Improved Flaw Characterization and Sizing in Pressure Tubes

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Statement of the Problem

Currently used CIGAR/ANDE techniques, hardware and software for data analysis sometimes do not provide sufficient information for flaw detection, characterization and accurate sizing or it is labour and time consuming to make a conclusion regarding flaw identification, characterization and dimensions.

There is a need to further improve flaw identification, characterization and sizing accuracy by modifying the existing CIGAR/ANDE techniques, hardware and software for data analysis.
Benefits

Improved techniques, hardware and software will provide more accurate measurements of flaw dimensions, allow estimating flaw root radius, and allow flaw to be shown in a 3D model.

It will provide improved flaw identification, characterization and sizing, which can lead to the improved efficiency of analysis, decreased number of required replicas, and decreased analysis time.
New-Developed Inspection Techniques and Software

1. Combined technique for flaw root radius assessment and flaw characterization
2. Depth measurement of sharp flaws
3. Assessment of flaw side inclination angle
4. Large probe NB technique
5. Off-axis flaw characterization and sizing
6. Software for flaw 3D-visualization based on various B-scans
Combined Technique for Root Radius Assessment - 1

The direct measurement of root radius cannot be done using existing inspection systems, due to large UT wavelength, large probe diameter, and other reasons.

The most reliable indirect method for root radius assessment is probably the combined technique.

Such technique can be implemented e.g. by connecting CW and CCW probes in parallel. Subsequently, three techniques can be realized simultaneously: CW PE, CCW PE, and PC. This technique can also be realized by using three standard B-scans, CW, CCW and PC, and data fusion software.
Combined Technique for Root Radius Assessment - 2

Combined B-scans of 0.3mm deep ID axial 60° V-notches with various root radii. Probes: CW & CCW, FL=40mm, f=15MHz, D=9.5mm, WP=20.6mm.

Root radius 40µm
Δt=0.15µs

Root radius 100µm
Δt=0.09µs

Root radius 200µm
Δt=0.06µs

Root radius 400µm
Δt=0.001µs
Combined Technique for Root Radius Assessment - 3

- Root radius, micrometers
- Time interval, $\Delta t$ microseconds

Graph showing the relationship between root radius and time interval.
Combined Technique for Flaw Characterization - 1

Tube cross-section and 2D combined B-scan of rectangular ID axial notch 0.5mm deep and 2.5mm wide with delay hydride crack (DHC) 0.8mm deep. Probes: CW & CCW, FL=40mm, f=20MHz, D=9.5mm, WP=20.6mm.
Combined Technique for Flaw Characterization - 2

2D combined B-scans of rectangular ID axial notch 1mm wide and 0.7mm deep with DHC 1mm deep (a) and without crack (b). Probes: CIGAR Head, CW & CCW, FL=40mm, f=20MHz, D=9.5mm, WP=20.6mm.
Combined Technique for Flaw Characterization - 3

2D combined B-scans of V-notch 45 degrees tip angle and 1mm deep with DHC crack 0.5mm deep (a) and without crack (b). Probes: CIGAR Head, CW & CCW, FL=40mm, f=20MHz, D=9.5mm, WP=20.6mm.
The large 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 reflections from the inside and outside tube walls. Therefore, the central part of a large transducer works as a small NB probe, while the peripheral parts work as small angle probes in the PE and/or PC modes. That is why transducer with large diameter can “see” flaw simultaneously at various angles and from different directions.
Large Probe NB Technique - 2

NB circumferential 2D B-images of various ID axial notches. Probe: FL=55mm, f=15MHz, D=0.5”, WP=15mm.
Large Probe NB Technique - 2

B-images of axial rectangular notches 0.5mm deep and 2.54mm wide with fatigue cracks ~1.2mm deep (a) and ~0.9mm deep (b). Probe: FL=55mm, f=15MHz, D=0.5”, WP=15mm.
A standard CIGAR shear wave probe in the PE mode can hardly detect the off-axis flaws because reflected signals do not return to the probe. That flaw can be detected in the NB and PC modes of operation, but only as a shadow because signal, reflected from flaw bottom, usually does not return to the probe. But shadow signal does not allow measuring flaw depth. Methods, based on probes angle-oriented in both directions, allow defining orientations of off-axis flaws and measuring their depths.
Off-Axis Flaw Characterization and Sizing - 2

Special angle probe head (a), PE double –angle B-images (b) and C-images (c) of 45 degrees off-axis V-notches: length 7mm, depth 0.75mm, off-axis angles 90, 75, 60, 45, 30, 15, and 0 degrees. Probe: CW/FW, FL=40mm, f=20MHz, D=9.5mm, WP=20.6mm, incident angles in axial and circumferential directions 23 degrees.
Off-Axis Flaw Characterization and Sizing - 3

PC double-angle B-images and C-images of off-axis V-notches: length 7mm, depth 0.75mm, off-axis angles 90, 75, 60, 45, 30, 15, and 0 degrees. Probes: CW/FW & CCW/BW, FL=40mm, f=20MHz, D=9.5mm, WP=20.6mm, incident angles in axial and circumferential directions 23 degrees.
Off-Axis Flaw Characterization and Sizing - 4

Quasi-NB B-images and C-images of 45 degrees off-axis V-notches: length 7mm, depth 0.75mm, off-axis angles 90, 75, 60, 45, 30, 15, and 0 degrees. Probe: FL=10mm, f=20MHz, D=6.35mm, WP=10mm, incident angles in axial and circumferential directions 5 degrees.
Circumferential angle 2D PE B-scan of 45 degrees off-axis V-notches: length 7mm, depth 0.75mm, off-axis angles 90, 75, 60, 45, 30, 15, and 0 degrees. Probe: cylindrically focused, FL=25mm, f=15MHz, D=9.5mm, WP=27mm.
3D-Visualization - 1

Time-of-flight 3D image of axial rectangular notch 0.5mm deep and 2.5mm wide with fatigue cracks 1.7mm deep and 1.5mm deep.
3D-Visualization - 2

Time-of-flight 3D image of 20 degrees V-notch 1mm deep with DHC crack 0.5mm deep and 3D image of axial rectangular notch 0.5mm deep and 2.5mm wide with fatigue crack 0.5mm deep.
3D-Visualization - 3

Time-of-flight 3D images of 45 degrees off-axis V-notch (L=10mm, w=0.15mm, d=0.5mm), of 45 degrees off-axis rectangular notch 0.75mm deep, and of seven 45 degrees V-notches: length 7mm, depth 0.75mm, off-axis angles 90, 75, 60, 45, 30, 15, and 0 degrees notch).
3D-Visualization - 4

Tube with engraved ID writing (letter lines are ~0.07mm deep and ~0.15mm wide) and two CW and CCW time-of-flight 3D images.
3D-Visualization - 5

Optical image of flaw replica and time-of-flight 3D image of flaw 5.5mm long and 2.5mm wide with maximum depth 0.083mm. Probe: NB ID focused, $D=6.35\text{mm}$, $WP=10\text{mm}$, $f=20\text{MHz}$, $FL=10\text{mm}$. Scale in depth direction is 10:1.
3D-Visualization - 6

Flaw K22-IND69: replica, standard CIGAR NB image, and images obtained after conversion of 3D NB CIGAR file into the Winspect file.

- Optical image of replica
- Standard CIGAR NB B-image of one cross-section
- Amplitude shadowing 2D NB C-scan
- Time-of-flight 3D image
3D-Visualization - 7

Time-of-flight 3D image of axial V-notch, based on data fusion: angle 60 degrees, depth 0.3mm, root radius 100µm.

Moving 3D-cursor to any point, the following flaw parameters in this point can be assessed: depth (circled in blue), root radius (circled in red), and flaw sides inclination angles (circled in black).
Conclusions

Novel techniques, hardware and software for data analysis can lead to improved flaw identification, characterization and sizing and also to reduced schedules and costs through:

- Decreased number of required replicas
- Improved data analysis
- Decreased analysis time
- Re-analysis of previously inspected flaws