Ultrasonic Inspection System for Automated Round-Bar-Testing Based on Phased Array Technique


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Automated testing of rods using conventional UT-technique

Testing system using water-jet coupling cartridge containing 15 conventional UT-transducers
The task

- Investigation of different testing approaches
- Simulations for adapted probe design
- Optimisation of the sound field to achieve 100%-covering
- Experimental proving using a bench-scale unit
- Optimisation to achieve high heading speed
- Transfer in a real industrial testing system
Phased Array-Concept for planar arrangements of linear Arrays

- Replacement of up to 45 conventional transducers
- Use of cheap linear arrays
- Optimisation of the heading speed by parallel operation of axial separated probes
- Adaption to different rod diameter is possible
- Planar transducer bottom does not allow for optimal adaption to the sample geometry
- Due to water path aperture of single elements is limited, thus several elements does not contribute significantly which lowers the SNR
Arrangement for a rod diameter of 60 mm using two 90°-circumferential arrays

Planar arranged element surface

Cylindrical arranged element surface
R = 60 mm

sound field in water

Sound field in steel
Long. wave

element size 12 x 12 mm², f = 5 MHz, rod diameter = 40 mm
Curved Linear Arrays

- 90° array containing 128 Elements, 5 MHz, 0.84 mm pitch, 60 mm radius
- Available as a standard product
- Replacement of up to 45 conventional transducers
- Optimisation of the heading speed by parallel operation and axial separation of the probes
- Adaption to different rod diameter is possible
- Curved transducer bottom allows for optimal adaption to the sample geometry
- High SNR

Element 1

Position 1 of the virtual probe (16 Elements, $\alpha = 0^\circ$)

Element 128

Position 113 of the virtual probe (16 Elements, $\alpha = 0^\circ$)

Material defect

sample (rod)
Comparison of the SNR between Linear Array and 90° curved Array

OEL3 (16 el., planar, 3 MHz, 1.5 mm)

Rod diameter: 45 mm
Hole diameter: 0.7 mm
Hole depth: 20 mm
Amplification: 36 dB
Angle of incidence: 0°
Reading point separation: 0.2 mm
Size of voxel: 0.6 mm
Beam width: 5.0 °

α = 0°, V = 36 dB  S/N = 12 dB

16 Elements (planar)

The curved PA-transducer yield a 20 dB higher signal

SNX070935 (128 el., curved, 5 MHz, 0.75 mm)

Rod diameter: 45 mm
Hole diameter: 0.7 mm
Hole depth: 20 mm
Amplification: 18 dB
Angle of incidence: 0°
Reading point separation: 0.1 mm
Size of voxel: 0.6 mm
Beam width: 5.0 °

α= 0°, V = 18 dB  S/N = 32 dB
Elementgroup 1 – 16 (curved)

SNX: response of the 0.7 mm sized hole, α = 0°, LW
Modelling using the package „Array-Calculus“
Different shapes of sound beam (LW)

Sound field of the longitudinal wave within a rod (Ø 45 mm)
for three different delay-configurations of the elements
Modelling using the package „Array-Calculus“
Different shapes of sound beam (TW)

Rod Ø 45 mm: narrow beam:
\[ \alpha = 45^\circ \]

Rod Ø 45 mm: broad beam:
\[ 35^\circ < \alpha < 50^\circ \]
### Experimental proving using a bench-scale unit with reference rod samples

- Diameters of 20 mm, 40 mm, and 60 mm
- Adjusting the sensitivity with a FBH (Ø 1.2 mm and 0.8 mm for vertical intromission of sound (LW))
- Adjusting the sensitivity using notches with a depth of 0.5 mm and 0.2 mm for angular intromission of sound (TW)

<table>
<thead>
<tr>
<th>Rod Diameter</th>
<th>FBH Ø</th>
<th>Notch Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 mm</td>
<td>0.8 mm</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>40 mm</td>
<td>1.2 mm</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>60 mm</td>
<td>0.7 mm</td>
<td>0.2 mm</td>
</tr>
</tbody>
</table>

**Diagram:**
- Adjusting rods with diameters of 20 mm, 40 mm, and 60 mm
- FBH and notches in different depths
Experimental set up

- PC
- Phased Array - COMPAS-XL 128
- Manipulator
- Immersion tank
- Probe SNX080705: 128 Elements, 0.84 mm pitch, r = 60 mm, f = 5 MHz
- Reference rod
Comparison of simulation and measurement: Determination of the axial sound field width

Simulation: sound field width perpendicular to the cross-section plane of the rod in a depth of 45 mm.

Axial width of the sound field
Simulation: 6.0 mm
Measurement: 6.3 mm

B-scan: FBH in 45 mm depth (rods Ø 60 mm)

A-scan: FBH Ø = 1.2 mm in a depth of 45 mm
Lateral width of the sound field using 16 elements D= 60 mm, FBH in 45 mm depth

**A-scan:** 1.2 FBH in $t = 45\text{ mm}$, -6 dB left side

**A-Bild:** 1.2 FBH in $t = 45\text{ mm}$ max. Amplitude

**A-Bild:** 1.2 FBH in $t = 45\text{ mm}$ -6 dB right side

Maximum Separation between 2 points of incidence is 10 elements
Volumen detection using angular longitudinal wave

Reference rod Ø = 60 mm, Reflector FBH 1.2 mm and FBH 0.8 mm

**A-scan:** Refl. 8 (FBH 1.2 mm, depth: 35 mm)

**A-scan:** Refl. 9 (FBH 0.8 mm, depth: 45 mm)
Volumen detection using broad longitudinal sound field

Reference rod Ø = 60 mm, Reflector FBH 1.2 mm and FBH 0.8 mm

A-scan: Refl. 8 (FBH 1.2 mm, depth: 35 mm)

A-scan: Refl. 9 (FBH 0.8 mm, depth: 45 mm)
Edge testing using transversal wave, reference rod, $\varnothing = 60$ mm left and right notch

A-scan: left notch: 0.2 mm

A-scan: left notch: 0.5 mm

A-scan: right notch: 0.2 mm

A-scan: right notch: 0.5 mm

$\alpha_1 = +45^\circ$

$\alpha_2 = -45^\circ$

Active elements: 59 - 75
Edge testing using a double transversal wave, reference rod, Ø = 60 mm left and right notch

A-scan: left notch: 0.2 mm
A-scan: right notch: 0.2 mm
A-scan: left notch: 0.5 mm
A-scan: right notch: 0.5 mm
Arrangement for a rod diameter of 60 mm using two 90°-circumferential arrays

Array 2

2 x 6 testing cycles with LW 0°
(a few areas which are not covered in surface near region)

Array 1

2 x 6 testing cycles with TW 45°
(whole surface near area can be covered)
Set up for an automated rod testing

- Reflectors
- Round bar
- Direction of motion
- Water chamber
- 90° arrays
- COMPAS-XXL 1
- COMPAS-XXL 2

Set up for an automated rod testing with reflectors, a round bar, and a water chamber. The direction of motion is indicated, and the setup includes COMPAS-XXL 1 and COMPAS-XXL 2.
Arrangement using 4 x 90° arrays mounted with axial separation at high testing speed to avoid phantom echos.
Successful detection of inside FBH with Ø 1.2 mm and Ø 0.8 mm in various depth.

 Slots with 0.2 mm and 0.5 mm depth can be detected with both shear waves and longitudinal waves.

 The reliable defect detection requires only 6 testing cycles within an angle of von 90°

 Advantage of the shear wave: high corner signal

 Reduction of the test cycles is possible by simultaneously using two sound fields in opposite direction.

 Testing of round bars with Ø 15 mm up to Ø 80 mm can be performed with the 90°-circumferencial array with 100% coverage and a corresponding heading speed larger than 1 m/s.
The project was supported by the Ministry of Economics and Technology.

Thanks for your attention
Determination of the heading speed for a rod diameter of 60 mm

**Parameters:**
- $C_{L_{\text{water}}} = 1480 \text{ m/s}$
- $C_{L_{\text{steel}}} = 5920 \text{ m/s}$
- $C_{T_{\text{steel}}} = 3250 \text{ m/s}$
- $\alpha = 45^\circ$
- $b = 30 \text{ mm}$
- $r = 30 \text{ mm}$

**Calculation:**

\[
\cos \alpha = \frac{r}{d} \rightarrow d = \frac{r}{\cos \alpha} \rightarrow d = 42.42 \text{ mm}
\]

**Time for propagating in water**

\[
v = \frac{s}{t} \quad \rightarrow \quad t = \frac{s}{v}
\]

\[
t = \frac{2 \cdot 0.030 \text{ m}}{1480 \text{ m/s}}
\]

\[
t = 0.000041 \text{ s}
\]

\[
t = 41 \mu\text{s}
\]

**Time for propagating in steel**

\[
v = \frac{s}{t} \quad \rightarrow \quad t = \frac{s}{v}
\]

\[
t = \frac{2 \cdot 0.042 \text{ m}}{3250 \text{ m/s}}
\]

\[
t = 0.000026 \text{ s}
\]

\[
t = 26 \mu\text{s}
\]

\[
t_{\text{total}} = t_{\text{water}} + t_{\text{steel}} = 41 \mu\text{s} + 26 \mu\text{s} = 67 \mu\text{s}
\]
Testing the edge area:
2 x 6 test cycles (SW both directions) using 10 kHz shooting rate
= 2 x 6 A–scans (each of which contains 128 Pixels) = 2 x 6 x 100 µs = 2 x 600 µs TW
(for 63 mm sound path in the A-scan)

Testing the center volume:
2 x 6 test cycles for vertical intromission of the LW using 3 kHz shooting rate
= 2 x 6 Prüffunktionen = 2 x 6 A–Bilder (mit 128 Pixel) = 2 x 6 x 300 µs = 2 x 1800 µs LW
(bei 63 mm Schallweg im A-Bild)

Gesamtzeit beim Einsatz von 2 COMPAS-XXL Steuergeräten (Parallelbetrieb):
6 x 100 µs + 6 x 300 µs = 2400 µs

Gewählter Messpunktabstand 2 mm:
V = 2 mm / 2400 µs = \textbf{0,833 m/s}

Gewählter Messpunktabstand 3 mm:
V = 3 mm / 2400 µs = \textbf{1,25 m/s}