Distance gain size diagrams in ultrasonic testing (DGS)

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Basic sizing methods in ultrasonic testing

An indication in an ultrasonic signal (A-Scan, see A-Scan) can be analyzed using the dynamic of the echo signal (half-amplitude technique) or the amplitude of the echo (DGS method). The half-amplitude technique is used for reflectors which dimensions are bigger than the sound beam of the used probe. In contrast the DGS method is used for reflectors smaller than the sound beam [1].

The Distance Gain Size (DGS) diagram was developed in 1958 by the German physicist Josef Krautkrämer and his brother Herbert Krautkrämer [2].

The DGS method is a non-destructive testing technique (NDT) to characterize defects in solid materials. This ultrasonic sizing technique relates the echo amplitude of a circular disc reflector to the amplitude of a flat bottom hole in the same depth or same distance. The resulting echo amplitude can manually compared with printed curves of the DGS diagram to analyze the defect [3]. Moreover, it is very difficult to measure the exact size if the defect has a skew [4].

Half-amplitude technique

With the half-amplitude technique, the length and the width of a defect can be measured by using the Pulse-Echo Setup (see: Ultrasonic Pulse-Echo Method).

![Figure 1: Step 1: Testing setup using the half-amplitude technique. (Source: Sebastian Gensler)](image)

![Figure 2: Step 1: A-Scan of the setup in figure 1 showing the initial pulse and the backwall echo. (Source: Sebastian Gensler)](image)
If the transducer moves over a test piece without a defect, the main part of the ultrasound energy is reflected by the backwall (see figure 1 and 2).

Once the transducer gets close to the defect, a part of the sound is reflected by the defect while the other part is reflected by the backwall. The closer the transducer gets to the defect the higher is the defect echo and the lower the backwall reflection (see figure 3 and 4).

If the transducer is located vertically above the defect, all of the transmitted ultrasound will be reflected by the defect and the maximum height of the defect echo amplitude is reached. There is no backwall echo (see figure 5 and 6).

For the half-amplitude technique, the height of the maximum defect amplitude (figure 6) will be searched (= Peaking Up). The transducer will be moved further until the maximum of the amplitude drops -6dB (figure 4). This is equal to the position where half of the sound beam hits the defect. By neglection of the attenuation and scattering, the amplitude of the backwall echo and the amplitude of the defect reflection are the same size at exact the half of the maximum amplitude.\[5\]
Theory

Depending on the used transmitter, there are specific DGS diagrams. In a normed DGS diagram (see figure 7) the distance $A$ between the scatterer and the probe is plotted on the horizontal axis (see formula 1). The Gain $V$ is plotted on the vertical axis (see formula 2).

**Formular 1:** $A = \frac{z}{N_s}$

- $A$ = Normalized defect distance
- $z$ = Reflector distance
- $N_s$ = Nearfield length of probe

**Formular 2:** $V = \frac{H_r}{H_0}$

- $V$ = Gain
- $H_r$ = Reflector amplitude height
- $H_0$ = Comparison amplitude height

Each line in the DGS diagram shows how the amplitudes obtained from different sizes of circular disc reflectors decrease as the distance between the probe and the reflector increases. The red curve shows the response of the backwall reflection (see figure 7) [6].

The dimensionless defect size $G$ is equal to the ratio between the size of the disc reflector ($D_r$) and the size of the piezo crystal ($D_s$) (formula 3).

**Formular 3:** $G = \frac{D_r}{D_s}$

- $G$ = Defect size (dimensionsless unit)
- $D_r$ = Diameter of reflector
- $D_s$ = Diameter of emitter

If the defect is in the far field of the transducer and $\frac{D_r}{\lambda} \gg 1$ the diameter $D_s$ can be calculated using formula 4.

**Formular 4:** $p_s = p_0 \frac{4z G^2}{\pi D_r^2}$
By assuming that \( p_{re} \approx p_0 \) the reflected sound pressure \( p_r \) of the transducer as an emitter and receiver is equal to formula 5.

\[
\text{Formular 5: } p_r = \frac{\pi D_r^2}{4 \lambda z} = p_0 \frac{\pi D_e^2 D_r^2}{16 \lambda^2 z^2}
\]

\( p_r = \text{Receiver sound pressure} \)
\( D_r = \text{Diameter of reflector} \)

The ratio of the reflection echo \( H_r \) and the comparative echo \( H_0 \) (e.g. 80 % screen height) are equal to the ratio of sound pressure of the reflection and the initial sound pressure (formula 6).

\[
\text{Formular 6: } \frac{H_r}{H_0} = \frac{p_r}{p_0}
\]

\( H_r = \text{Reflected amplitude} \)
\( H_0 = \text{Comparative amplitude} \)

Now the defect size can be calculated by using the comparative echo. Therefore, the reflection diameter \( D_r \) simplifies to (formula 7) \(^2\).

\[
\text{Formular 7: } D_r = \frac{4 z}{D_e z} \sqrt{\frac{H_r}{H_0}}
\]

**Testing using DGS diagrams**

**Setup for testing**

The DGS curves are already implemented in modern digital testing instruments. Based on a reflection calibration on the backwall or a circular shaped reflector in known depth, the transceiver and material properties of all curves can be calculated automatically. Only the curve of the selected reflector size will be displayed \(^2\).

**Restrictions**

There are two different procedures for DGS method:

- Reference lines procedure.
- Reference height procedure.

To choose the right technique it is essential to know the restrictions for each procedure (see Table 1).

<table>
<thead>
<tr>
<th>Table 1: Restrictions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reference height procedure</strong></td>
</tr>
<tr>
<td>Only valid for perpendicular and angle transducers</td>
</tr>
<tr>
<td>Exact evaluation only in far field possible</td>
</tr>
<tr>
<td>Relatively fast preparation before testing</td>
</tr>
<tr>
<td>Echo estimation complex</td>
</tr>
</tbody>
</table>
Reference lines procedure [3]

To get an overview how to read a DGS diagram with the reference line procedure, figure 8 shows the graph of the backwall and just one graph of a circular disk reflector $D_{KSR}$. The procedure calculates a reference line and every signal of a defect that exceeds this line is categorized as a critical defect.

The procedure can be divided into 4 steps:

- Distance adjustment,
- Sensitivity adjustment,
- Display evaluation,
- Correction of transducer.

![DGS diagram for reference lines procedure. (Source: Sebastian Gensler)](image)

Some further information are given in the DGS diagram (see figure 8):

- Probe type (in this case AM4R-8x9-38),
- Used reflector block (K2) and amplitude correction value $\Delta V_{K2}$
- Reference block correction value,
- Sound attenuation.

The determination of the equivalent reflector size $D_{KSR}$ is based on the comparative of two echo amplitudes. Therefore the echo of an unknown reflector is compared with the echo of a known one or a reference reflector. For testing with a straight beam probe, where the sound beam is perpendicular to the transducer, the backwall can be used for the reference echo. For angle beam probes there is no backwall which is oriented perpendicular to the sound beam (see figure 9). Therefore reference blocks are used to get a reference echo. In this case the reference block K2 is used which has a radius of 25 mm (green vertical line). The amplitude correction value $\Delta V_{K2}$ corrects the differences between the signal of a cylindrical surface reference block and the reference signal from a flat backwall (see figure 8).

At first the distance will be calibrated by using formular 8.

**Formular 8:** 

$$ s_b = \frac{2d\alpha^{1.5}}{cos(\alpha)} $$

$s_b$ = Distance calibration value

$d$ = Thickness

$\alpha$ = Angle of sound beam
With a thickness of the test sample $d$ (see figure 9) of 40 mm, the calibration value is equal to 136 mm. In the diagram the next nearest value 150 mm (blue vertical line) is used (see figure 9).

In the second step $\Delta V$ (see formular 9) is calculated to adjust the sensitivity. Therefore the calibration distance and the backwall curve are marked in the diagram (figure 8).

Formular 9: $\Delta V = \Delta V_{\text{reference echo}} - \Delta V_{\text{calibration echo}}$

$\Delta V = \text{Difference between reference and calibration echo}$

$\Delta V_{\text{reference echo}} = \text{Value of reference echo}$

$\Delta V_{\text{calibration echo}} = \text{Value of calibration echo}$

The reference height $H_0$ is defined with the intersection point that is given with the highest point of the circular disc line and the sound path. Afterwards the gain difference of different sound paths are calculated (see table 3). The expected echo $H_r$ will be calculated with formular 10.

Formular 10: $\frac{H_r}{H_0} = 10^{\frac{-\Delta V}{20}}$

$H_r = \text{Reflected amplitude}$

$H_0 = \text{Comparative amplitude}$

$\Delta V = \text{Difference between reference and calibration echo}$

The registering gain $V_R$ is equal to the gain which adjusts the echo on a constant screen height (e.g. 80 %) and adding the different correction values (see formular 11).

Formular 11: $V_R = V + \Delta V_{k2} + \Delta V_T + \Delta V$

$V_R = \text{Registering gain}$

$V = \text{Gain}$

$\Delta V_{k2} = \text{Correction value for reference block K2}$

$\Delta V_T = \text{Transducer correction value}$

In conclusion, the echo height exceed is calculated by formular 12.

Formular 12: $\Delta H_u = \Delta V_U = V_U - V_R$

$\Delta H_u = \text{Echo difference}$

$V_U = \text{Instrument gain}$

$V_R = \text{Reflection echo}$
To give a quantitative statement about the location and size, the echo height exceed will be filled in negative gain direction on the reference line. The defect reflects the sound worse than the reflector $D_{KSR}$ with 2 mm radius in the same depth. The difference is equal to $\Delta H_w$ (see figure 8).

**Example**

The following steps make the theory more touchable by using an example test sample. Before testing, some values are already given by the materials or diagram (see table 2).

<table>
<thead>
<tr>
<th>Table 2: Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test object</td>
</tr>
<tr>
<td>Probe</td>
</tr>
<tr>
<td>Register limit</td>
</tr>
<tr>
<td>Reference block</td>
</tr>
<tr>
<td>Amplitude correction value</td>
</tr>
<tr>
<td>Sound attenuation</td>
</tr>
</tbody>
</table>

Gain at K2 to achieve the screen height to 80% ($H_0 = 80\%$): $V = 18dB$

The distance calibration value can be calculated by formular 13 with the thickness $d = 40mm$ (see table 2) and the angle of the transducer (see figure 9).

Formular 13: $s_b = \frac{2d + 1.2}{\cos(\alpha)} = \frac{2 \times 40 \text{ mm} + 1.2}{\cos(45^\circ)} = 136 \text{ mm} \rightarrow 150 \text{ mm}$

$s_b = \text{Distance calibration value}$

$d = \text{Thickness}$

$\alpha = \text{Angle of sound beam}$

To construct the reference line at the value $V_{\text{reference height}}$ (see figure 8) the screen height must be calculated at each distance $s$ by using $\Delta V_i$ and formular 10. The results of this calculation are listed in Table 3.

<table>
<thead>
<tr>
<th>Table 3: Calculation of reference line</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s$ (mm)</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>15</td>
</tr>
<tr>
<td>60</td>
</tr>
<tr>
<td>80</td>
</tr>
<tr>
<td>200</td>
</tr>
<tr>
<td>350</td>
</tr>
</tbody>
</table>

Formular 14: $\Delta V = \Delta V_{\text{reference height}} - \Delta V_{\text{calibration height}} = 18dB - 2dB = 16dB$

$\Delta V = \text{Difference between reference and calibration echo}$

$\Delta V_{\text{reference height}} = \text{Height of reference echo}$

$\Delta V_{\text{calibration height}} = \text{Height of calibration echo}$

Formular 15: $V_R = V + \Delta V_{K2} + \Delta V_T + \Delta V = 18dB - 3.5dB + 0dB + 16dB = 30.5dB$
\[ V_R = \text{Registering gain} \]
\[ V = \text{Gain} \]
\[ \Delta V_{K2} = \text{Correction value for reference block K2} \]
\[ \Delta V_T = \text{Transducer correction value} \]

To examine the signals, the gain control at the equipment is set to the value of the registering gain \( V_R \). Every signal that reach or exceed the reference line must be recorded. While testing, the echo height difference \( \Delta H_u \) (see formular 16) for registered signals can be read directly on the display. Afterwards the reflector size can be estimated using the DGS diagram.

For a defect at 60 mm depth the needed gain for \( H_0 = 80\% \) screen height is equal to \( V_u = 34\text{dB} \). The value \( \Delta H_u \) gives information about the reflection behavior of the defect.

Formular 16: \( \Delta H_u = \Delta V_U = V_U - V_R = 34\text{dB} - 30,5\text{dB} = 3,5\text{dB} \)

\( \Delta H_u = \text{Echo difference} \)
\( V_U = \text{Instrument gain} \)
\( V_R = \text{Reflection echo} \)

The height difference \( \Delta H_u \) can be plot into negative gain direction at 60 mm (see figure 8) and leads to a bigger reflector size than the reference line with a disk reflector of 2 mm at \( V_{\text{reference height}} \). In conclusion, the defect reflects the ultrasound 3,5 dB better than the 2 mm disk reflector.

Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A )</td>
<td>Normalized flaw distance</td>
<td>-</td>
</tr>
<tr>
<td>( z )</td>
<td>Reflector distance</td>
<td>m</td>
</tr>
<tr>
<td>( N_f )</td>
<td>Nearfield length of probe</td>
<td>-</td>
</tr>
<tr>
<td>( V )</td>
<td>Gain</td>
<td>dB</td>
</tr>
<tr>
<td>( H_r )</td>
<td>Reflected amplitude</td>
<td>%-screen height</td>
</tr>
<tr>
<td>( H_0 )</td>
<td>Comparative amplitude</td>
<td>%-screen height</td>
</tr>
<tr>
<td>( G )</td>
<td>Flaw size</td>
<td>-</td>
</tr>
<tr>
<td>( D_r )</td>
<td>Diameter of reflector</td>
<td>m</td>
</tr>
<tr>
<td>( D_e )</td>
<td>Diameter of emitter</td>
<td>m</td>
</tr>
<tr>
<td>( p_s )</td>
<td>Emitter sound pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>( p_0 )</td>
<td>Initial sound pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>Wavelength</td>
<td>m</td>
</tr>
<tr>
<td>( p_r )</td>
<td>Receiver sound pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>( p_{fr} )</td>
<td>Initial sound pressure of reflector</td>
<td>Pa</td>
</tr>
<tr>
<td>( s_p )</td>
<td>Distance calibration value</td>
<td>mm</td>
</tr>
<tr>
<td>( d )</td>
<td>Thickness</td>
<td>mm</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>Angle of sound beam</td>
<td>(^\circ)</td>
</tr>
<tr>
<td>( \Delta V_{\text{reference echo}} )</td>
<td>Value of reference echo</td>
<td>dB</td>
</tr>
<tr>
<td>( \Delta V_{\text{calibration echo}} )</td>
<td>Value of calibration echo</td>
<td>dB</td>
</tr>
<tr>
<td>( \Delta V_{K2} )</td>
<td>Correction Value for reference Block K2</td>
<td>dB</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>--------</td>
<td>----------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>ΔV_T</td>
<td>Transducer correction value</td>
<td>dB</td>
</tr>
<tr>
<td>ΔV</td>
<td>Difference between reference and calibration echo</td>
<td>dB</td>
</tr>
<tr>
<td>V_U</td>
<td>Instrument gain</td>
<td>dB</td>
</tr>
<tr>
<td>V_R</td>
<td>Reflection echo</td>
<td>dB</td>
</tr>
<tr>
<td>ΔH_u</td>
<td>Height difference</td>
<td>dB</td>
</tr>
</tbody>
</table>

**Literature**


