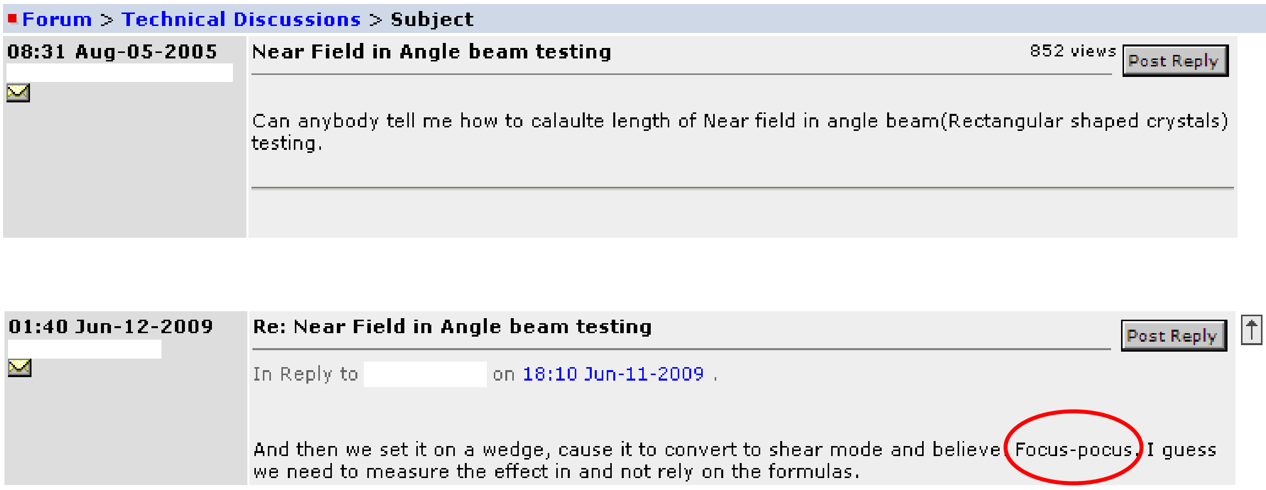
THE IDEAL ANGLE BEAM PROBE FOR DGS EVALUATION

Wolf KLEINERT, York OBERDOERFER, Gerhard SPLITT,
GE Sensing & Inspection Technologies GmbH, Huerth, Germany

Introduction

The discussion about the near field length of rectangular transducers and particularly about rectangular transducer in angle beam probes is quite old but has never been solved satisfactorily and ever and anon gives rise to new questions
(Source: http://www.ndt.net/forum/thread.php?forenID=1&rootID=8596#):


Forum > Technical Discussions > Subject

08:31 Aug-05-2005 | Near Field in Angle beam testing | 852 views | Post Reply

Can anybody tell me how to calaulte length of Near field in angle beam(Rectangular shaped crystals) testing.

01:40 Jun-12-2009 | Re: Near Field in Angle beam testing | Post Reply

In Reply to on 18:10 Jun-11-2009 .

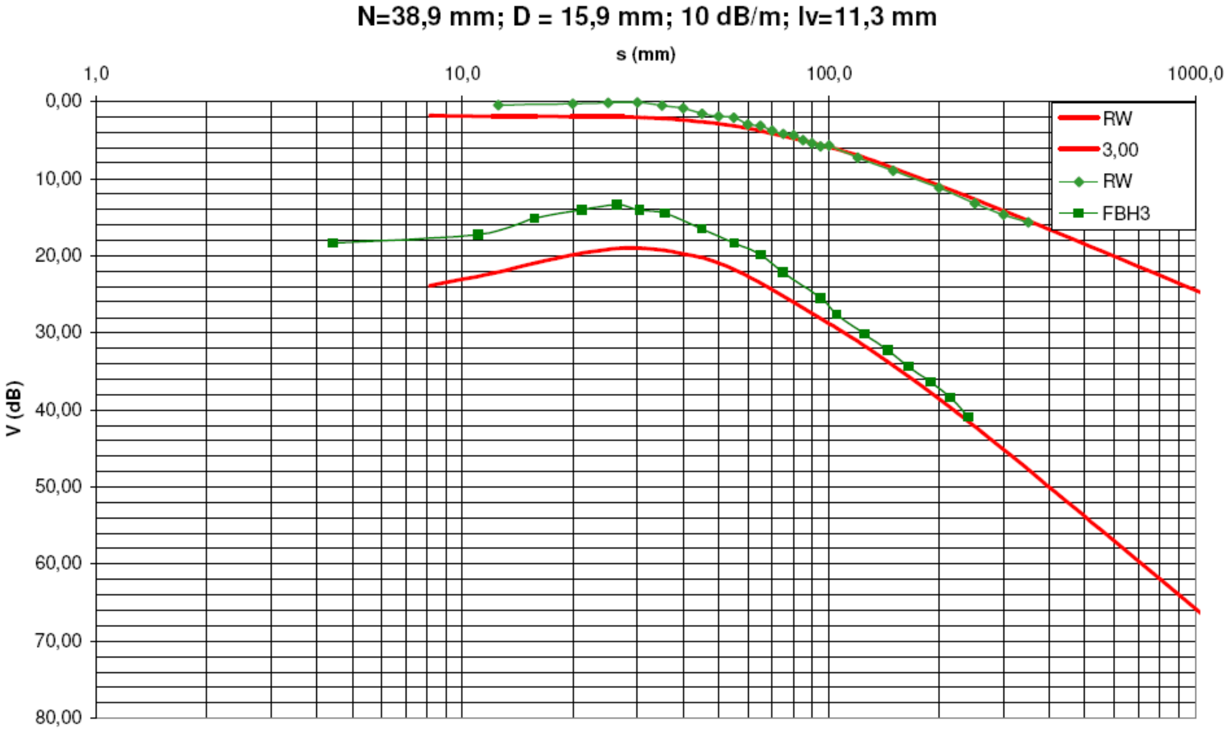
And then we set it on a wedge, cause it to convert to shear mode and believe Focus-pocus, I guess we need to measure the effect in and not rely on the formulas.

Keeping this in mind and moving on to DGS measurements one has to consider that knowing the near field length is quite essential when deriving the special DGS-diagram for a given probe from the general one as published in codes e.g. EN583-2. Furthermore, the origin of the general DGS diagram lies in DGS-diagrams taken or calculated for straight beam probes, which account for circular transducer shapes. To compensate this, the codes instruct to equalize a squared transducer with a circular one that has the same near field length leading back to the problem described above. In addition to that, the results of the refraction at the interface of probe's wedge and material and the hence distorted sound field is not taken into account when adopting the general DGS diagram for the use with angle beam probes.

Nowadays modern digital instruments with highly linear display and much better resolution compared to old analog devices with luminescent screens, being state-of-the-art at a time when DGS evaluation was introduced, give much better accuracy of reading and thus a much better possibility to quantize the deviation of DGS measurements from the ideal case when using angle beam probes.
In this article, results from recent measurements and the evaluation with the published DGS diagrams are presented. Furthermore, the origin of the deviation shall be examined more thoroughly and a model will be presented, which was derived from above considerations and show much better correspondence with traditional diagrams.

Recent Measurements

Recent measurements taken in the Probe Lab of GE Sensing & Inspection Technologies in Huerth, Germany confirm that the DGS accuracy of angle beam probes is not as good as the DGS accuracy using circular straight beam probes. The measurements shown below as an example were taken with a SWB 60-2 angle beam probe having a 2 MHz, 14 by 14 mm^2 transducer, on a customized test block containing 3mm flat-bottom holes at various depth and a continuous flat back wall with 60° inclination:



In this diagram corrections for attenuation (10 dB/m) were used. The rectangular transducer was recalculated to a circular transducer (Refer to J. und H. Krautkraemer, Werkstoffpruefung mit Ultraschall, 5. Auflage). For this circular transducer the special DGS diagram shown above was calculated.
One should note that the deviation between given curve and measured data can be quite significant especially in the near field though the reader should keep in mind, that a minimal distance A from the transducer of 0,7 N (N=near field length) is recommended (Reference: EN 583-2). Following this recommendation for this example the minimum sound path would be 16 mm.

This fact is known since the application of the DGS method using non-circular transducer was proposed and evaluated, e.g. refer to: *Bemerkungen über die Nahfeldlängen-Bestimmung bei Ultraschall Kolbenstrahlern verschiedener Form*, Udo Schlengermann, Materialprüfung 16 (1974) Nr. 5 Mai. Another discussion about the near field length of angle beam probes, which finally lead to deviations or uncertanties in DGS sizing can be found in: *On the determination of near-field length of angle probes for ultrasonic materials testing*, Rainer Frielinghaus, Udo Schlengermann, Materialprüfung 9 (1967) Nr. 12 Dezember.

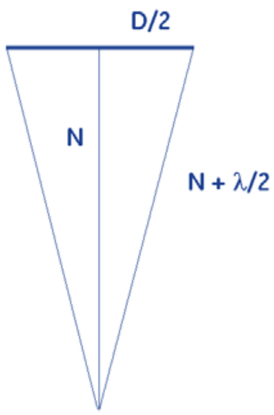
To compensate this deviation caused among others by geometric conditions of the wedge and the refraction at the interface between wedge and material some manufacturer of angle beam probes with rectangular transducers, publish correction algorithms to better match the measurement results to the DGS curves[1]. Internal evaluations (data not shown here) have revealed that the proposed geometric factors approximates the measured data to the published curves but improves the overall result only slightly.

The next paragraphs will discuss the propagation of sound as valid for straight-beam probes a little bit more in detail and how these principles can be transferred to angle beam probes. The result will be a more reverse model to solve the problem instead of simple approximations.

Preconditions used in this paper

Only two preconditions, well-known from literature (e.g J. und H. Krautkraemer, Werkstoffpruefung mit Ultraschall, 5. Auflage) are used for all calculations described in this paper:

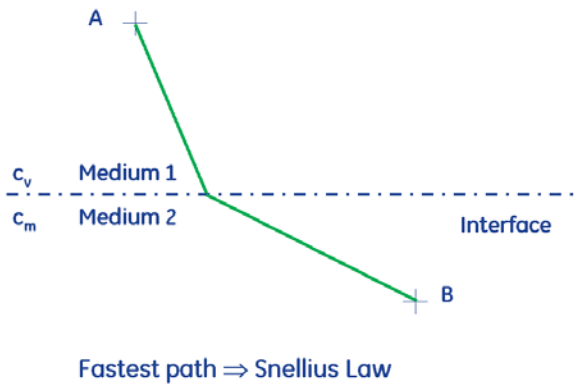
Definition of the near field length N of a circular transducer with diameter D without delay line:



At the end of the near field the difference between the central beam and an edge beam defining the outer perimeter of the transducer is $\lambda/2$ (or equivalent, the time of flight difference between central and edge beam is T/2), with λ = wave length in the material, T = 1/f and f = probe frequency.

Fermat's principle / principle of least time

The path of least time for ultrasonic waves from a point A in a first medium to a point B in a second medium (different sound velocities c_v and c_m in these two mediums) follows Snells' Law at the interface between the two mediums.

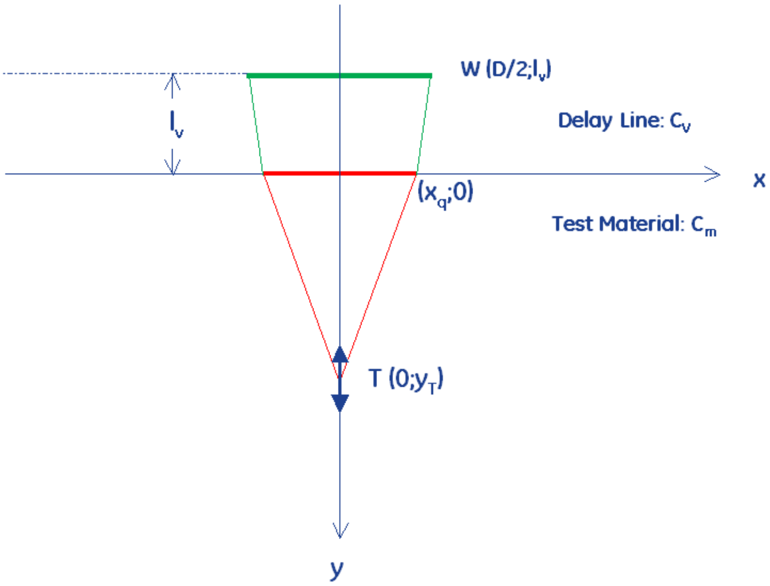


[1] E.g. Introduction to Phased Array Ultrasonic Technology Applications, R/D Tech Guideline, R/D Tech inc., 2004 pages 46-49

DGS considerations for straight beam probes (circular transducer) with delay line l_v

In order to transfer the condition of a straight-beam probe without delay line to an angle beam probe with wedge and therefore with delay line, an intermediate step is done by discussing a straight-beam probe with delay line. This represents nothing more than a generalized situation of an immersion probe and should still allow correct DGS-evaluation.

Deriving the near field length N_{FERMAT}



Here the time of flight t from point W to point T is calculated in dependency of y_T:

$$t = \frac{1}{c_v} \sqrt{\left(\frac{D}{2} - x_q\right)^2 + l_v^2} + \frac{1}{c_m} \sqrt{x_q^2 + y_T^2} \tag{1}$$

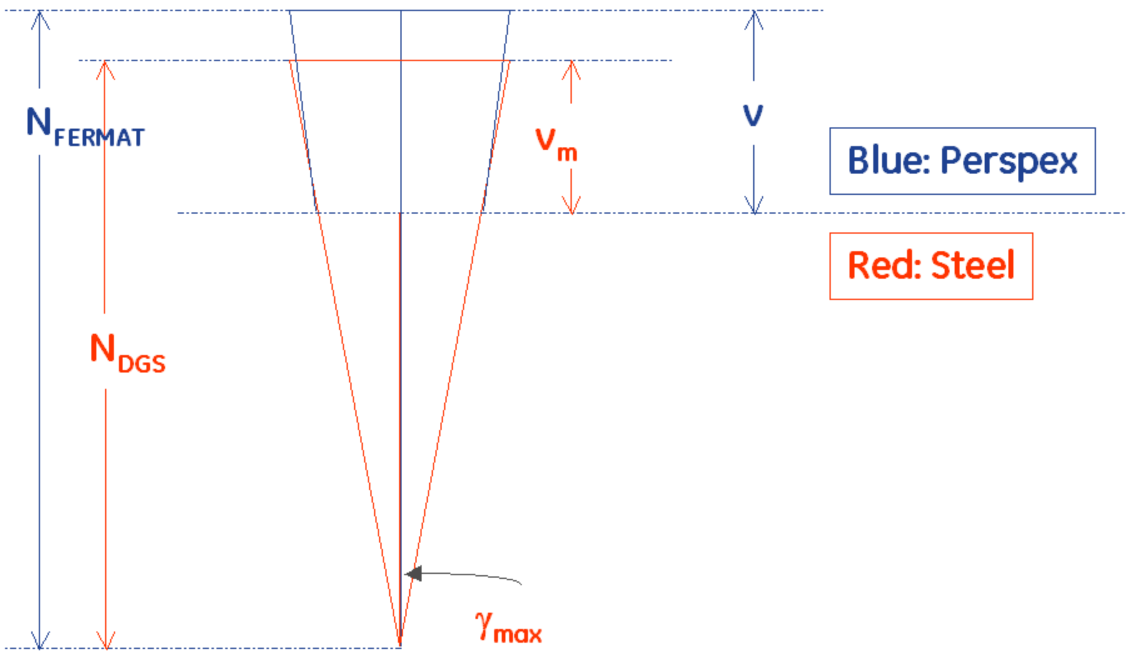
In order to calculate the least time of flight from point W to point T the derivative of (1) has to be determined (2) and to be identified with zero (3):

$$\frac{\partial\, t}{\partial\, x_q} = -\frac{1}{c_v} \frac{\frac{D}{2} - x_q}{\sqrt{\left(\frac{D}{2} - x_q\right)^2 + l_v^2}} + \frac{1}{c_m} \frac{x_q}{\sqrt{x_q^2 + y_T^2}} \tag{2}$$

$$\frac{\partial\, t}{\partial\, x_q} = 0 \tag{3}$$

The equation above can be solved using the Newton method resulting in x_q.

In a second step y_T is varied until the time of flight difference Δt between the central beam and the edge beam equals T/2 with T = 1/f and f = probe frequency.



To calculate the near field length of a circular transducer completely in steel (trans) the angle γ_{max} is used and the fact that the difference between the central beam and one edge beam needs to be $\lambda/2$:

$$N_{DGS} = \frac{\lambda \ \cos\left(\gamma_{max}\right)}{2\left[1 - \cos\left(\gamma_{max}\right)\right]} \tag{4}$$

The corresponding transducer diameter D is calculated by:

$$D = \sqrt{4 \ N \ \lambda + \lambda^2} \ \approx \ \sqrt{4 \ N \ \lambda} \tag{5}$$

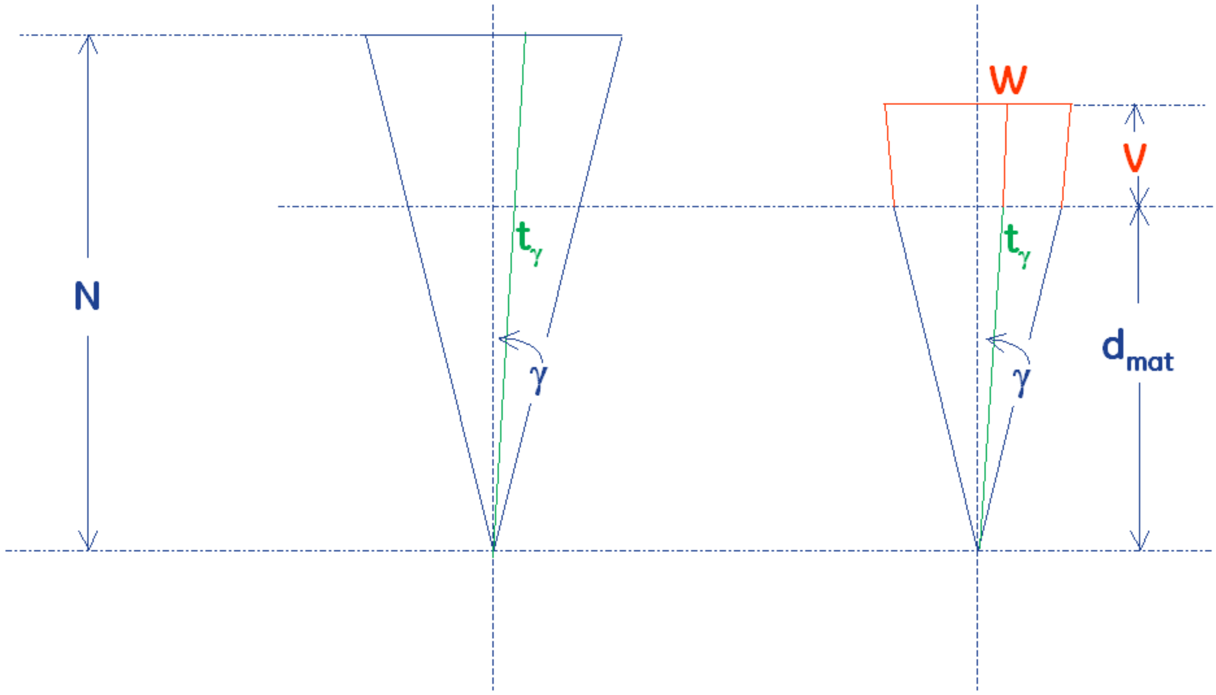
Whereas the delay line v_m to be used for DGS evaluation results then in:

$$v_m = N_{DGS} - N_{FERMAT} + v \tag{6}$$

Constructing a circular probe with delay line behaving like a circular probe without delay line

In the following the construction method is described which will be later used for the construction of DGS angle beam probes.

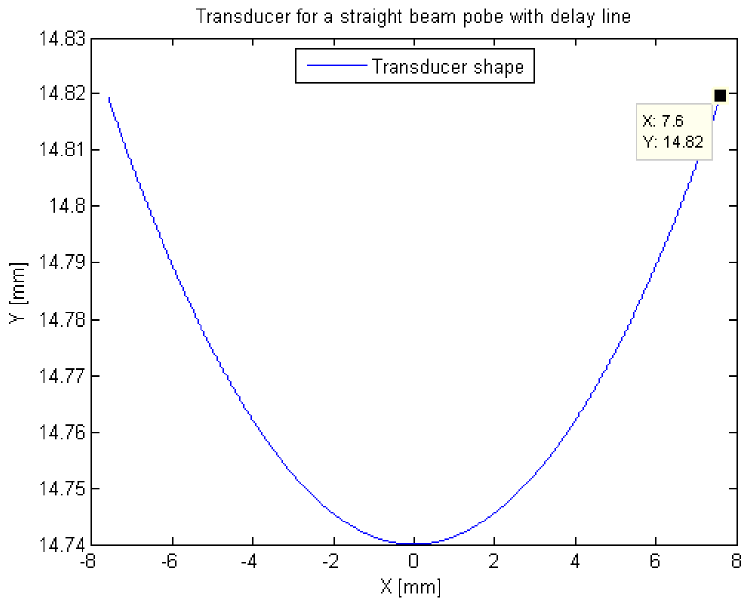
The following sketch illustrates the method used:



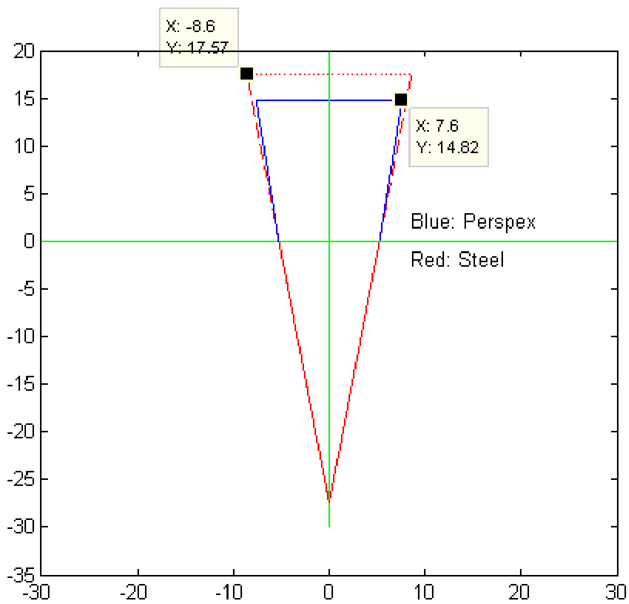
On the left side the straight beam probe without delay line is illustrated. On the right side is the constructed straight beam probe with the given delay line length of v.

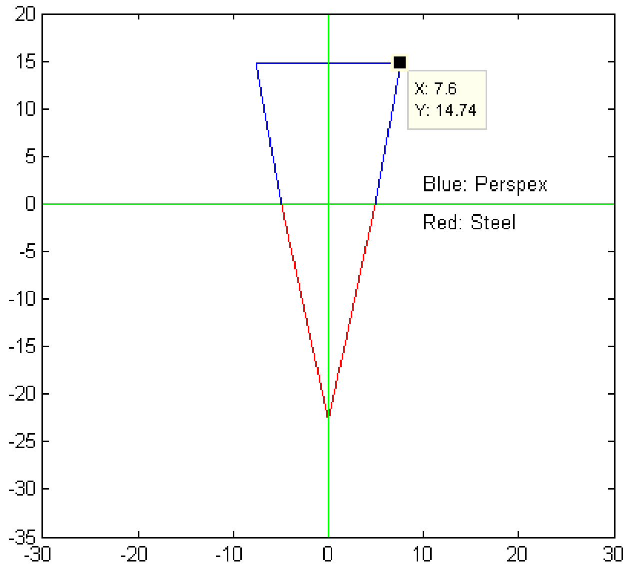
For each angle γ the corresponding time of flight t_γ in the probe without delay line is calculated. With the same angle γ and the same time of flight t_γ the sound beam in the probe with delay line is constructed using Snells' law at the interface between test material and the delay line material, resulting in the transducer point W. Repeating this procedure for all angles γ (on both sides of the central beam) results in a point cloud defining the transducer shape of the constructed probe with delay line.

The result is surprising since the constructed transducer is not flat but shaped as a paraboloid.



The slight paraboloid shape results in a defocusing effect. The following figures compare the probe used for construction (red) and the resulting probe with the paraboloid transducer (blue, left figure) and a probe having a flat transducer with the same size (width) as the paroboloid transducer (right figure). The longer near field length to be seen in the left figure shows the defocusing effect.





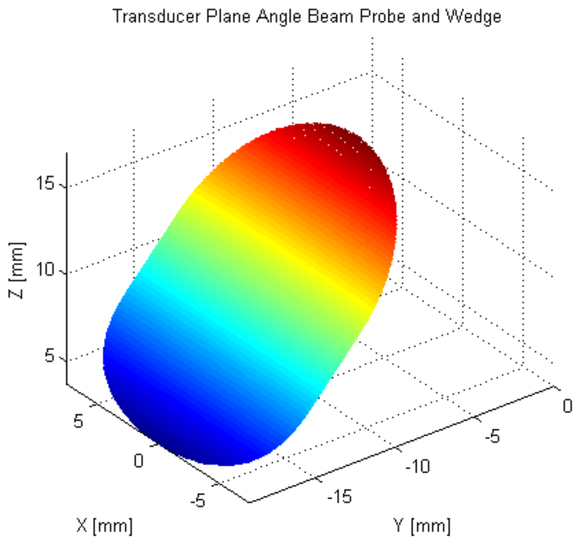
In this case the delay v_m used for the DGS diagram is calculated by:

$$v_m = v\,\frac{c_m}{c_v} \tag{7}$$

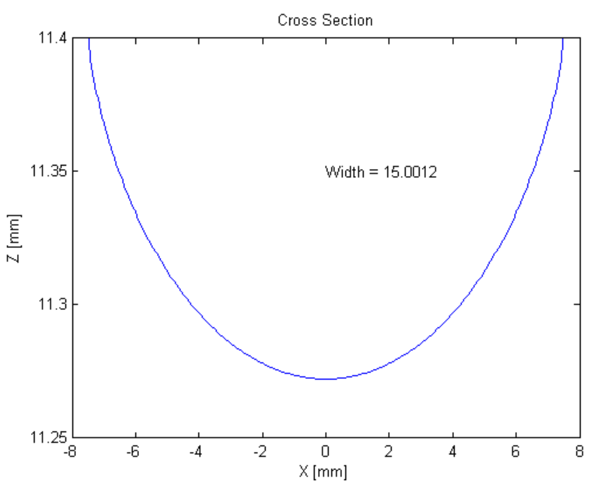
For these constructed probes the well known near field formula is no longer valid, due to the defocusing effect. For DGS evaluation the near field length N and the diameter D of the probe used for construction, and v_m, as described, above is used.

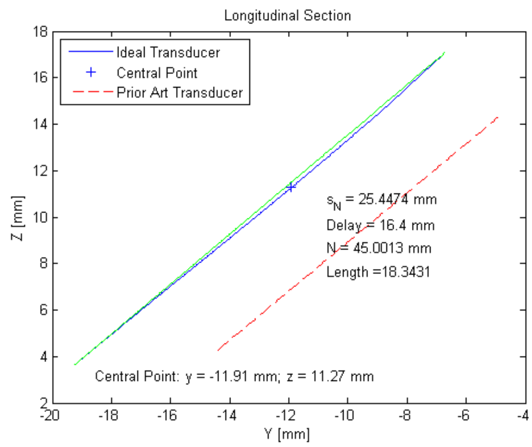
Constructing DGS angle beam probes

The above described construction method is not only applicable to straight beam probes with delay line but also to angle beam probes when the probe used for construction is tilted in the material and all other construction steps are made in the same order. Caused by the refraction of the rotational-symmetric but tilted sound field, the 3-dimensional consideration yields an interesting transducer shape.

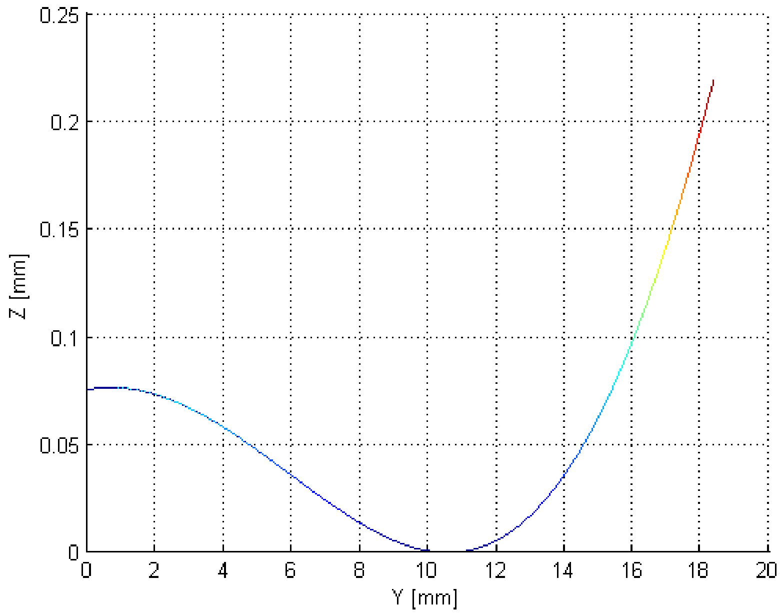


The following two figures show a cross and a longitudinal section through the transducer where one can clearly observe the bended shape:

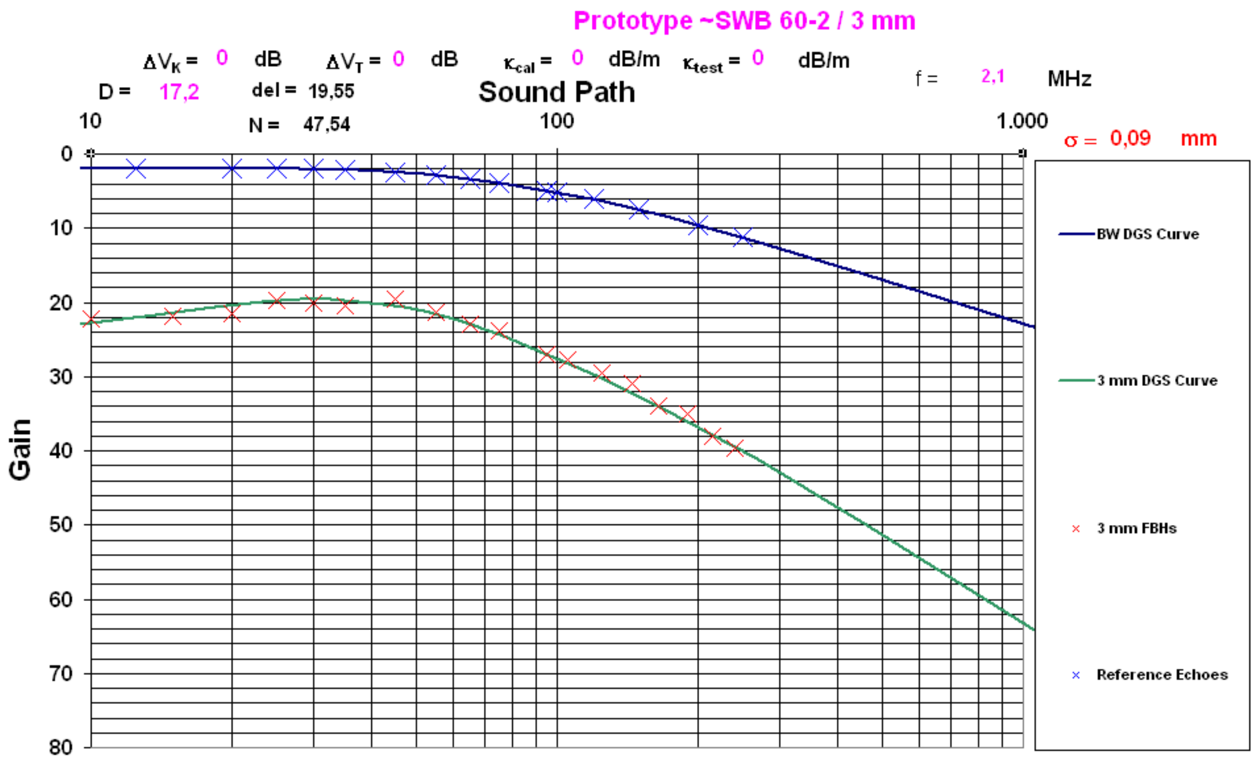




After an appropriate coordinate transformation the longitudinal section can be seen in more detail:



One has to obey that – of course – the wedge accommodating the transducer has to show exactly the same feature at its surface.
A prototype designed in this way and meant to be equivalent to a SWB 60-2 was tested measuring the same above mentioned 3 mm FBHs at GE Sensing & Inspection Technologies in Huerth:

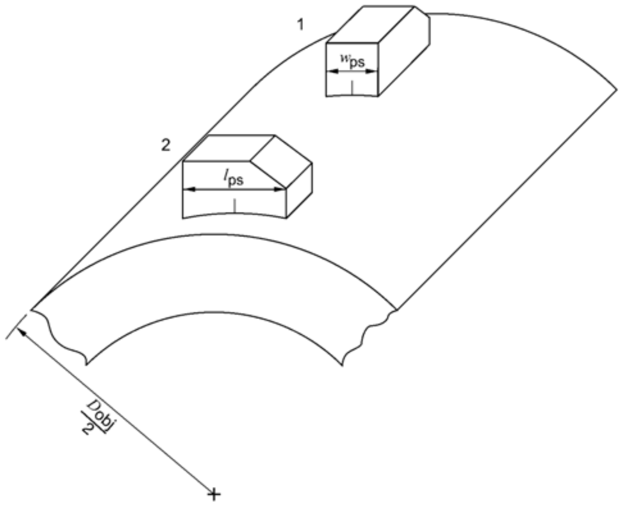


This new probe shows a noticeable good agreement with the DGS-diagram over the complete measurement range. The deviation from the expected gain values at a given depth decreased to a standard deviation σ of only 0.09 mm, taking all measured values into account.

Curved coupling surfaces

In the European Standard EN 583-2 the DGS method is described. For curved surfaces this Standard requests under certain circumstances that the probes are matched to the surface of the test piece.

For concave test surfaces the Standard EN 583-2 requests matching of the delay line of the probe to the surface of the test piece in all cases unless the diameter is large enough to ensure good coupling. (The following figure is taken from the European Standard EN 583-2)



For convex surfaces matching is required when:

$$D_{obj} < 10\, l_{ps} \tag{8}$$
$$D_{obj} < 10\, w_{ps} \tag{9}$$

where D_{obj} is the diameter of the test piece, l_{ps} the length of the probe and w_{ps} the width of the probe.

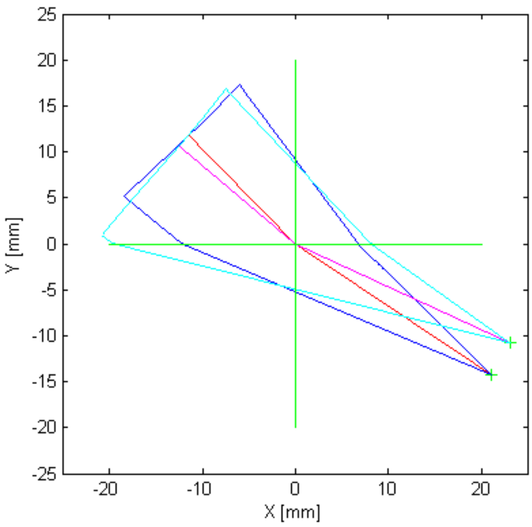
In these cases the EN 583-2 does not allow the use of the DGS method. The model described above can nevertheless be easily expanded to curved coupling surfaces to ensure even in these cases the validity of the DGS method.

Transferring this model to phased array probes

Modeling phased array probes

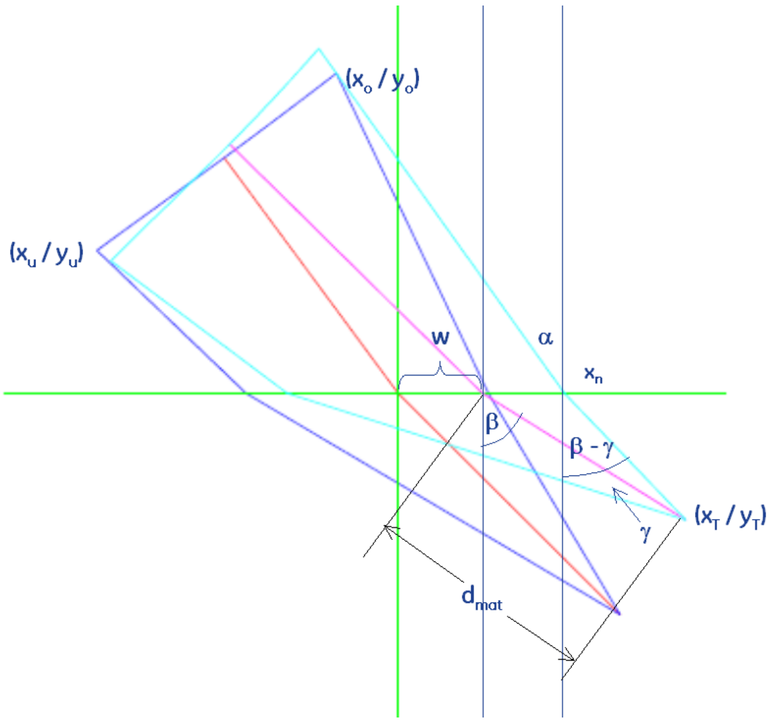
To transfer this model to phased array probes the plane perpendicular to the transducer through the longitudinal section of the transducer is evaluated.

For the original transducer on the wedge, the longitudinal section of the transducer is constructed according to the model described. Additionally the desired virtual transducer is constructed accordingly.



Virtual transducer

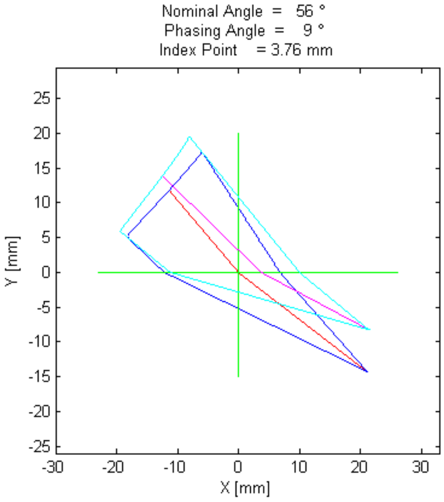
To be able to calculate the required delay laws, the constructed virtual transducer needs to undergo a coordinate transformation:

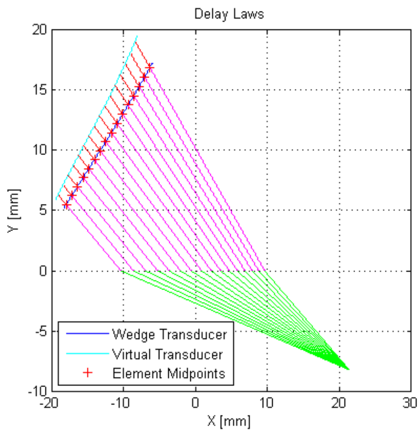


The task to perform is, to calculate d_{mat} and the shift of the sound index point w in a way that the edge sound beams of the virtual transducer are going through the corresponding edges of the original transducer.

<u>Positive phasing angles</u>

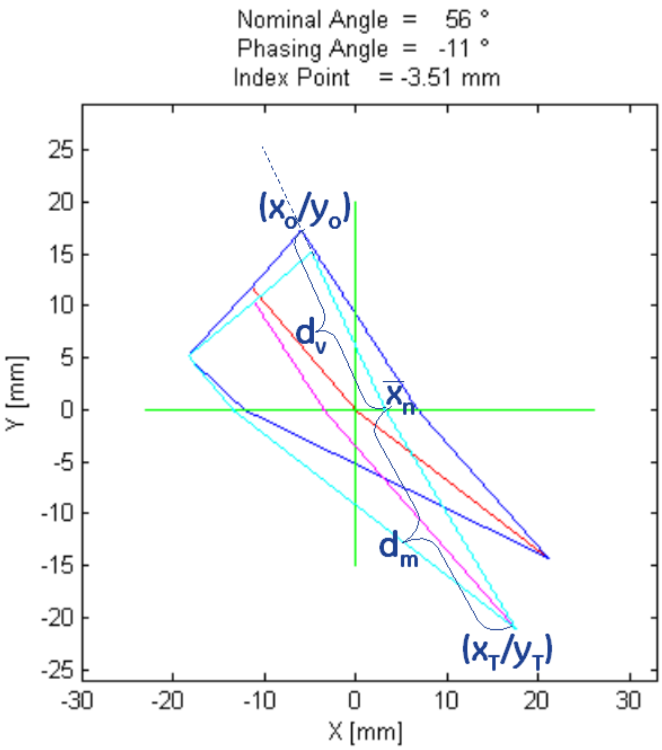
For positive phasing angles the delay laws can be directly calculated by comparing the location and orientation of original and simulated transducer where the delays can be derived from the resulting distances belonging to the respective elements of the phased array probe:





<u>Negative phasing angle</u>

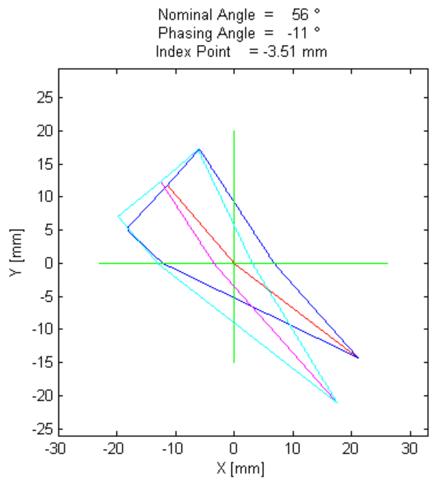
In order to calculate the delay laws for negative phasing angles, a further calculation is needed to ensure that the upper edge of the virtual transducer is aligned with the upper edge of the original transducer:

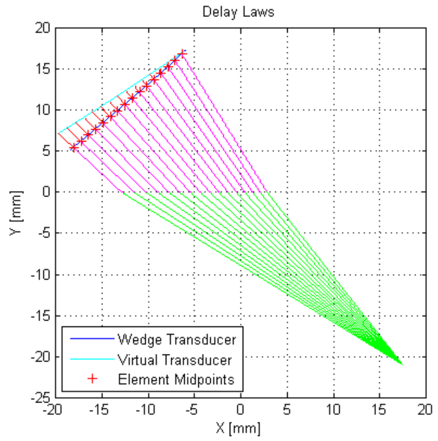


Following this requirement the following formula for the near field length can be deduced:

$$N_{DGS} = \frac{c_m}{c_v}\sqrt{(\overline{x}_n - x_o)^2 + y_o^2} + \sqrt{(x_T - \overline{x}_n)^2 + y_T^2} - \frac{\lambda_m}{2} \tag{10}$$

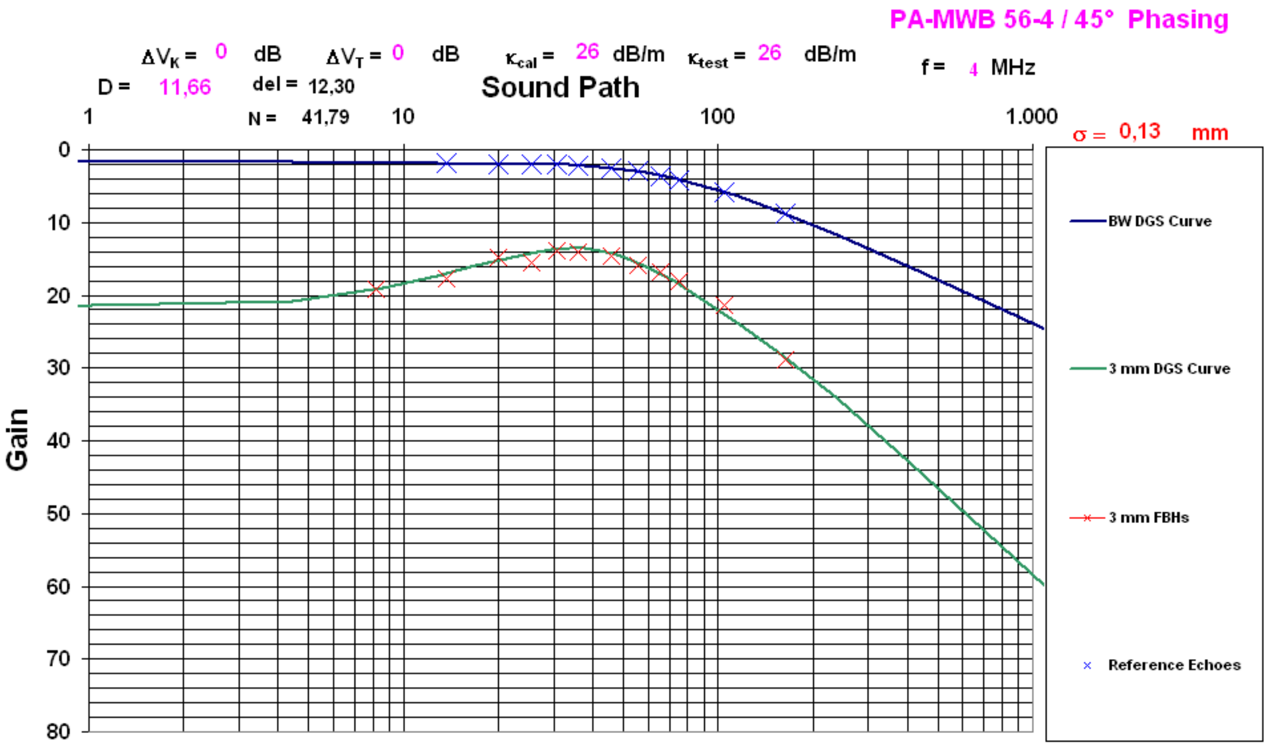
The following figures show an example of the corrected virtual transducer for negative phasing angles and a sketch illustrating the calculation of the corresponding delay laws:



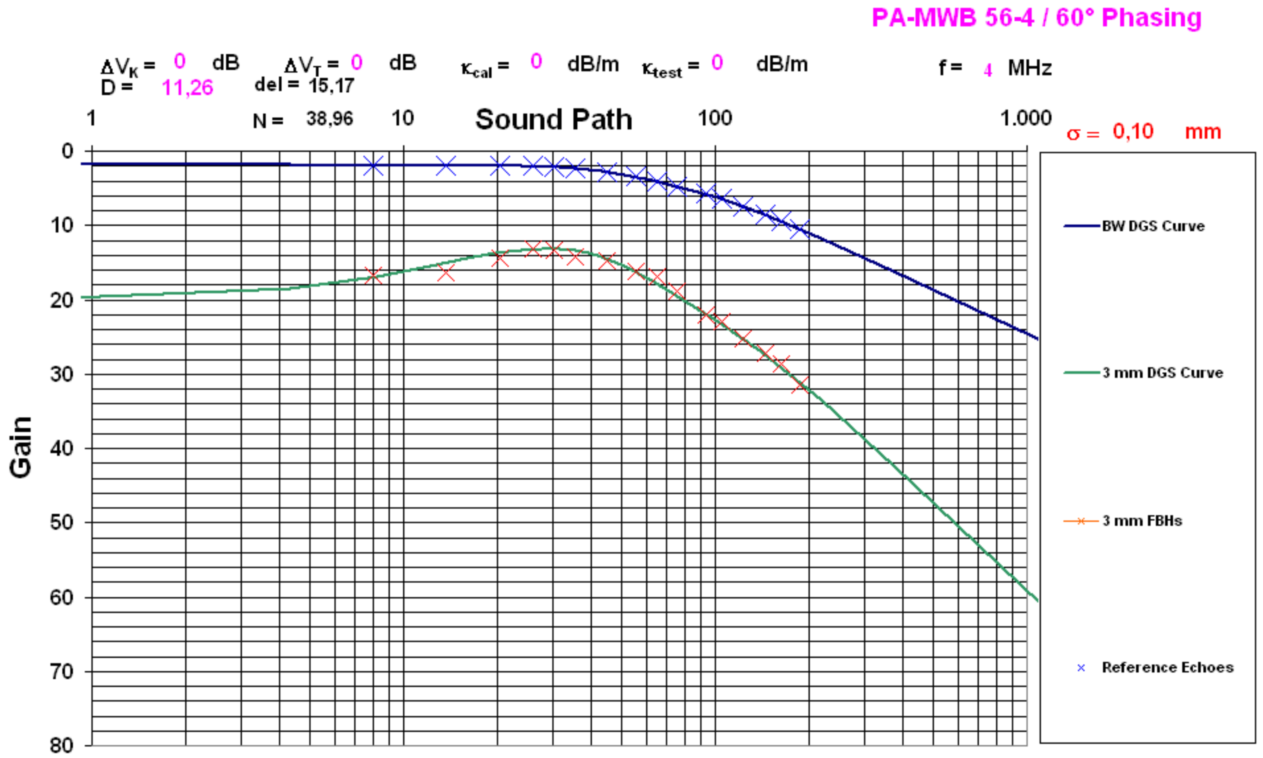


DGS evaluation using phased array probes at different angles

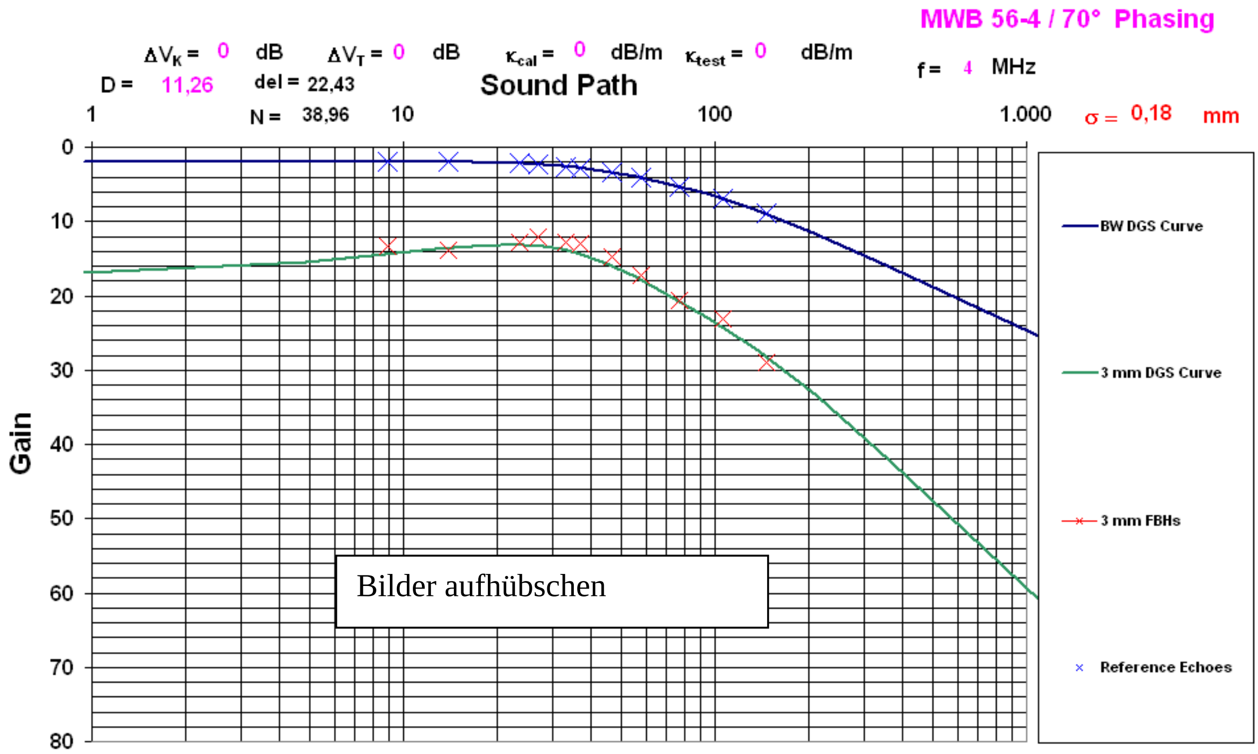
Beside others a phased array probe was built mimicking an MWB 56-4 type of probe, with the transducer being divided into 16 equal broad elements. The wedge angle at the center point of the transducer was defined to result in a 56° inclined shear wave in steel. Measurements were done at 3mm FBH at 45, 60 and 70° using a Phasor XS from GE Sensing & Inspection Technologies with delay laws calculated as described above.



PA-MWB 56-4 / 45° Phasing
ΔV_K = 0 dB
ΔV_T = 0 dB
κ_cal = 26 dB/m
κ_test = 26 dB/m
f = 4 MHz
D = 11,66
del = 12,30
N = 41,79
Sound Path
σ = 0,13 mm
Gain
BW DGS Curve
3 mm DGS Curve
3 mm FBHs
Reference Echoes



PA-MWB 56-4 / 60° Phasing
ΔV_K = 0 dB
ΔV_T = 0 dB
κ_cal = 0 dB/m
κ_test = 0 dB/m
f = 4 MHz
D = 11,26
del = 15,17
N = 38,96
Sound Path
σ = 0,10 mm
Gain
BW DGS Curve
3 mm DGS Curve
3 mm FBHs
Reference Echoes



Though following the presented model the transducer shape would be different from the used transducer for the three different angles, one can directly see from the results that also for phased array probes the agreement of expected and measured gain values at given distances is noticeably accurate and lies in the same range as for the single element angle beam probe shown above.

Summary

With these novel angle beam probes the same precision of DGS sizing can be achieved as known from circular straight beam probes without ***"Focus-pocus"***, as long as the transducer shape is calculated as described in this paper: ***"Focus-Physics"***. The following table gives a summary of the results achieved with a 4 MHz phased array angle beam probe with 16 elements. The standard deviation σ_{ERS} gives a good overview showing the deviation in mm from the equivalent reflector size (ERS) respectively from the diameter of the flat bottom holes measured:

PA-MWB 56-4 Prototype Evaluation Summary				
Angle	FBH [mm]	σ_{ERS} [mm]	Phasing Angle	Δ [%]
45°	1	0,06	-11°	6,0%
45°	3	0,13	-11°	4,3%
60°	3	0,10	4,5°	3,3%
70°	1	0,07	17,5°	7,0%
70°	3	0,18	17,5°	6,0%