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

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Abstract

Heavy rotor forgings, in particular for the power generation market, are highly stressed components and the ultrasonic inspection is the most important method to guarantee a sufficient material quality throughout the volume. This is why more and more heavy rotor forgings have to be inspected using automated inspection systems guaranteeing a high probability of detection for possible flaws, good documentation as well as highly repeatable inspection.

In contrast to manual inspection, automated inspection does not allow for an optimization of a flaw reflection by moving the probe, as the probe is continuously moved over the part surface in distinct scan lines, resulting in a distinct pattern of inspection points. To ensure full volume coverage using overlapping ultrasonic beams from neighboring inspection points, a precise definition of an examination grid is required.

To assure that all critical errors are detected, multiple scan directions have to be applied as per VGB-R 504 M [1] to inspect the complete volume, resulting in a high inspection duration. Moreover most of the rotor forgings have a low sound attenuation, resulting in low pulse repetition rates and even longer inspection times. An ideal inspection grid will therefore make sure the full forging volume is covered by the inspection and reduce the inspection duration to a necessary minimum at the same time.

Several standards currently specify an examination grid for manual inspection, which are not simply transferrable to automated inspection.

This paper presents a solution to this problem, developed by the subcommittee “Automated UT” of the national German society for NDE (DGZfP).

Keywords: UT, ultrasonic testing, automated, optimization, examination grid, phased-array, forgings, steel, shafts, discs, power generation

Figure 1: Automated shaft and disc inspection system [2]
1. Introduction

Rotating forgings like gas and steam turbine rotors, generator shafts, and wind turbine shafts are usually highly stressed both from a mechanical and a thermal standpoint. To satisfy the ever higher need for power-output, efficiency and start-up-time, while providing a longer life time, the requirements for rotor forgings and in particular for the inspection increased over the last decades [3] leading to the requirement to use automated inspection systems [4] (see Fig. 1).

One of the key factors determining the reliability of an ultrasonic inspection is the examination grid, meaning the distance between two adjacent pulses in scanning direction $d_x$ and the distance between two adjacent laps in index direction $d_y$. However the current requirements for this key factor are unsatisfactory for automated inspections, as shown in the following.

2. Requirements in Current Standards

The analysis of the requirements established in current standards shows which aspects need to be detailed for automated inspections:

SEP1923 [5] requires adjacent laps to overlap by at least 15% of the size of the active element. Apparently, as no requirements are given in scanning direction, SEP1923 assumes a high pulse-repetition-rate and slow probe movement (SEP1923 requires for manual inspections that the scanning speed should not exceed 100 mm/s). Moreover the shape and size of the sound bundle are not taken into account.

The requirements of EN 10228-3[6] are very similar to SEP1923 – only it requires an overlap of at least 10% of the effective active element size and a maximum scan speed of 150 mm/s for manual inspections. For automated inspection both EN 10228-3 and SEP1923 have no requirement for a maximum scan speed.

![Figure 2: -6 dB sound bundles touching. Zones not covered by the -6 dB sound bundles are shaded.](image)

$(D_x, D_y$: -6 dB sound bundle diameter in x and y direction $d_x, d_y$: increment in x and y direction) [2]
Similar to SEP1923 and EN 10228-3, ASTM A 418 \([7]\) requires “the search unit shall be indexed approximately 75% of the transducer width with each pass of the search unit” with a maximum scanning speed for both manual and automated inspection of 152.4 mm/s.

While SEP1923, EN 10228-3, and ASTM A 418 base the requirements on the size of the probe in index direction, EN 583-1 \([8]\) and the IIW Handbook Automated Ultrasonic Testing Systems \([9]\) take the size of the -6 dB sound beam in scan and index direction within the component into account. These standards require touching of adjacent -6 dB ultrasonic beams within the inspection volume with an inspection speed adapted to the minimum sound beam dimensions and the pulse repetition rate.

ASTM E 2375 \([10]\) finally is also based on the -6 dB sound beam and it requires an overlap of at least 20% of the effective beam width size in index direction and limits the scanning speed by the detectability of the reference reflectors.

As most heavy rotor forgings show a low sound attenuation, low pulse-repetition-rates are used, meaning that the requirements of SEP1923, EN 10228-3, and ASTM A 418 are not appropriate for the inspection of heavy rotor forgings. The requirements of EN 583-1 and the IIW Handbook Automated Ultrasonic Testing Systems are better suited however they only require that the -6 dB sound bundles touch. This leads to the situation that some zones are not inspected with the required sensitivity (see Fig 2). The requirements established in ASTM E 2375 lead to a very similar situation resulting that some zones are not inspected with the required sensitivity (even that they are smaller compared to EN 583-1 and the IIW Handbook). Moreover, compared to all existing standards, it would be helpful for the calculation of the examination grid to provide the necessary formulas.

3. Definition of an Examination Grid

To establish an appropriate examination grid for heavy rotor forgings the subcommittee automated UT within the German Society of Non-Destructive Testing (DGZfP) started the development of rules for the determination of an optimal examination grid including the necessary math. The standard is currently in review and will be published by DGZfP soon \([2]\). This paper gives an overview of the results.

An examination grid is defined by the movement in two directions: scan and index. Hereby the increment in scan direction between one ultrasonic pulse and the next is \(d_s\) and the distance between two adjacent laps in index direction is \(d_y\). The form of an ultrasonic beam at a particular soundpath \(s\) can be simplified by an ellipse with the dimensions \(D_x(s)\) and \(D_y(s)\) (see Fig. 2 – \(D_x(s)\) and \(D_y(s)\) represent the -6 dB beam dimensions in scan and index direction). Therefore the grid at a certain soundpath \(s\) is defined by those four parameters (\(d_s\), \(d_y\), \(D_x(s)\), and \(D_y(s)\)).

Due to the beam spread the overlap is in general higher for a longer sound path. However in the case of curved surfaces and angle probes, the overlap can actually increase or decrease at long soundpaths, compared to flat surfaces. Therefore an inspection volume must be specified, defined by a minimum and maximum soundpath \((s_1\) and \(s_2)\), wherein the chosen examination grid must fulfill the overlap requirements.

The following will first show how a given examination grid can be rated, second how to calculate the sound beam dimensions for different scan situations and finally give a guide how to use this knowledge to establish an optimal examination grid for the inspection.
### 3.1 Examination Grid Rating

To rate the quality of a selected grid \((d_x, d_y)\) for a certain inspection situation with the -6 dB beam dimensions \((D_x(s), D_y(s))\), two rating factors are introduced. The normalized grid rating \(R_n\) gives the minimum number of pulses of a particular scan sampling every point in the inspected volume. The average grid rating \(R_d\) on the other hand defines how often (in average) each point is sampled. It is important to understand that a high average rating does not ensure that the complete volume is inspected. Therefore \(R_n\) is the requirement to guarantee a sufficient overlap, \(R_d\) is optional to help establishing an optimal examination grid.

#### 3.1.1 Normalized Examination Grid Rating

The normalized examination grid rating \(R_n\) is defined by:

\[
R_n = \frac{D_x^2 D_y^2}{D_x^2 d_x^2 + D_y^2 d_y^2}.
\]

![Figure 3: Different normalized examination grid ratings \(R_n\)]

- upper left: \(R_n = 0.5\) (ultrasonic beams touching);
- upper right: \(R_n = 1\) (at least single sampling \(\equiv\) gapless);
- lower left: \(R_n = 2\) (at least double sampling);
- lower right: \(R_n = 4\) (at least quadruple sampling)

(Red: No inspection; Gray: at least single sampling (darker = more often)) [2]

Using this definition \(R_n = 1\) guarantees a gapless inspection, every point is inspected at least one time. \(R_n = 2\) results in double sampling, meaning every point is at least inspected twice (see Fig. 3).

Ultrasonic inspection specifications can reference the new examination grid standard by the definition of \(R_n\) along with the definition of an inspection volume. For most inspections \(R_n = 1\) will be sufficient. However some inspection situations may require a different \(R_n\).

For a given \(R_n\), for every part, scan, probe and scan direction the -6 dB beam dimensions \((D_x, D_y)\) within the inspection volume allow for the selection of a grid \((d_x, d_y)\). The ratio between \(d_x\) and \(d_y\) is then used to optimize the examination grid for a minimum \(R_d\) and thus for a minimum inspection time.
3.1.2 Average Examination Grid Rating

\( R_d \) is defined as:

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

and defines how often (in average) each point is sampled. Meaning the higher \( R_d \) the more pulses are necessary to cover the complete surface. The example in Fig. 4 shows an optimized grid on the left hand, and a grid with a \( \sim 15\% \) higher inspection cost on the right side, both cases with the identical normalized grid rating \( R_n \).

![Figure 4: Different average examination grid ratings \( R_d \) left: \( R_n = 1; R_d = \pi/2 \approx 1.6 \); right: \( R_n = 1; R_d = \pi/\sqrt{3} \approx 1.8 \) [2]]

In most cases the optimal grid will be achieved with a minimum \( R_d \) when selecting:

\[
d_x = \frac{D_x}{\sqrt{(2 \cdot R_n)}} \quad \text{and} \quad d_y = \frac{D_y}{\sqrt{(2 \cdot R_n)}}.
\]  

By the definition of the two different examination grid ratings, a sufficient overlap can be guaranteed while minimizing the inspection effort at the same time.

3.2 Determination of the Ultrasonic Beam Dimensions

To establish an examination grid using both rating factors, the first step is the calculation of the beam diameters \( D_x(s) \) and \( D_y(s) \) for the sound path \( s \) within the volume to be inspected. The following text shows how to calculate the beam dimensions using geometrical considerations and providing analytical solutions. If available, simulation results can be used to replace those solutions.

In the far field the determination of the beam diameters \( D_x(s) \) and \( D_y(s) \) of normal straight beam probes on a plane inspection surface is based on the probes angle of divergence \( \varphi \):

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

For dual element probes the calculation is usually based on the size of the focal point

\[
D_x = 2 \cdot FB \quad \text{and} \quad D_y = 2 \cdot FL.
\]
The examination grid is always established on the inspection surface. Therefore the projections of the beam diameters to the surface have to be used. In case of straight beam probes on plane inspection surfaces the projection diameters are equal to the beam diameter. For the calculation of the beam diameters in case of curved inspection surfaces or angle beam probes, the following shows how to calculate the projections of the beam diameters. To simplify the understanding we will calculate the projected beam diameters $D'$, and then use these to replace the beam diameters $D_x$ and $D_y$ to determine the examination grid ratings.

### 3.2.1 Angle Probe on a Plane Surface

Figure 5 shows an angle beam probe with the probe angle $\alpha$ and the beam spread $\varphi$ on a plane surface. To calculate the effective beam diameter, the beam width at sound path $s$ is projected to the inspection surface, yielding a projected beam diameter

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

(6)

![Figure 5: Projection of the -6 dB beam bundles to the examination surface [2]](image)

### 3.2.2 Normal Probe on a Plane Surface

In case of straight beam probes on plane inspection surfaces the projected diameter is equal to the normal beam diameter

$$D' = D.$$  

(7)
### 3.2.3 Angle Probe on a Convex Surface (for example: OD)

Inspecting a heavy rotor forging from a convex surface, e.g. in radial-tangential direction from the outer diameter surface, the situation is shown in Fig. 6 with the outer diameter $D_1$.

![Figure 6: Projection of the -6 dB beam bundles to a convex examination surface [2](image)](image)

This leads to the following mathematical solution:

$$D' = \left( \arcsin \left( \frac{D_1}{2r} \cdot \sin(\alpha + \varphi) \right) - \arcsin \left( \frac{D_1}{2r} \cdot \sin(\alpha - \varphi) \right) \pm 2 \cdot \varphi \right) \frac{\pi}{180^\circ} \cdot \frac{D_1}{2} \tag{8}$$

with

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

and

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

with $D'_+$ which has to be used in the case $s > D_1/2 \cdot \cos(\alpha)$

and $D'_-$ in the case $s \leq D_1/2 \cdot \cos(\alpha)$.

### 3.2.4 Straight Beam Probe on a Convex Surface

This case simplifies the solution of the general case in equation 8 with $\alpha = 0^\circ$:

$$D' = \left( \arcsin \left( \frac{D_1}{D_1 - 2 \cdot s} \cdot \sin(\varphi) \right) \pm \varphi \right) \frac{\pi}{180^\circ} \cdot D_1 \tag{9}$$

with $D'_+$ which has to be used in the case $s > D_1/2$

and $D'_-$ in the case $s \leq D_1/2$. 
3.2.5 Dual Element Probes on a Convex Surface

For the projected dimension of a dual element probe on a convex surface the following formula shall be used:

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

(10)

3.2.6 Angle Probe on a Concave Surface (for example: ID)

In the case of an inspection from a concave surface, for example when inspecting from the surface of a central bore \(D_2\) the projected beam diameter can be calculated using the following solution (see Fig. 7):

\[
D' = \left( \arcsin\left(\frac{D_2/2}{r} \cdot \sin(\alpha + \varphi)\right) - \arcsin\left(\frac{D_2/2}{r} \cdot \sin(\alpha - \varphi)\right) + 2 \cdot \varphi \right) \cdot \frac{\pi}{180} \cdot \frac{D_2}{2}
\]  

(11)

with

\[ r = \sqrt{s^2 + \left(\frac{D_2}{2}\right)^2 + 2 \cdot s \cdot \left(D_2/2\right) \cdot \cos(\alpha)}. \]

Figure 7: Projection of the -6 dB beam bundles to a concave examination surface [2]

3.2.7 Normal Probe on a Concave Surface

This solution simplifies in the case of a probe with \(\alpha = 0^\circ\):

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

(12)

3.2.8 Normal Probe on a Concave Surface

For the projected dimension of a dual element probe on a concave surface the following formula shall be used:

\[ D' = \frac{D \cdot D_2}{(D_2 + 2 \cdot s)}. \]  

(13)
3.2.9 Normal Probe on a Concave Surface

Depending on the scans different formulas have to be used in scanning and index direction to determine the dimensions of the sound bundle $D_x$ and $D_y$. Table 1 summarizes which formulas are applicable:

**Table 1: Formulas to use for the calculation of the sound bundle dimensions for different scans**

<table>
<thead>
<tr>
<th>Scan from</th>
<th>Sound propagation direction</th>
<th>Scanning direction $D_x$</th>
<th>Index direction $D_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faces</td>
<td>axial</td>
<td>(4)</td>
<td>(4)</td>
</tr>
<tr>
<td></td>
<td>axial dual element</td>
<td>(5)</td>
<td>(5)</td>
</tr>
<tr>
<td></td>
<td>axial / radial</td>
<td>(4)</td>
<td>(6)</td>
</tr>
<tr>
<td></td>
<td>axial / tangential</td>
<td>(6)</td>
<td>(4)</td>
</tr>
<tr>
<td>Outer Diameter</td>
<td>radial</td>
<td>(9)</td>
<td>(4)</td>
</tr>
<tr>
<td></td>
<td>axial dual element</td>
<td>(10) with (5)</td>
<td>(5)</td>
</tr>
<tr>
<td></td>
<td>radial / axial</td>
<td>(9)</td>
<td>(6)</td>
</tr>
<tr>
<td></td>
<td>radial / tangential</td>
<td>(8)</td>
<td>(4)</td>
</tr>
<tr>
<td>Inner Diameter</td>
<td>radial</td>
<td>(12)</td>
<td>(4)</td>
</tr>
<tr>
<td></td>
<td>radial dual element</td>
<td>(13) with (5)</td>
<td>(5)</td>
</tr>
<tr>
<td></td>
<td>radial / axial</td>
<td>(12)</td>
<td>(6)</td>
</tr>
<tr>
<td></td>
<td>radial / tangential</td>
<td>(11)</td>
<td>(4)</td>
</tr>
</tbody>
</table>

4. Determination of the Examination Grid

For the definition of the parameters of the examination grid, the normalized grid rating $R_n$ and the examination zone (minimum and a maximum soundpath ($s_1$ and $s_2$)) have to be specified for each scan, depending on the design of the product. A gapless inspection is recommended. For highly stressed areas and for the evaluation of indications it can be necessary to choose a higher $R_n$.

Depending on this definition of the parameters, an optimal examination grid for the actual inspection has to be established by the inspector and depends on the used equipment. This can be done using the following steps:

a) Definition of the minimum and maximum soundpath ($s_1$ and $s_2$) depending on the defined examination zone
b) Calculation of the projection of the sound bundle dimensions $D_x$ and $D_y$ both for $s_1$ and $s_2$ (either by using the analytical formulas provided in this paper or by simulation calculations)
c) Calculation of the optimized examination grid $d_x$ and $d_y$ both for $s_1$ and $s_2$ considering the specified normalized examination grid rating $R_n$
d) Selection of the actually used examination grid ($d_x$ and $d_y$) depending on the results in step c).

If both selected values are not bigger than the calculated values, it is ensured that the required normalized grid rating is achieved. If at least one value is chosen larger, or if both values are
selected freely, the selected grid needs to be tested at both $s_1$ and $s_2$ whether the required normalized grid rating is achieved with the selected values.

Note: The calculation of the examination grid for inspections on the outer diameter of components without a central bore, can lead to a excessively large $d_x$. It is recommended to limit the pulse distance by:

$$d_x \leq \frac{\varphi}{180^\circ} \cdot \pi \cdot D_1.$$  \hspace{1cm} (14)

5. Summary

This paper has presented the mathematical tools for the determination of an optimized inspection grid for automated ultrasonic inspection in dependence of the scan directions and applied probes.

With the introduction of the normalized grid rating $R_n$ boundary conditions for gapless and multiple sampling inspections are given and with the introduction of the average grid rating $R_d$ a way is presented to optimize the inspection effort.

Finally it must be pointed out that only with the normalized grid rating $R_n$ defined along with the inspection volumes and zones by the purchaser of a forging as a specified requirement, the presented method can be used by the manufacturer to decide on an appropriate inspection grid. We advise an agreement between purchaser and manufacturer to prevent excessive inspection duration and cost.

References

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