Ultrasonic Inspection of Tubes without Probe Rotation

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Ability to perform the UT inspection of tube without mechanical rotation of probe module will result in:

1. Significant simplification of the delivery system.
2. Decrease of the inspection time due to increase of the axial speed of the inspection system.
3. Increase of reliability and sensitivity of the inspection system because of absence of mechanical vibrations, possible jams, electromagnetic interference from rotary motor, and so on.

In general, the possibility to get rid of rotation is very attractive, because it leads to significant technical and financial benefits. Of course, the absence of rotation should not compromise sensitivity and resolution of the inspection system.
Different Approaches

1. Circular phased array.

2. Single-element Normal Beam (NB) tube-probe, and 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. Circular Clock-Wise (CW) or Counter-Clock-Wise (CCW) transducers with curved teeth for axial flaw detection.
Circular Phased Array

One-dimensional (1D) circular cylindrical phased array or even two-dimensional (2D) cylindrical matrix array

Advantages: electronic focusing, high resolution in circumferential direction, electronic steering of the UT beam, and high electronic scanning speed.

Shortcomings: high cost, large size, special complex pulser-receiver, difficulty to make high-frequency array with large number of small elements, long multi-wire cable, inability to inspect small tubes (e.g. steam generator tubes), low resolution in axial direction.

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Concept: Tube-Probe and Cone-Probe - 1

Longitudinal UT beam in water

Refracted longitudinal UT beam in tube wall

Working cylindrical surface of tube-probe

Tube inside surface

Tube outside surface

Longitudinal UT beam in tube wall

Refracted shear UT beam in tube wall

Working conical surface of cone-probe

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Tube-Probe and Cone-Probe - 2

Working surfaces of probes covering 360°

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Tube-probes have lower sensitivity, resolution, signal-to-noise ratio, and accuracy of measurement than standard focused transducers routinely used with rotating probe modules because, any circular transducer, instead of concentrating acoustic beam in one spot, transmits UT waves in all circumferential directions and then receives all reflected signals simultaneously.

However, angle cone-probes have good sensitivity, resolution, and signal-to-noise ratio. In the reception mode, 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. There are no reflections from the “clean” part of the tube, which contains no flaws. Such probes can detect only circumferential but not axial flaws.
Axially Positioned Probes with Attached Mirrors

- Transducer
- Conical mirror
- Longitudinal waves in water
- Longitudinal waves refracted in tube
- Acoustic beams
- Standard axially positioned transducer

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Prototypes of Probes with Conical Mirrors

- Transducer holder
- Mirror holder
- Conical mirror
- Clips
- Conical mirrors

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“Three-tooth” probe providing 25 degrees incident angle (involute shape). Probe has high sensitivity for axial flaw detection.
Schematics of angle circular probe (involute shapes) for axial flaw detection: “three-tooth” probe providing incident angle 19 degrees and picture of respective 3D plastic model of this circular probe obtained after 3D printing:
Eccentrically Positioned Circular Cone-Probe

Transducer transmits and receives signals at angle in circumferential and axial directions, and therefore circumferential and axial flaws can be detected.

Time position of the response determines circumferential coordinate of the flaw. However, incident angles in circumferential direction are different.

Refracted shear acoustic beams in tube wall

Longitudinal acoustic beams in water

Eccentric tube-probe or cone-probe or standard probe with conical mirror

Minimum water-path

Maximum water-path

Tube inside surface

Tube outside surface

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So-called “quasi-NB” technique is using UT waves transmitted at small incident angle (just a few degrees). Since the respective UT beam propagates and reflects at angle, only a small portion of the transmitted wave, reflected from the clean area of smooth tube surface, returns to the probe. As result, the ID and OD responses are weak. At the same time, a much larger portion of the transmitted wave, reflected from a flaw, comes back to the probe in the reception mode.
2D PE NB (tube-probe) axial B-scan of HX tube (ID=13.5mm, WT=1.2mm) with six flaws: OD and ID pits (D=1.57mm and d=0.8mm), OD and ID axial notches (l=5mm, w=0.36mm and d=0.8mm), and OD and ID circumferential notches (l=5mm, w=0.36mm and d=0.8mm).
2D PE angle BW probe axial B-scan of HX tube with six flaws. Probe: cone-probe, f=10M, D=25mm, base angle 65°.
2D PE quasi-NB axial B-scan of HX tube with six flaws. Probe: NB ring-probe, flat, f=10MHz, 40° conical mirror, incident angle 5°.
2D PE NB axial B-scan, circumferential B-scan and 2D amplitude shadowing C-scan of HX tube with six flaws. Axial coordinate $z=10\text{mm}$, ID pit ($D=1.57\text{mm}$ and $d=0.8\text{mm}$) at $z=20\text{mm}$, OD axial notch ($l=5\text{mm}$, $w=0.36\text{mm}$) and Probe: Standard Trustie NB with flat 45 degrees mirror, $f=20\text{MHz}$, $FL=20\text{mm}$, $D=4.1\text{mm}$.
Flaw circumferential position (coordinate) can be determined using the non-rotating angle probe positioned eccentrically in relation to the tube in the BW mode of operation by measuring response time-of-flight.
Flaw circumferential width can be determined using the non-rotating NB probe by measuring the response duration (or “thickness”), which correlates to the “circumferential width” of the flaw. The wider notch, the “thicker” its response is. This occurs because the first reflected pulse comes from the normal direction, then (later in time due to a larger distance) signals from the “angle” directions come.

2D NB PE B-scan of 3 ID circumferential scrapes: 25mm, 27mm and 29mm circumferential widths, 7mm axial length, and 0.5mm, 0.576mm and 0.65mm radial depths). Probe: f=10MHz, D=9.5mm, flat with conical mirror.
The results of the NB axial B-scans, BW angle axial B-scans, and quasi-NB axial B-scans demonstrate that, using all these techniques and employing non-rotating probes, a flaw can be characterized in the following way:

1. Flaw can be detected.
2. The ID and OD flaws can be distinguished.
3. Flaw axial position (coordinate) can be determined.
4. Flaw axial length (dimension in the axial direction) can be measured.
5. Flaw depth (dimension in the radial direction) can be measured.
6. Flaw circumferential position (coordinate) can be determined using the non-rotating angle probe, positioned eccentrically in relation to the tube in the BW mode of operation, by measuring response time-of-flight.
7. Flaw circumferential width can be determined using the non-rotating NB probe by measuring response duration. The wider notch, the “thicker” its response is.
Conclusions

Inspection without rotation is very attractive, and leads to significant technical and financial benefits, because it gives a possibility to simplify the delivery system, decrease the inspection time, and get rid of mechanical vibrations, possible jams, and electromagnetic interference.

A few different concepts of UT inspection of tubes without probe rotation were investigated. The most promising are techniques using tube-probe and cone-probe. These techniques are simple, not expensive, and provide high sensitivity at circumferential flaw detection.

Technique using circular transducer with curved teeth is more expensive, but it provides good sensitivity at axial flaw detection.