Flaw Detection and Characterization Using Ultrasound

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Abstract

Results of the ultrasonic inspection of tubes sometimes are not satisfactory due to inability to characterize a flaw (i.e. determine its type, shape, orientation and dimensions). It is therefore worthwhile to develop some special simple approaches, which could significantly improve inspection capabilities. Such approaches include new techniques and novel ultrasonic transducers (e.g. a large normal beam probe, a few transducers working simultaneously in parallel and “looking” at the flaw from a variety of angles and directions, non-rotating probes, “tangential beam” technique, collimating probes, guided wave technique, and non-contact laser-UT technique) and also modification of the existing software for data analysis. As a result, it is possible to improve various inspection capabilities, identify flaw type, “reproduce” its shape and orientation, characterize flaw, determine its main parameters, and size it.

Keywords: ultrasonic inspection, novel techniques and probes, improved flaw characterization and sizing.

1. INTRODUCTION

Ultrasonic (UT) methods, currently used for tube inspection, are not always adequate for flaw characterization. Utilities occasionally experience problems trying to characterize a flaw (particularly, crack or an off-axis flaw) and define its shape, orientation, and size. Typically, the Normal Beam (NB) longitudinal waves and angle shear waves employing the Pulse-Echo (PE) and Pitch-Catch (PC) techniques are used for tube testing to detect, characterize, and size flaws located within the tube wall, on the Inside Diameter (ID) or on the Outside Diameter (OD) [1]. (Terms ID and OD are also used in context of the inside and outside surfaces, respectively). Modified or newly-developed inspection techniques, UT probes, and software should be employed to improve flaw identification and characterization, increase sensitivity and accuracy of measurements, decrease analysis time, improve efficiency of analysis, and decrease number of required replicas [2-9].

2. EQUIPMENT AND SPECIMENS

A computerized scanning rig with a calibrated UT system was employed for experiments. The UT system includes the Winspect™ data acquisition software, a SONIX STR-8100 digitizer card, and a UTEX UT-340 pulser-receiver. Standard techniques and probes [1] and novel techniques and probes [2-9] with different center frequencies, various aperture diameters and different focal lengths were used for testing. The rationale was to determine techniques and probes, which could provide the best and fast flaw characterization and high sizing accuracy. The scanning rig was configured to mount the tube specimen filled with water on the turntable. Transducers were put in the appropriate positions inside the tube. Then 3D B-scans, covering flaws and gating the respective NB, PE and/or PC responses, were performed.

A large number of specimens of different tubes (Pressure Tube (PT), Steam Generator (SG) tube, Feeder Pipe (FP), and Heat Exchange (HX) tube) with various types of flaws were used for testing. These specimens contained pits, cracks, hydrided areas, rectangular and V-notches
(symmetric and asymmetric) with various widths, depths, orientation angles (axial, circumferential and off-axis notches), root angles, inclination angles, and root radii. Rationale was to determine the ability and sensitivity of different techniques and probes to characterize various flaws (particularly cracks and off-axis flaws), to determine their orientations and shapes, to estimate their root radii and inclination angles, and to size these flaws (particularly, the small ones). Special software, presenting 3D (isometric) images of flaws, based on the time-of-flight NB, angle PE, and angle PC 3D B-scans, was developed. The rationale was to produce flaw 3D-images, based on different UT techniques and probes.

3. “QUASI-TOMOGRAPHY” - COMBINED TECHNIQUE

The ability to combine information, obtained by using different UT techniques and probes, and then “reconstruct” the flaw, is the main advantage of the classic tomographic method [2]. During the last thirty years there has been considerable interest in UT computed tomography, because of its significant potential abilities. The X-ray computed tomography (CT), photon emission tomography, positron emission tomography, and magnetic resonance imaging (MRI) tomography are well known techniques, which produce very accurate images of an object’s internal features, as well as information about the object’s geometry and material characterization. At the same time, the most popular X-ray CT and MRI tomography provide only one type of images in the transmitted waves depicting, respectively, either the X-ray absorption index distribution, or proton relaxation time distribution in the object cross-section.

UT tomography is based on the insonification of each area of the test object by acoustic waves, originating from transducers, positioned around the object and able to transmit and receive signals from different directions and at various angles. Every cross-sectional 2D image can be obtained using e.g. the procedure, at which the first transducer transmits a short UT pulse and all other transducers (including the transmitter) receive the reflected and transmitted signals. Then the second transducer begins to transmit the UT pulses, and the procedure described above is repeated. Then the entire process is applied to the third transducer as a transmitter and so on, until each of the transducers had acted as a transmitter. The main advantage of the UT computed tomography is its ability to generate cross-sectional images (tomograms) of internal structure of the test object accurately depicting distributions of four different material parameters in the transmitted and reflected waves: acoustic impedance, UT velocity, material density, and attenuation index, thus providing high resolution 2D and 3D images. This method can be named "multi-parametric UT tomography". It is obvious that technique, which gives images depicting simultaneously distributions of four different physical parameters across a cross-section, has significant advantages in detectability, sensitivity, accuracy, resolution, and reliability, in comparison with method using only one physical parameter, thus significantly increasing the probability of detection and greatly improving characterization and sizing of "abnormal" areas. On the other hand, one should not forget that resolution of the UT tomographic system is always lower than resolution of the X-ray tomograph, because the “ideal theoretical resolution” is about half of the wavelength, and the UT wavelength is always much greater than electromagnetic wavelength in the X-ray range. However, UT tomography is a very complicated and expensive technique, because such approach is based on the sophisticated hardware (mechanical and electronic) and very special software. Therefore, UT tomography is still on the development stage only, and commercial UT tomographs are not available. So, it is worthwhile to try to
develop some special simplified "approximate" tomographic method, i.e. “quasi-tomographic” approach for the tube testing, which will be, on the one hand, rather accurate, and on the other hand, comparatively simple. This method will significantly improve the inspection capability by employing only a few probes, “looking” at the flaw at various angles and from different directions, a few rather simple tomographic techniques, and software combining information obtained from these probes.

Techniques and probes, currently used in the inspection systems for tube testing, allow already “seeing” flaw at various angles and from different directions. Longitudinal and shear waves propagating in the axial and circumferential directions, PE and PC techniques, NB and angle probes are used to detect, characterize and size flaws in tubes. In order to develop a “quasi-tomographic” method, the information, obtained using different techniques and probes, should be combined together. To realize a “quasi-tomographic” technique, one can use a simple method, which just combines information from different transducers [2-3], e.g. by using special software superimposing different responses. The other idea is to connect simultaneously e.g. two angle probes (say, two circumferentially positioned transducers (Clock-Wise (CW) and Counter-Clock-Wise (CCW) shear wave probes) to pulser-receiver working in the PE mode. As a result, both transducers will simultaneously transmit UT signals and both will receive the responses. Each transducer will receive its own signals, reflected from the tube ID and OD, and also signals, transmitted by other probe and reflected from tube surfaces. Subsequently, three techniques will be realized simultaneously: angle CW PE, angle CCW PE, and angle PC. The obtained “combined” image will contain responses typical for these three techniques. In other words, the obtained image will look like three interposed images: CW PE, CCW PE, and PC. This “combined technique” can be realized as 3D or 2D B-scanning at different incident angles and at various probe positions [2-5].

Responses from different probes can be easily distinguished (see Figs. 1-9 below). While the PC response shows depth and width of the notch tip, the lengths and durations of the angle PE responses (CW and CCW) can characterize two inclination angles of the notch and even its root radius, which can be assessed rather accurately, because this technique is based on high axial measurement resolution in the direction of the UT beam trajectory (due to importance, this issue is analyzed separately in Section 13). Typical 2D combined circumferential B-scans of different ID notches with cracks in the PT are presented in Figs. 1-4, which clearly demonstrate that combined technique allows detecting and characterizing even tight and shallow cracks (e.g. delay hydride cracks). Fig. 5 shows combined circumferential B-scan of V-notch in the PT ID. In this combined scan three probes are connected in parallel [2-4] to pulser-receiver working in the PE mode (NB + CW PE + CCW PE + PC). Circumferential 2D combined (CW PE + CCW PE + PC) B-scan of 2.5” diameter FP with axial 1mm deep segment OD notch is presented in Fig. 6. Circumferential 2D combined (Forward (FW) PE + Backward (BW) PE + PC + NB) B-scan of SG calibration tube, containing seven OD circumferential notches 0.1mm wide with different depths, is presented in Fig. 7. Another combined technique (BW PE + “quasi-PC”), used for a small diameter SG tube testing, is presented in Fig. 8 (schematic of this technique) and Fig. 9 (axial combined BW PE + “quasi-PC” 2D B-scan). In this so-called “quasi-PC” technique, one can use one small standard probe working in the PE mode, and attach it to the special two-step acoustic mirror. This mirror allows exciting shear UT wave within the SG tube wall and receiving the UT wave, coming out of the tube wall, by the same probe.
**Figure 1.** Picture of radial-circumferential PT cross-section and circumferential 2D combined (CW + CCW + PC) B-scan of ID rectangular axial notch 2.54mm wide 0.5mm deep in the PT with fatigue crack 0.8mm deep. Probes: focal length FL=40mm, center frequency f=20MHz, aperture diameter D=9.5mm, water-path WP=19mm, and incident angle $\alpha=27^\circ$.

**Figure 2.** Circumferential 2D combined (CW + CCW + PC) B-scans of the ID V-notch (1mm deep and 45° tip angle) in the PT with delay hydride crack 0.5mm deep (left) and without crack (right). Probes: FL=40mm, f=20MHz, D=9.5mm, WP=18mm, $\alpha=27^\circ$. Color scale is in Fig. 1.

**Figure 3.** Circumferential 2D combined (CW + CCW + PC) B-scans of rectangular axial notch (1mm wide and 0.7mm deep) with delay hydride crack 1mm deep (left) and without crack (right). Probes: FL=40mm, f=20MHz, D=9.5mm, WP=18mm, $\alpha=27^\circ$. Color scale is in Fig. 1.
Figure 4. Circumferential 2D combined (CW PE + CCW PE + PC) B-scan of axial rectangular ID notch 0.5mm deep and 2.5mm wide in the PT with fatigue crack ~1mm deep. Probes: FL=40mm, f=15MHz, D=0.5”, WP=18mm, \( \alpha = 27^0 \). Color scale is shown in Fig. 1.

Figure 5. Circumferential 2D combined (NB + CW + CCW + PC) B-scan of 90\(^0/60^0\) ID axial V-notch 0.5mm deep in the PT. CW and CCW probes: FL=40mm, f=15MHz, D=9.5mm, WP=18mm, \( \alpha = 30^0 \). NB probe: FL=100mm, f=15MHz, D=0.5”, FL=4”, WP=20mm. Color scale is shown in Fig. 1.

Figure 6. Circumferential 2D combined (CW + CCW + PC) B-scan of 2.5” diameter FP with calibration axial segment OD notch (1mm deep and 1mm diameter). Probes: f=10MHz, FL=38mm, D=6.35mm, WP=15mm, \( \alpha = 16^0 \). Color scale is shown in Fig. 1.
**Figure 7.** a - small “hybrid” probe with three piezo-elements. b - circumferential 2D combined (FW + BW + PC + NB) B-scan of 7 OD circumferential notches 0.1mm wide with different depths in SG calibration tube (ID=11.4mm, wall thickness 1.24mm). Probes: f=15MHz, FL=6mm, D=2mm, WP=4mm, $\alpha=21^\circ$ for FW and BW angle probes. Color scale is in Fig. 1.

**Figure 8.** “Imagine-3D” beam tracing simulation of combined technique (BW PE + “quasi-PC”), showing acoustic beams transmitted from probe, reflected from the 1$^{st}$ mirror, refracted and reflected within the SG tube wall (ID=11.4mm, wall thickness 1.24mm), reflected from the 2$^{nd}$ mirror, and received by probe.
Figure 9. Axial combined (BW PE + “quasi-PC”) 2D B-scan of seven circumferential OD rectangular notches 0.15mm wide with depths 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, and 0.6mm in SG tube (ID=11.4mm, wall thickness 1.24mm). Probe: f=15MHz, FL=10mm, D=3mm, WP=9mm, $\alpha$=22°. Color scale is shown in Fig. 1

4. NORMAL BEAM TECHNIQUE USING LARGE DIAMETER PROBE AND MULTIPLE REFLECTIONS

The large diameter NB probe works not only as a NB transducer, but also, due to its large diameter, this probe transmits and receives the UT waves at various angles, particularly after multiple reflections from the ID and OD. When UT beam passes many times through the area containing a shallow flaw, then even the very weak changes lead (due to the “accumulation effect” after multiple reflections within the tube wall) to some also weak but already distinguishable features of the received UT response. This effect can be also called the “self-amplification” of a weak feature: it is similar to the constructive interference.

Emphasize that during detection and characterization of shallow flaws, the efficiency of “feature accumulation” effect achieves maximum usually at the 3rd reflection, because of the distortion, shift and inclination of the flaw responses after each reflection. Therefore, the flaw image (i.e. flaw shape, orientation and dimensions), obtained as a result of “feature accumulation” effect after multiple reflections, becomes vague, fuzzy and unclear with composite shape and contour. At the same time, during material characterization, the “feature accumulation” effect achieves maximum efficiency approximately at the 7th reflection, because the UT beam, passing through the area of material with specific physical parameters, “feels” their influence many times. Thus, it works like a constructive interference. For example, if the UT beam passes through the area of material with stress concentration (created e.g. due to fatigue), where speed $C$ of propagation of the UT wave is slightly greater than speed $C$ in a “normal” area, then after each reflection from the tube wall the UT response arrives earlier and earlier in comparison with the response related to the “normal” area. Of course, the concept of multiple reflections and “feature accumulation” is valid not only for a NB probe, but also for any angle probe.

The large diameter transducer can be represented as a number of small probes stuck together. The central part of a large transducer works as a small NB probe, while the peripheral parts of
this transducer work as small angle probes in the PE and/or PC modes of operation [2-5]. That is why transducer with a large diameter can “see” flaw simultaneously at various angles and from different directions [5]. 2D circumferential B-scans, performed, by using a large diameter probe, on a few PT specimens, containing various ID flaws, are presented in Figs. 10-11.

Figure 10. Circumferential 2D NB B-image of axial shallow ID segment notch 0.05mm deep in the PT. Probe: NB, D=9.5mm, FL=50mm, f=15MHz, WP=29mm. Color scale is in Fig. 1.

Figure 11. Circumferential 2D NB B-image of ID axial rectangular notch 0.5mm deep and 2.54mm wide with fatigue crack 0.9mm deep in the PT. Probe: NB, FL=55mm, f=15MHz, D=0.5”, WP=15mm. Color scale is shown in Fig. 1.

2D circumferential B-image of multiple OD reflections, obtained using PT specimen containing area of material with stress concentration (created due to fatigue), is presented in Fig. 12. The stress (fatigue) area (around 0°) can be distinguished, because of the “feature accumulation” effect, after multiple reflections (starting approximately at the 9th OD reflection), as amplitude drops and distortions of the vertical lines slightly convex to the left due to a greater speed of propagation of the UT wave in the stress area (circled in red). Based on the known formulae for elastic parameters and measuring the amplitude decrease from one reflection to the other and time shift between neighboring responses, a few material parameters (acoustic impedance, UT wave longitudinal and shear speeds of propagation, density, various moduli of elasticity, Poisson's ratio, and Lame constants) can be determined for the normal and stressed areas. The obtained values can be used for stress (fatigue) level characterization and in general for material characterization: stiffness, compliance, compressibility, strength, flexibility, and so on.
Figure 12. Circumferential NB PE B-scan of the PT with fatigue (stress) area around 0° (circled in red). Probe: NB, D=9.5mm, FL=50mm, f=15MHz, WP=30mm. Color scale is in Fig. 1.

2D circumferential B-scan, performed on a FP specimen with OD axial 1mm deep segment notch by using a large diameter probe, is shown in Fig. 13.

Figure 13. Circumferential 2D NB B-scan of 2.5” diameter FP with OD axial 1mm deep segment (1mm diameter) notch. Probe: NB, f=10MHz, FL=38mm, D=6.35mm, WP=15mm. Color scale is shown in Fig. 1.

The effect of the “feature accumulation” due to the multiple reflections can be also used to detect a “dry contact” between two metal surfaces, as it was described in [6] for detection of areas with dry contact between PT and calandria tube (CT) (see Fig. 14). Another example is detection of “dry contact” area between PT and spacer (see Fig. 15). After multiple reflections within the PT wall, the area with a dry PT/CT contact in Fig. 14 was detected, because at each reflection from the PT outside surface, a very small portion of UT energy from the impinging longitudinal acoustic wave leaks into the CT due to the dry contact between roughness peaks on the PT and CT surfaces. That is why amplitude of the UT wave, reflected from the area with dry contact, should be slightly lower than amplitudes of the waves, reflected from the “clean” areas. Multiple reflections “amplify” this effect, and that is why the dry PT/CT contact can be detected approximately after twelve reflections, see a small amplitude drop (a few percent of the absolute amplitude) in the central area about 0° on the circumferential 2D B-scan in Fig. 14.
Figure 14. Circumferential NB PE 2D B-scan of the PT/CT area with dry contact. Probe: NB, $f=10\text{MHz}$, $FL=40\text{mm}$, $D=9.5\text{mm}$, $WP=27\text{mm}$. Color scale is shown in Fig. 1.

Figure 15. Axial PE 2D B-scan of the PT with spacer touching the outside surface. Angle cylindrically focused probe ($f=5\text{MHz}$, $D=9.5\text{mm}$, $FL=40\text{mm}$, $WP=18\text{mm}$), $\alpha=21^\circ$. Color scale is shown in Fig. 1.

Fig. 15 clearly demonstrate that garter spring, just touching the PT OD (i.e. without any load) can be detected as an amplitude peak by using angle beam PE UT response from cylindrically focused probe. Large size angle probe provides multiple reflections from area of “dry contact” between PT OD and spacer. Only transducers, “stretched” in the circumferential direction, can detect spacer without load, because these probes receive reflections from contacts between many spacer coils and the PT OD. Standard spherically focused probes cannot detect the contact between only one coil and the PT OD, because such contact provides a very weak UT response.

Also note that indirect UT assessment of spacer wear can be performed based on the direct detection and sizing of the “fretting marks” on the PT OD. It is logical to assume that spacer wear marks are strongly correlated to the PT OD marks, because wear should be mutual on the both friction surfaces: spacer coils and PT OD. Currently used UT techniques and probes (angle probes in the PE mode and/or NB probe 1st, 2nd or multiple OD reflections) can provide a good detectability and measurement accuracy of the PT OD flaws.

The effect of the “feature accumulation” can be also used to detect the PT area with increased hydride content and assess its concentration (i.e. material characterization). Such technique is based on changes in the amplitude and spectrum of the UT pulse, which occur due to scattering on the hydride platelets, when UT pulse passes through the hydrided area, see Figs. 16-18.
It is obvious that response changes, related to the hydride concentration, are weak (see Figs. 16-18). At the same time, signal fluctuations due to various changes in surface roughness and material microstructure (e.g. grain size, material morphology, imperfections, inhomogeneities, etc.) might be significant. This type of noise is inherent to the PT, and can never be completely suppressed. So the challenge is to distinguish a weak signal variation, related to hydride concentration, on the background of fluctuations due to the structure noise. Note that more sensitive and reliable results can be obtained using changes, caused by the hydride platelets scattering in signal spectrum, particularly when resonant scattering occurs. When UT frequency equals to the resonant frequency of hydride platelets (i.e. when the average platelet length equals to the half-wavelength of UT signal), then maximum scattering on the platelets occurs. It leads to the maximum difference between acoustic pulses (amplitude and spectrum) passed through the hydrided and non-hydrided areas. When the UT waves with resonant frequencies of the platelets are scattered on these platelets, then contribution of these frequencies in the spectrum of the received signal is weaker for the hydrided area. Respectively, the obtained spectrum is shifted to the low-frequency area, see example presented in Fig. 19 below.

![Figure 16](image1.png)

**Figure 16.** PC shear wave axial B-scan of the PT sample with 80ppm hydride concentration band (see arrows) located from -40mm to +5mm.

![Figure 17](image2.png)

**Figure 17.** PC shear wave axial B-scan of PT sample with 40ppm hydride concentration band (see arrow) located from -40mm to -10mm. Color scale is shown in Fig. 16.
Figure 18. PC shear wave axial B-scan (signal is rectified) of PT sample with three hydrided bands: 20ppm hydride concentration band located at z<0mm, 60ppm band at 0<z<50mm, 40ppm hydride concentration band at 50<z<100mm, and non-hydrided band at z>100mm. Color scale is shown in Fig. 1.

Figure 19. Spectra of two A-scans derived from NB axial B-scan of PT with 80ppm hydride concentration band. Probe: NB, f=20MHz, D=8mm, flat, WP=20mm. For hydrided area the high-frequency contribution of the 12th shear wave OD reflection within the range 22-32MHz is approximately 3 times smaller than for the non-hydrided area.

Analyzing Figs. 10-15, one can clearly see that it is quite possible to characterize flaw and evaluate flaw dimensions and/or perform material characterization.
5. CHARACTERIZATION AND SIZING OF ANGLE FLAWS

A standard shear wave probe in the PE mode can hardly detect the off-axis (angle) flaws (particularly flaws oriented approximately at $\pm 45^\circ$ to the tube axial axis), because the UT beam after reflections from the bottom and lateral faces of such flaw, propagates at angle and therefore does not return to the probe. Such a flaw can be detected in the NB and PC modes of operation, but only as a shadow in the main NB or PC response, because the UT wave after reflections from the bottom and the lateral faces of the flaw propagates at angle and therefore does not return to the probe. Recall also, that obtained shadow does not allow measuring depth of the flaw. A few novel methods [5], such as technique employing cylindrically focused probe and others allow distinguishing angle orientations of the off-axis flaws and sizing their depths.

As an example, a technique employing cylindrically focused probe, allows distinguishing angle orientations of the off-axis flaws and sizing their depths on a single B-scan, see Fig. 20. Indications in Fig. 20 demonstrate that, unlike the standard NB and PC amplitude shadowing C-scans, which can also represent flaw orientation, this method allows determining simultaneously the flaw angle orientation and also flaw depth on a single 2D circumferential B-scan. This method is very reliable, because it has a few indications correlated to the orientation of a flaw.

Figure 20. Pictures of PT and its replica, and circumferential angle 2D PE B-scan of seven ID off-axis V-notches (7mm long and 0.75mm deep with 45$^\circ$ root angle) oriented at the following angles to the tube axial axis: 90$^\circ$ (circumferential notch), 75$^\circ$, 60$^\circ$, 45$^\circ$, 30$^\circ$, 15$^\circ$, and 0$^\circ$ (axial notch) in the PT ID. Probe: cylindrically focused FL=25mm, f=15MHz, D=9.5mm, WP=27mm, $\alpha=6^\circ$. Color scale is shown in Fig. 1.
6. **TUBE TESTING WITHOUT PROBE ROTATION**

Ability to perform UT inspection of tubes without probe rotation significantly simplifies the delivery system and decreases the inspection time by increasing axial speed of the inspection system. Moreover, rotation always leads to mechanical vibrations, electromagnetic noise from the rotating motor, radial shifts, possible jams, and other problems. Different approaches were analyzed in [7]. As an example, schematics of two techniques, employing the single element (not a phased array!) circular normal beam tube-probe and circular angle cone-probe, both covering simultaneously $360^0$ in the circumferential direction are presented in Figs. 21-22. Picture of the respective probes are shown in Fig. 23.

![Figure 21. Schematics of NB circular tube-probe.](image1)

![Figure 22. Schematics of angle shear wave circular cone-probe.](image2)

![Figure 23. Circular probes covering $360^0$: NB tube-probe (a) and angle cone-probe (b).](image3)
Solutions, similar to ones presented in Figs. 21-22, can be also obtained using standard focused axially-positioned probe with attached conical mirrors, see Figs. 24-26.

Figure 24. Schematic of NB probe, containing axially positioned standard focused transducer with attached 45° conical mirror.

Figure 25. Schematic of angle shear wave probe, containing axially positioned standard transducer with attached 35° conical mirror.

Figure 26. Circular probes covering 360°, containing axially positioned standard focused transducer with attached 45° and 35° conical mirrors to realize NB and angle probe techniques.

2D axial PE NB and PE BW B-scans performed on a HX tube specimen, containing various ID and OD flaws, by using circular tube-probe and cone-probe, are presented in Figs. 27-28.
Figure 27. 2D PE NB axial B-scan of steel HX tube (ID=13.5mm, WT=1.2mm) with six flaws: OD pit (D=1.57mm and d=0.8mm) at axial coordinate z=10mm, similar ID pit at z=20mm, OD axial notch (l=5mm, w=0.36mm and d=0.8mm) at z=30mm, similar ID axial notch at z=40mm, similar OD circumferential notch at z=50mm, and similar OD circumferential notch at z=60mm.

Probe: NB circular tube-probe, flat, f=10MHz, WP=18mm. Color scale is shown in Fig. 1.

Figure 28. 2D PE angle BW axial B-scan of steel HX tube (ID=13.5mm, WT=1.2mm) with six flaws: OD pit (D=1.57mm and d=0.8mm) at z=10mm, similar ID pit at z=20mm, OD axial notch (l=5mm, w=0.36mm and d=0.8mm) at z=30mm, similar ID axial notch at z=40mm, similar OD circumferential notch at z=50mm, and similar OD circumferential notch at z=60mm.

Probe: angle circular cone-probe, flat, f=10MHz, WP=18mm, α=19°. Color scale is in Fig. 1.
2D axial PE NB B-scans and PE BW B-scans performed by using circular tube-probe and cone-probe, on the PT specimen with row of OD pits, are presented in Fig. 29.

![Image of 2D PE axial B-scans](image)

**Figure 29.** 2D PE axial B-scans of PT with angle row of OD pits 0.7mm wide and 0.7mm deep and picture of this PT. Probes: standard axially oriented, positioned concentrically and eccentrically with attached 45° and 35° conical mirrors, f=10MHz, FL=100mm, D=9.5mm. Color scale is shown in Fig. 1.

The circular probes give ability not only to detect various flaws (ID and OD pits, axial and circumferential notches), but they also allow sizing flaws. Figs. 27-29 show that flaw length and position in the axial direction can be easily measured. Flaw depth in the radial direction can be estimated by measuring time-of-flight of the respective response for the NB tube-probe and the response duration for the cone-probe (since duration of the UT response for angle probe always depends on the flaw depth). Flaw width and position in the circumferential direction can be also estimated by using some special techniques described in [7]: e.g. probes positioned eccentrically in relation to the tube, circular equiangular probes creating angle beam in the circumferential direction, and others.

Note that non-rotating technique can be also used as a fast screening detection technique; after which, if necessary, a detailed scanning of areas with detected flaws can be performed by employing standard techniques.

### 7. TANGENTIAL BEAM TECHNIQUE

One of the main problems in the UT inspection of tubes is the depth measurement of shallow flaws. Standard techniques allow measuring depth of flaws which are deeper than ~0.2mm only. Preliminary experiments show that tangential UT beam in the PE mode may give a possibility not only to detect but also measure depth of the very shallow ID and OD flaws: about ~15μm deep. This technique provides good (almost linear) correlation between measurement results
and flaw actual depths. If one excites within tube wall the UT shear wave propagating tangentially to the tube ID, then even a shallow flaw (scratch, pit or crack), located at the ID, would be a good reflector for such UT beam, since this flaw blocks the beam to the maximum extent. Any other technique will give a worse reflection. To create such “tangential” acoustic beam one should use a large angle of incidence for the beam entering the tube. After refraction at the ID, the beam reflects from the OD and propagates almost tangentially to the ID (see Fig. 30). Any shallow flaw even slightly elongated in the radial direction will efficiently reflect the UT beam, since this flaw blocks its way of propagation. Time and angle ranges of the obtained PE response depend on the flaw depth.

![Diagram of acoustic waves](image)

**Figure 30.** Tangential PE UT beam technique.

2D circumferential B-scans, performed by using a tangential beam technique on a few PT specimens containing various ID flaws, are presented below in Figs. 31-32. These scans clearly show that even the very shallow flaws (about 15-50µm) can be reliably detected.

![B-scan image](image)

**Figure 31.** Circumferential 2D CW PE B-scan of four shallow axial ID V-notches (30° tip angle) with depths 0.05mm, 0.1mm, 0.15mm, and 0.2mm in the PT. Probe: f=20MHz, flat, D=8mm, WP=18mm, α=33°. Color scale is shown in Fig. 1.
Note that tangential beam technique also provides a strong interface reflection directly from extremely shallow surface-open flaws (down to ~5μm), if probe incident angle is large enough (about 40°). At the smaller incident angles the interface response amplitude quickly decreases. Recall that UT probes, used in the tangential beam technique for shallow flaws detection and sizing, should have a high center frequency (i.e. small wavelength), because otherwise a shallow flaw will not be detected.

Presented results clearly demonstrate that tangential beam technique allows reliably detecting very shallow flaws by using the interface and corner responses and also measuring depth of the shallow ID flaws down to ~0.015-0.02mm deep by using duration and/or length of the corner responses. Flaws about ~15μm deep can be detected and sized at the limit of sensitivity, while flaws about ~10μm deep cannot be detected by using the corner responses.

8. 3D-VISUALIZATION OF NB, CW, CCW, AND PC 3D B-SCANS

Using different 3D time-of-flight B-scans, the orientation, shape, and dimensions of flaws can be determined. Special software, that can automatically measure parameters of various responses and generate 3D image of the flaw, was developed. Obtained 3D images provide convenient and reliable information concerning flaw identification, characterization and sizing. Typical 3D time-of-flight images of various flaws are presented in Figs. 33-37 below.

Images in Figs. 33-37 demonstrate that software used for data processing can definitely lead to a decrease in the number of required replicas, which should be taken and analyzed to determine flaw shape, orientation, and dimensions. This provides savings in terms of valuable outage time and worker dose uptake. This software also provides convenient and reliable information on flaw orientation, geometry, and dimensions. It will lead to simplification, improved efficiency, reliability and decreased time of data analysis. Using this software, the old stored inspection data can be revisited, re-analysed and compared with the most recent inspection data. All these advantages will allow developing more accurate and reliable procedures, instructions and guidelines concerning flaw identification, characterization and sizing.
**Figure 33.** Time-of-flight 3D image derived of 3D NB PE B-scan of axial rectangular ID notch (25mm long, 2.5mm wide and 0.5mm deep) in the PT with two fatigue cracks ~1.7mm deep. Probe: NB, D=9.5mm, FL=45mm, f=15MHz, WP=12mm. Scale 5:1 in the depth direction.

**Figure 34.** Time-of-flight 3D image derived of NB PE 3D B-scan of two-step axial ID rectangular notch (primary notch 0.15mm deep, 2.5mm wide, and 25mm long; secondary notch 0.076mm deep, 0.15mm wide, and 3mm long in the centre of primary notch) in the PT. Probe: NB, FL=10mm, f=20MHz, D=6.35mm, WP=10mm. Scale 10:1 in depth direction.

**Figure 35.** Optical image of replica of the ID flaw (~5.5mm long, ~2.5mm wide with maximum depth ~0.083mm) in the PT and time-of-flight 3D image derived of 3D NB PE B-scan of flaw. Probe: NB, D=6.35mm, f=20MHz, FL=10mm, WP=10mm. Scale 10:1 in the depth direction.
Figure 36. Time-of-flight 3D image derived of CW, CCW and CPC fused scans of ID axial V-notch (0.3mm deep with 60° root angle and root radius 100μm). Probes: CW and CCW, FL=33mm, f=10MHz, D=9.5mm, WP=20.6mm, α=25°. Scale 10:1 in depth direction.

Note that moving 3D-cursor in Fig. 36 to any point, the following flaw parameters at this point can be assessed: depth (circled in green at the bottom of the image), root radius (circled in red), and flaw side inclination angle (circled in blue). Recall that flaw root radius is a very important flaw parameter for risk assessment, because this radius determines the degree of the stress concentration and, respectively, the probability of crack growth.

Figure 37. Optical image of replica of a few very shallow debris frets from reactor fuel channel (~3.9mm long, ~3.4° wide with maximum depths ~0.11-0.13mm) and time-of-flight 3D image derived of 3D NB PE B-scan of these flaws. Probe: NB, D=6.35mm, f=20MHz, FL=10mm, WP=10mm. Scale 10:1 in the depth direction.
9. PROBE OFFSET INFLUENCE

Due to the PT deformations the positions of all UT probes tend to change and deviate from the nominal values. The total deformation (due to the irradiation, temperature and aging effects) consists of a few components: PT axial elongation, diametrical expansion, wall thinning, tube sag, and also off-centering of the Rotating Probe Module. All these factors lead to the variations in the probe water-paths. This, in turn, entails changes in the UT beam trajectory, reflection and refraction angles, focusing, and UT pulse time-of-flight. All these changes affect performance of the UT probes and ability of the inspection system to detect, characterize and size flaws. Therefore, these factors affect flaw probability of detection and sizing accuracy. To meet the inspection requirements, all UT probes should perform at various offsets. The ranges of offsets of the each probe were calculated [8] based on the effect of the each deformation component, code requirements, inspection specifications, and current procedures and practices for flaw detection and sizing. The obtained results allowed determining the ranges of offsets, within which each probe could meet the requirements. It turned out [8] that both pairs of shear wave probes (axial and circumferential) in the PC modes of operation and 20MHz NB probe do not meet the requirements approximately within the half of the required range of offsets. In addition, their sensitivity is extremely non-uniform within the required range of offsets.

For example, the 20MHz NB probe does not meet the requirements on resolution, sensitivity, and sizing accuracy within the offset ranges from -3 mm to -2 mm and from +3 mm to +8 mm (see Fig. 3). The whole required offset range for this probe lies from -3 mm to +8 mm at the end of PT life - 30 years. One can see in Fig. 38a that at zero offset the flaw can be reliably detected and accurately sized, while at the offsets equal to -2 mm and +3 mm, flaw is detected at the limit of sensitivity (Figs. 38b-38c) and its dimensions cannot be measured. If offset is <-2mm or >+3mm, flaw cannot be detected at all.

Figure 38. 2D NB PE B-scans at the middle of the notch derived from 3D NB PE B-scans of the ID axial calibration notch 6.35mm long, 0.15mm wide and 0.15mm deep. Probe: NB, f=20MHz, D=6.35mm, FL=10mm. a - offset is 0mm, b - offset is -2mm, c - offset is +3mm. Color scale is shown in Fig. 1.

In addition, sensitivity of this probe is non-uniform and highly variable within the required range of offsets: the response amplitudes vary about ~30 dB, within the specified range of the offsets (see Fig. 39).
Based on the obtained results, the modification of both pairs of existing PC probes and 20MHz NB probe should be performed in order to meet the requirements and obtain uniform sensitivity within the required range of offsets. This modification can be based on usage of the novel probes with “logarithmic” acoustic lenses providing stretched focal zones and uniform sensitivity [9]. Such probes meet the requirements within the whole required range of offsets.

Any standard spherically focused probe provides a good frontal resolution in the focal point, which leads to high sensitivity and accuracy of measurement only in one narrow area in the axial direction – in the focal spot. However, before and after focal point the frontal resolution of a standard spherically focused probe quickly deteriorates, which leads to the low sensitivity and poor accuracy of measurement outside the focal area.

Probably, the best solution of this problem is to use probe with a stretched focal zone, which can provide good frontal resolution, high sensitivity and good accuracy of measurement within the whole required range. Such probe contains special “logarithmic” acoustic lens and forms narrow weakly diverging UT beam, i.e. this probe has a stretched focal zone. The concept of the “logarithmic” acoustic lens is presented below in Fig. 40. Such a lens forms a narrow weakly diverging acoustic beam throughout the required axial range. The central part of the lens focuses the UT waves close to the transducer (see blue rays in Fig. 40), while the peripheral parts of the lens focus the UT waves far from the transducer (see red rays in Fig. 40), and the medium parts of the lens focus the UT waves in the middle of the focal zone (see green rays in Fig. 40). In other words, a logarithmic lens is a focusing acoustic lens with a varying focal length: small for the central part of the lens and large for the peripheral parts of the lens. As result, the acoustic field created by such transducer has a stretched focal zone, where the UT beam is narrow and collimated. Such probe creates needle-like narrow and weakly diverging acoustic beam. Picture of the UT transducers with different diameters, various center frequencies, and different logarithmic acoustic lenses (spherical and cylindrical), i.e. focusing the UT beams within different required axial ranges, are shown in Fig. 41 below. Such probes are very useful when flaw position is unknown or variable.
Figure 40. Schematic of the acoustic field and measured acoustic field formed by the probe with “logarithmic” acoustic lens. Color scale is shown in Fig. 1.

Figure 41. UT transducers with different diameters, various center frequencies, and different logarithmic acoustic lenses (spherical and cylindrical), i.e. and focusing the UT beams within different required axial ranges.

10. GUIDED WAVE TECHNIQUE

UT guided wave (GW) method can be a reliable and rapid technique for assessing the condition of tubes by detecting various flaws. The idea of the UT detection of flaws located far from a transducer is based on the excitation of the traveling acoustic GW, propagating along the tube in the axial or circumferential direction. The term “guided” is used, because the UT wave travels along the tube guided by its geometric boundaries. Different types of the UT waves can be used
for inspection: longitudinal, shear, surface, torsional, and Lamb waves. Each of these waves has its advantages and limitations. Signals reflected from geometric irregularities, material imperfections and/or defects are detected in the PE mode. As a result, the location of the defect and sometimes its size can be determined. Because of the long-inspection range, the GW inspection technology is useful for quickly surveying a structure for defects, including areas that are difficult to access directly. Typically, the sensitivity of GW technique is lower than sensitivity of standard UT methods.

Fig. 42 shows beam-tracing simulations for surface and shear/longitudinal waves, respectively, propagating along the tube length.

Circumferential PE B-scans using surface waves, propagating in the axial direction, have been performed to detect circumferential ID notches (Fig. 43) using contact non-focused angle probe (f=2.5MHz and D=12.5mm) with prism fitting the ID of a large diameter tube.

Figure 42. Beam tracing simulations of surface axial wave, propagating tangentially to tube surface (a), and of shear/longitudinal wave propagating within the tube wall (b).

Figure 43. PE circumferential B-scan. Tube ID=18” and WT=10mm with ID circumferential notch 0.15mm wide and 0.3mm deep. Probe: contact angle surface wave containing plexiglass prism with curved surface fitting the tube ID, f=2.5MHz, D=12.5mm, flat, α=60°. Distance between probe and notch is ~800mm. Color scale is shown in Fig. 1.
The GW technique, using acoustic wave propagating around the tube in the circumferential direction, does not need a rotation of the probe. In Fig. 44 the beam-tracing simulations of surface and shear waves, excited within the tube wall and propagating around the tube in the circumferential direction are shown.

A few Axial PE B-scans, detecting axial ID notches and based on the technique shown in Fig. 44 and presented below in Figs. 45-47, show how large diameter tube (ID=18”, WT=10mm) can be inspected from the ID by using the GW technique employing surface wave propagating within ~1m long inspection range in the circumferential direction. The angle probe, transmitting this surface wave, should be moved only axially; and at the same time it will inspect the whole surface of the tube. Time-of-flight of the received signal reflected from the ID axial flaw depends on the distance between probe and flaw in the circumferential direction. That is how circumferential position of the flaw can be measured.

**Figure 44.** Beam tracing simulation of surface wave propagating tangentially to the tube ID surface in the circumferential direction (a) and of shear wave propagating within the tube wall in circumferential direction (b).

**Figure 45.** PE axial B-scan. Tube ID=18” and WT=10mm with ID axial notch 0.15mm wide and 0.1mm deep. Probe: contact angle surface wave with prism fitting the tube ID, f=2.5MHz, D=12.5mm, flat, α=60°, surface wave refraction angle β=90°. Circumferential distance between probe and notch is ~180° (i.e. ~720mm). Color scale is shown in Fig. 1.
Figure 46. PE axial B-scan. Tube ID=18" and WT=10mm with ID axial notch 0.15mm wide and 0.3mm deep. Probe: contact angle surface wave with prism fitting the tube ID, $f=2.5\text{MHz}$, $D=12.5\text{mm}$, flat, $\alpha=60^\circ$, $\beta=90^\circ$. Distance between probe and notch $\sim180^\circ$ (i.e. $\sim720\text{mm}$). Color scale is shown in Fig. 1.

Figure 47. PE axial B-scan. Tube ID=18" and WT=10mm with one circumferential ID notch 0.15mm wide and 0.5mm deep and two axial ID notches 0.15mm wide and 0.5mm & 1mm deep located $\sim180^\circ$ (i.e. $\sim720\text{mm}$) apart. Probe: contact angle surface wave with prism fitting the tube ID, $f=2.5\text{MHz}$, flat, $D=12.5\text{mm}$, $\alpha=60^\circ$, $\beta=90^\circ$. Distance between probe and first 0.5mm deep axial notch is $\sim90^\circ$ (i.e. $\sim360\text{mm}$), distance between probe and 0.5mm deep circumferential notch is $\sim180^\circ$ (i.e. $\sim720\text{mm}$), distance between probe and 1mm deep axial notch is $\sim340^\circ$ (i.e. $\sim1360\text{mm}$), and distance between probe and axial welded joint is $\sim360^\circ$ (i.e. $\sim1440\text{mm}$). Color scale is shown in Fig. 1.
Images presented in Figs. 44-46 show that GW technique employing surface waves is promising. It allows detecting shallow (from 1% to 10% wall thickness) axial ID notches located at the large distances from the probe. Moreover, this technique can also detect circumferential ID notches using reflections from edges. However, this method cannot be used for OD flaws and flaw depth measurement, because surface wave propagates only along the ID surface. To detect the OD flaws and measure flaw depth, the shear GW technique employing shear waves (see Fig. 43), can be used. Recall that during field inspection, the GW reflections from elbows, valves and welds can be used as the reference points.

Another group of experiments was performed on a feeder pipe (OD=73mm and WT=5.2mm) ~3m long with two elbows and notch (Fig. 48a). Results are presented in Fig. 48b. They show that it is quite possible to detect signals reflected from both elbows and circumferential OD notch 0.5mm deep, 0.15mm wide and 10mm long.

**Figure 48.** UT GW setup (a) for inspection of a long feeder pipe with two elbows and circumferential OD notch (0.5mm deep, 0.15mm wide and 10mm long) and result of testing (b) - A-scan. Probe: contact angle surface wave with prism, f=2.5MHz, incident angle 90°. Distance between probe and 1st elbow ~1.4m, between probe and 2nd elbow ~2.7m, between probe and notch ~2.8m, and between probe and pipe end ~2.9m.
11. RESONANCE INSPECTION METHOD (RESONANCE SPECTROSCOPY)

Sometimes spectrum of the received UT signal can be very efficient for part inspection. As an example, some results, obtained using the UT contact method (resonance inspection method or acoustic resonance spectroscopy) for porcelain insulated cutouts testing are presented below. Using this technique one can detect the presence of crack and characterize the material property by analysing the acoustic response of the insulator. The idea of the contact resonance inspection method is based on tapping a cutout by impact hammer, “listening” to its vibration response using accelerometer, attached to the cutout, and performing a Fourier analysis of the received signals. The obtained “spectral signature” of a cutout (vibration behaviour) depends on the cutout size, material, internal imperfections (e.g. cracks), and other factors.

Development and testing of methodology of UT resonance technique was performed on the samples of new and used (with and without visible cracks) cutouts made by different manufacturers. Experimental setup consisted of impact hammer, accelerometer, charge amplifier, and real time spectrum analyzer (see Fig. 49). Accelerometer, connected to spectrum analyzer, was attached to the cutout by wax.

![Figure 49. Accelerometer and impact hammer used for cutout testing.](image)

After the impact excitation by impact hammer, the spectrum of the received acoustic signal from accelerometer was watched on the screen of spectrum analyzer connected to computer. The averaging procedure has been used as a statistical signal processing and allowed eliminating the most serious random errors related to the variations in accelerometer installation and impact hammer hitting force.

Typical spectra of the un-cracked and cracked cutouts are presented in Figs. 50-51. The obtained results were consistent and robust, i.e. “spectral signatures” of different cutouts of the same type even at various tapping forces and accelerometer attachments were similar. This
consistency is very important, since it demonstrates that UT resonant method can be practically used for cutouts testing.

![Graph showing amplitude vs frequency for un-cracked and cracked cutouts.](image)

**Figure 50.** Averaged spectrum of the un-cracked cutout. Red curve is the trend-line.

![Graph showing amplitude vs frequency for cutout with large visible crack.](image)

**Figure 51.** Averaged spectrum of cutout with large visible crack. Red curve is the trend-line.

The obtained results (compare Figs. 50 and 51) show that difference between spectra of the un-cracked and cracked cutouts is substantial. Besides the ability to detect cracked cutouts, the developed technique allows distinguishing new and old cutouts and also cutouts made by different manufactures. Moreover, using UT resonance inspection method based on the cutout spectrum analysis, it is possible not only to detect the large existing cracks, but also estimate the cutout condition and predict crack appearance (by detecting the incipient crack).
12. NON-CONTACT LASER-ULTRASONIC TESTING

Sometimes it is necessary to perform inspection of parts without direct mechanical contact between components of the inspection system and part under test. As an example, some results, obtained using laser-ultrasonic (laser-UT) technique and equipment for testing the porcelain insulators located on the high-voltage transmission lines towers, are presented below.

One of the most promising inspection techniques for insulator testing is the UT method (resonance inspection method or acoustic resonance spectroscopy), which can detect the presence of a crack (“puncture”) by analysing the acoustic response of the insulator. This method involves hitting the test object and determining its vibration behaviour in the time domain and/or via a Fourier analysis in the frequency domain. Cracks reveals themselves as a peak-reflection signal in the time domain and as a change in the insulator vibration spectrum in the frequency domain.

Laser induced excitation and optical detection of acoustic waves in materials has been studied for many years. It is a completely non-contact method, and the inspection system can be utilized remote from the work-piece. Non-contact laser-UT inspection method, employing pulse laser excitation and optical interferometer reception, demonstrated sufficient sensitivity to distinguish between insulator samples with and without cracks in the shell. The non-contact excitation can be achieved by heating test object locally using a generation laser: short pulse and high peak power laser. Non-contact measurement (see Fig. 52) is done by using detection laser (long pulse laser with long coherence length) and optical interferometer, which measures spectrum and amplitude of the reflected optical signal.

![Figure 52. Schematic of laser-UT inspection technique.](image-url)
The presence of an internal crack in the insulator affects the characteristics of the acoustic signature of insulator and respectively the parameters of the reflected optical response: phase, amplitude and spectrum. As result, acoustic responses of the cracked and un-cracked insulators to the generation laser pulse excitation are different, and these differences can be reliably detected by detection laser and optical interferometer in time and frequency domains.

The testing has been performed on the cracked and un-cracked insulators model 50-KIP. The cracked samples had one, two and three large visible cracks (about a few centimeters long). The testing system consisted of generation laser - Q-switched Nd:YAG oscillator model CFR200 (Quantel, USA) and optical interferometer (model Quartet, Bossa Nova Technologies, Culver City, CA, USA), see Fig. 53.

![Figure 53. Setup of laser-UT inspection system for insulator testing.](image)

Signals of the cracked insulators in the time domain have peaks (probably, crack reflections) positioned at 50-260μs, which are not present in the responses of the un-cracked insulators (see Fig. 54). Signals of the un-cracked insulators have peaks within the range 270-310μs, which are generated by the acoustic waves travelling around the insulator circumference. These peaks are not seen in the responses of the cracked insulators (see Fig. 54), because in such samples the UT waves cannot go around due to reflections from the cracks.
Figure 54. Time-domain signals of cracked and un-cracked insulators.

Spectra of the cracked insulators are concentrated at low frequencies (below 80kHz) and do not have the high-frequency components (at ~300kHz) and also duplets and triplets, which are typical for spectrum of the un-cracked sample (Fig. 55). Probably, the reason is the excitation of various types of waves and vibrations, which can exist only in an un-cracked insulator, because cracks reflect the waves and therefore block their propagation within the sample.

Figure 55. Spectra of cracked and un-cracked insulators.
Non-contact laser-UT inspection method demonstrated that it had a sufficient sensitivity to distinguish between defective and sound samples and even between insulators containing one, two, and three large visible cracks. Simple criteria of the defectiveness were used to differentiate between sound and defective insulators.

The non-contact examination of insulators was performed at rather small distance between inspection system and insulator: about ~50cm. At the same time, in practice rather large distance is required: about ~30m (this is the distance between truck on the ground and insulator located on the high-voltage tower). There are two options in developing a prototype of the non-contact laser-UT inspection system for practical application. The first option is to develop a system consisting of two parts: small measurement head, which can be positioned close to the insulator, and large processing unit, positioned far away and connected to measurement head by fiber-optic cable. The second option is to develop system, consisting of powerful generation laser, emission optics, reception laser, collection telescope, and other units, located at significant distance from the insulator under test.

13. FLAW ROOT RADIUS ASSESSMENT

Flaw root radius (RR) is a very important parameter for pressure tube risk assessment, because it determines degree of stress concentration and probability of crack growth. Unfortunately, the direct measurement of RR cannot be performed, because of a few reasons:

1. The typical wavelength $\lambda$ of the UT wave, generated by shear wave angle probe with center frequency $f=10$MHz used for PT inspection ($\lambda=c/f=0.235$mm, where $c\approx2.35$mm/µs is the speed of propagation of shear UT wave in ZrNb). Respectively, the resolution which this wave can provide is about $0.5\lambda\approx120$µm. Subsequently, if flaw RR is less than ~0.1mm, then transducer most probably will not “notice” it. It means, the small RR (about 30-50µm) cannot be assessed.

2. The other reason is the diameter of the acoustic beam, which is much larger than the flaw RR. It means that only a small portion of the transmitted UT wave impinges on the flaw root and reflects from it.

3. Even this weak wave, reflected from the small area of the flaw root, which usually has a complex shape, is very diverging. Therefore, only a small fraction of the reflected wave goes back in the direction of probe and impinges on it, while the major portion of the reflected wave misses the transducer.

The most reliable indirect method for RR assessment is probably the combined technique, which employs simultaneously the circumferential PC (CPC) response and both CW and CCW PE responses from left and right sides of the notch (see Section 3). Using it, the time interval $\Delta t$ between center of the CPC notch response and intersection point of the CW/CCW responses can serve as criterion of RR assessment. Fig. 56 shows in the large scale how interval $\Delta t$ between center of the PC response and intersection point of the CW/CCW responses can be measured. Fig. 57 below shows how these time intervals $\Delta t$ are measured for notches with different RR. The physical reason, why interval $\Delta t$ depends on the flaw RR, is related to analysis of the PC, CW and CCW responses based on the physical acoustics approximation. The CPC reflection always comes earlier than PE CW and PE CCW reflections are starting (they start from the root portions of the flaw), because the CPC time-of-flight is smaller than PE time-of-flight from flaw.
root. As result, the cross-over of CW and CCW responses is always positioned later in time than the CPC response. The CW and CCW responses for a flaw with large RR are separated by a wide angle range; therefore the crossover of these responses (in comparison with flaw with the same depth but small RR) is positioned closer to the PC response.

Emphasize that in order to measure time interval $\Delta t$, it is not necessary to use a novel technique – combined CW+CCW+CPC B-scan. The same images, as shown in Figs. 56-57, can be obtained using special software for data fusion and standard CW, CCW and CPC B-scans.

**Figure 56.** Circumferential combined PE CW+PE CCW+CPC B-scans of symmetric axial V-notch (depth $d=0.3\text{mm}$, width 0.5mm, $60^\circ/60^\circ$, RR=$0.1\text{mm}$). Probes: CW+CCW, $f=15\text{MHz}$, FL=39mm, D=9.5mm, WP=20.6mm, $\alpha=25^\circ$. Color scale is shown in Fig. 1.

**Figure 57.** Circumferential combined PE CW+PE CCW+CPC B-scans of symmetric axial V-notches: depth $d=0.3\text{mm}$, width 0.5mm, $60^\circ/60^\circ$, root radii 0.04mm (a), 0.1mm (b), 0.2mm (c), and 0.4mm (d). Probes: CW+CCW, $f=15\text{MHz}$, FL=39mm, D=9.5mm, WP=20.6mm, $\alpha=25^\circ$. Color scale is shown in Fig. 1.
Based on the results, obtained on symmetric, asymmetric and off-axis V-notches with various RR, the correlation between $\Delta t$ and RR for a wide range of RR was generated: see Fig. 58.

**Figure 58.** Correlation between $\Delta t$ and RR.

The proposed combined technique is using the indirect method of RR estimation based on the measurement of time interval $\Delta t$, see Figs. 56-57. The combined uncertainty $\delta t_{\text{comb}}$ of this measurement determines the accuracy of RR assessment. If time difference $\Delta t$ is accurately measured, then flaw RR can be correctly estimated. The combined uncertainty $\delta t_{\text{comb}}$ depends on many parameters (variations in flaw shape and position, temperature changes leading to variations in probe parameters and UT beam trajectory, changes in inspection system parameters, variations in probe parameters and position, human errors, and others), but the major factor, which usually determines the value of this uncertainty, is the measurement resolution $\delta t$ of the UT pulse time-of-flight.

Time measurement resolution $\delta t$ (the smallest measured increment) depends on three major parameters related to each other: probe center frequency $f$, probe bandwidth $BW$, and digitization (sampling) rate. Currently used inspection systems have probes with $f=10\text{MHz}$, $BW=100\%$, and acquisition cards with 125MHz digitization rate. These parameters allow providing time measurement resolution $\delta t=0.008\mu\text{s}$. Used acquisition cards allow, if necessary, increasing the digitization rate up to 500MHz. In addition, the up-sampling procedure can be also employed, which will lead to a further increase of the digitization rate and respectively to a better time measurement resolution $\delta t$. Recall that for this purpose, the digitization (sample) rate should be high enough to reproduce signals digitally.

The upper frequency of shear wave probes with center frequency 10MHz is $\sim20\text{MHz}$ at -20dB level. It means that Nyquist frequency, which should be at least twice greater than the upper frequency, is supposed to be greater than 40MHz for these probes. (The Nyquist frequency, i.e.
the highest frequency that can be accurately represented, is about one-half of the sampling rate). Subsequently, the sampling rate should be at least twice greater than the corresponding Nyquist frequency. Currently used digitization rate is more than sufficient to correctly reproduce the shape of UT responses. As result, the response positions and time interval between responses can be accurately measured. Note that obtained resolution $\delta t = 0.008 \mu s$ can be further improved by using wide-band probes with higher frequency and acquisition card with higher digitization rate, because at these conditions system will be able to transmit and receive short UT pulses without distortions, correctly reproduce them in the digital form, and accurately measure all time intervals.

High resolution in time $\delta t$ can be easily recalculated in the resolution $\delta s$ of spatial measurement $\delta s = c \cdot \delta t = (2.35 \cdot 0.008) / 2 \approx 0.01 \text{mm} = 10 \mu \text{m}$. The obtained result, spatial resolution $\delta s \approx 10 \mu \text{m}$, means that all spatial measurements, including RR estimation, can be performed with high accuracy. It occurs because the proposed method of RR assessment is based on the combined indirect technique, where high measurement resolution, about $10 \mu \text{m}$, is achieved in the direction of the UT beam trajectory. Recall that such high axial resolution of the test system is based on the wide-band high-frequency UT probes and high digitization rate of acquisition card.

However, recall that combined uncertainty $\delta_{\text{comb}}$ is determined not only by the time resolution $\delta t$ (although this is a major component), but also by many other factors mentioned above. That is why the combined uncertainty $\delta_{\text{comb}}$ will be always greater than uncertainty $\delta t$.

14. DATA PROCESSING AND STRUCTURE INTEGRITY ASSESSMENT

Strictly speaking, all obtained data, if possible, should be statistically processed [10]. It means that in order to perform detection, the detection criterion, data probability distribution (e.g. discrete binomial distribution of detection measurements or continuous normal probability density distribution), probability of detection (POD), confidence level, and cumulative POD should be determined. For noise analysis such parameters as the noise probability density distribution and probability of false positive should be defined. The results of measurements, such as sizing criteria, mean values, confidence probabilities, minimum required number of measurements, and standard deviations of samples related to the flaw depth, width and length measurements should be calculated.

If necessary, flaws can be measured using some other independent techniques: mechanical measurements, replication, another NDE technique, or destructive measurements. As result, the true values of flaw dimensions will be defined. Using these true values and mean values obtained during UT examination, the measurement errors will be determined. Based on the obtained results, the UT inspection system should be calibrated using reference samples.

The measurement uncertainties, related to the impacts of various essential parameters affecting the detection, noise, and flaw depth, width and length measurements, should be determined.

Then structure condition assessment should be performed, based on information related to the flaw type, shape, dimensions, position and orientation, and also on estimation of probability of structure failure (tube rupture) and structure integrity evaluation. Flaw growth rate and deterioration rate of the tube should be also determined, in other words, the obtained results
should be correlated to the remaining strength of the test tube and used, in accordance with the appropriate codes and standards, to calculate the remaining life time of the tube. If the UT testing is used for material characterization, then obtained results (size of the detected area with parameters which differ from “normal”, its location, and “severity level” should be correlated to the material rate of deterioration and remaining life time of the structure under test.

15. CONCLUSIONS

1. Sometimes results of the UT inspection of tubes are not satisfactory due to inability to detect and characterize flaw (i.e. determine its type and shape) and size it. To improve the inspection performance, one should apply different methods and probes, which e.g. allow “seeing” flaw at various angles. The information, obtained by using various transducers and methods, should be combined.

2. Data processing and combination of different techniques and probes (combined technique, technique based on the multiple reflections of the large diameter NB probe, technique based on the cylindrically focused probe, tangential beam technique, and others) give a possibility to “reproduce” the flaw, determine its type and position, and rather accurately size the flaw.

3. Modified or novel UT techniques, probes, software, and data analysis procedures (non-rotating probes, GW technique, collimating probes, 3D visualization software package, and others) were developed to improve flaw identification, characterization and sizing.

4. Such novel techniques, probes and software packages lead to more accurate determination of the flaw type, orientation and shape, improved accuracy of flaw sizing and estimation of its root radius, decreased analysis time, and improved efficiency of analysis. All this, in turn, will lead to a decrease in the number of required replicas, and provide savings in terms of valuable outage time and worker dose uptake.

5. Based on the obtained results, the measurement data, if possible, should be statistically processed, and the respective structure condition assessment (calculation of remaining lifetime of the test tube) should be performed.

16. REFERENCES


