Chapter 2
State of the Art: DAC and DGS

Abstract A brief introduction of the recording of DAC curves is given. The DGS method is presented in more details. The development of the DGS method is described. How to derive a special DGS diagram for a certain probe from the general DGS diagram is explained as well as the necessary adaptations for sound attenuation and other influences. Examples for sizing using the DGS method is given for a straight beam probe and for an angle beam probe.

The state of the art of the two techniques DAC and DGS will be discussed in the following. Using DAC curves does not need a lot of explanation. The understanding of the distance–gain–size (DGS) method will require more details.

2.1 Distance Amplitude Curve

As already described in the introduction of this book, recording of a DAC curve is straightforward. Each echo of each side-drilled hole in the reference block has to be maximized and the echo peak has to be marked on the screen of the ultrasonic instrument keeping the gain setting constant. The marked echo peaks are connected by a line using an appropriate pen. Today's ultrasonic instruments have functions providing help for recording the DAC curve and the curve will be displayed on the screen electronically. As mentioned before, the reference block is ideally manufactured from the same material as the specimen under test. In this case, the material characteristics such as sound attenuation and absorption are taken into account automatically. The disadvantages of this method are the cost of the reference blocks and the time-consuming recording procedure.

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2.2 Distance–Gain–Size Method

The DGS method has been developed in 1959 by the Krautkrämer [1] brothers for flat circular transducers. In the far field, the general DGS diagram has been calculated theoretically [2] while in the range of the first few near field lengths, measurements were taken to define the curves. The calculated curves are straight lines in the logarithmic presentation of the DGS diagram. Following is an important quotation from the Krautkrämer book [1]:

> ...since the local fluctuations in the near field depend quite sensitively on the pulse length and the transmitter design. In the intermediate range therefore the general DGS diagram can only give approximate results but for a particular transmitter design a special DGS diagram can of course be established by experiment.

Figure 2.2 is a digitized version of the general DGS diagram published in EN IS0 16811:2012 [3], Fig. 1.3. Comparing Figs. 2.1 and 2.2 shows how important this quotation is. The DGS diagram is in the near field heavily dependent on the bandwidth of the probe. Later in this book, the bandwidth-dependent calculation of the DGS diagram for the entire range of sound paths will be discussed in detail.

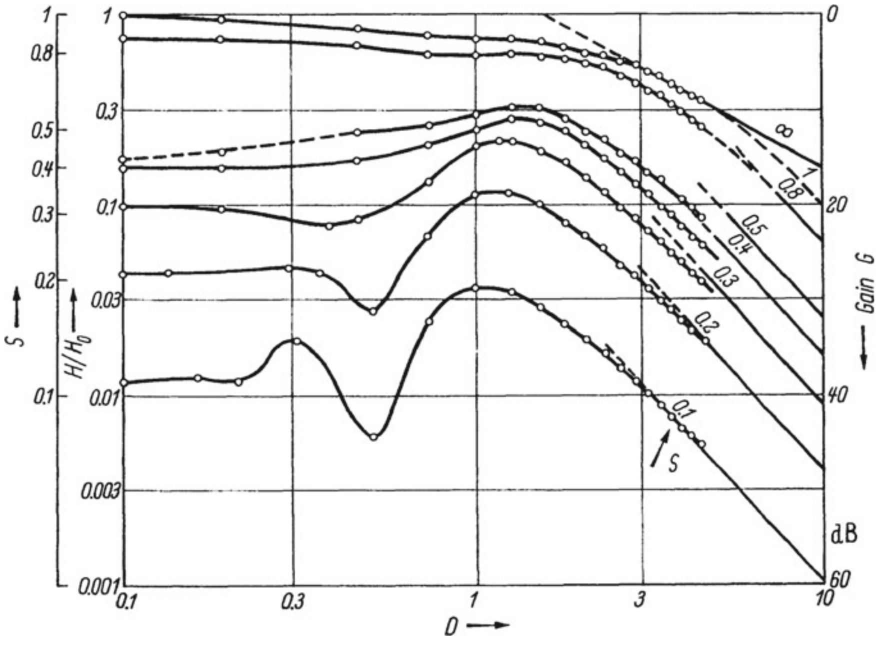


Fig. 2.1 Figure from the Krautkrämer book [1]

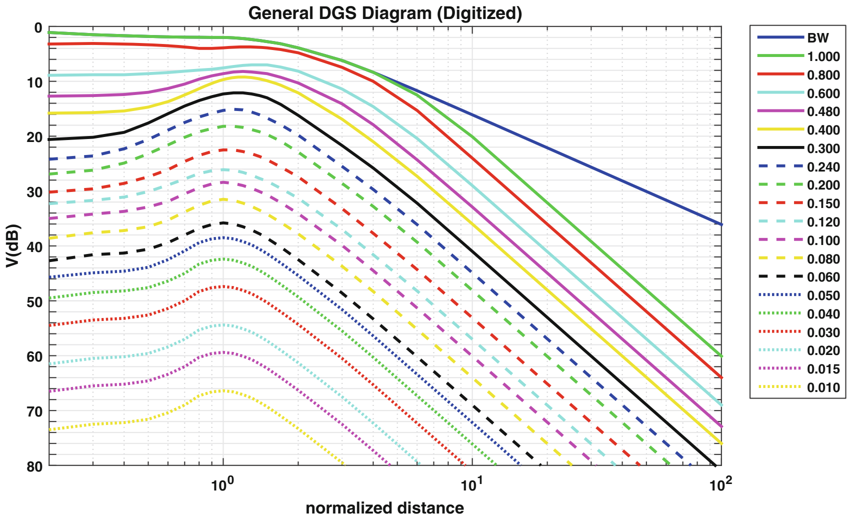


Fig. 2.2 Digitized general DGS diagram

2.2.1 EN ISO 16811:2012

The dependency of the DGS diagram on the bandwidth seems to be forgotten. In the standard EN ISO 16811:2012 [3], a general DGS diagram is published, Fig. 1.3. The bandwidth dependency is not mentioned in detail. But the use of the DGS method is limited to sound paths larger than 0.7 near field lengths, presumably to avoid deviations based on the bandwidth-dependent variations in the near field.

It was not known to the author when the general DGS diagram published in the EN ISO 16811:2011 was developed. Presumably, the development of this diagram was at a time when different circumstances were valid

- Mainly narrow band probes were used.
- A resolution of 0.1 dB for gain setting was not available.
- At this time, the equivalent reflector size was derived by manual interpolation in the logarithmic scale. Today, ultrasonic instruments calculate the equivalent reflector size and display it with a resolution of a tenth of a millimeter.

Therefore, deviations in the evaluation, particularly in the near field and in the intermediate range, were not detected or even accepted.

2.2.2 DGS Evaluation

In this section, the method how to derive a special DGS diagram for a certain probe from the general DGS diagram will be discussed. To fulfill this task, the distances on the x-axis in the general DGS diagram have to be multiplied with the near field length of the probe used. In addition, the size indication (G in the general DGS diagram, Fig. 1.3) has to be multiplied with the diameter of the transducer.

2.2.2.1 Straight Beam Probe

As mentioned in the introduction, the DGS method has been developed for straight beam probes with flat spherical transducers [2]. For this example, a probe with the following parameters will be used:

- frequency: $f = 2\,\text{MHz}$
- diameter: $D = 10\,\text{mm}$
- sound velocity in the test material: $c = 5{,}920\,\text{m/s}$
- the length of the delay is negligible.

The first step is to calculate the near field length N of the probe using the effective diameter D_{eff}, with $D_{eff} = 0.97\,D$, utilizing the following formula:

$$N = \frac{D_{eff}^2 - \lambda^2}{4\,\lambda} \approx \frac{D_{eff}^2}{4\,\lambda} \tag{2.1}$$

where λ is the wavelength.

To derive the special diagram for this probe, the digitized general DGS diagram is taken, refer Fig. 2.2. The values of the x-axis are multiplied with the near field length N and the size indication G is multiplied with the diameter D of the transducer. The result is shown in Fig. 2.3.

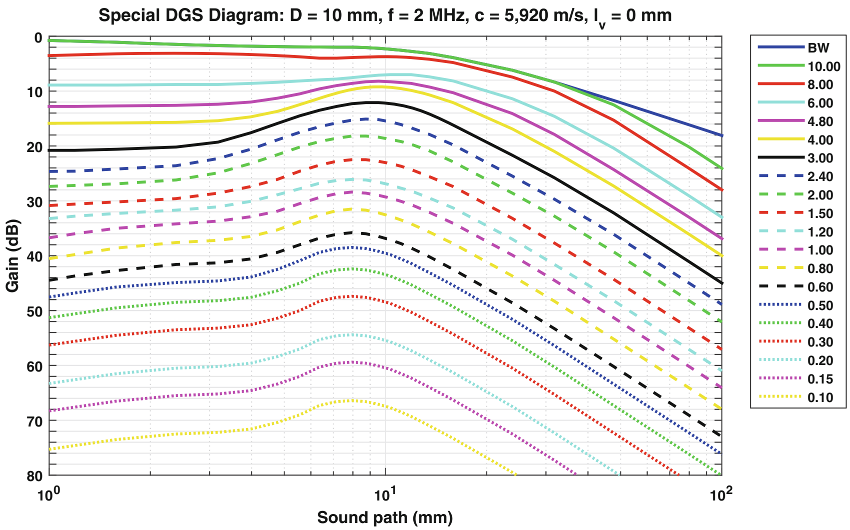


Fig. 2.3 Special DGS diagram for a straight beam probe

To evaluate a reflector, applying the DGS method, a reference echo is required. In this example, the reference echo is taken from the planar back wall of a 40 mm thick test block. Let the gain setting needed to have this reference echo at 80 % screen height be $G_r = 16.8$ dB. A reflector is detected at a sound path of 20 mm. This echo as well is set to 80 % screen height with a gain setting of $G_d = 44.2$ dB. The gain difference ΔG of these two gain settings is calculated

$$\Delta G = G_d - G_r = 44.2\,\text{dB} - 16.8\,\text{dB} = 27.4\,\text{dB} \tag{2.2}$$

For the evaluation using the DGS method, a point at a sound path of 40 mm on the back wall curve is marked. A second point is marked at ΔG below the first point on the back wall curve. A parallel to the x-axis through the second point is drawn up to the intersection with a line perpendicular to the x-axis at a sound path of 20 mm. This intersection point is the result of the DGS evaluation. At the curve with the intersection point, the equivalent reflector size can be read. In the example given, the equivalent reflector size (ERS) is 1.0 mm, Fig. 2.4. If the intersection point is between two curves, an interpolation between these two curves is required.

2.2.2.2 Angle Beam Probe

As mentioned before, the DGS method was developed for straight beam probes with planar spherical transducers. But, later on, the DGS method was as well applied to angle beam probes [1]:

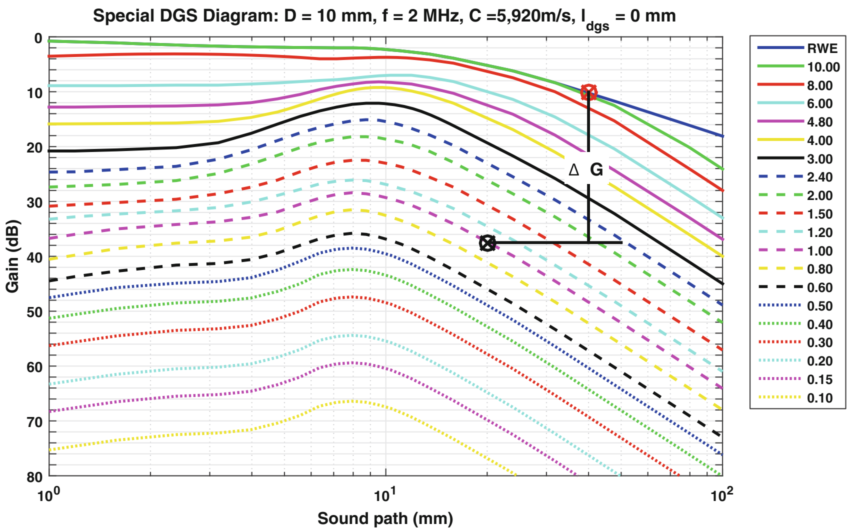


Fig. 2.4 DGS evaluation for a straight beam probe

DGS diagrams have also been established for transverse waves when used with so-called angle probes, cf. Chaps. 19 and 20.

In Chap. 3, it will be seen that the DGS method can lead to oversizing reflectors when conventional angle beam probes are used. First, the state of the art of the DGS evaluation using angle beam probes will be discussed. Usually, angle beam probes have rectangular transducers. With angle beam probes, the DGS evaluation is a bit more complex

- For the rectangular transducer a so-called equivalent circular transducer has to be determined.
- The delay line is not negligible.
- With transverse waves, normally, the sound attenuation has to be taken into account.
- The reference echo is usually taken from the arc of the calibration standard K1 or K2. In this case, the amplitude correction value ΔV_k has to be considered because the arc has a different reflectivity as a flat back wall.
- When using higher frequencies, the sound attenuation in the calibration standard has to be taken into account as well.
- If the surface qualities of the calibration standard and the specimen under test are different, a transfer correction ΔV_t has to be applied.

For calculating the equivalent circular transducer, a correction value based on the side ratio of the rectangular transducer is required [1], refer to Table 2.1. In this table, the following identifiers are used:

- a: half of the larger side of the rectangular transducer
- b: half of the smaller side of the rectangular transducer
- h: correction value

The near field length N of the angle beam probe can be calculated according to the state of the art

$$N = h\,\frac{a^2}{\lambda} \tag{2.3}$$

Table 2.1 Correction values for rectangular transducers [1]

Ratio of sides b/a	Correction value h
1.0	1.37
0.9	1.25
0.8	1.15
0.7	1.09
0.6	1.04
0.5	1.01
0.4	1.00
0.3	0.99
0.2	0.99
0.1	0.99

with λ being the wave length in the test material. Now, using Eq. (2.1), the diameter D of the equivalent circular transducer can be derived

$$D \approx \sqrt{4\,\lambda\,N} \tag{2.4}$$

According to the state of the art, the delay length has to be converted using the so-called near field equivalent

$$l_{dgs} = l_p\,\frac{c_d}{c_m} \tag{2.5}$$

with:

- l_p: physical delay in the wedge of the probe
- l_{dgs}: delay to be considered when deriving the special DGS diagram
- c_d: sound velocity in the wedge of the probe
- c_m: sound velocity in the test material

With the known frequency f of the probe, all values needed to derive the special DGS diagram are now known.

As an example, an angle beam probe with the following data will be used:

- frequency: 4 MHz
- transducer: $8 \times 9\,\text{mm}^2$
- delay: 7 mm
- sound velocity in the wedge 2.73 km/s

The sound velocity in the test material is 3.255 km/s. The probe delay l_p is converted using the ratio of the sound velocities resulting in $l_{dgs} = 5.9\,\text{mm}$. For the near field length, the result is $N = 30.8\,\text{mm}$ and the diameter of the equivalent circular transducer yields $D = 10\,\text{mm}$. The resulting special DGS diagram is represented in Fig. 2.5.

Note:

The DGS diagram is not corrected, for example, the sound attenuation or any other influence. All possible influences have to be corrected manually by adapting the measured dB values accordingly. The following additional parameters are required for the DGS evaluation for angle beam probes:

- ΔV_k: The amplitude correction value specifies by how many dB the echo from the arc of the calibration standard used is higher than the echo from a flat back wall at the same sound path. This value can be taken from the data sheet of the used probe.
- κ_k: Sound attenuation in the calibration standard. This value can be estimated or better measured.
- κ_m: Sound attenuation in the test material. This value has to be measured.
- ΔV_t: transfer correction. This value is required to compensate for different surface qualities of the calibration standard and the test specimen. This value needs to be measured.

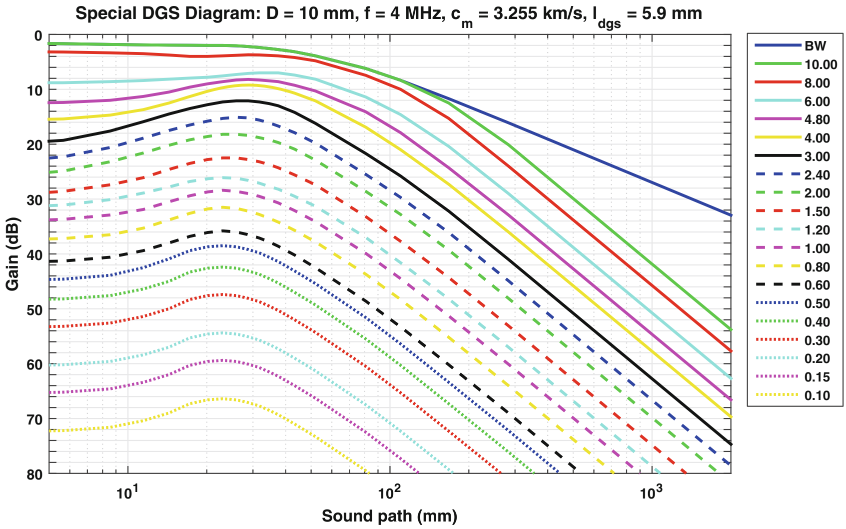


Fig. 2.5 Special DGS diagram for an angle beam probe

An example is given deriving the special diagram for the used probe. With this probe, the reference echo is taken from the 25 mm arc in the calibration standard K2. In the data sheet of this probe, the amplitude correction value ΔV_{K2} is given.

Measurement of the Sound Attenuation in the Calibration Standard:

For measuring the sound attenuation in the calibration standard, the K1 block will be utilized. This can be done because both calibration standards K1 and K2 are made from the same material. To determine the sound attenuation both a V and a W through transmission is measured. In both cases, the echo amplitude is set to 80 % screen height and the necessary gain settings are noted. This measurement must be taken using a pair of probes equivalent to the probe used for the DGS evaluation. Figure 2.6 illustrates the V and W through transmission. The thickness of the calibration standard K1 is $d = 25$ mm. The sound paths s_v for the V through transmission and s_w for the W transmission are calculated from the angle of incidence β and d

$$s_v = \frac{d}{\cos\beta} \tag{2.6}$$
$$s_w = \frac{2\,d}{\cos\beta}$$

For the example with the angle of incidence $\beta = 60°$ the sound paths result in $s_v = 50$ mm and $s_w = 100$ mm. These sound paths are marked on the back wall curve in the special DGS diagram of the probe used and the gain difference between these two points are read from the diagram, Fig. 2.7. In this example, the gain

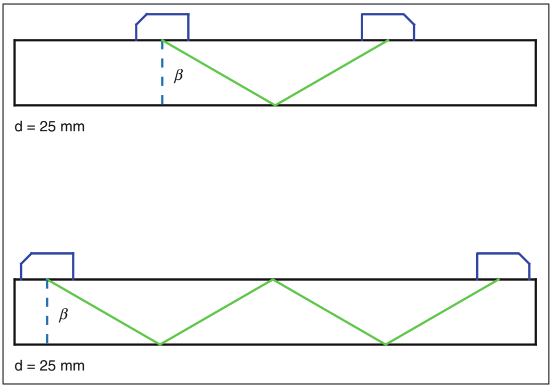


Fig. 2.6 V and W through transmission

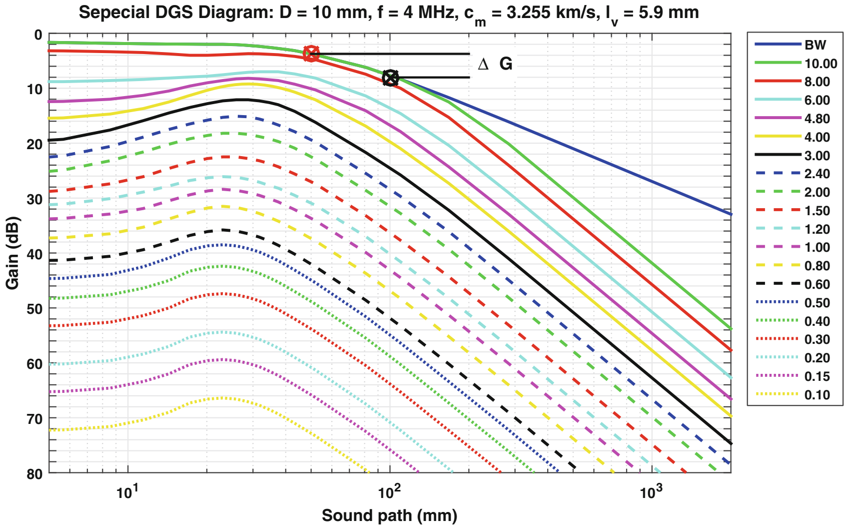


Fig. 2.7 Determination of the sound attenuation

difference read from the DGS diagram amounts to $\Delta G = 3.9\,\text{dB}$. Let the measured gain difference between V and W through transmission be 5 dB. This difference results from two influences, one is the difference based on the different sound paths read from the DGS diagram and the other one is the influence of the sound attenuation. That means, in the example, the influence of the sound attenuation having a sound path difference of 50 mm amounts to $\Delta G_k = 5\,\text{dB} - 3.9\,\text{dB} = 1.1\,\text{dB}$. Knowing this value enables the calculation of the sound attenuation κ_k in the calibration standard

$$\kappa_k = \frac{1.1}{2 \times 50} \frac{\text{dB}}{\text{mm}} = 0.011 \frac{\text{dB}}{\text{mm}} = 11 \frac{\text{dB}}{\text{m}} \tag{2.7}$$

The sound attenuation κ_m is determined accordingly. Let us assume that the result would be

$$\kappa_m = 15\,\frac{\text{dB}}{\text{m}}$$

In the next step, the transfer correction ΔV_t has to be derived. Therefore, the gain values and the sound paths of the V through transmissions on the calibration block and on the test specimen have to be known. The gain difference of these two measurements is due to several influences

- transfer correction
- different sound paths
- sound attenuation in the calibration block
- sound attenuation in the test specimen

To determine the transfer correction, three influences have to be eliminated from the measured gain difference. First, we need the sound path in the calibration block, which is already known from the example as 50 mm. Let us assume that the sound path for the through transmission on the test piece is 100 mm. With this the influences of the sound attenuations can be derived

$$\begin{aligned} V_k &= \frac{2 \times 50 \times 11}{1000}\,\text{dB} = 1.1\,\text{dB} \\ V_m &= \frac{2 \times 100 \times 15}{1000}\,\text{dB} = 3.0\,\text{dB} \end{aligned} \tag{2.8}$$

Let the gain value for setting the echo of the through transmission on the calibration standard to 80 % screen height be $G_k = 9.8\,\text{dB}$, and the gain setting for the measurement on the test piece be $G_m = 17.6\,\text{dB}$ accordingly. Since the DGS diagram does not take any sound attenuation into account the measured values have to be adapted accordingly. The measured gain values have to be corrected due to the sound attenuations. If no sound attenuation were active, the resulting echoes would have a larger amplitude; therefore, the gain settings have to be corrected by

$$\begin{aligned} &G_k - 1.1\,\text{dB} \\ &G_m - 3.0\,\text{dB} \end{aligned}$$

The difference of these two values results, using the assumed values, to 5.9 dB. The influence based on the different sound paths is 3.9 dB as already known from the DGS diagram for these sound paths. With this the transfer correction results in $\Delta V_t = 2\,\text{dB}$.

Now, all values needed for the DGS evaluation are known. Let the gain setting for 80 % screen height of the reference echo from the 25 mm arc of the calibration block K2 be $G_{K2} = 6\,\text{dB}$. An echo of a reflector found at a sound path of 45 mm requires a gain setting of $G_R = 36.6\,\text{dB}$ for the screen height of 80 %.

First, the measurement value of the **reference echo** is corrected for the use of the DGS method. If no sound attenuation would be existing, the echo would be higher than 80 %. The measured gain setting has to be reduced by the value of the sound attenuation $V_{\kappa\ K2}(25\,\text{mm})$

$$G_{K2} - V_{\kappa\ K2}(25\,\text{mm})$$

If the reference echo came from a plane back wall the echo would be lower by ΔV_{K2}, therefore, the gain value needs to be increased by ΔV_{K2}

$$G_{K2} - V_{\kappa\ K2}(25\,\text{mm}) + \Delta V_{K2} \tag{2.9}$$

Now, the correction of the measured gain setting for the **reflector** is performed accordingly for the sound attenuation $V_{\kappa\ m}$ in the test material. The measured gain setting is reduced by the value of the sound attenuation in the test material

$$G_R - V_{\kappa\ m}(45\,\text{mm})$$

Would the surface quality of test piece be as good as the surface of the calibration block, the resulting echo from the reflector would be larger by ΔV_t than 80 % screen height. The correction results accordingly

$$G_R - V_{\kappa\ m}(45\,\text{mm}) - \Delta V_t \tag{2.10}$$

Now, all corrections for the DGS evaluation are done. The difference of the two corrected values for the reflector echo, Eq. (2.10), and the corrected value for the reference echo, Eq. (2.9), can be derived

$$\Delta V = G_R - V_{\kappa\ m}(45\,\text{mm}) + V_{\kappa\ K2}(25\,\text{mm}) - G_{K2} - \Delta V_t - \Delta V_{K2} \tag{2.11}$$

The values for the sound attenuation have to be calculated

$$V_{\kappa\ K2}(25\,\text{mm}) = \tfrac{2\times25\times11}{1000}\,\text{dB} = 0.55\,\text{dB}$$
$$V_{k\ m}(45\,\text{mm}) = \tfrac{2\times25\times11}{1000}\,\text{dB} = 1.35\,\text{dB}$$

The amplitude correction value ΔV_{K2} from the probe used for the example is zero. All values needed are now known and can be used in Eq. (2.11)

$$\Delta V = (36.6 - 1.35 + 0.55 - 6 - 2 - 0)\,\text{dB} = 27.8\,\text{dB} \tag{2.12}$$

With this gain difference, the DGS evaluation can be performed. For the reference echo, a point at a sound path of 25 mm is marked on the back wall curve of the DGS diagram. At $\Delta V = 27.8\,\text{dB}$ below this point a parallel line to the x-axis is drawn. At the intersection of this line with the sound path of 45 mm the equivalent reflector size (ERS) can be read from the DGS diagram; in the example, the result is $ERS = 1.2\,\text{mm}$ (Fig. 2.8).

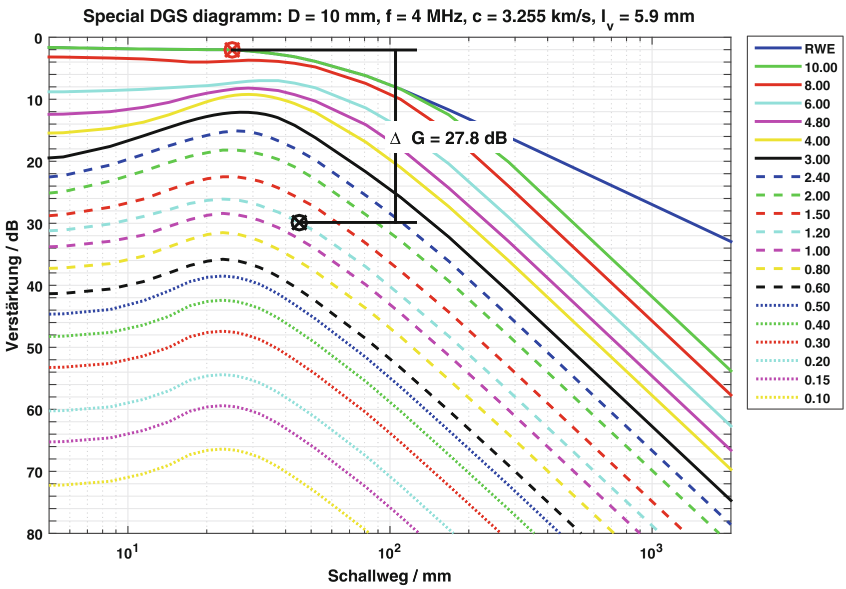
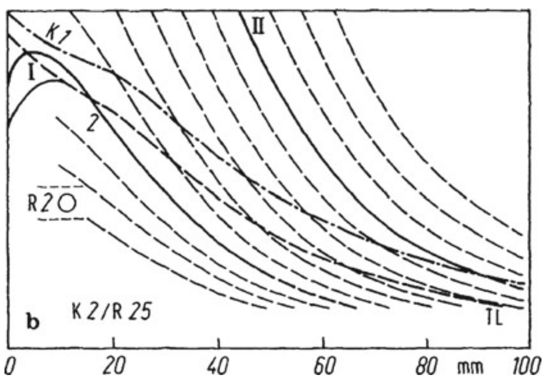


Fig. 2.8 DGS evaluation for a measurement using an angle beam probe

2.2.2.3 DGS and Ultrasonic Instruments

The DGS evaluation seems to by quite complex and sophisticated. But in earlier times, with analog ultrasonic instruments, DGS scales (design Kraukrämer) were used, Fig. 2.9. In today's digital ultrasonic instruments, DGS functionality is incorporated supporting the operator significantly. Already, in 1993, a patent *Flaw Detector incorporating DGS, US 5,511,425* was filed by Krautkrämer. In 1996, the patent was granted. Figure 2.10 shows the screen of a modern digital ultrasonic instrument with an incorporated DGS function. The curve for the selected equivalent reflector size is

Fig. 2.9 DGS scale design Krautkrämer [1]



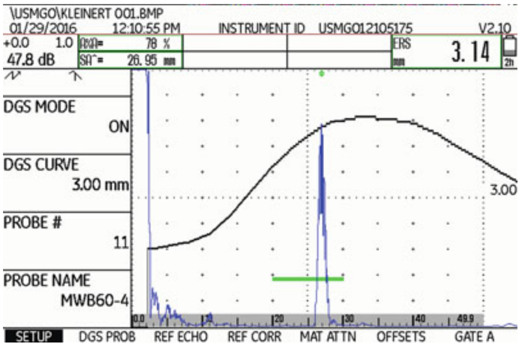


Fig. 2.10 Ultrasonic instrument with a DGS curve and DGS evaluation

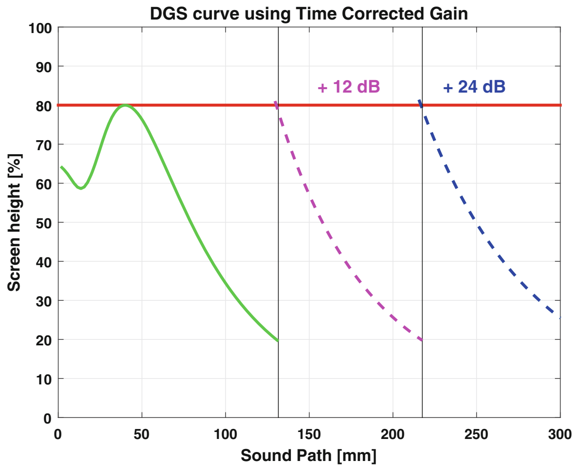


Fig. 2.11 Ultrasonic instrument with Time Corrected Gain according to a DGS curve

displayed on the screen. The actual ERS of the echo under evaluation can directly be read from the screen; in the figure, the value is $ERS = 3.14$ mm. Alternatively, Time Corrected Gain (TCG) can be used. This function ensures that all echoes just reaching the DGS curve are set to 80 % screen height automatically (Fig. 2.11).

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