scan-plans for transverse and laminar defects were implemented in order to meet the high productivity and sensitivity requirements.

For the validation of the developed scan plans several reference tubes with multiple reference defects were used.

Fig. 10 shows the example of a heavy-walled reference tube with inner (ID) and outer (OD) longitudinal and oblique notches from 0° to +75° with 7.5° stepping (cw and ccw orientation), inner and outer transverse defects, 10% wall thickness reduction and lamination defects FBH 3.2mm in 25%, 50% and 75% depth.

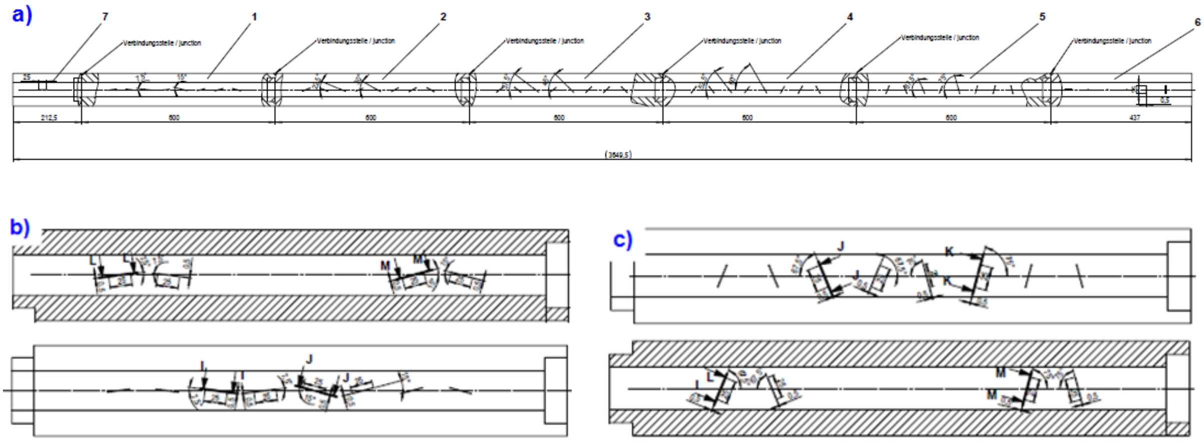


Fig. 10 a) Heavy walled test tube 101.8mm x 28mm, b) Exemplary test tube piece no. 1 with ID and OD oblique notches from 7.5° to 15° cw and ccw, c) Exemplary test tube piece no. 5 with ID and OD oblique notches from 67.5° to 75° cw and ccw

3.6.3 Special Challenges: Heavy-Walled Tubes and a Large Oblique Defect Range

The test for tube inner and outer surface defects is implemented by local immersion with the "pulse-echo" method, using shear waves generated from compression waves incident on the outer surface of the tube. So as to reach the outer tube surface, the wave bounces first on the inner surface, as shown in Fig. 11 in the case of longitudinal defects. An incident angle of approximately 40° on the defect is preferred.

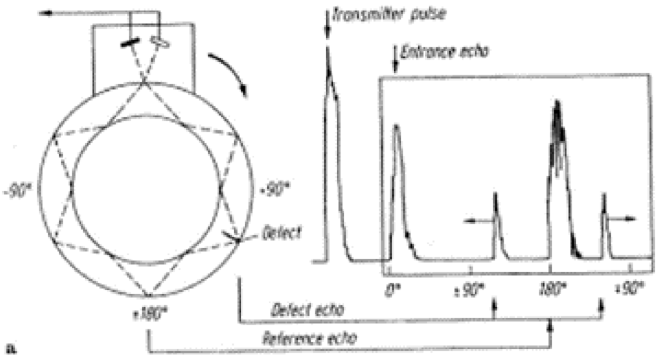


Fig. 11 Pulse-Echo Technique in tubes, schematic

On standard-walled tubes, with low WT/D ratios, the geometry approximates a plate where the incident angle for a defect located either on the inner or outer surface is the same. The more this WT/D ratio increases, the further the condition moves away from the plate case, (Table 1)

Table 1. Incident angle in water to obtain 40° incident angle on the defects [9]

WT/D	0.02	0.1	0.15	0.2	0.3
OD DEFECT	17.1°	17.1°	17.1°	17.1°	17.1°
ID DEFECT	15.4°	13.6°	11.9°	10.2°	6.8°

For WT / D ratios lower than 0.2, a good compromise for the incident angle on internal and external notches is possible. Beyond this limit, two separate shots with different angles of incidence are necessary.

The incidence angle in water shall be decreased to detected ID defects. In addition to the direct converted shear wave, the shear wave generated by the refracted compression wave can be used [10].

This analysis can be extended for oblique defects, but taking into account that the higher the inclination, the higher the critical WT/D ratio is for these defects (the closer to the plate case).

3.6.4 Oblique Defect Detection ±75°

The Linear Phased Array technique makes possible the use of electronic steering of the ultrasound beam for oblique defects detection. Combined with a mechanical tilted Phased Array probe the different pulser delays for the array elements are used to generate a steered sound beam with a dedicated oblique emission angle. Suitable receiver delay laws allow the detection of the defect echoes with a pre-defined incidence angle (reconstruction angle).

In order to perform gapless testing for a certain defect orientation range, after the transmission of an ultrasound pulse (shot) with a given steering angle, several reconstructions, in a certain angular span around it, are done to evaluate the echo signals received. (Fig. 12).

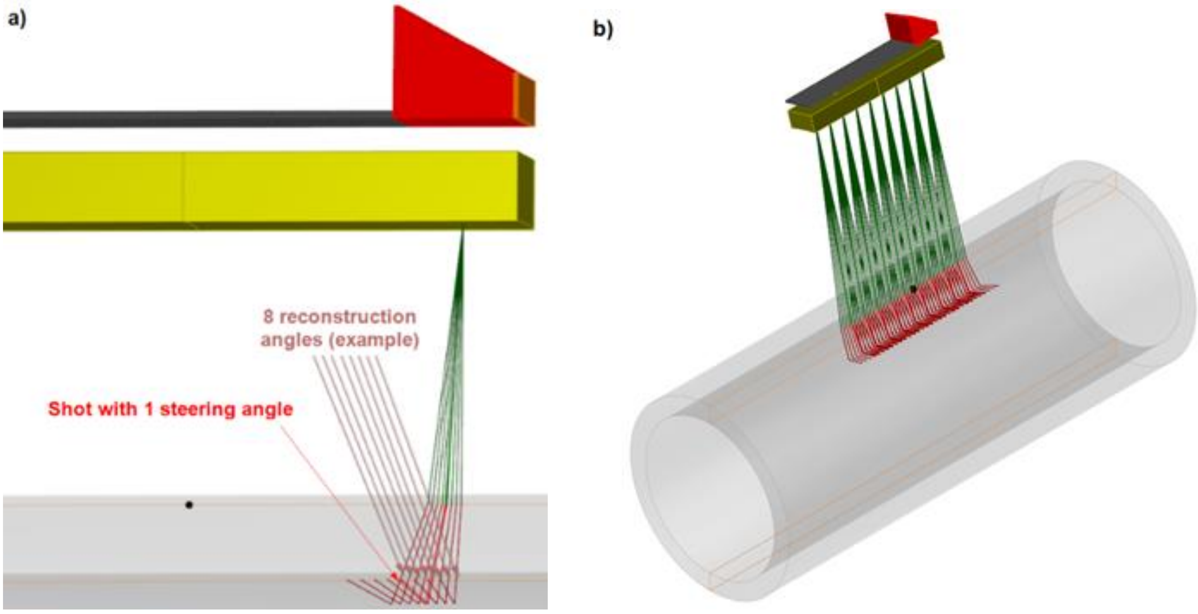


Fig. 12 Oblique flaw detection with Phased Array a) 1 shot with 8 reconstruction angles b) multiple shots of the probes with the respective reconstructions

With the ECHOGRAPH-PAUT electronics several transmission shots with different steering angles can be applied and compute in parallel multiple reconstruction angles per shot. With appropriate numbers of shots and reconstruction angles per shot, one probe set (cw and ccw) is able to cover a wide range of ID and OD oblique defects.

To implement the inspection of the oblique defect range ±75°, a total number of 3 probe sets was finally required.

The high parallels evaluation capacity of the ECHOGRAPH-PAUT electronics made it possible to keep a high effective pulse repetition frequency in spite of the heavy post-processing. As a consequence, oblique flaw inspection can be performed with optimal virtual probes overlap (axial pulse density) and enhanced productivity compared to PAUT systems not performing full-parallel electronics and multiple reconstructions per shot. This is particularly noticeable on thick-wall tubes

An example of measurement results for ±30° flaw detection is shown in Fig. 13.

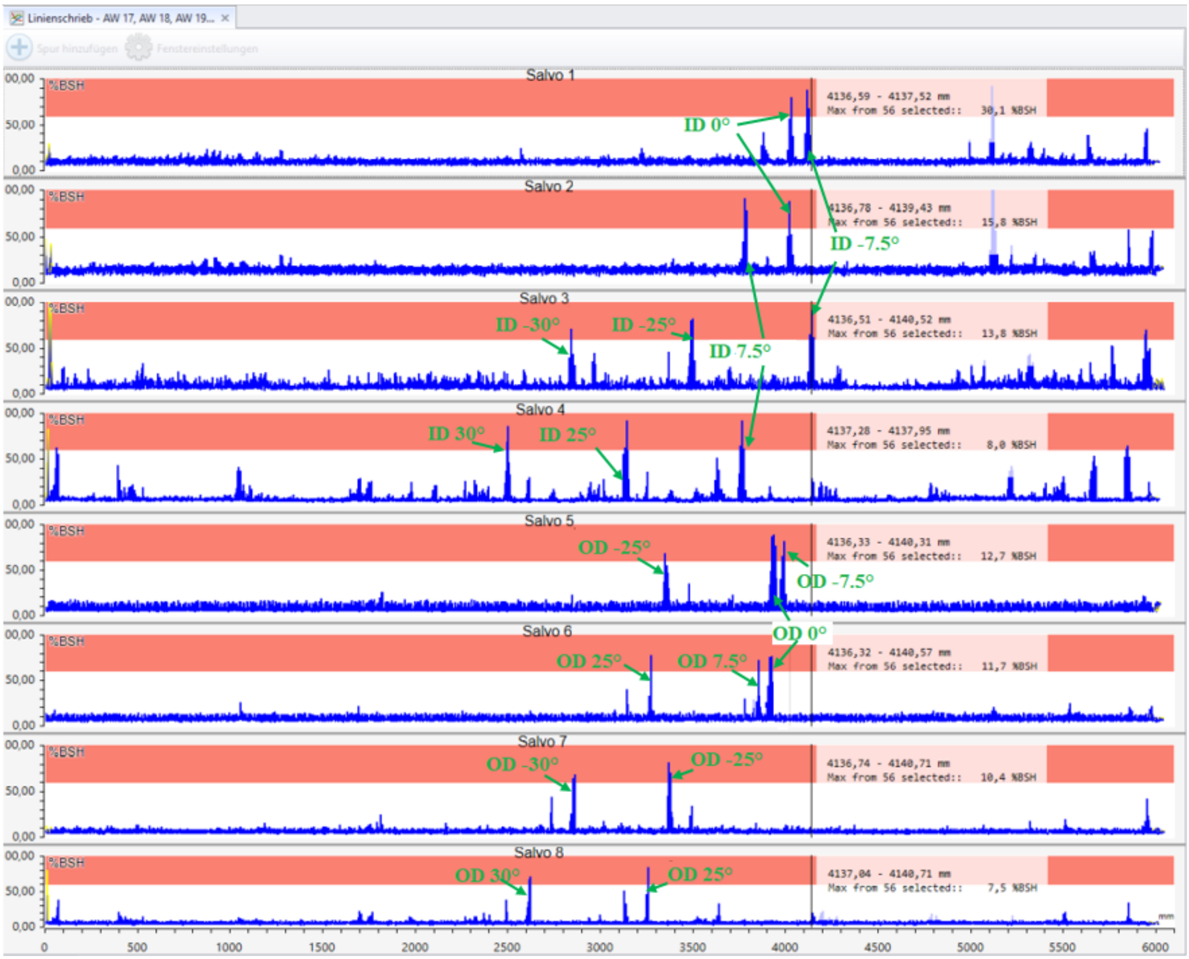


Fig. 13 Example of ±30° flaw detection (probe cluster 1) in heavy-walled reference tube

On heavy-walled tubes, separated OD / ID shots and mode-converted waves are used when convenient, as indicated by standards (for longitudinal defects [10]). The implementation is challenging, since compression sound waves are also introduced into the material and, as a result, multiple indications of the same defect with different sound paths are obtained.

Appropriate simulations to determine the suitable transmission and reception angles, optimized gate setting based on application tests and the powerful ECHOGRAPH-PAUT electronics finally made possible to perform ±75° range oblique defects testing on heavy-walled seamless tubes.

3.6.5 Improved Transverse Defects Testing

F or transverse testing the phased array probe faces the tube axis (no mechanical tilt angle). Electronic beam steering is used to get the optimum reflection from OD and OD transverse notches. Mirrored angles (refer to Fig. 14 a) are used for testing both in forward and backward direction (both sides of the transverse defects).

The UT beam profile is crucial for transverse defect testing, the reasons being the narrow angle of to the inspection helix (<19° average for the diameter range) resulting in a negligible probe axial displacement when passing over the defect. As a consequence of this negligible axial advancement, the dynamic repeatability for transverse notches is directly affected by the UT beam profile along the probe.

Typically, a large number of virtual probes are required to obtain sufficient overlap (repeatability) and to maximize the scan track width. Fig. 14 b) shows an example of the probe scan in axial direction indicating the overlap between the sound beams of the virtual probes for an OD transverse notch.

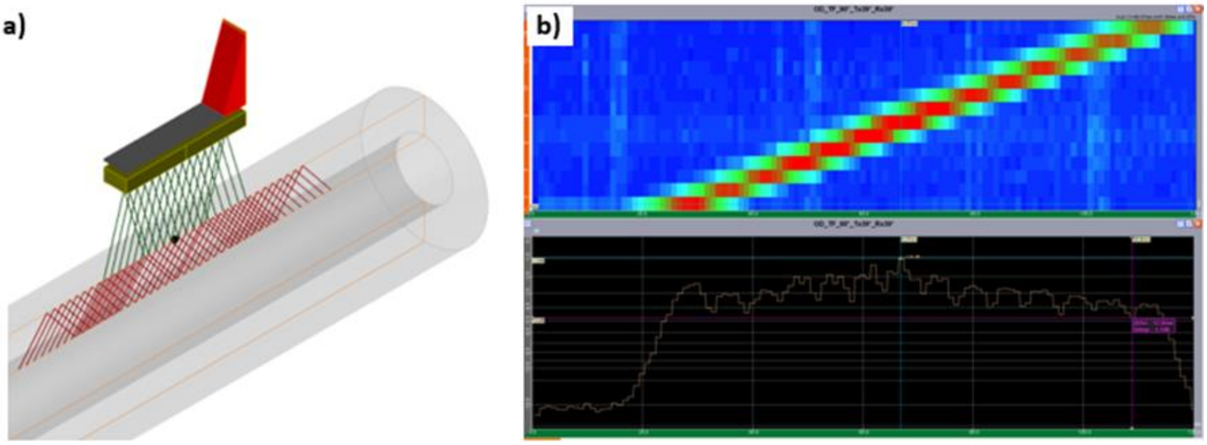


Fig. 14 Transverse flaw detection with Phased Array a) Electronic steering in forward and backward direction using 14 shots each b) Example for UT beam profile along the probe (electronic scan direction) for the OD transverse notch

However, a large number of sequenced virtual probes either compromises the productivity or requires a higher PRF which may lead to a poor signal to noise ratio.

The ECHOGRAPH-PAUT electronics can fire multiple virtual probes in parallel, what reduces the PRF required to fulfil the same productivity requirements. Fig. 15 shows an example of the signal to noise ratio reduction when using 2 virtual probes firing in parallel. On the example, the PRF could be reduced by 32% while keeping the same rotation speed.

Despite the full parallel capacity of the electronics, it is not as easy to fire more than 2 virtual probes in parallel due to ultrasonic crosstalk. However, this configuration allows us to reach an adequate circumferential pulse density at high speed and particularly, good overlap, which is relevant for transverse flaw testing.

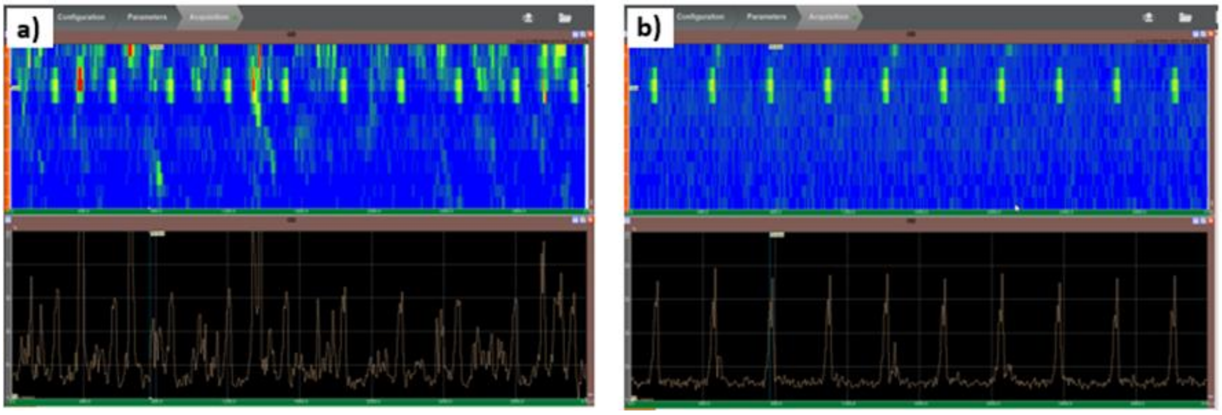


Fig. 15 Signal to noise ratio during radial tube rotation at 1.5m/s on OD transverse notch position (10 rotations) with PRF set for a) simple sequential probe firing and b) firing sequence with 2 virtual probes in parallel

3.6.6 Wall Thickness Measurement and Laminar-type Defect Detection

ECHOGRAPH Electronics high parallel processing capacity can be harnessed for a narrow pulse RPD and APD.

From a single shot, different reconstructions optimized to measure the tube wall thickness and to detect FBHs are applied.

As a consequence of the small area, high sensibility virtual probes are needed for small laminar-like defects. On the other hand, The UT beam coverage is crucial for a good dynamic repeatability. As a consequence, a large number of virtual probes are required to obtain sufficient overlap (RPD and APD) and to maximize the scan track width.

3.7 ECHOVIEW Functions for RPTR-PAUT

3.7.1 Probe Sensitivity Adjustment

The function is used to adjust the sensitivity of each virtual probe with the corresponding reference defect.

A Wizard menu supports the operator in the assignment of the various reference defects in the reference tube to the reconstructions of the corresponding test functions (LO, OF, WT, LAM) and automatically calculates the optimal adjustment sequence.

Following this configuration, each cluster is automatically moved along the corresponding reference defect selected for adjustment, completing high-resolution scans around each one.

The sensitivity adjustment is based on the amplitude of the reflected echoes. To cope with the reference defects and UT beam inhomogeneities and ensure a repeatably and convergent adjustment process, the test distance in the axial and circumferential directions on the tube surface must be significantly smaller than the reference defect length and the aperture effective width. A grid of 1x1 mm is normally sufficient for any test function.

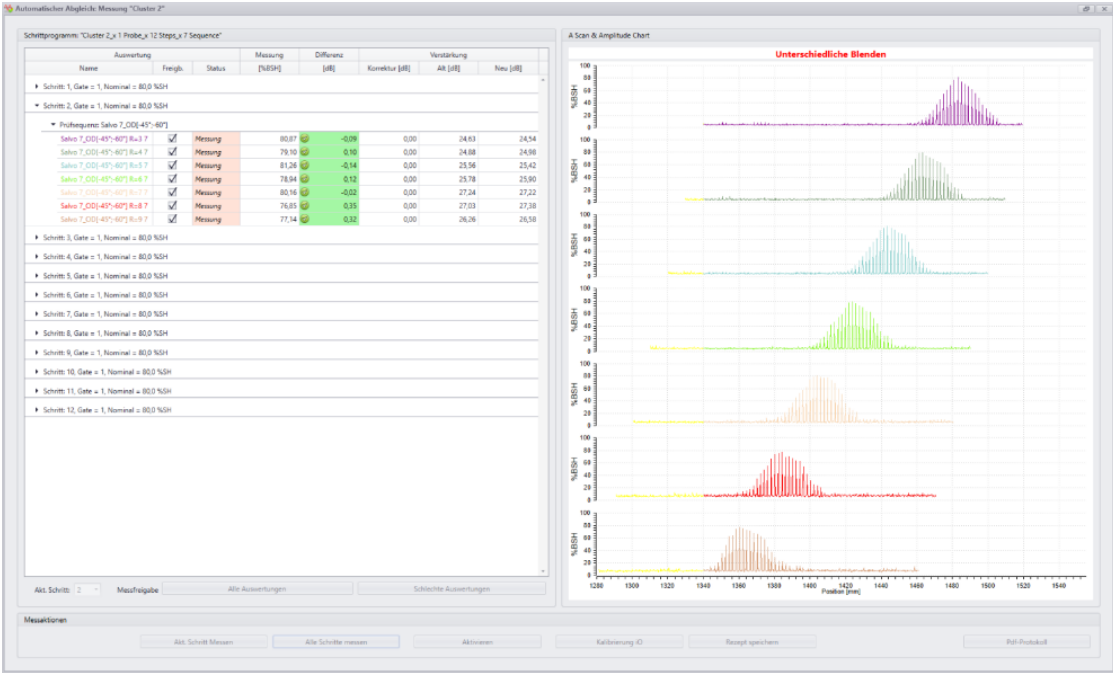
ECHOVIEW automatically determines the sensitivity differences to the target and adapts the gains accordingly. For each test point the echo amplitude is evaluated. The maximum for each aperture is compared with the target value and the difference is applied as gain correction.

Usually, only a few reference defects with an angle in the oblique range of the cluster are available. The inclusion on the of a reference tube of one defect per reconstruction angle would be unrealistic and worthless considering the whole impact on costs and setup time. The reconstruction angles not having a corresponding reference defects are adjusted by means of an interpolation function.

The adjustment results are displayed online (see Fig. 16).

The resulting adjustment setup is finally stored in the data base and can be reloaded on the next instance of the same tube order for a quick machine configuration.

According to the quality procedures from the customers the adjustment shall be periodically checked with the reference tube in dynamic mode (production standard speed) every 4 hours which will be automatically indicated by the software. In case any reference defect is not detected during the dynamic test runs, the corresponding probe sensitivity adjustment has to be re-checked.



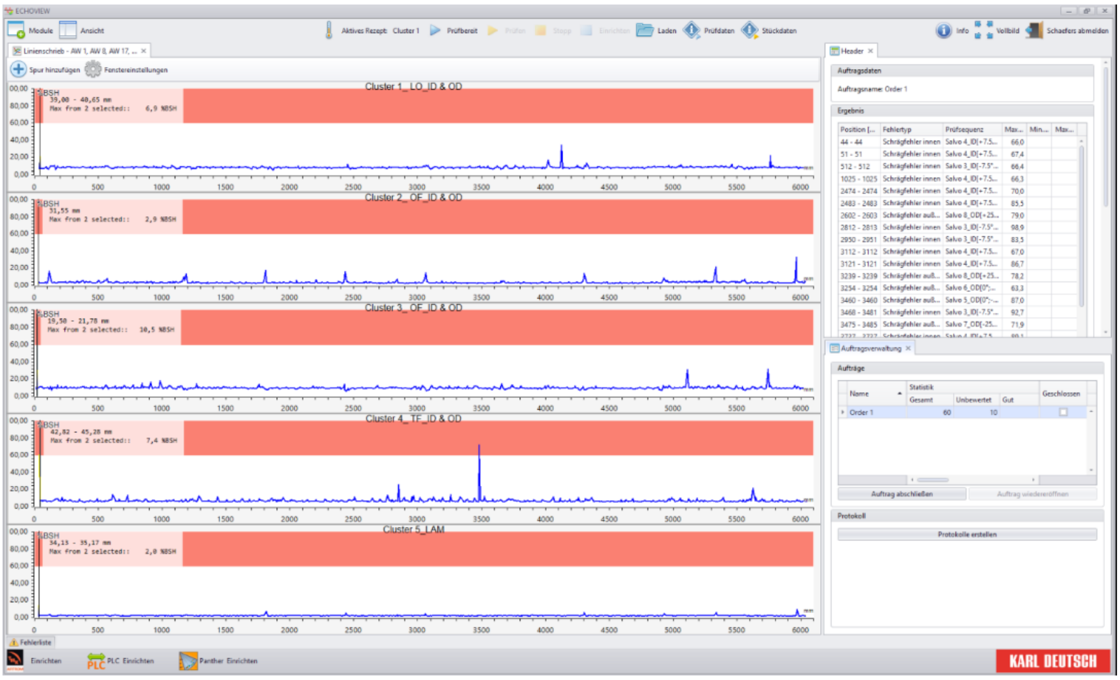
Schrittprogramm: "Cluster 2_x 1 Probe_x 12 Steps_x 7 Sequence"

Auswertung			Messung	Differenz	Verstärkung		
Name	Freigb.	Status	[%BSH]	[dB]	Korrektur [dB]	Alt [dB]	Neu [dB]
Schritt: 1, Gate = 1, Nominal = 80,0 %SH							
Schritt: 2, Gate = 1, Nominal = 80,0 %SH							
Prüfsequenz: Salvo 7_OD[-45°;-60°]							
Salvo 7_OD[-45°;-60°] R=3 7	☑	Messung	80,87	-0,09	0,00	24,63	24,54
Salvo 7_OD[-45°;-60°] R=4 7	☑	Messung	79,10	0,10	0,00	24,88	24,98
Salvo 7_OD[-45°;-60°] R=5 7	☑	Messung	81,26	-0,14	0,00	25,56	25,42
Salvo 7_OD[-45°;-60°] R=6 7	☑	Messung	78,94	0,12	0,00	25,78	25,90
Salvo 7_OD[-45°;-60°] R=7 7	☑	Messung	80,16	-0,02	0,00	27,24	27,22
Salvo 7_OD[-45°;-60°] R=8 7	☑	Messung	76,85	0,35	0,00	27,03	27,38
Salvo 7_OD[-45°;-60°] R=9 7	☑	Messung	77,14	0,32	0,00	26,26	26,58
Schritt: 3, Gate = 1, Nominal = 80,0 %SH							
Schritt: 4, Gate = 1, Nominal = 80,0 %SH							
Schritt: 5, Gate = 1, Nominal = 80,0 %SH							
Schritt: 6, Gate = 1, Nominal = 80,0 %SH							
Schritt: 7, Gate = 1, Nominal = 80,0 %SH							
Schritt: 8, Gate = 1, Nominal = 80,0 %SH							
Schritt: 9, Gate = 1, Nominal = 80,0 %SH							
Schritt: 10, Gate = 1, Nominal = 80,0 %SH							
Schritt: 11, Gate = 1, Nominal = 80,0 %SH							
Schritt: 12, Gate = 1, Nominal = 80,0 %SH							

Fig 16 Adjustment menu in the ECHOVIEW software showing the gain correction screen (actual gain values vs. target values) on the left side and real-time display of the amplitudes of the activated reconstructions on the right side.

3.7.2 ECHOVIEW Test Results Representation

The test results are represented in a configurable strip chart screen, displaying the events and amplitudes over the tested length. Fig. 17 shows a typical template, displaying two amplitude strip charts per cluster (ID and OD defect testing). The strip chart is generated in real-time during the testing such that the operator can constantly monitor the status of the inspection. In addition, the statistics of the batch and a defect table are displayed.



Auftragsdaten

Auftragsname: Order 1

Ergebnis

Position [...	Fehlertyp	Prüfsequenz	Max...	Min...	Max...
44 - 44	Schrägfehler innen	Salvo 4_ID[+7.5...	66,0		
51 - 51	Schrägfehler innen	Salvo 4_ID[+7.5...	67,4		
512 - 512	Schrägfehler innen	Salvo 3_ID[-7.5°...	66,4		
1025 - 1025	Schrägfehler innen	Salvo 4_ID[+7.5...	66,3		
2474 - 2474	Schrägfehler innen	Salvo 4_ID[+7.5...	70,0		
2483 - 2483	Schrägfehler innen	Salvo 4_ID[+7.5...	85,5		
2602 - 2603	Schrägfehler auß...	Salvo 8_OD[+25...	79,0		
2812 - 2813	Schrägfehler innen	Salvo 3_ID[-7.5°...	98,9		
2950 - 2951	Schrägfehler innen	Salvo 3_ID[-7.5°...	83,5		
3112 - 3112	Schrägfehler innen	Salvo 4_ID[+7.5...	67,0		
3121 - 3121	Schrägfehler innen	Salvo 4_ID[+7.5...	86,7		
3239 - 3239	Schrägfehler auß...	Salvo 8_OD[+25...	78,2		
3254 - 3254	Schrägfehler auß...	Salvo 6_OD[0°;...	63,3		
3460 - 3460	Schrägfehler auß...	Salvo 5_OD[0°;-...	87,0		
3468 - 3481	Schrägfehler innen	Salvo 3_ID[-7.5°...	92,7		
3475 - 3485	Schrägfehler auß...	Salvo 7_OD[-25...	71,9		

Aufträge

Name	Statistik			Geschlossen
	Gesamt	Unbewertet	Gut	
Order 1	60	10		☐

Fig 17. Example of strip chart representation in ECHOVIEW

Conclusions

The extension of the Linear Phased Array technique for the detection of defects skewed up to ± 75 ° on normal and heavy-walled tubes was presented.
In the case of heavy-walled tubes, the optimization of the angle of incidence and sometimes the use of mode-converted waves for the reliable detection of internal and external defects is essential. The best possible ultrasound configuration, the respective highly sensitive phased array probes and new probe clusters for fast coupling via an acoustically transparent membrane were developed by KARL DEUTSCH.
The probe cluster for transverse defects and for wall thickness measurement and lamination-like defects testing has also been newly developed.
Excellent test results with high sensitivity and signal-to-noise ratio and high throughput were achieved.
Several full parallel ECHOGRAPH-PAUT electronic modules with a total of around 1000 test channels are used to implement around 10000 test functions.
A high-speed test with parallel shot sequences and multiple parallel reconstructions in reception are important features.
Therefore, high test sensitivity, repeatability and productivity can be guaranteed for the entire new production matrix at TMK-ARTROM. The testing machine will go into operation in the first half of 2022.

Fig 18 ECHOGRAPH-RPTS PAUT System during commissioning at TMK-ARTROM workshop in Slatina, Romania.

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