Determination of an Optimal Examination Grid for the Automated Ultrasonic Inspection of Heavy Rotor Forgings

DGZfP Committee Ultrasonic Testing
Subcommittee Automated UT
Automated Shaft Inspection System
Saarschmiede, Völklingen
Terms

- $d_x$: Increment in scan direction (Defined by pulse repetition rate and examination speed)
- $d_y$: Distance between two adjacent laps in index direction
- $D_x, D_y$: Dimensions of the ultrasonic beam
Automatisierte Disc Inspection System
Schmiedewerke Gröditz
Automated Shaft Inspection System
GE Sensing & Inspection Technologies, Alzenau
Automated Shaft Inspection System
KARL DEUTSCH Prüf- und Messgerätebau GmbH + Co KG, BGH Siegen
Determination of an Optimal Examination Grid for the Automated Ultrasonic Inspection of Heavy Rotor Forgings

- Introduction & Motivation
- Requirements in Current Standards
- Definition of an Examination Grid
  - Normalized Grid Rating $R_n$
  - Average Grid Rating $R_d$
- Determination of the Ultrasonic Beam Dimensions
- Determination of the Examination Grid
- Summary
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**Determination of an Optimal Examination Grid for the Automated Ultrasonic Inspection of Heavy Rotor Forgings**

<table>
<thead>
<tr>
<th>Automated UT</th>
<th>Multiple Scans</th>
<th>Low Sound Attenuation</th>
</tr>
</thead>
</table>
| • Required for heavy rotor forgings  
  • Limited optimization regarding flaw reflection  
  • Recorded in distinct pattern  
  • Full volume coverage required | • Required by VGB-R 504 M | ⇒ Limited pulse repetition rates  
  ⇒ Limited inspection speed  
  ⇒ High inspection duration |

⇒ Cost of ultrasonic inspection depends directly on examination grid  
  (both in scanning and index direction)
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Requirements in Current Standards
EN 10228-3:1998 - Non-destructive testing of steel forgings

**Requirement**
- Overlap of at least 10% of the effective active element size
- No requirement in scan direction

**Issues for AutoUT**
- Apparently assumes a high pulse-repetition-rate and slow probe movement.
- Shape and size of the sound bundle not considered
Requirements in Current Standards
EN 583-1:1998 - Ultrasonic examination - General principles

**Requirement**
- Based on size of -6 dB beam
- Requirement in scan and index direction
- The beam of two adjacent -6 dB beams have to touch

**Issues for AutoUT**
- Some zones are not inspected with the required sensitivity
- No formulas provided how to determine an examination grid
Requirements in Current Standards
ASTM E 2375 - 08 - Ultrasonic Testing of Wrought Products

Requirement

• Based on size of -6 dB beam
• Index direction: Overlap of at least 20% of the effective beam width size
• Scan direction: Scanning speed limited by detectability of the reference reflectors

Issues for AutoUT

• Some zones are not inspected with the required sensitivity
• No formulas provided how to determine an examination grid
## Requirements in Current Standards Summary

<table>
<thead>
<tr>
<th>Standard</th>
<th>Overlap Requirement</th>
<th>Additional Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN 10228-3</td>
<td>Overlap of at least 10% of the</td>
<td>• No requirement in scan direction (or only by limitation of scanning speed)</td>
</tr>
<tr>
<td></td>
<td>effective active element size</td>
<td>• Overlap of the beams – however not considering the volume to be inspected</td>
</tr>
<tr>
<td>SEP1923</td>
<td>Overlap of at least 15% of the</td>
<td>• Unclear:</td>
</tr>
<tr>
<td></td>
<td>active element size</td>
<td>• Effective element size</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Transducer width</td>
</tr>
<tr>
<td>ASTM A 418</td>
<td>Indexing by 75% of the transducer</td>
<td>• Some zones are not inspected with the required sensitivity</td>
</tr>
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<td></td>
<td>width</td>
<td>• No formulas provided how to determine an examination grid</td>
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<tr>
<td>EN 583-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IIW Handbook</td>
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<td>effective beam width size</td>
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**Determination of an Optimal Examination Grid for the Automated Ultrasonic Inspection of Heavy Rotor Forgings**

### Automated UT
- Required for heavy rotor forgings
- Limited optimization regarding flaw reflection
- Recorded in distinct pattern
- Full volume coverage required

### Multiple Scans
- Required by VGB-R 504 M

### Low Sound Attenuation
- Limited pulse repetition rates
- Limited inspection speed

⇒ High inspection duration

⇒ Cost of ultrasonic inspection depends directly on examination grid (both in scanning and index direction)

### Motivation
- Existing standards define examination grids for manual inspection
  ⇒ Not simply transferable to automated
  ⇒ Start of development of an Optimal Examination Grid for the Automated Ultrasonic Inspection
### DGZfP Committee Ultrasonic Testing
### Subcommittee Automated UT

#### UT System Manufacturers

<table>
<thead>
<tr>
<th>Name</th>
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<tbody>
<tr>
<td>Peter Archinger</td>
<td>GMH Prüftechnik</td>
<td>Nürnberg</td>
</tr>
<tr>
<td>Otto Alfred Barbian</td>
<td></td>
<td>Blieskastel</td>
</tr>
<tr>
<td>Dr. (USA) Wolfram Deutsch</td>
<td>Karl Deutsch</td>
<td>Wuppertal</td>
</tr>
<tr>
<td>Dr. sc. techn. Peter Kreier</td>
<td>Innotest</td>
<td>Eschlikon/CH</td>
</tr>
<tr>
<td>Roland Reimann</td>
<td>AREVA NP</td>
<td>Erlangen</td>
</tr>
<tr>
<td>Udo Schlengermann</td>
<td>NDT Syst. &amp; Services</td>
<td>Erftstadt</td>
</tr>
<tr>
<td>Herbert Willems</td>
<td></td>
<td>Stutensee</td>
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</table>

#### Forging Manufacturers (Users)

<table>
<thead>
<tr>
<th>Name</th>
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<tbody>
<tr>
<td>Kay Drewitz</td>
<td>Schmiedewerke</td>
<td>Gröditz</td>
</tr>
<tr>
<td>Dr.-Ing. Alexander Zimmer</td>
<td>Saarschmiede</td>
<td>Völklingen</td>
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#### OEM

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<th>Name</th>
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<tr>
<td>Frank W. Bonitz</td>
<td>Westinghouse</td>
<td>Mannheim</td>
</tr>
<tr>
<td>Mathias Böwe</td>
<td>BASF SE</td>
<td>Ludwigshafen</td>
</tr>
<tr>
<td>Klaus Conrad</td>
<td>Siemens AG Energy</td>
<td>Mülheim</td>
</tr>
<tr>
<td>Dr.-Ing. Werner Heinrich</td>
<td>Siemens AG Energy</td>
<td>Berlin</td>
</tr>
<tr>
<td>Dr. Johannes Vrana</td>
<td>Siemens AG Energy</td>
<td>München</td>
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#### Research Institutes

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<tr>
<th>Name</th>
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<tr>
<td>Dr. Gerhard Brekow</td>
<td>BAM</td>
<td>Berlin</td>
</tr>
<tr>
<td>Wolfgang Kappes</td>
<td>Fraunhofer IZFP</td>
<td>Saarbrücken</td>
</tr>
<tr>
<td>Hans Rieder</td>
<td>Fraunhofer ITWM</td>
<td>Kaiserslautern</td>
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Definition of an Examination Grid Situation

Longitudinal Section

- Longitudinal section through adjacent beams

Horizontal Section

A: Directly at the probe

B: At the end of the near field

C: At 3.5 times near field
Definition of an Examination Grid
Normalized Grid Rating $R_n$

Definition of $R_n$

$$\frac{1}{R_n} = \frac{d_x^2}{D_x^2} + \frac{d_y^2}{D_y^2}$$

$R_n = 1 –$ Gapless (at least single sampling)

- $d_x$: Increment in scan direction
- $d_y$: Distance between two adjacent laps in index direction
- $D_x, D_y$: Dimensions of the ultrasonic beam
### Definition of an Examination Grid

**Normalized Grid Rating \( R_n \)**

<table>
<thead>
<tr>
<th>Definition of ( R_n )</th>
<th>( R_n = 2 ) – At least double sampling</th>
</tr>
</thead>
</table>
| \[
\frac{1}{R_n} = \frac{d_x^2}{D_x^2} + \frac{d_y^2}{D_y^2}
\] | |

- \( d_x \): Increment in scan direction
- \( d_y \): Distance between two adjacent laps in index direction
- \( D_x, D_y \): Dimensions of the ultrasonic beam

---

**Diagram:**
- \( D_x \)
- \( D_y \)
- \( d_x \)
- \( d_y \)
### Definition of an Examination Grid

**Normalized Grid Rating \( R_n \)**

<table>
<thead>
<tr>
<th>Definition of ( R_n )</th>
<th>( R_n = 0.5 ) – Beams touching</th>
<th>( R_n = 1 ) – Gapless</th>
</tr>
</thead>
</table>
| \[
\frac{1}{R_n} = \frac{d_x^2}{D_x^2} + \frac{d_y^2}{D_y^2}
\] | ![Image of beams touching](image1.png) | ![Image of gapless](image2.png) |
| \( R_n = 2 \) – Double Sampling | \( R_n = 4 \) – Quadruple Sampling |
| ![Image of double sampling](image3.png) | ![Image of quadruple sampling](image4.png) |

- \( d_x \): Increment in scan direction
- \( d_y \): Distance between two adjacent laps in index direction
- \( D_x, D_y \): Dimensions of the ultrasonic beam

**Overlap:**

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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ECNDT 2014

Dr. Johannes Vrana
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Average Grid Rating $R_d$

**Definition of $R_d$**

$$R_d = \frac{D_x \cdot D_y \cdot \pi}{4}$$

**Example: $R_d = 1$**

- $d_x$: Increment in scan direction
- $d_y$: Distance between two adjacent laps in index direction
- $D_x$, $D_y$: Dimensions of the ultrasonic beam

Area of $-6$ dB beam

Examintion Grid

Area of ex. grid
### Definition of an Examination Grid

#### Average Grid Rating \( R_d \)

<table>
<thead>
<tr>
<th>Definition of ( R_d )</th>
<th>( R_n = 1; R_d \approx 1.81 )</th>
<th>( R_n = 1; R_d \approx 1.57 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ R_d = \frac{D_x}{d_x} \cdot \frac{D_y}{d_y} \cdot \frac{\pi}{4} ]</td>
<td>![Diagram 1]</td>
<td>![Diagram 2]</td>
</tr>
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</table>

- \( d_x \): Increment in scan direction
- \( d_y \): Distance between two adjacent laps in index direction
- \( D_x, D_y \): Dimensions of the ultrasonic beam

\( \Rightarrow \) Optimized Examination Grid
Definition of an Examination Grid

Average Grid Rating $R_d$

Definition of $R_d$

$$R_d = \frac{D_x}{d_x} \cdot \frac{D_y}{d_y} \cdot \frac{\pi}{4}$$

Optimized Examination Grid

- Optimized examination grid in the case of:
  $$d_x = \frac{D_x}{\sqrt{(2 \cdot R_n)}} \quad \text{and} \quad d_y = \frac{D_y}{\sqrt{(2 \cdot R_n)}}$$

- $d_x$: Increment in scan direction
- $d_y$: Distance between two adjacent laps in index direction
- $D_x, D_y$: Dimensions of the ultrasonic beam

Optimizing the Examination Grid
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• Longitudinal section through adjacent beams

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Grid Rating

\[
\frac{1}{R_n} = \frac{d_x^2}{D_x^2} + \frac{d_y^2}{D_y^2} \\
R_d = \frac{D_x}{d_x} \cdot \frac{D_y}{d_y} \cdot \frac{\pi}{4}
\]
Definition of an Examination Grid
How to calculate the sound bundle – Basic Situation

Normal Straight Beam Probe on a Plane Surface

\[ D = 2 \cdot s \cdot \tan(\varphi) \]

Dual Element Probe on a Plane Surface

\[ D_x = 2 \cdot FB_6 \quad D_y = 2 \cdot FL_6 \]

- \( d_x \): Increment in scan direction
- \( d_y \): Distance between two adjacent laps in index direction
- \( D_x, D_y \): Dimensions of the ultrasonic beam
- \( s \): Soundpath
- \( FB_6, FL_6 \): Focal Width & Length
Definition of an Examination Grid Situation

Scans

- Different scans required

![Scans Diagram]

radial
radial / axial
axial/radial
axial
radial
radial / tangential
axial / radial
axial / tangential
## Definition of an Examination Grid Situation

<table>
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<th>Convex</th>
<th>Concave</th>
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<tr>
<td>Angle</td>
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</table>
Definition of an Examination Grid
How to calculate the sound bundle

Angle Probe on a Plane Surface

• Probe moved on the surface of the component

• Examination grid $d_x$ an $d_y$ established at the surface

• Beam changes within the part

$D_x' = \frac{2 \cdot s \cdot \cos(\alpha) \cdot \sin(2 \cdot \varphi)}{\cos(2 \cdot \varphi) + \cos(2 \cdot \alpha)}$

⇒ For the calculation of the examination grid the projection of the beam to the surface is necessary
Definition of an Examination Grid
How to calculate the sound bundle

Angle Probe on a Plane Surface

• Probe moved on the surface of the component
• Examination grid $d_x$ an $d_y$ established at the surface
• Beam changes within the part

\[
D'_x = \frac{2 \cdot s \cdot \cos(\alpha) \cdot \sin(2 \cdot \varphi)}{\cos(2 \cdot \varphi) + \cos(2 \cdot \alpha)}
\]

\[
D_y = 2 \cdot s \cdot \tan(\varphi)
\]
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Definition of an Examination Grid
How to calculate the sound bundle

Normal Straight Beam Probe on Convex Surface

\[ D = 2 \cdot s \cdot \tan (\varphi) \quad D_y = 2 \cdot s \cdot \tan (\varphi) \]

\[ D_x' = \left( \arcsin \left( \frac{D_1}{D_1 - 2 \cdot s} \cdot \sin(\varphi) \right) \pm \varphi \right) \cdot \frac{\pi}{180^\circ} \cdot D_1 \]

Dual Element Probe on Convex Surface

\[ D_x = 2 \cdot FB_6 \quad D_y = 2 \cdot FL_6 \]

Corrected by:

\[ D_x' = \frac{D_x \cdot D_1}{|D_1 - 2 \cdot s|} \]
Definition of an Examination Grid
How to calculate the sound bundle

Angle Probe on a Convex Surface

• E.g. from the outer diameter surface $D_1$

$$D_1' = \left( \arcsin \left( \frac{D_1/2}{r} \cdot \sin(\alpha + \varphi) \right) - \arcsin \left( \frac{D_1/2}{r} \cdot \sin(\alpha - \varphi) \right) \pm 2 \cdot \varphi \right) \cdot \frac{\pi}{180^\circ} \cdot \frac{D_1}{2}$$

with

$$r = \sqrt{s^2 + (D_1/2)^2 - 2 \cdot s \cdot (D_1/2) \cdot \cos(\alpha)}$$

and

$$r \geq \begin{cases} D_1/2 \sin(\alpha + \varphi) & \text{for } \alpha > 0 \\ D_1/2 \sin[\varphi] & \text{for } \alpha = 0 \\ D_1/2 \sin[\alpha - \varphi] & \text{for } \alpha < 0 \end{cases}$$

with

$$D_1'' = \begin{cases} \text{in the case } & s > D_1/2 \cdot \cos(\alpha) \\ \text{in the case } & s \leq D_1/2 \cdot \cos(\alpha) \end{cases}$$

$$D_1' = 2 \cdot s \cdot \tan(\varphi)$$
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Definition of an Examination Grid
How to calculate the sound bundle

Normal Straight Beam Probe on Concave Surface

\[ D_y = 2 \cdot s \cdot \tan(\varphi) \]

\[ D_x' = \left( \varphi - \arcsin \left( \frac{D_2}{D_2 - 2 \cdot s} \cdot \sin(\varphi) \right) \right) \cdot \frac{\pi}{180} \cdot D_2 \]

Dual Element Probe on Concave Surface

\[ D_x = 2 \cdot FB_6 \]

\[ D_y = 2 \cdot FL_6 \]

Corrected by:

\[ D_x' = \frac{D_x \cdot D_2}{D_2 + 2 \cdot s} \]
Definition of an Examination Grid
How to calculate the sound bundle

Angle Probe on a Concave Surface

• E.g. from the inner diameter surface $D_2$

\[
D_s^* = \left( \arcsin \left( \frac{D_2 f^2}{r} \cdot \sin(\alpha + \phi) \right) - \arcsin \left( \frac{D_s f^2}{r} \cdot \sin(\alpha - \phi) \right) + 2 \cdot \phi \right) \cdot \frac{\pi}{180} \cdot \frac{D_2}{2}
\]

with $r = \sqrt{s^2 + (D_s f^2)^2 + 2 \cdot s \cdot (D_s f^2) \cdot \cos(\alpha)}$

\[
D_s = 2 \cdot s \cdot \tan(\phi)
\]
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Determination of the Examination Grid

Necessary Specifications

• For each scan
  • Normalized Grid Rating $R_n$ (gapless recommended)
  • Examination zone
    • Minimum soundpath $s_1$
    • Maximum soundpath $s_2$
Determination of the Examination Grid

Necessary Specifications

• For each scan
  • Normalized Grid Rating $R_n$ (gapless recommended)
  • Examination zone
    • Minimum soundpath $s_1$
    • Maximum soundpath $s_2$

Determination of Examination Grid

• Calculation of the projection of the sound bundle dimensions both for $s_1$ and $s_2$
  • $s_1$: $D_{x1}$, $D_{y1}$
  • $s_2$: $D_{x2}$, $D_{y2}$
• Calculation of the optimized examination grid both for $s_1$ and $s_2$ considering the specified normalized examination grid rating $R_n$
  • $s_1$: $d_{x1}$, $d_{y1}$
  • $s_2$: $d_{x2}$, $d_{y2}$
• Selection of the actually used examination grid $d_x$ and $d_y$
Determination of the Examination Grid

Determination of Examination Grid

• Calculation of the projection of the sound bundle dimensions both for \( s_1 \) and \( s_2 \)
  • \( s_1 : D_{x_1}, D_{y_1} \)
  • \( s_2 : D_{x_2}, D_{y_2} \)
• Calculation of the optimized examination grid both for \( s_1 \) and \( s_2 \) considering the specified normalized examination grid rating \( R_n \)
  • \( s_1 : d_{x_1}, d_{y_1} \)
  • \( s_2 : d_{x_2}, d_{y_2} \)
• Selection of the actually used examination grid \( d_x \) and \( d_y \)

Check of Examination Grid

• OK if both selected values are not bigger than the calculated values
  • \( d_x \) vs. \( d_{x_1}, d_{x_2} \)
  • \( d_y \) vs. \( d_{y_1}, d_{y_2} \)
• Otherwise needs to be tested by calculating \( R_n \) using \( d_x \) and \( d_y \) for both \( D_{x_1}, D_{y_1} \) and \( D_{x_2}, D_{y_2} \)
Determination of the Examination Grid

Example

Disc

\[ D_1 = 1500 \text{ mm}, \quad D_2 = 300 \text{ mm}, \quad L = 300 \text{ mm} \]

Examination Grid

<table>
<thead>
<tr>
<th>Scan</th>
<th>( s_1 ) (mm)</th>
<th>( s_2 ) (mm)</th>
<th>( D'_{x1} ) (mm)</th>
<th>( D'_{x2} ) (mm)</th>
<th>( D_{y1} ) (mm)</th>
<th>( D_{y2} ) (mm)</th>
<th>( R_n )</th>
<th>( d_{x1} ) (mm)</th>
<th>( d_{x2} ) (mm)</th>
<th>( d_{y1} ) (mm)</th>
<th>( d_{y2} ) (mm)</th>
<th>( d_x ) (mm)</th>
<th>( d_y ) (mm)</th>
<th>( R_{n1} )</th>
<th>( R_{n2} )</th>
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<tbody>
<tr>
<td>Faces, axial, straight</td>
<td>100</td>
<td>300</td>
<td></td>
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<td>1</td>
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</table>
## Determination of the Examination Grid

**Example**

**Disc**

\[ D_1 = 1500 \text{ mm}, \quad D_2 = 300 \text{ mm}, \quad L = 300 \text{ mm} \]

<table>
<thead>
<tr>
<th>Examination Grid</th>
<th>s₁ (mm)</th>
<th>s₂ (mm)</th>
<th>D'ₓ₁ (mm)</th>
<th>D'ₓ₂ (mm)</th>
<th>Dᵧ₁ (mm)</th>
<th>Dᵧ₂ (mm)</th>
<th>Rₙ</th>
<th>dₓ₁ (mm)</th>
<th>dₓ₂ (mm)</th>
<th>dᵧ₁ (mm)</th>
<th>dᵧ₂ (mm)</th>
<th>dₓ (mm)</th>
<th>dᵧ (mm)</th>
<th>Rₙ₁</th>
<th>Rₙ₂</th>
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<tr>
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<td>100</td>
<td>300</td>
<td>12.9</td>
<td>38.8</td>
<td>12.9</td>
<td>38.8</td>
<td>1</td>
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</table>
## Determination of the Examination Grid

**Example**

**Disc**

\[ D_1 = 1500 \text{ mm}, \quad D_2 = 300 \text{ mm}, \quad L = 300 \text{ mm} \]

**Examination Grid**

<table>
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<tr>
<th>Scan</th>
<th>( s_1 ) (mm)</th>
<th>( s_2 ) (mm)</th>
<th>( D'_{x1} ) (mm)</th>
<th>( D'_{x2} ) (mm)</th>
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<th>( D_{y2} ) (mm)</th>
<th>( R_n )</th>
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<th>( d_y ) (mm)</th>
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<td>9.1</td>
<td>27.4</td>
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Determination of the Examination Grid

Example

Disc

\[ D_1 = 1500 \text{ mm}, \quad D_2 = 300 \text{ mm}, \quad L = 300 \text{ mm} \]

<table>
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<tr>
<th>Examination Grid</th>
<th>s_1 (mm)</th>
<th>s_2 (mm)</th>
<th>( D'_{x1} ) (mm)</th>
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<th>( d_{y} ) (mm)</th>
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<th>( R_{n1} )</th>
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## Determination of the Examination Grid

**Example**

**Disc**

\[ D_1 = 1500 \text{ mm}, \quad D_2 = 300 \text{ mm}, \quad L = 300 \text{ mm} \]

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<th>( D_{y_1} ) (mm)</th>
<th>( D_{y_2} ) (mm)</th>
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**Determination of the Examination Grid Example**

Disc

\[ D_1 = 1500 \text{ mm}, \quad D_2 = 300 \text{ mm}, \quad L = 300 \text{ mm} \]

**Examination Grid**

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<th>( s_2 ) (mm)</th>
<th>( D'_{x1} ) (mm)</th>
<th>( D'_{x2} ) (mm)</th>
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<th>( D_{y2} ) (mm)</th>
<th>( R_n )</th>
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<th>( d_{x2} ) (mm)</th>
<th>( d_{y1} ) (mm)</th>
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<th>( d_y ) (mm)</th>
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<td>OD, radial, straight</td>
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</table>
## Determination of the Examination Grid

Example

**Disc**

\[D_1 = 1500 \text{ mm}, \quad D_2 = 300 \text{ mm}, \quad L = 300 \text{ mm}\]

### Examination Grid

<table>
<thead>
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<th>Scan</th>
<th>(s_1) (mm)</th>
<th>(s_2) (mm)</th>
<th>(D_{x1}) (mm)</th>
<th>(D_{x2}) (mm)</th>
<th>(D_{y1}) (mm)</th>
<th>(D_{y2}) (mm)</th>
<th>(R_n)</th>
<th>(d_{x1}) (mm)</th>
<th>(d_{x2}) (mm)</th>
<th>(d_{y1}) (mm)</th>
<th>(d_{y2}) (mm)</th>
<th>(d_x) (mm)</th>
<th>(d_y) (mm)</th>
<th>(R_{n1})</th>
<th>(R_{n2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faces, axial, straight</td>
<td>100</td>
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</table>
# Determination of the Examination Grid Example

## Disc

\( D_1 = 1500 \text{ mm}, \; D_2 = 300 \text{ mm}, \; L = 300 \text{ mm} \)

<table>
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<tr>
<th>Scan</th>
<th>( s_1 ) (mm)</th>
<th>( s_2 ) (mm)</th>
<th>( D'_{x1} ) (mm)</th>
<th>( D'_{x2} ) (mm)</th>
<th>( D'_{y1} ) (mm)</th>
<th>( D'_{y1} ) (mm)</th>
<th>( R_n )</th>
<th>( d_{x1} ) (mm)</th>
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<th>( d_x ) (mm)</th>
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<tr>
<td>Faces, axial, straight</td>
<td>100</td>
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<td>12.9</td>
<td>38.8</td>
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</tr>
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</table>
## Determination of the Examination Grid

### Example

**Disc**

\[ D_1 = 1500 \text{ mm}, \ D_2 = 300 \text{ mm}, \ L = 300 \text{ mm} \]

| Examination Grid | Scan | \( s_1 \) (mm) | \( s_2 \) (mm) | \( D_{x1} \) (mm) | \( D_{x2} \) (mm) | \( D_{y1} \) (mm) | \( D_{y2} \) (mm) | \( R_n \) | \( d_{x1} \) (mm) | \( d_{x2} \) (mm) | \( d_{y1} \) (mm) | \( d_{y2} \) (mm) | \( d_x \) (mm) | \( d_y \) (mm) | \( R_{n1} \) | \( R_{n2} \) |
|------------------|------|----------------|----------------|-----------------|-----------------|-----------------|-----------------|------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|------|----------------|
| Faces, axial, straight | 100  | 300  | 12.9  | 38.8 | 12.9  | 38.8 | 1 | 9.1  | 27.4 | 9.1  | 27.4 | 9  | 9  | 1.03  | 9.3  |
| Faces, axial/tang., 45° | 100  | 424  | 13.4  | 40.1 | 6.6  | 19.9 | 1 | 9.5  | 40.1 | 4.7  | 19.9 | 9  | 4.5 | 1.09  | 9.8  |
| OD, radial, straight | 120  | 600  | 20.4  | 393  | 15.5  | 77.6 | 1 | 13.1 | 280  | 11.0 | 55  | 13  | 10.5 | 1.05  | 52   |
| OD, radial, straight, dual-element, | 5  | 120  | 5    | 14   | 1    | 3.6 | 9.9 | 3.5  | 10  | 1.02 |
| OD, radial/tang., 14° | 120  | 728  | 21.3  | -    | 15.5  | -   | 2 | 9.6  | -   | 7.8  | -   | 9.5 | 7.5  | 2.1  | -   |
| OD, radial/tang., 45° | 350  | 1061 | 161  | 141  | 24    | 70  | 1 |       |       |       |       |       |       |       |       |

\[ D_1 = 1500 \text{ mm}, \ D_2 = 300 \text{ mm}, \ L = 300 \text{ mm} \]
**Determination of the Examination Grid Example**

**Disc**

\[ D_1 = 1500 \text{ mm}, \quad D_2 = 300 \text{ mm}, \quad L = 300 \text{ mm} \]

**Examination Grid**

<table>
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<th>s_2 (mm)</th>
<th>D'_x1 (mm)</th>
<th>D'_x2 (mm)</th>
<th>D_y1 (mm)</th>
<th>D_y2 (mm)</th>
<th>R_n (mm)</th>
<th>d_x1 (mm)</th>
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## Determination of the Examination Grid

**Example**

### Disc

\[ D_1 = 1500 \text{ mm}, \quad D_2 = 300 \text{ mm}, \quad L = 300 \text{ mm} \]

### Examination Grid

<table>
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### Determination of the Examination Grid Example

**Disc**

\[D_1 = 1500 \text{ mm}, \ D_2 = 300 \text{ mm}, \ L = 300 \text{ mm}\]

#### Examination Grid

<table>
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<tr>
<th>Scan</th>
<th>(s_1) (mm)</th>
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### Determination of the Examination Grid

Example

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\[ D_1 = 1500 \text{ mm}, \quad D_2 = 300 \text{ mm}, \quad L = 300 \text{ mm} \]

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Determination of an Optimal Examination Grid for the Automated Ultrasonic Inspection of Heavy Rotor Forgings

- Introduction & Motivation
- Requirements in Current Standards
- Definition of an Examination Grid
  - Normalized Grid Rating $R_n$
  - Average Grid Rating $R_d$
- Determination of the Ultrasonic Beam Dimensions
- Determination of the Examination Grid
- Summary
Determination of an Optimal Examination Grid for the Automated Ultrasonic Inspection of Heavy Rotor Forgings

Summary

• Current standards
  • Not sufficient for the determination of an examination grid for automated UT

• New DGZfP Guideline “US 07”
  • Harmonizes the calculation of the examination grid
  • Defines
    • Normalized Grid Rating
    • Average Grid Rating
    • How to calculate the UT beam dimensions
  • Optimizes the inspection speed

• Can be adopted to other applications
Thanks for paying attention to all the formulas.

\[ D_x' = \left( \arcsin \left( \frac{D_1}{D_1 - 2 \cdot s} \cdot \sin(\varphi) \right) \pm \varphi \right) \cdot \frac{\pi}{180^\circ} \cdot D_1 \]

\[ R_n = \frac{1}{D_x'^2 + D_y'^2} \]

\[ D_y' = \frac{D x \cdot D_1}{|D_1 - 2 \cdot s|} \]

\[ D_x' = \left( \arcsin \left( \frac{D_1/2}{r} \cdot \sin(\alpha + \varphi) \right) - \arcsin \left( \frac{D_1/2}{r} \cdot \sin(\alpha - \varphi) \right) \right) \cdot \frac{\pi}{180^\circ} \cdot \frac{D_1}{2} \]

with \( r = \sqrt{s^2 + (D_1/2)^2 - 2 \cdot s \cdot (D_1/2) \cdot \cos(\alpha)} \)

and \( r \geq \begin{cases} \frac{D_1}{2} \sin(\alpha + \varphi) & \text{for } \alpha > 0 \\ \frac{D_1}{2} \sin(\alpha - \varphi) & \text{for } \alpha < 0 \\ \frac{D_1}{2} \sin|\alpha| & \text{for } \alpha = 0 \end{cases} \)

with \( D_x' \) in the case \( s > D_1/2 \cdot \cos(\alpha) \)

and \( D_x' \) in the case \( s \leq D_1/2 \cdot \cos(\alpha) \)

\[ D' = \frac{2 \cdot s \cdot \cos(\alpha) \cdot \sin(2 \cdot \varphi)}{\cos(2 \cdot \varphi) + \cos(2 \cdot \alpha)} \]

\[ R_d = \frac{D x}{d x} \cdot \frac{D y}{d y} \cdot \frac{\pi}{4} \]