ULTRASONIC INSPECTION OF TUBES WITHOUT ROTATION

Alex Karpelson
Kinectrics Inc., Toronto, Ontario, Canada

Abstract

Ability to perform ultrasonic inspection without probe rotation significantly simplifies the delivery system and decreases the inspection time by increasing axial speed of the inspection system. Different approaches are analyzed: normal beam tube-like probe covering simultaneously 360^0, similar angle cone-like probe for circumferential flaw detection, standard axially positioned probe with attached conical mirror, standard shear wave probe positioned circumferentially at large incident angle and covering 360^0 due to multiple reflections within the tube wall, special circular transducer with curved dents covering 360^0 and used for axial flaw detection.

1. Introduction

Ultrasonic (UT) testing of different tubes (pressure tubes, feeder pipes and steam generator tubes) is a commonly used method of inspection. Various techniques and inspection systems are employed for tube examination. However, sometimes there are serious problems with complex delivery system and UT inspection time because of necessity to provide 100% volumetric coverage of the tube by rotating the probe module. Ability to perform the UT inspection without mechanical rotation of probe module will lead to significant simplification of the delivery system and decrease of the inspection time due to increase of the axial speed of the inspection system. Moreover, the necessity of rotation decreases reliability and sensitivity of the inspection system because of mechanical vibrations, radial shifts, possible jams, electromagnetic interference, and so on. Therefore in general, the possibility to get rid of the rotation is extremely attractive, and it will lead to significant financial benefits.

Any potential inspection system without rotation should be compatible with the existing test system, and its performance should not be worse in comparison with standard system.

A few different approaches with access from within the tube were investigated and described below:

1. Circular phased array.
2. Single-element normal beam (NB) tube-probe, covering simultaneously 360^0 and similar cone-like probes oriented at angle as forward-looking (FW) or backward-looking (BW) probes for circumferential flaw detection.
3. The same solutions can be achieved using standard axially positioned probe with attached conical mirror.
4. Special circular clock-wise (CW) or counter-clock-wise (CCW) transducers with curved dents covering 360^0 for axial flaw detection.
5. Non-concentrically axially positioned standard probe with conical mirror.

6. Circumferentially positioned shear wave probe transmitting UT beam at large incident angle; such beam due to multiple reflections will propagate 360^0 within the tube wall in circumferential direction.

2. Circular phased array

One of the most typical solutions is to apply a one-dimensional (1D) circular cylindrical phased array or even two-dimensional (2D) cylindrical matrix array instead of a single transducer (see Fig.1). At the time being some industrial companies develop and manufacture the UT inspection systems with phased arrays for tube testing.

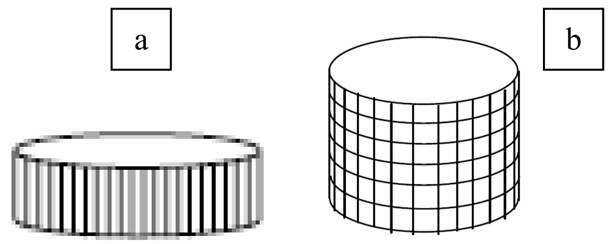

Figure 1. Schematics of 1D circular cylindrical array (a) and 2D cylindrical matrix array (b).

Of course, phased array has significant advantages: electronic focusing; high resolution in circumferential direction; electronic steering of the UT beam; and high electronic scanning speed. On the other hand, e.g. the 1D circular cylindrical phased array for tube inspection has a number of serious disadvantages: high cost; special complex pulser-receiver; difficulty to make 10-15MHz circular phased array with large number of small elements, which could work in radiation field and with long multi-wire cable; large size; inability to inspect small tubes (e.g. steam generator tubes); low resolution in axial direction; need to have specially trained personnel; and others.

3. Tube-probe and cone-probe for circumferential flaw detection

Normal beam (NB) circular probe and angle shear wave circular probe, covering simultaneously 360^0, which can be used for circumferential flaw detection, are shown in Figs. 2 and 3.

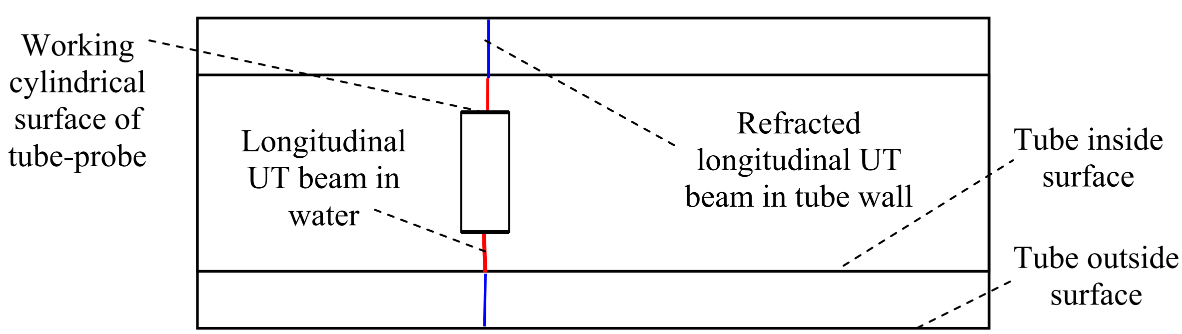

Figure 2. Schematics of NB tube-probe.

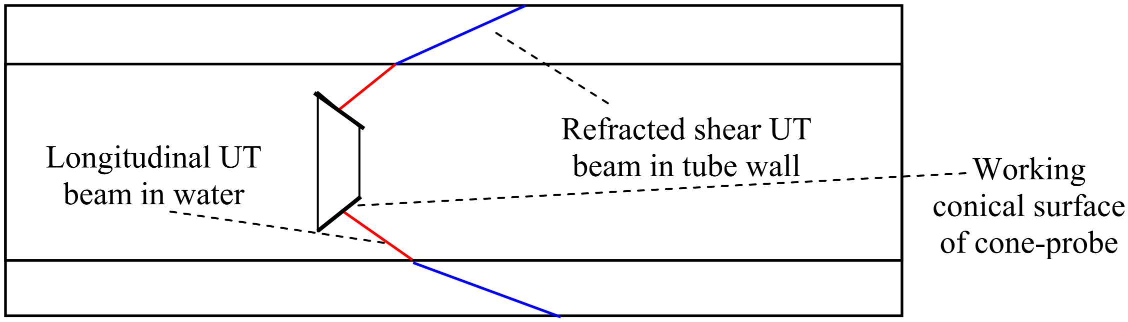

Figure 3. Schematics of angle shear wave cone-probe for circumferential flaw detection.

The UT beam from these circular transducers impinges simultaneously on the whole inner surface of the tube along the circle and covers 360^0. As a result, the whole tube in circumferential direction can be examined simultaneously. The beam reflected from the tube will return to the transducer.

At the first sight, such probes working without mechanical rotation have lower sensitivity, resolution, signal-to-noise ratio, and accuracy of measurement than standard focused transducers routinely used with rotating probe modules for tube inspection. It happens because, unlike standard focused probes, any circular transducer, instead of concentrating acoustic beam in one spot, transmits UT waves in all circumferential directions around 360^0 and then receives all reflected signals simultaneously. As a result, in comparison with signals, transmitted and received by standard probe, the amplitude of the signal, transmitted by circular transducer in any concrete circumferential direction, will be lower; amplitude of the signal, reflected from the flaw and then received by the probe, will be, respectively, much lower; and finally, even this very weak "useful" response, received by transducer, should be detected at the background of strong reflected noise-signals, coming to the probe from all directions.

This reasoning is correct for NB tube-probes in Fig.2. However, fortunately, it is not valid for angle shear wave cone-probes in Fig.3.

Angle cone-robes will probably have pretty good sensitivity, resolution, and signal-to-noise ratio. This assumption is based on the following physical reasoning. In the transmission mode, angle circular transducer radiates the UT waves in all directions around 360^0, but only a small portion of the transmitted acoustic power impinges on the area where flaw is, and then after reflection from the flaw returns back to the transducer. As a result, in the reception mode, only a small part of the transducer surface works: all remaining working surface of the probe is passive, because it receives no signals. Therefore, sensitivity of such transducer is lower in comparison with a standard one, because average acoustic pressure on the probe surface is small. At the same time, there are no reflections from the "clean" part of the tube, which contains no flaws; and subsequently the angle circular transducer receives no other acoustic signals. It means that one can use high gain in order to obtain a large amplitude signal, and signal processing methods (such as averaging, filtering, or autocorrelation) in order to suppress the noise. As a result, it is quite possible to get high sensitivity, resolution and signal-to-noise ratio for angle circular transducer without rotation.

Thus, angle shear wave cone-probes (see Fig. 3) probably have rather high resolution and sensitivity for circumferential flaw detection, they are simple and not expensive, but these transducers cannot detect axial flaws.

Note that if these probes are positioned non-concentrically in relation to the tube, then even the circumferential coordinate of the flaw can be determined by measuring time-of-flight of the received signal in PE mode, because distances between working portion of the probe and related area of the tube are different for various parts of the transducer.

4. Axially positioned probe with attached mirror for circumferential flaw detection

Solutions, similar to ones presented in Figs. 2 and 3, can be obtained using standard focused axially-positioned probe with attached conical mirror, see Figs. 4 and 5.

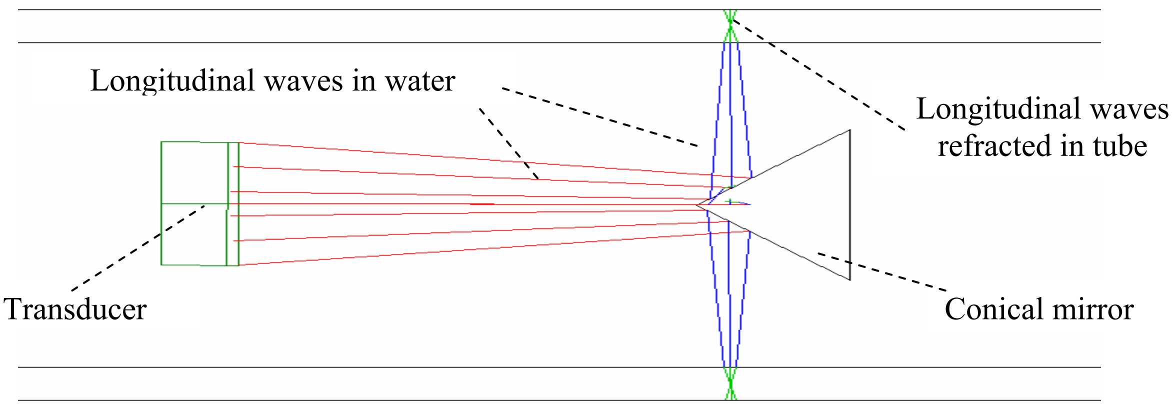

Figure 4. Schematics of NB probe, containing axially positioned standard focused transducer with attached 45^0 conical mirror.

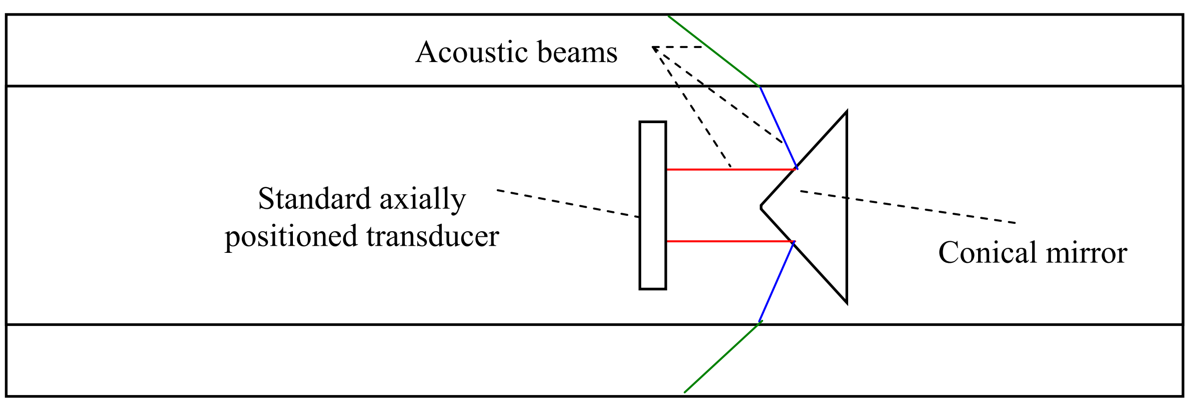

Figure 5. Schematics of angle shear wave probe, containing axially positioned standard transducer with attached 35^0 conical mirror for circumferential flaws detection.

Note that again (as in section 3) the NB probe (standard transducer with attached 45^0 conical mirror shown in Fig. 4), cannot be employed because of a low sensitivity and very strong background reflection from the tube, which will mask weak flaw responses. At the same time, the angle shear wave probe (standard transducer with attached conical mirror shown in Fig. 5) is very simple, covers simultaneously 360^0, and has rather high sensitivity for circumferential flaw detection (see explanation in section 3). However, such transducer cannot detect axial flaws. Experiments, performed using Figs. 4 and 5 schematics, are described below, and corresponding 2D axial B-scans are presented in section 6.

Note, that if probe with attached conical mirror is positioned non-concentrically in relation to the tube, then the circumferential coordinate of the flaw can be determined by measuring response time-of-flight, see section 6 for details.

5. Circular transducer with curved dents for axial flaw detection

Single-element shear wave angle probe, containing a few identical dents, can be used for axial flaw detection. Such probe covers simultaneously 360^0; it transmits and receives signals at the same incident angle in circumferential direction (see Fig. 6).

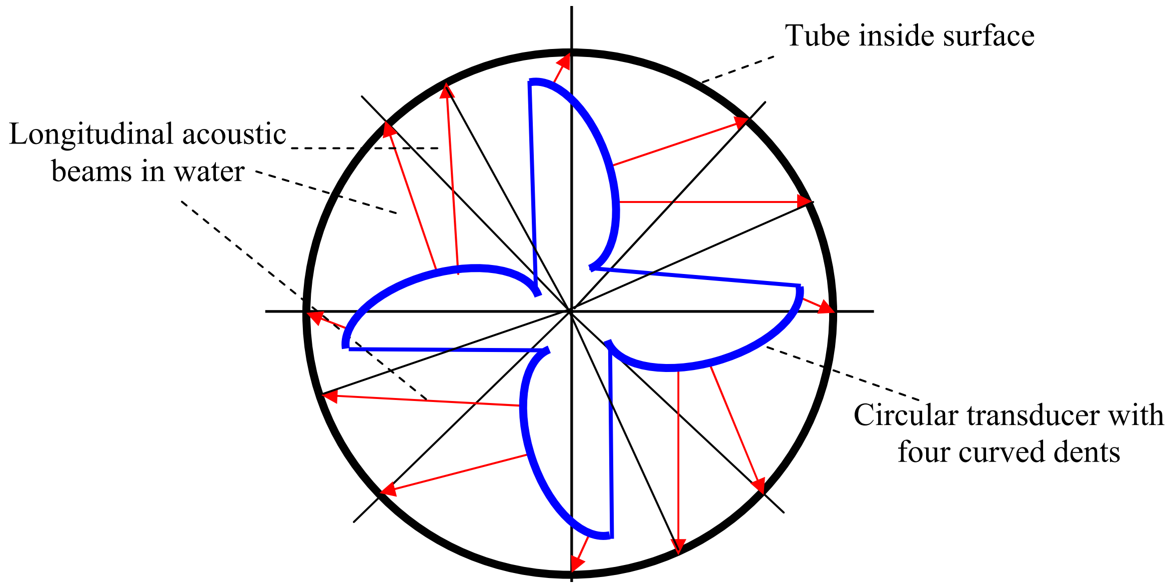

Figure 6. Schematic of angle shear wave circular transducer with four curved dents for axial flaws detection; UT beams impinge on the tube surface everywhere at the same incident angle.

Although such a probe is rather complex, it covers simultaneously 360^0 and, at the same time, has rather high sensitivity for axial flaw detection, but due to its "multi-dent" symmetrical shape, this transducer cannot measure unequivocally the circumferential coordinate of the detected axial flaw. Moreover, such probe cannot detect circumferential flaws. Note, that similar solution can be obtained if one employs standard axially positioned probe with attached 45^0 conical mirror, whose cross-section has shape presented in Fig. 6.

6. Eccentrically positioned circular probe.

Eccentrically positioned (in relation to the tube) NB tube-probe or angle cone-probe or axially oriented standard probe with attached conical mirror (top view) is shown in Fig. 7.

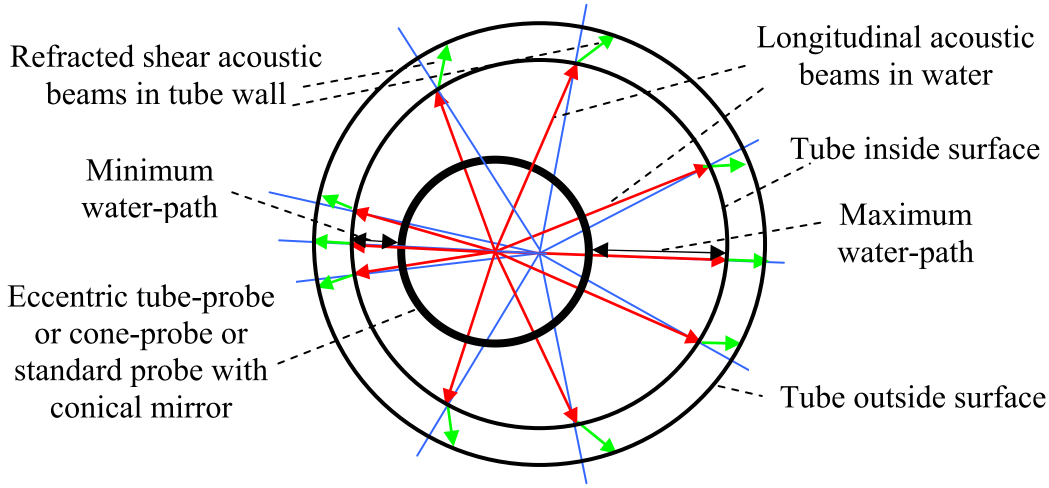

Figure 7. Schematic of top view of NB tube-probe or angle shear wave cone-probe positioned eccentrically in relation to the tube (or eccentrically positioned and axially oriented standard probe with attached conical mirror) for axial flaw detection.

Such a transducer transmits and receives signals at angle in circumferential direction, and therefore axial flaws can be detected. However, the incident angles are different for various radial directions. Moreover, if axial flaw is located on the line connecting centers of pipe and probe (i.e. either at minimum or maximum water-path), then no angle waves can be generated. Nevertheless, using, e.g. two of such probes, positioned eccentrically in relation to the tube (one with radial offset in X-direction, but the other with offset in Y-direction), it will be possible to detect and size any axial flaw. Picture of prototype of a standard axially positioned probe with attached conical mirror, used for experiments, is presented in Fig.8.

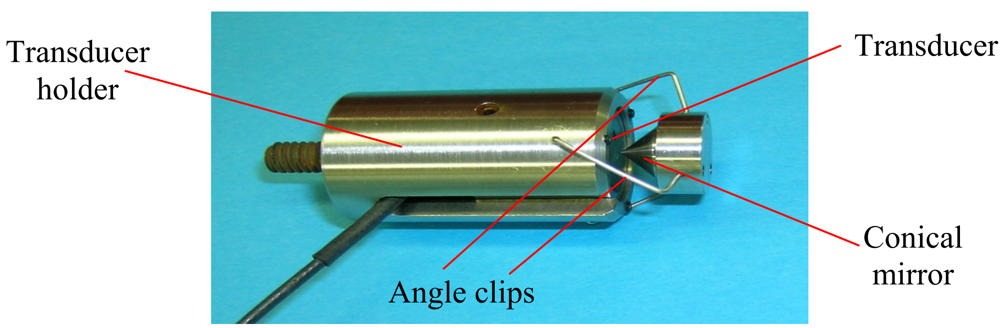

Figure 8. Picture of axially positioned standard probe with attached conical mirror.

In this prototype the conical mirror has been attached to the transducer body by three thin steel clips oriented at angle. Such a design does not create blind spots during probe axial motion. Any flaw will be detected, because acoustic beam after reflection from conical mirror always spreads in the axial direction. Two mirrors 45^0 and 35^0 were made for this probe. The 45^0 mirror provides NB propagating in radial direction; this mirror has been designed for axial flaws detection in accordance with schematics shown in Figs. 4 and 7. The 35^0 mirror provides angle beam propagating at angle to the tube axial axis; this mirror has been designed for circumferential flaws detection according to schematics presented in Figs. 5 and 7.

The experiments were performed using computerized scanning rig with rotary and three axial motions, Winspect software for data acquisition, SONIX STR-81G card, and UTEX UT-340 pulser-receiver. The tested tube filled with water, was positioned on the rotary table, and transducer was located inside it. Using prototype shown in Fig. 8, three different series of pressure tube testing were performed.

At first, schematics presented in Figs. 4 and 5 were tested. 2D axial B-scans of pressure tube with angle row of pits on the outside surface, performed using Fig. 8 probe-prototype with 45^0 and 35^0 attached conical mirrors, are shown in Figs. 9 and 10, respectively. Note, that multiple responses from tube inside diameter (ID) and outside diameter (OD) are related to multiple reflections of the UT wave within the tube wall.

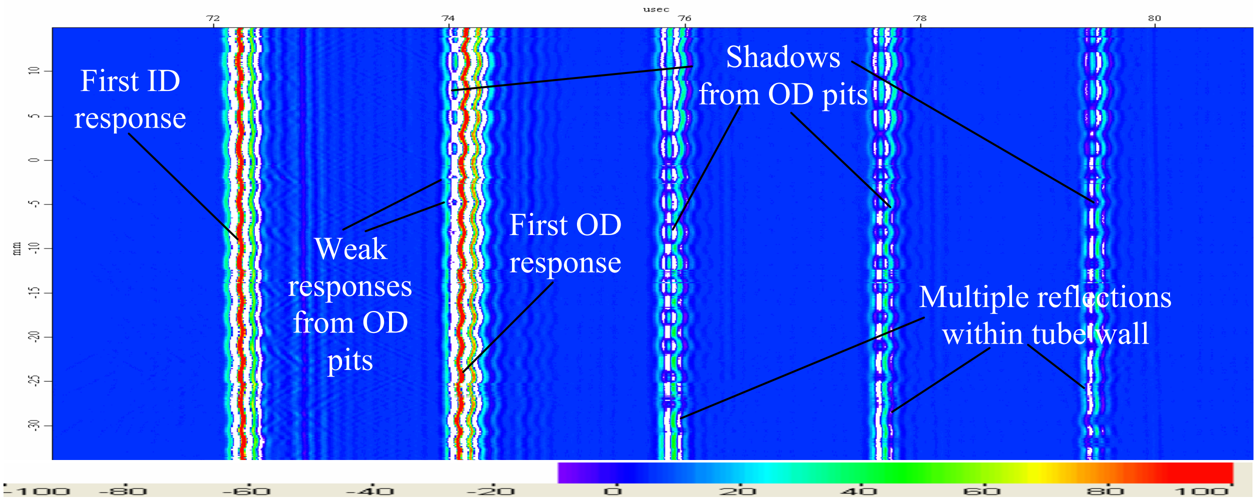

Figure 9. PE NB axial B-scan of pressure tube with angle row of OD pits 0.7mm wide and 0.7mm deep. Axially positioned probe with attached 45^0 conical mirror. Probe: center frequency f=10MHz, focal length FL=100mm, diameter D=9.5mm, water-path WP=45mm.

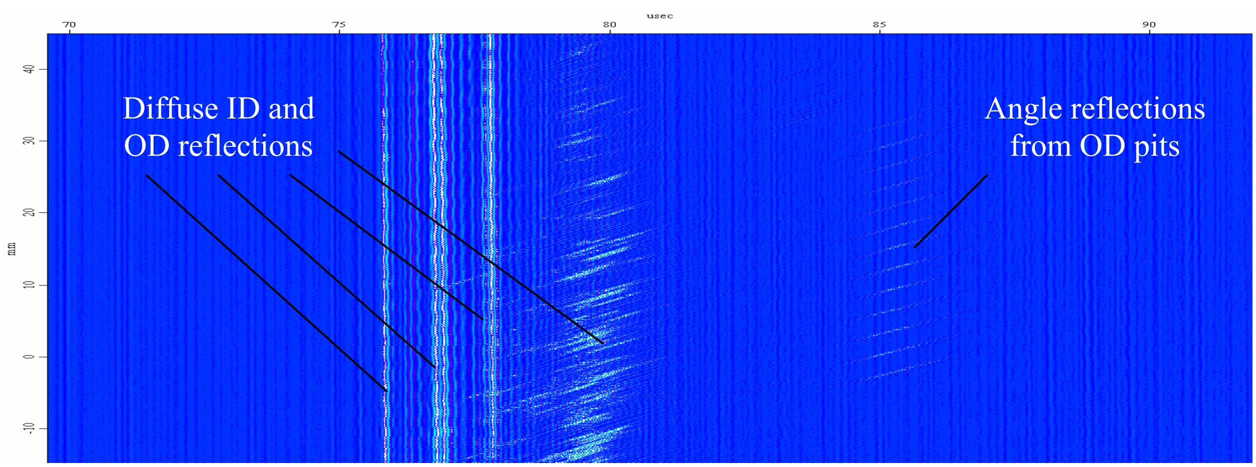

Figure 10. PE angle shear wave axial B-scan of pressure tube with angle row of OD pits 0.7mm wide and 0.7mm deep. Axially positioned probe with attached 35^0 conical mirror. Probe: f=10MHz, FL=100mm, D=9.5mm, WP=45mm. Color scale is shown in Fig. 9.

As one can see in Fig. 9, responses from pits are really very weak, while background reflections from tube surfaces (inside and outside) are strong, and therefore they mask flaw responses. Only pit shadows can be detected. It means that NB probe really has a low sensitivity and resolution to flaw detection. Angle beam technique (Fig.10) does not have NB reflections, therefore ID/OD diffuse reflections are much weaker and angle responses from pits are clearly detected. Recall that techniques, presented in Figs. 4 and 5, cannot determine the circumferential coordinate of the flaw; that is why the angle row of pits looks like axial row in Figs. 9 and 10.

Then the second series of experiments was performed to investigate Fig. 7 technique with eccentrically positioned probe. Pressure tube, containing one rectangular axial notch on the inside surface, was rotated in order to obtain the PE response of the notch at its different rotary positions regarding immovable transducer. Goal of the test was to determine angle range, where flaw can be detected. Typical circumferential B-scan of the sample tube is shown in Fig. 11.

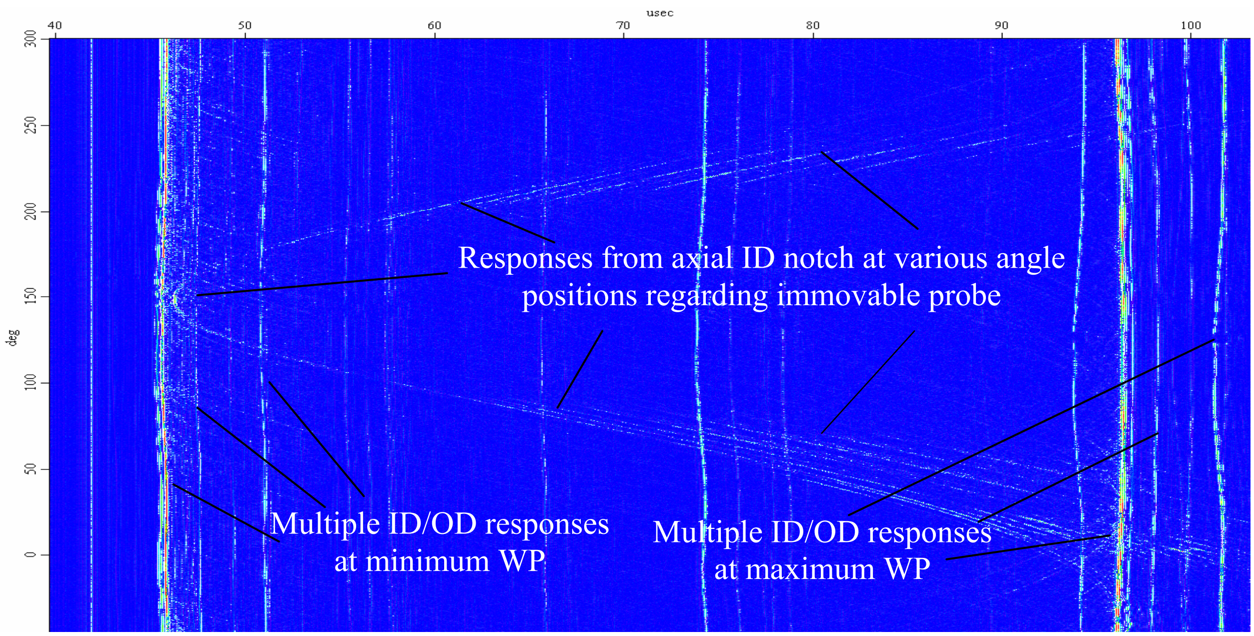

Figure 11. PE 360^0 circumferential B-scan of pressure tube with one axial rectangular ID notch 2.5mm wide and 0.5mm deep. Axially positioned probe with attached 45^0 conical mirror was located eccentrically in relation to the tube. Probe: f=10MHz, FL=100mm, D=9.5mm, minimum water-path between tube and mirror WP=20mm (signal arrives at 45μs), maximum WP=60mm (signal arrives at 97μs). Color scale is shown in Fig. 9.

As one can see, there are two sets of vertical lines – NB responses from tube at minimum and maximum water-paths (WP), shown in Fig. 7, and one curved line looking like a half-cycle – this is the angle response from notch at its different rotary positions. Thus, the immovable transducer working in the PE mode can detect notch located at any angle within the range from 0^0 to 360^0. The position of the notch response depends on the rotary coordinate of notch and, respectively, the response time-of-flight.

Finally, the third series of experiments was performed: axial B-scans of pressure tube with angle row of pits on the outside surface and tube with two axial rectangular notches on the inside surface positioned 180^0 apart. These scans were performed using eccentrically positioned axial probe with 45^0 and 35^0 attached conical mirrors, see Figs. 12-14.

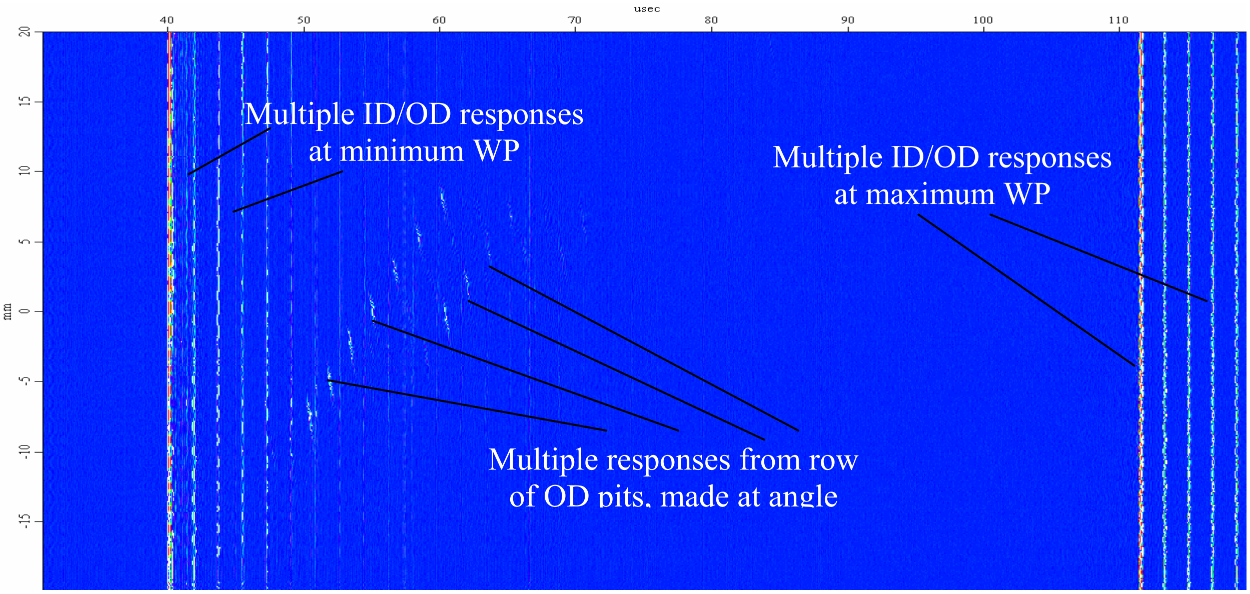

Figure 12. PE axial B-scan of tube with angle row of OD pits 0.7mm wide and 0.7mm deep. Axially positioned probe with attached 45^0 conical mirror was located eccentrically in relation to the tube. Probe: f=10MHz, FL=100mm, D=9.5mm, minimum WP=18mm (signal arrives at 40µs), maximum WP=64mm (signal arrives at 111µs). Color scale is shown in Fig. 9.

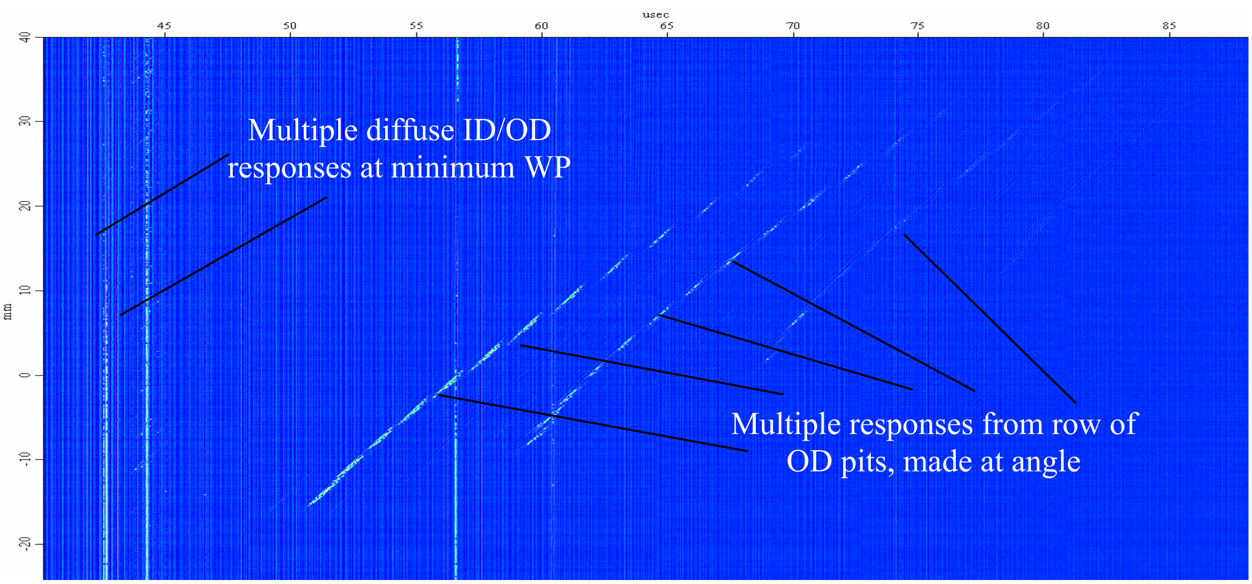

Figure 13. PE axial B-scan of tube with angle row of OD pits 0.7mm wide and 0.7mm deep. Axially positioned probe with attached 35^0 conical mirror was located eccentrically in relation to the tube. Probe: f=10MHz, FL=100mm, D=9.5mm, minimum WP=18mm (signal arrives at 40µs), maximum WP=64mm (signal arrives at 111µs). Color scale is shown in Fig. 9.

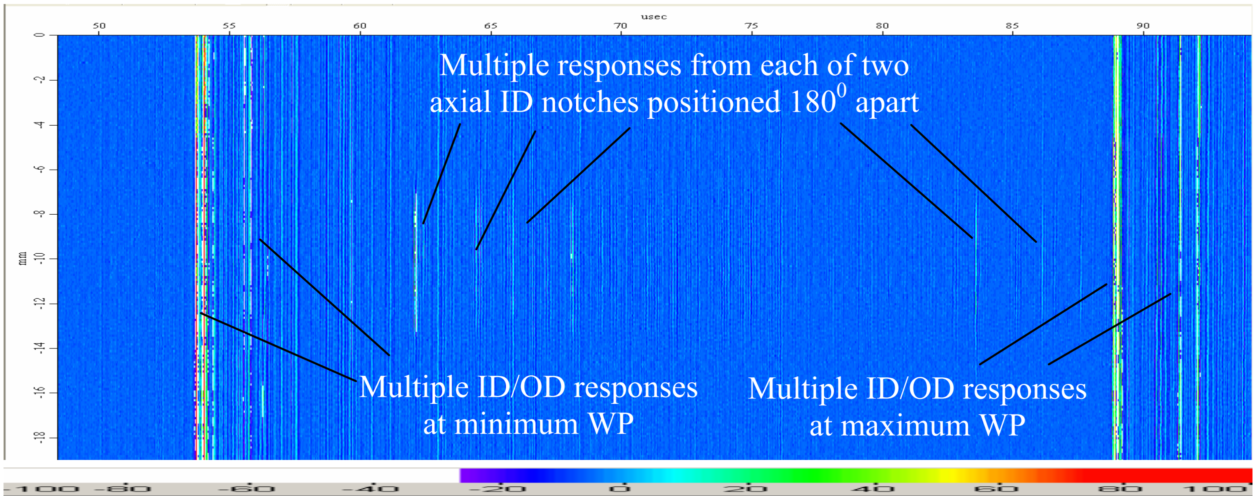

Figure 14. PE axial B-scan of PT with two axial ID notches 0.15mm wide and 0.15 and 0.076mm deep positioned 180^0 apart. Axially positioned probe with attached 45^0 conical mirror was located eccentrically in relation to the tube. Probe: f=10MHz, FL=100mm, D=9.5mm, minimum WP=30mm (signal arrives at 54μs), maximum WP=50mm (signal arrives at 89μs).

Note, that multiple responses from tube walls and flaws are related to multiple reflections of the UT wave within the tube wall. Figs. 12 and 14, where 45^0 mirror was used, have multiple strong NB reflections from tube wall at minimum WP and maximum WP; while Fig. 13, where 35^0 mirror was applied, has only weak diffuse reflections at minimum WP. Responses in Figs. 12-14 show that eccentrically positioned (in relation to the tube) and axially oriented probe with attached conical mirror can detect without rotation flaws located at any angle within the range from 0^0 to 360^0.

Moreover, this technique allows determining the circumferential coordinate of the flaw: that is why images in Figs. 12 and 13 show the angle rows of pits (compare with Figs. 9 and 10), and Fig. 14 shows two axial notches, whose responses arrive at different times.

Probe shown in Fig. 8 is simple and cheap, but it has relatively low and non-uniform resolution and sensitivity and signal-to-noise ratio depending on flaw position. However, two-probe method should compensate all these drawbacks.

7. Shear wave multi-skip technique.

Shear wave multi-skip technique is based on the multiple reflections of the initial longitudinal wave in water transmitted by the probe and impinging on the tube inside surface at angle and also multiple reflections of the shear wave propagating within the tube wall at angle. Transducer, working in PE mode and placed inside the tube at offset, will excite the shear wave propagating at angle within the tube wall (see Fig. 15). Such a wave during its propagation will be reflected many times from the tube ID and OD. As a result, significant portion of the tube wall (bottom portion in Fig. 15) will be tested by this wave. At the same time, the initial longitudinal wave in water (red rays) will be reflected (blue rays) and go to the right area of the tube, where it will create another shear wave propagating at angle within the tube wall. Subsequently, the second portion of the tube (right portion) will be tested similar to the first area. But because of the new reflection at the interface water/tube, the longitudinal wave in water (purple rays) will go to the third portion of the tube, where it will again create the shear wave propagating at angle within the tube wall (top portion). As a result, the third region of the tube will be tested similar to the first and second areas. By choosing the proper transducer orientation and placement, the whole tube (360^0 in circumferential direction) can be examined simultaneously.

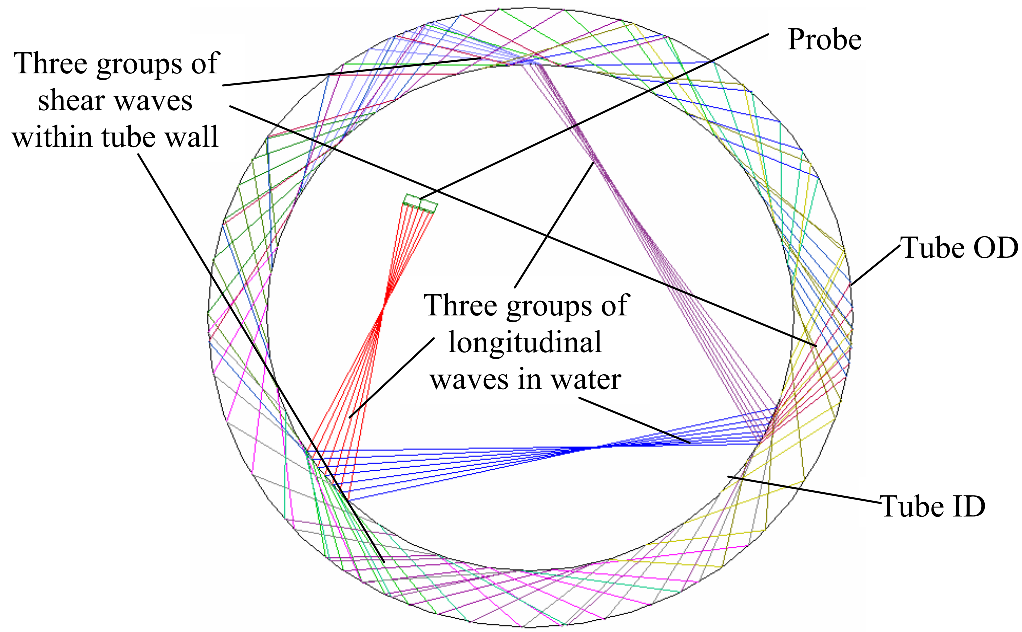

Figure 15. Ray-tracing simulation of shear wave multi-skip technique.

This concept, to some extent, is similar to the guided wave technique, where term "guided" is used, because wave travels along the medium guided by its geometric boundaries. If there is no flaw on the wave path, no reflected signal returns to the probe. If there is a flaw (on the inside surface, outside surface or inside the tube material), the PE response will come back to the transducer.

The preliminary experiments to test the proposed shear wave multi-skip technique were performed using different transducers. The measurements were done in the PE mode. Transducer was placed at offset and oriented at angle to the pressure tube inside surface in order to excite the required shear waves within the tube wall and the reflected longitudinal waves in water. During testing, the tube sample with ID notch was rotated in order to obtain the PE response of the notch at its different rotary positions regarding transducer. Typical circumferential B-scan of the sample tube with rectangular axial ID notch is shown in Fig. 16. The obtained responses represent three groups of shear waves generated within the tube wall in three different areas of the tube (see Fig. 15) and reflected from the notch. Thus, the immovable transducer working in the PE mode can detect the notch located at any angle within the range from 0^0 to 360^0. The position of the notch response depends on the rotary coordinate of notch and, respectively, the response time-of-flight. In order to improve the results (i.e. to make reflections from the notch stronger and more uniform, and to get rid from the "acoustic noise" – the diffuse ID reflections), one can use a few probes, each covering not the whole 360^0 but only 180^0 or even 120^0.

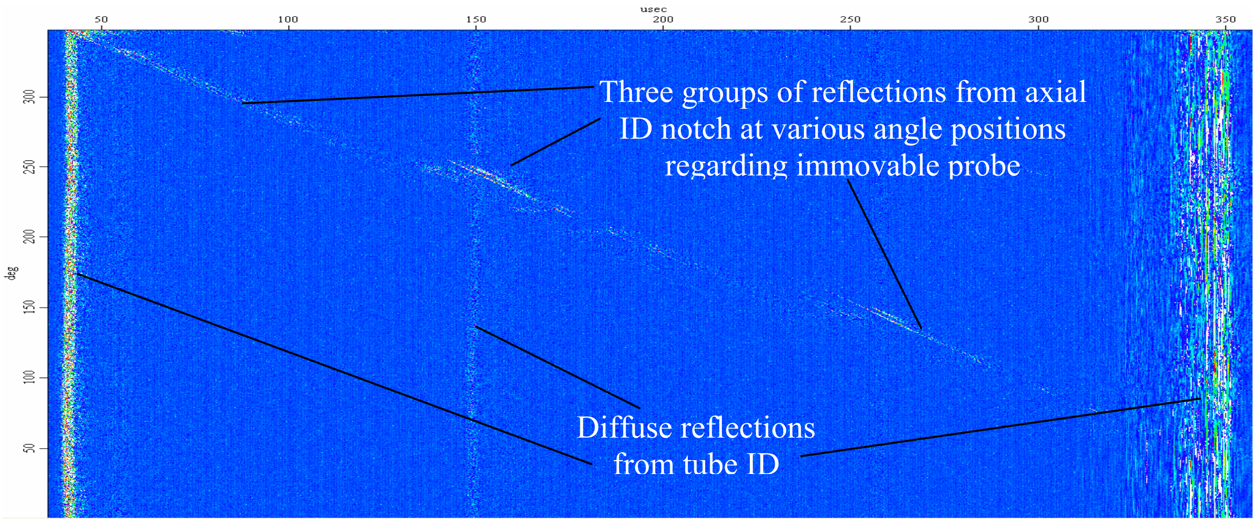

Figure 16. Circumferential PE B-scan of axial rectangular ID notch 0.5mm deep and 2.5mm wide. Probe: D=9.5mm, f=10MHz, FL=40mm, WP=22mm, offset 13mm, incident angle 36^0. Color scale is given in Fig. 9.

Shear wave multi-skip technique is very simple and cheap, but it provides relatively low and non-uniform sensitivity and resolution for axial flaw detection. Two-transducer method should compensate these drawbacks. Note, that shear wave multi-skip method cannot be used for circumferential flaw detection.

8. Conclusions.

- A few different concepts of UT inspection of tubes without probe rotation were investigated. These concepts include phased array application, various methods employing single circular transducer, and shear wave multi-skip technique. Inspection without rotation is very attractive, and will lead to significant financial benefits, because it will give a possibility to simplify the delivery system, decrease the inspection time, and get rid of mechanical vibrations, radial shifts, possible jams, and electromagnetic interference.
- The most promising are techniques using tube-probe and cone-probe. They are simple and not expensive, and at the same time provide rather high resolution and sensitivity at circumferential flaw detection.
- Methods, employing standard axially positioned probe with attached conical mirror are even simpler and cheaper, and provide pretty good resolution and sensitivity at circumferential flaw detection.
- Although technique using circular transducer with curved dents is more complex and expensive, it should provide good resolution and sensitivity at axial flaw detection.
- Two-transducer method, employing eccentrically positioned circular probes, is simple, not expensive, and provides good resolution and sensitivity at axial flaw detection.
- Two-transducer method, using shear wave multi-skip technique, is very simple and cheap, and it should provide good resolution and sensitivity at axial flaw detection.